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Lean Six Sigma Tools for Optimizing Manufacturing Small and Medium Enterprises: A Systematic Literature Review

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ABSTRACT

Objective: Manufacturing small and medium-sized enterprises (SMEs) face growing competitive pressures due to operational inefficiencies, high defect rates, equipment unreliability and resource constraints. Lean Six Sigma (LSS), which combines Lean waste-reduction with Six Sigma's data-driven quality-improvement approach, has emerged as an effective methodology for enhancing operational performance. This study synthesizes recent empirical evidence on the application and outcomes of LSS in manufacturing SMEs.

Methods: A Systematic Literature Review (SLR) was conducted using peer-reviewed journal articles and conference papers indexed in the Scopus database between 2021 and 2025. Studies were identified through a structured Boolean search strategy and screened using predefined inclusion and exclusion criteria. Bibliometric analysis, keyword co-occurrence mapping, and comparative evaluation were used to identify research trends, key LSS tools, and associated performance outcomes.

Results: Findings reveal increasing scholarly interest in LSS implementation within manufacturing SMEs. Strong relationships were identified between LSS tools and performance indicators such as productivity, efficiency, lead-time reduction and quality improvement. Commonly applied tools include DMAIC, Value Stream Mapping, 5S, Kaizen, TPM, SMED and Statistical Process Control. Reported outcomes include defect reductions of up to 70%, productivity gains exceeding 20%, reduced cycle times, and improvements in Overall Equipment Effectiveness of 15-20%.

Conclusion: LSS significantly improves operational and quality performance in manufacturing SMEs. Emerging evidence also highlights the integration of LSS with Industry 4.0 technologies, supporting data-driven continuous improvement and sustainable competitiveness.

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1. Introduction

Manufacturing small and medium-sized enterprises (SMEs) operate in increasingly competitive and technologically dynamic environments where efficiency, quality and operational agility are critical for survival and long-term competitiveness. Global manufacturing markets are characterized by intense competition, rising production costs, volatile supply chains and growing customer expectations for high-quality products delivered within shorter lead times. Although SMEs constitute a substantial proportion of manufacturing firms globally, there is no universally accepted definition of an SME. Definitions vary across countries and institutions according to factors such as the number of employees, annual turnover and total assets. The Organization for Economic Co-operation and Development (OECD, 2023) classifies SMEs as enterprises employing fewer than 250 employees, while the World Bank generally categorizes SMEs as firms employing between 10 and 300 employees, depending on national contexts. Given the international scope of the reviewed studies, this review adopts the OECD classification as a guiding framework while recognizing that individual studies may utilize country-specific definitions. Consequently, the manufacturing SMEs included in this review are manufacturing organizations operating within the employee and turnover thresholds defined by their respective national SME frameworks.

Within this context, manufacturing organizations are increasingly adopting structured operational improvement methodologies to enhance productivity, reduce defects and optimize resource utilization. One of the most widely adopted improvement frameworks in manufacturing systems is Lean Six Sigma (LSS), which integrates Lean manufacturing principles focused on waste elimination with Six Sigma's data-driven quality management approach to reduce process variation and improve process capability (Nascimento et al., 2020; Pongboonchai-Empl et al., 2024).

Lean manufacturing emphasizes the elimination of non-value-adding activities, improved workflow efficiency and reduced production lead times through practices such as Just-in-Time (JIT), continuous improvement (Kaizen) and visual management systems. Six Sigma complements these principles by introducing statistical tools and structured problem-solving methodologies designed to identify root causes of defects and improve process stability. The integration of these two approaches within Lean Six Sigma provides organizations with a comprehensive improvement framework capable of enhancing operational efficiency, improving product quality and strengthening overall organizational performance (Shou et al., 2020; Mittal et al., 2023). Central to Lean Six Sigma implementation is the structured DMAIC improvement cycle, which guides organizations through the phases of defining operational problems, measuring performance, analyzing root causes, implementing improvement initiatives and establishing control mechanisms to sustain improvements. Within this framework, a range of analytical and operational tools are commonly applied, including Value Stream Mapping (VSM), 5S, Kaizen, Kanban, Poka-Yoke, Fishbone diagrams, Pareto analysis, Failure Mode and Effects Analysis (FMEA) and Statistical Process Control (SPC). These tools enable organizations to systematically identify inefficiencies, prioritize opportunities for improvement and optimize production systems. Empirical evidence from manufacturing contexts indicates that the application of Lean Six Sigma methodologies can lead to substantial improvements in operational performance, including reductions in defect rates, improvements in production efficiency, reductions in cycle time and enhanced equipment reliability through maintenance practices such as Total Productive Maintenance (TPM) (Lucantoni et al., 2025; Gomaa, 2025).

While Lean Six Sigma has historically been associated with large multinational manufacturing corporations, recent studies highlight its growing relevance to SMEs, which constitute a significant share of manufacturing firms globally. Manufacturing SMEs often face persistent operational challenges such as limited financial resources, outdated equipment, inefficient production systems and inadequate process control mechanisms. These challenges frequently result in high defect rates, excessive rework, long production cycles and unstable equipment performance. Consequently, Lean Six Sigma has emerged as a valuable improvement methodology that helps SMEs address operational inefficiencies and improve manufacturing performance. Empirical studies show that the systematic application of LSS tools can significantly improve productivity, reduce waste and enhance process reliability within SME manufacturing environments (Papageorgiou, 2022; Swarnakar, 2023).

The integration of Lean Six Sigma (LSS) with Industry 4.0 technologies represents an important advancement in modern manufacturing improvement systems. Traditionally, LSS focuses on structured process improvement through waste elimination, statistical quality control and the DMAIC cycle. However, emerging digital technologies such as the Internet of Things (IoT), artificial intelligence and cyber-physical systems enhance these practices by enabling real-time process monitoring, predictive maintenance and data-driven decision-making. As a result, Industry 4.0 technologies act as digital enablers, strengthening the effectiveness of Lean Six Sigma tools and improving operational visibility and process optimization (Pongboonchai-Empl et al.,2024). Furthermore, integrating digital technologies with Lean practices enables organizations to transition from traditional reactive improvement approaches to intelligent, predictive operational systems that support smart, sustainable manufacturing (Tortorella, Giglio & Van Dun, 2021). Consequently, the conceptual framework proposed in this study positions the DMAIC methodology as the central improvement mechanism, while Industry 4.0 technologies function as enabling tools that enhance measurement accuracy, analytical capability and continuous operational monitoring.

Recent literature suggests that integrating Industry 4.0 technologies with Lean Six Sigma (LSS) is transforming traditional continuous improvement approaches into intelligent, data-driven operational systems. Technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Digital Twins, Cyber-Physical Systems (CPS), Big Data Analytics, and Cloud Computing provide organizations with enhanced capabilities for real-time monitoring, predictive maintenance, automated root cause analysis, and process optimization. The integration of these technologies strengthens the DMAIC methodology by improving data collection accuracy during the Measure phase, enabling advanced analytics during the Analyze phase, and supporting predictive control mechanisms during the Control phase (Pongboonchai-Empl et al., 2024; Tortorella et al., 2021). Consequently, Industry 4.0 technologies are increasingly viewed as strategic enablers of Lean Six Sigma rather than independent operational improvement initiatives. Despite this growing interest, the literature remains fragmented regarding which Industry 4.0 technologies are most frequently integrated with Lean Six Sigma and how these technologies influence operational outcomes in manufacturing SMEs. Furthermore, limited evidence exists regarding the long-term sustainability, scalability and implementation challenges of Industry 4.0-enabled Lean Six Sigma systems within resource-constrained SME environments. These gaps justify the need for a systematic synthesis of recent evidence and highlight important opportunities for future research.

Despite the growing body of research examining Lean Six Sigma applications in manufacturing organizations, several important limitations remain within the current literature. Existing studies are largely fragmented and predominantly based on isolated case studies or individual tool applications, making it difficult to obtain a comprehensive understanding of how Lean Six Sigma tools collectively influence operational performance in manufacturing SMEs. While individual case studies provide valuable insights into specific improvement initiatives, they often fail to provide a broader synthesis of empirical findings across different manufacturing contexts. Previous research frequently focuses on individual Lean or Six Sigma tools rather than analyzing their integrated application within structured improvement frameworks such as DMAIC. As a result, limited attention has been given to understanding how different LSS tools interact within a holistic operational improvement system in SME manufacturing environments. This lack of synthesis makes it difficult for both researchers and practitioners to identify the most effective combinations of tools to improve manufacturing performance. The rapid emergence of digital manufacturing technologies associated with Industry 4.0 has begun to reshape the operational landscape of modern manufacturing systems; however, the extent to which these technologies are integrated with Lean Six Sigma practices remains underexplored. Technologies such as the Internet of Things (IoT), digital twins, and machine learning are increasingly applied to support predictive maintenance, real-time production monitoring, and data-driven decision-making. Yet the literature provides limited systematic evidence explaining how these technologies complement or enhance Lean Six Sigma methodologies in SME manufacturing environments. Although the number of Lean Six Sigma publications has increased in recent years, there is limited bibliometric and keyword-based analysis mapping.

Addressing these gaps is essential for advancing scholarly understanding of Lean Six Sigma implementation in manufacturing SMEs and for providing practical guidance to organizations seeking to improve operational performance through structured improvement methodologies. A systematic synthesis of recent research can provide valuable insights into the evolution of Lean Six Sigma research, the operational impact of specific improvement tools, the evolution of research trends, dominant themes and emerging topics within Lean Six Sigma research focused specifically on manufacturing SMEs. Without such synthesis, it remains difficult to identify the most influential research directions, commonly applied improvement tools and their corresponding operational outcomes.ls and the emerging integration between Lean Six Sigma and digital manufacturing technologies.

Therefore, this study conducts a Systematic Literature Review (SLR) of Lean Six Sigma implementation in manufacturing SMEs published between 2021 and 2025. The study seeks to consolidate recent empirical evidence and identify key research trends within the field. Specifically, the study aims to:

1. Analyze bibliometric trends in Lean Six Sigma research related to manufacturing SMEs over the past five years.
2. Identify co-occurring keywords linking Lean Six Sigma tools with key manufacturing performance indicators.
3. Determine the most frequently applied Lean Six Sigma tools and Industry 4.0 technologies and evaluate their operational outcomes in manufacturing SMEs.
4. Analyze the role of Industry 4.0 technologies in enhancing Lean Six Sigma implementation and identify emerging research gaps and future research directions for manufacturing SMEs.

By addressing these objectives, the study contributes to the literature by providing a consolidated understanding of Lean Six Sigma applications in SME manufacturing environments, highlighting the most influential improvement tools, and identifying emerging research directions that link Lean Six Sigma with Industry 4.0 technologies. The findings are expected to provide both theoretical insights for researchers and practical guidance for manufacturing managers seeking to implement Lean Six Sigma as a strategic operational improvement framework.

2. Materials and Methods

This research adopts a Systematic Literature Review (SLR) approach, which systematically collects and evaluates scholarly articles to present thorough and unbiased findings (Mohamed Shaffril, Samsuddin & Abu Samah, 2021; Al-Zubidy & Carver, 2019). The SLR process, adapted from the framework proposed by Carrera-Rivera et al. (2022), consists of five distinct steps summarized in Figure 1.

1. Selecting databases: selecting the right database is crucial for literature reviews, as source quality impacts research reliability (Carrera-Rivera et al., 2022). This study uses Scopus for its extensive coverage of high-quality, peer-reviewed literature. Scopus prioritizes reputable journals through a rigorous verification process, ensuring access to credible materials (Abalkina, 2024:395; Baas et al., 2020). Its advanced search features help identify key studies and emerging topics, making it essential for high-quality research.
2. Formulating keywords: In this phase of keyword development, the keywords were utilized as search terms to identify pertinent documents. Boolean operators were employed to enhance search effectiveness: the "AND" operator was instrumental for locating sources that contained all specified keywords, while "OR" facilitated the discovery of sources that included either keyword. Furthermore, the use of parentheses () allowed for the grouping of keywords, establishing a specific search order. The asterisk (*) enabled the search for variations of the keywords and quotation marks ("") were employed to find exact phrases as they appeared within the texts. The developed keywords string is: ("Lean six sigma" or "Lean six*" or "LSS" or "Lean sigma" or "DMAIC" or "Value stream mapping" or "VSM" or "5s" or "Kaizen" or "continuous improvement" or "poka-yoke" or "Kanban*" or "root cause analysis" or "5why*" or "five why*" or "fishbone" or "Ishikawa" or "RCA" or "Pareto*" or "failure mode and effect analysis" or

"FMEA" or "statistical process control" or "SPC" or "SIPOC") AND ("Small and medium enterprises" or "SME*" or "Small and medium-enterprises") AND ("Manufacturing" or "production" or "shop floor").

3. Identifying relevant search locations: In the Scopus database, a thorough search was conducted using specific aforementioned keywords from the titles, abstracts and keyword sections of published documents. This method helps gather only the most relevant data, making the literature analysis in the field more accurate and focused.
4. Applying filters (including inclusion and exclusion criteria): The documents retrieved with the search string underwent a meticulous filtering process based on specific criteria. To ensure the information's relevance and timeliness, only documents published between 2021 and 2025 were considered. This approach focuses on the latest research findings and developments in the field. Additionally, the selection was limited to English-language conference papers and journal articles to maintain the quality and academic rigour of the data, including only peer-reviewed works. This combination of criteria is designed to provide a comprehensive and reliable overview of the most recent scholarly contributions.
5. Document review: Following the previously outlined steps, a thorough review of the documents will be conducted to ensure that only studies demonstrating the practical application of Lean Six Sigma (LSS) tools within manufacturing small and medium-sized enterprises (SMEs) are included in the study results.

This approach aims to capture empirical evidence of the outcomes of implementing LSS tools in these organizations.

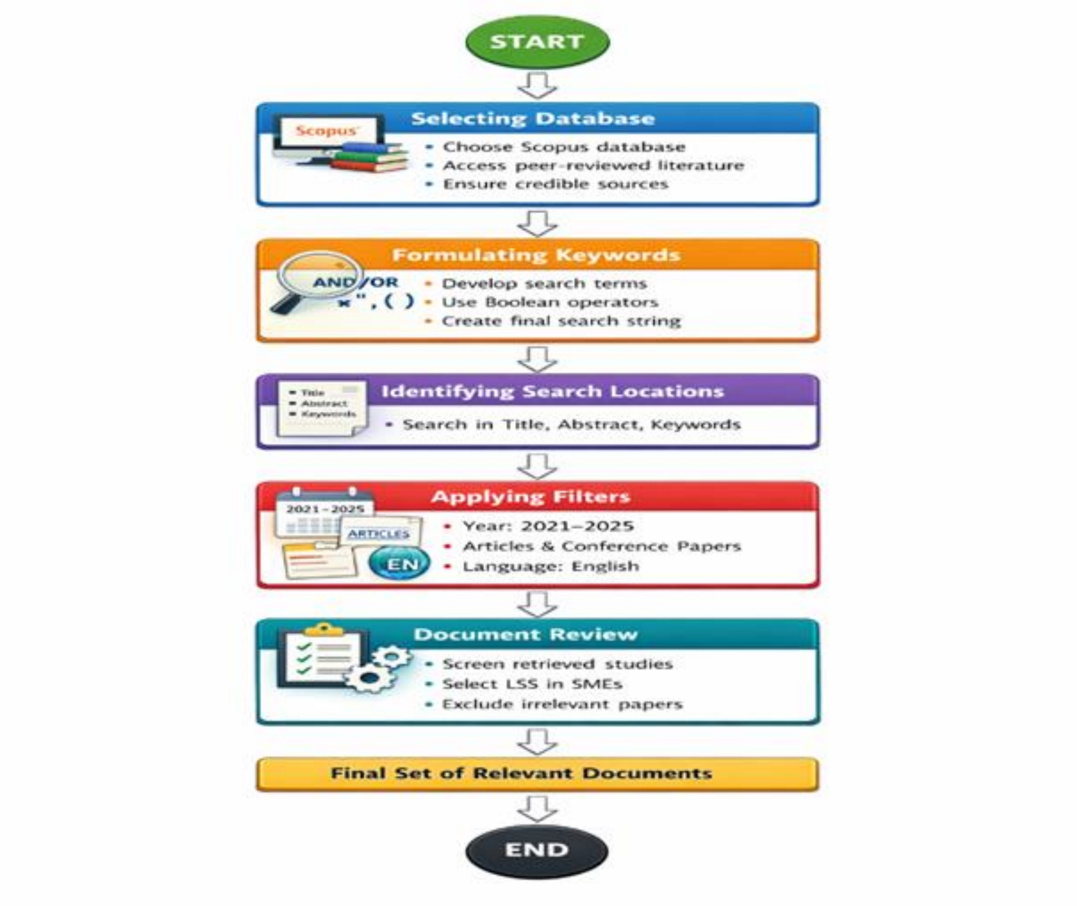

Figure 1. Summary of the systematics literature review methodology

3. Results

The comprehensive collection of sources gathered across steps 1-4 of the methodology yielded 404 documents. As a result, the forthcoming findings section will present three key analyses: a bibliometric analysis examining patterns and trends in the literature; a keyword co-occurrence analysis exploring relationships among frequently used terms; and an application analysis assessing the practical implications of the research. Each of these analyses is carefully aligned with the three (3) secondary objectives, providing a thorough understanding of the data.

3.1 Bibliometric Analysis

The annual research output from the years 2021 to 2025 is depicted in Figure 2, offering a comprehensive overview of trends and fluctuations. Notably, 2021 recorded the lowest research output of the entire period.

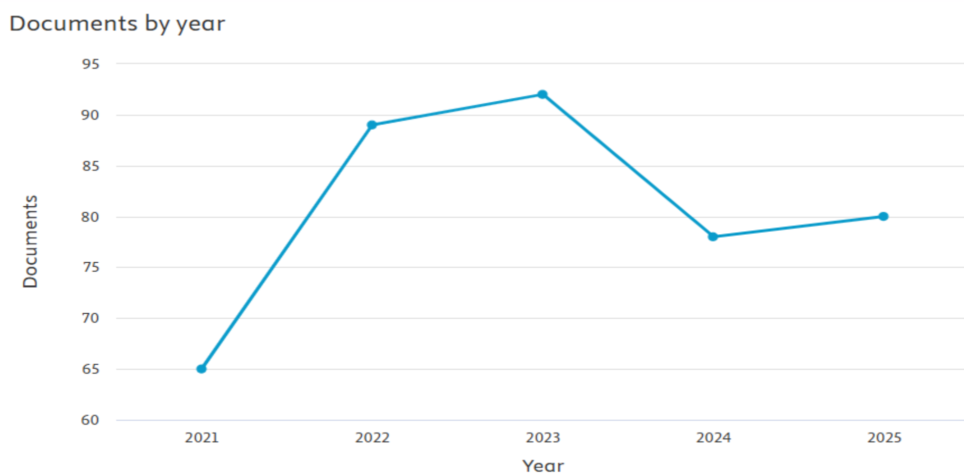

Figure 2. Annual output of document of LSS tools in manufacturing SMEs

This decline in productivity could be attributed to the significant focus on COVID-19 and subsequent recovery efforts, which may have redirected resources and attention away from other research areas. In 2022, output increased from 65 to 89 documents, a 26.9% increase. This surge could indicate a renewed vigour in research activities as the global community began to adapt to the pandemic's challenges. The upward trend continued into 2023, although at a more modest pace, reaching a peak of 92 published documents. This peak represents the highest level of research output recorded during the 2021-2025 timeframe. However, in 2024, research output decreased by 15.2% compared to the previous year. This decline suggests potential challenges or shifts in research focus that warrant further exploration to understand its underlying causes. In 2025, a slight rebound occurred, with a modest 2.5% increase in output, bringing some optimism for recovery. The reasons behind the decrease in 2024 remain an area for investigation, as they could provide insights into the influences on research productivity during this period.

The data in Figure 3 shows the contributions of the top 10 countries to the specified topic, revealing that Peru leads with a remarkable total of 133 documents.

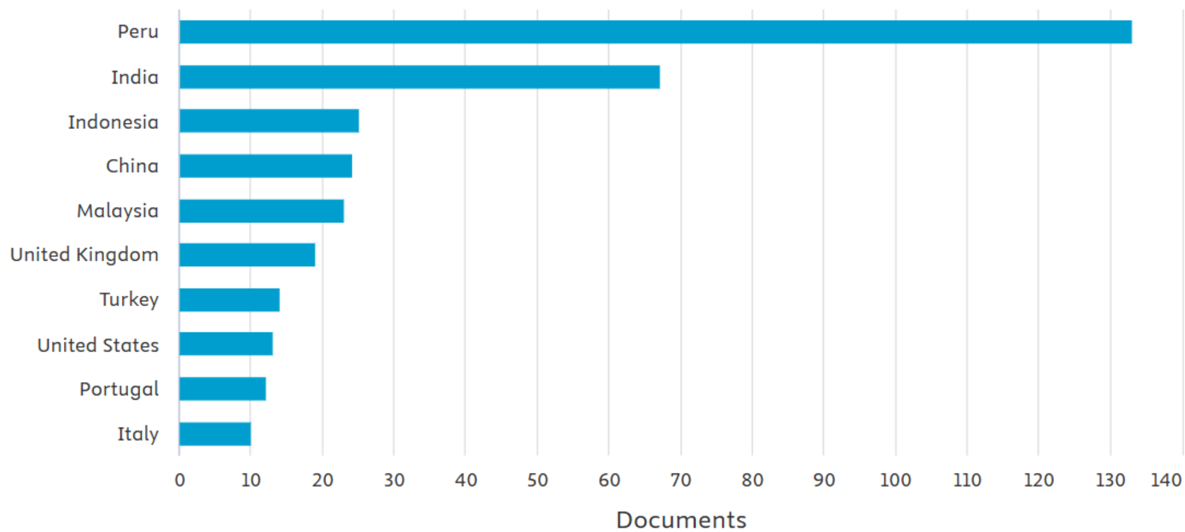

Figure 3. Top Ten (10) countries with published documents on LSS tools in manufacturing SMEs

This positions Peru at the forefront, demonstrating a strong engagement with the subject matter. Following closely, India ranks second with 67 documents, indicating a substantial 49.6% difference between the two countries. Interestingly, the other nations that round out the top ten have significantly lower contributions, each producing fewer than 30 documents. This stark contrast in output underscores a noteworthy trend, especially given the participation of prominent global research leaders like China and the United States, whose involvement in this area appears surprisingly limited. The limited output from these major players prompts a deeper examination of the factors affecting their research contributions and calls for further investigation into potential barriers or opportunities for growth in their engagement with the topic. Figure 3 shows Peru leading with 133 documents, followed by India with 67 documents, a difference of 49.6%. All the other countries in the top ten (10) have outputs less than 30. This low output, especially for countries leading in research such as China and the United States, requires further investigation.

Figure 4a and 4b present the distribution of reviewed publications by document type. The final dataset consisted of both peer-reviewed journal articles and conference papers. Journal articles represented the dominant publication type, reflecting the maturity of Lean Six Sigma research within manufacturing SMEs. Conference papers accounted for a smaller proportion of the literature and primarily focused on emerging applications and technological developments associated with Industry 4.0 integration.

Figure 4a illustrates the relative proportions of articles (57.4%) and conference papers (42.6%) within the dataset. This distribution demonstrates a balanced pattern of research dissemination, with journal articles slightly dominating.

Figure 4b illustrates the Top 10 sources that significantly contributed to the research topic over the past five years. Notably, the Proceedings of the Local International Multi-Conference for Engineering Education and Technology emerged as the leading source, publishing a remarkable total of 33 documents during the 2021-2025 period. The figure further provides insights into other key contributors, highlighting the diversity of sources that have informed the topic.

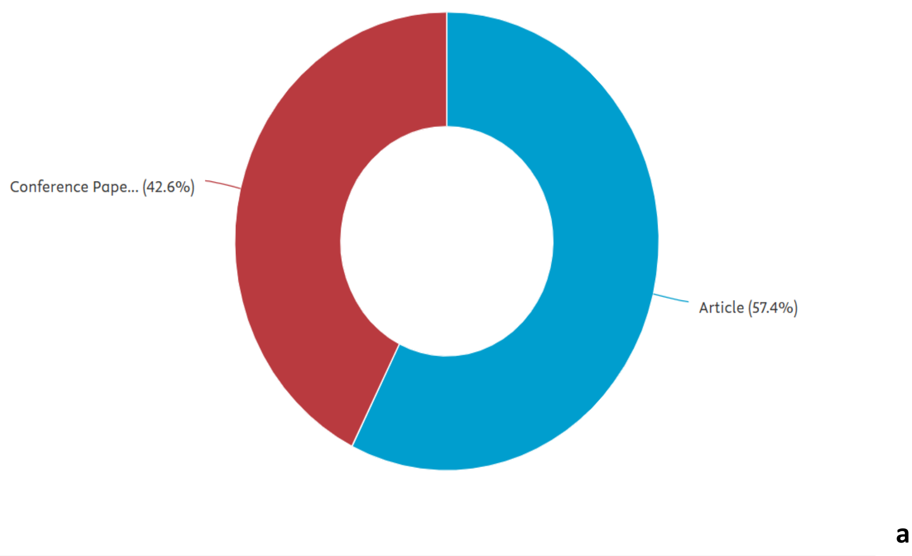

Figure 4a. Summary of documentation type

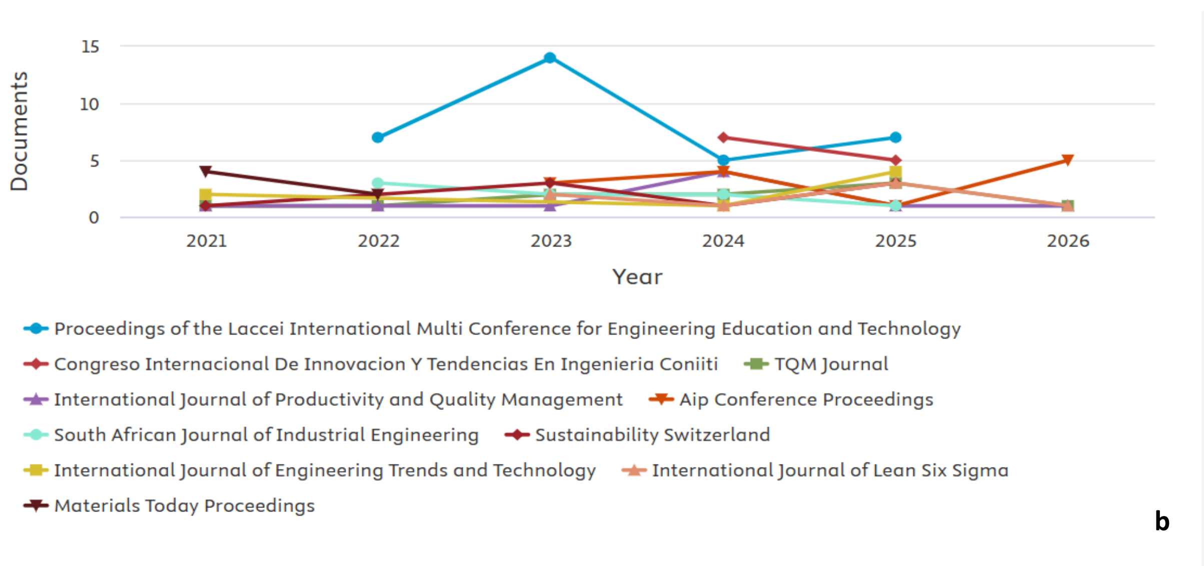

Figure 4b. Top 10 sources per year

3.2 Keywords Co-occurrence Analysis

This section provides a detailed analysis of keyword co-occurrences and trends through two visualization methods: (i) the Network visualization map (referenced as Figure 5) and (ii) the Overlay visualization map (referenced as Figure 6). In the Network visualization map, the size of each node represents the frequency of keyword usage, with larger nodes indicating that a keyword is used more often in the related literature. This visual representation allows for quick identification of key topics within the research domain. Furthermore, nodes that share the same colour form a cluster, indicating stronger interrelationships among those keywords based on their co-occurrence in the selected publications (Kemeç & Altınay, 2023). The arrangement of nodes also plays a crucial role, as the distance between them reflects the strength of the relationship between the keywords. Specifically, shorter distances indicate a stronger association, suggesting that these keywords frequently appear together in the same contexts and discussions (Martins et al., 2024).

The Overlay visualization map offers additional insights, particularly by relating the keywords to their publication years. This map uses a colour gradient that transitions from dark blue to green, then to yellow, representing the timeline from 2021 to 2025. This visualization allows researchers to observe not only the popularity of keywords over time but also trends in their usage, highlighting how topics may be gaining or losing relevance in recent research.

Overall, these visual tools facilitate a deeper understanding of the landscape of academic discourse surrounding the study area. Based on Figure 5, the most frequently used keywords with larger nodes include lean manufacturing, lean production, Six Sigma, Lean Six Sigma, SMED, agile manufacturing systems, 5S, TPM and SMEs. Furthermore, a co-occurrence analysis was conducted to examine potential relationships between manufacturing processes and key performance indicators that co-occur with LSS tools. Figure 5 shows that in the green cluster, TPM and 5s co-occur with order fulfilment and efficiency, while poka-yoke co-occurs with work standardization, production efficiency and setup time. Additional co-occurrences include Kanban with cycle time and warehouses; Just-in-time production with inventory control; preventive maintenance and line balancing; Kaizen with lead time and line balancing; DMAIC with sustainability and quality control; Value Stream Mapping (VSM) with sales, customer satisfaction and human resource management.

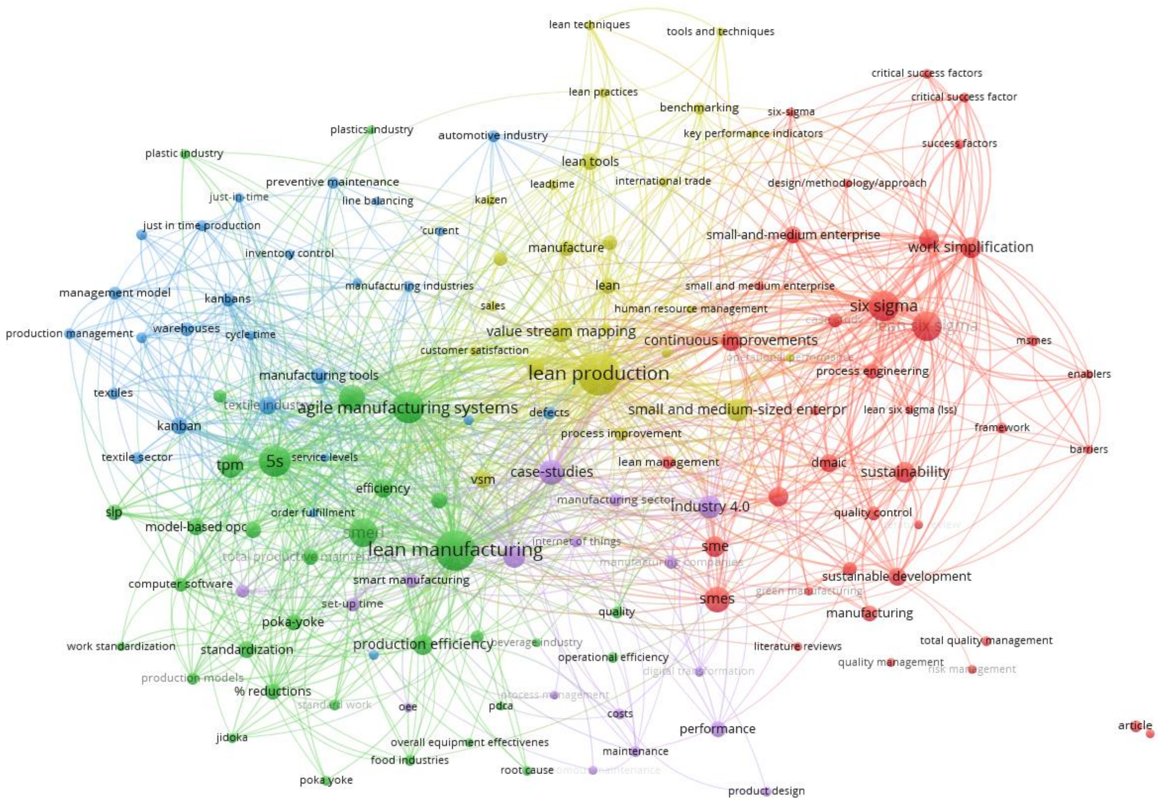

Figure 5. Keywords Network Visualization Map

The relationship between these co-occurring keywords necessitates a more comprehensive and detailed examination. Exploring the association and contextual relevance of each keyword can reveal significant connections that underscore their importance within a specific field. This in-depth analysis could unveil various patterns and trends, demonstrating how these terms interact and influence one another. Gaining insights into their interdependencies can enhance overall understanding of the topic and provide a more nuanced perspective.

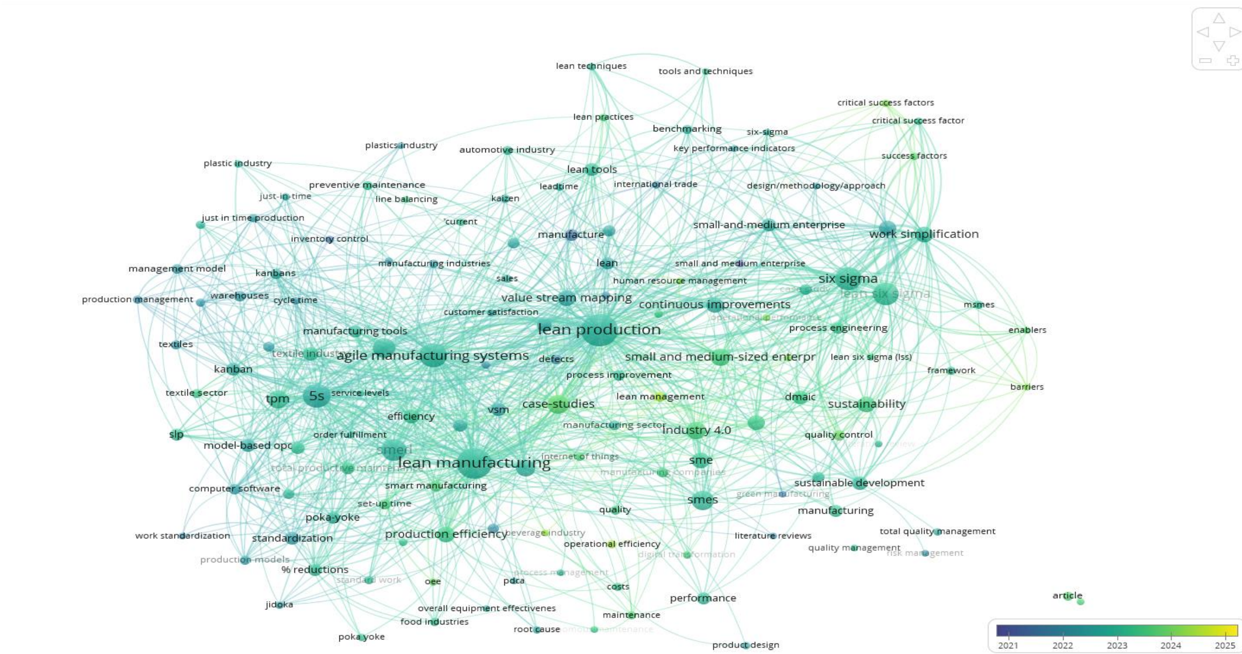

Figure 6. Keywords overlay Visualization Map

The overlay visualization map illustrated in Figure 6 provides a detailed representation of keywords categorized by their publication year. This analysis was conducted in conjunction with Figure 2, which showcased the annual publication outputs spanning from 2021 to 2025. A close examination of the overlay visualization reveals a notable scarcity of dark-blue nodes, corresponding to keywords from documents published in 2021. This pattern is similarly observed with the green and yellow nodes, representing the years 2024 and 2025, respectively. In contrast, a predominance of lighter blue nodes is evident, indicating a substantial concentration of keywords from 2022 and 2023. This observation is consistent with the findings outlined in section 3.1, which reveal a markedly low output in 2021, followed by a significant surge in publications during 2023 and 2024 and a subsequent decline in output during 2024 and 2025. The term "Industry 4.0" stands out as a light green node, symbolizing its prominence in 2024. This visual representation may suggest a rationale for the decrease in publications on the Lean Six Sigma (LSS) topic during that period. It may suggest that researchers shifted their focus to Industry 4.0 studies, thereby diverting attention and resources away from LSS-related research.

3.3 Lean Six Sigma tool applied in Manufacturing SMEs

Table 1 provides a synthesis of the major Lean Six Sigma tools identified in the reviewed studies. The table summarizes the purpose of each tool and highlights recent empirical evidence demonstrating its contribution to operational improvement in manufacturing SMEs. The various Lean Six Sigma tools identified in the reviewed literature are presented and discussed in the Findings section to provide a comprehensive synthesis of their applications and operational outcomes in manufacturing SMEs.

Table 1. Lean Six Sigma (LSS) Tools and Supporting Empirical Evidence

LSS Tool	Description	Purpose	Supporting Authors (2020–2025)
DMAIC	Structured five-phase improvement methodology (Define, Measure, Analyze, Improve, Control).	Provides a data-driven roadmap for reducing defects and improving sustainable performance.	Pongboonchai-Empl *et al.* (2025); Wang *et al*. (2025)
VSM (Value Stream Mapping)	Visual mapping of material and information flows to identify waste and bottlenecks.	Reduces lead time and improves process flow efficiency.	Pekarcikova *et al*. (2025); Ahmad (2024)
Pareto Analysis	80/20 prioritization tool identifying the most significant defect contributors.	Focuses improvement efforts on high-impact causes.	Tsarouhas *et al*. (2024); Pawar *et al.* (2021)
5S	Workplace organization method: Sort, Set in order, Shine, Standardize, Sustain.	Improves workplace efficiency, safety and process stability.	Tahasin *et al.* (2021); Shahriar *et al.* (2022)
Five Whys	An iterative questioning technique to uncover root causes.	Identifies fundamental causes of process problems.	Rodrigues *et al*. (2020); Mogatusi, Takalani & Gupta (2025)
Fishbone (Ishikawa Diagram)	Cause-and-effect diagram categorizing potential sources of variation.	Systematically analyses root causes of quality issues.	Suparno e*t al*. (2021); Mičieta *et al*. (2021)
FMEA	Risk assessment tool that identifies failure modes and prioritizes risk.	Prevents defects by mitigating high-risk failure modes.	Salah *et al*. (2023); Braglia *et al*. (2021); Ashkani & Ilkhani (2026).
Kanban	Visual pull-based production control system limiting work-in-progress.	Improves workflow responsiveness and reduces inventory.	Braga, Naves & Gomes (2020); Pekarcikova *et al*. (2025)
Kaizen	Continuous incremental improvement philosophy involving employees.	Builds a culture of operational excellence.	Omoush *et al.* (2020); Okpala *et al.* (2024)
Poka-Yoke	Error-proofing mechanisms preventing defects at source.	Minimizes human error and ensures right-first-time production.	Vergara *et al.* (2025); Lv, Guo & Lv, (2022)
Gemba Walk	Direct observation of processes at the workplace.	Provides real-time operational insights for improvement.	Romero *et al.*(2020); Mičieta et al. (2021)
SPC (Statistical Process Control)	Use of statistical control charts to monitor process variation.	Distinguishes between common and special cause variation.	Woodcock *et al.* (2025); Sanchez-Marquez & Vivas, (2020)
JIT (Just-in-Time)	Lean philosophy delivering products in the right quantity at the right time.	Reduces inventory waste and shortens lead times.	Yu *et al*. (2024); Khoza *et al*. (2022)
TPM (Total Productive Maintenance)	Proactive maintenance system maximizing equipment effectiveness.	Reduces downtime and improves reliability.	Lucantoni e*t al.* (2025); Chundhoo *et al.* (2025)

3.4 Evaluation of Lean Six Sigma (LSS) Tools in Small and Medium-Sized Manufacturing Enterprises (SMEs)

Table 2 summarizes recent empirical studies (2024-2025) examining the implementation of Lean Six Sigma (LSS) and related lean manufacturing tools across manufacturing sectors. The evidence indicates that the systematic application of LSS methodologies consistently improves operational performance, particularly in defect reduction, productivity enhancement, process efficiency and equipment reliability. These findings reaffirm Lean Six Sigma's effectiveness in addressing operational inefficiencies and improving manufacturing performance.

A key observation from Table 2 is the strong contribution of LSS tools to quality improvement and defect reduction. Several studies reported substantial decreases in non-conformities and process variability following the application of root-cause analysis and statistical improvement techniques. Filho et al. (2025) applied Kaizen, fishbone analysis, 5 Whys, SMED and 5S in tyre manufacturing, reducing defects from 3.0% to 1.4% while shortening cycle time by 30 seconds. Ren et al. (2025) used DMAIC, SPC and FMEA to improve assembly precision in electric vehicle components, reducing non-conformities from 10% to 3% and decreasing scrap and rework. Comparable improvements were also observed in garment manufacturing, where defect rates declined from 3% to 1.25%, highlighting the effectiveness of structured LSS problem-solving tools in improving product quality.

Another notable trend concerns productivity improvements and operational efficiency. Lean Six Sigma practices were frequently shown to eliminate non-value-adding activities and optimize production flow. Ramasu and Kanakana-Katumba (2025) implemented value stream mapping, 5S, Kaizen and line balancing in a textile SME, improving production efficiency from 29.17% to 87.5% while reducing the number of workstations from 12 to 4. Apte et al. (2025) combined DMAIC with Quality Function Deployment (QFD), reducing process time from 860 minutes to 678 minutes and increasing productivity by 21.16%. These results demonstrate the ability of lean tools such as value stream mapping and Kaizen to streamline workflows and enhance operational performance.

Table 2 also highlights improvements in equipment performance and maintenance efficiency through the integration of Lean Six Sigma with maintenance approaches such as Total Productive Maintenance (TPM) and Single Minute Exchange of Die (SMED). Moreno et al. (2025) reported that applying TPM, SMED and machine learning increased Overall Equipment Effectiveness (OEE) from 61.87% to 80.86%, while reducing defect rates and setup times. Gonzales-Vera et al. (2025) improved OEE from 64.27% to 82.70% by integrating SMED, TPM, automation and Internet of Things technologies.

These findings suggest that combining LSS with structured maintenance practices significantly enhances equipment utilization and production stability. Table 2 reveals a growing integration of Lean Six Sigma with Industry 4.0 technologies. Aldouri (2025) developed a digital twin-enabled JIT-Kanban framework that reduced inventory by 47%, decreased lead time by 28% and improved schedule adherence from 68% to 92%. IoT-enabled Kaizen systems have enabled real-time inventory monitoring and reduced operational errors. These developments indicate that modern lean implementations increasingly incorporate digital technologies to enhance data visibility, predictive decision-making and real-time process optimization.

Based on the aforementioned findings, Figure 7 provides a comprehensive overview of the relative frequency of Lean Six Sigma (LSS) applications across key operational improvement areas for the period spanning 2024 to 2025. The data indicate that Productivity Improvement emerged as the most frequently targeted area, underscoring its pivotal role in enhancing organizational efficiency and driving performance gains. This emphasis on productivity reflects a broader strategy to streamline processes and maximize outputs across the manufacturing sector. Furthermore, the figure highlights topics such as Downtime and Equipment Reliability, Lead Time and Flow Inefficiencies, and also Defect and Quality Improvement. These areas highlight the critical importance of ensuring process stability and reliability within Lean environments. Addressing downtime and improving equipment reliability can significantly reduce operational delays, while focusing on lead times and flow inefficiencies helps optimize workflow and minimize bottlenecks. Moreover, the commitment to reducing defects and improving quality is essential for maintaining high standards of output and customer satisfaction.

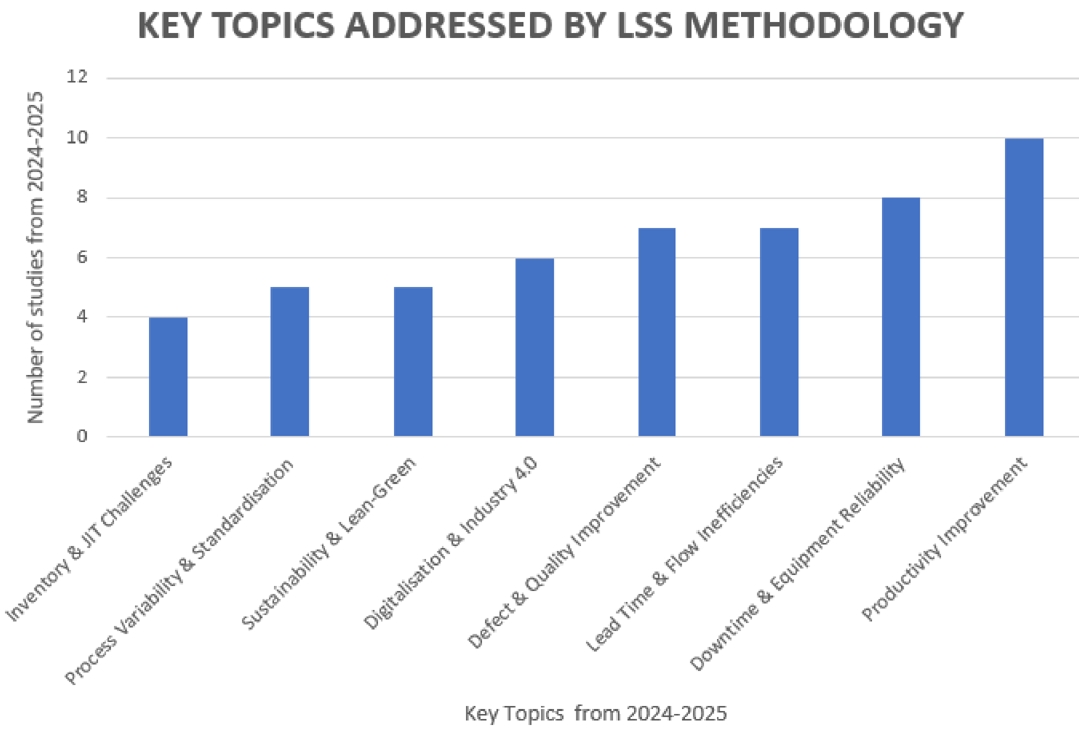

Figure 7. Key topics addressed by LSS from 2024-2025

In contrast, the areas of Digitalization and Industry 4.0, Sustainability and Lean-Green, although still emerging, indicate a growing recognition of the need to integrate technological advancements and environmental considerations into existing continuous improvement frameworks. This gradual shift suggests that organizations are beginning to explore how digital tools and sustainable practices can complement traditional LSS methodologies, enhancing overall operational effectiveness and resilience.

Overall, Figure 7 clearly illustrates the strategic focus of LSS interventions on productivity and reliability, while also signaling an ongoing evolution toward integrating digital transformation and sustainability initiatives into modern operations research. This dual focus suggests a comprehensive approach to operational excellence that prioritizes immediate performance metrics while acknowledging the importance of future-oriented practices in an increasingly complex business landscape.

3.5 Lean Six Sigma Applications Across Manufacturing Industries

The reviewed studies demonstrate that Lean Six Sigma has been successfully implemented across a diverse range of manufacturing industries. Although the primary objective of most implementations is to improve operational performance, the specific challenges addressed vary with industry characteristics. Table 3 presents the industry-specific applications of Lean Six Sigma (LSS) in small and medium-sized enterprises (SMEs) in manufacturing. The reviewed studies demonstrate the widespread adoption of LSS methodologies across diverse manufacturing sectors, including tyre, textile, automotive, plastic, metalworking, food, chemical, steel, and bakery industries. Various LSS tools such as 5S, Kaizen, DMAIC, Total Productive Maintenance (TPM), Value Stream Mapping (VSM), and Single-Minute Exchange of Die (SMED) have been applied to address operational inefficiencies, reduce waste, improve quality, and enhance productivity. The table highlights the versatility of LSS as a continuous improvement approach that delivers measurable operational improvements across diverse manufacturing environments.

Table 2. Integration of Lean Six Sigma with industry 4.0 technologies

Year	Author/s	Study Title	Objective of the study / Problem faced	Applied LSS Tool/s	Outcome	Recommended Future Studies
2025	Filho, W.M.M., Yoshimura, S.L., Marques, A.S., ... Alves, M.A.L., Ferreira, W.G.	Application of Lean Manufacturing Tools to Reduce Defect Incidence in Tire Production	Reduce defect rates caused by process variability and lack of standardization in tyre production.	Kaizen, fishbone, Five why's, SMED and 5S	Defect reduced from an average of 3.0% to 1.4%; 30-second reduction in cycle time resulting in additional output of 1 358.	Automated sensors detect residual steam, while temperature–pressure data support predictive maintenance. The approach should be extended to other tyre types and curing stations with long-term monitoring of mould lifespan and product uniformity.
2025	Ramasu T.K., Kanakana-Katumba M.G.	Implementation of a Lean Manufacturing Approach to Improving Productivity in SMEs: A Case Study in a Cloth Manufacturing Company	Improve productivity and eliminate non-value-added activities in textile SME.	VSM, 5S, Kaizen, Line Balancing	Reduced workstations from 12 to 4 and increased efficiency from 29.17% to 87.5%. Balance delay decreased from 70.83% to 12.5%.	Comparative SME studies to examine the impact of sustainability performance.
2025	Apte, D., Hatte, P., Pradhan, V.	Productivity improvement in manufacturing	Align customer requirements with production specifications to improve productivity.	DMAIC, 5S QFD	Process time reduced by 182 minutes, from 860 to 678 and productivity increased by 21.16%.	Digital QFD-Six Sigma integration.
2025	Kumar, R., Kumar, A., Kumar, R.	Integrating Lean and Green Strategies and Their Effect on Manufacturing Industry Performance: An Empirical Study	Examine impact of integrated Lean-Green strategies on performance.	Kaizen, Lean practices, GTPM, 5S, Kanban, SMED	Economic performance improved by 25.8%, while environmental performance had an increase of 35%.	Circular economy integration; longitudinal validation.
2025	Aldouri, S.N.M.	Digital Twin-Enabled Just-In-Time and Kanban Implementation Framework for Industry 4.0 Transformation in SMEs	Develop digital twin-enabled JIT-Kanban framework for SME transformation.	JIT, Kanban, Digital Twin	Inventory decreased by 47%, lead time decreased by 28% and setup time decreased by 52%. OEE increased by 39% and schedule adherence improved from 68% to 92%.	AI-enabled predictive lean systems.
2025	Fayyaz, A., Liu, C., Xu, Y., Farooq, A., Ahmed, S.	Linkages between lean six sigma, green manufacturing, circular economy and operational performance in manufacturing organizations of a developing country	Analyze the relationships between LSS, green manufacturing, the circular economy and performance.	DMAIC, 5S	Defect rate 15% reduction; Process cycle time experienced 20% reduction; Productivity improved by 30%; Operational cost reduced by 10%; statistically significant decline in Process variability reduction	Cross-country validation; innovation mediation.
2025	Ren, Y., Zhang, B., Zhang, M., Hu, F., Huang, H.	Deploying Lean Six Sigma to Improve the Assembly Precision of NEV Component: Evidence from Chinese SME	Improve assembly precision and reduce variability in NEV components.	DMAIC, SPC, SIPOC, FMEA, Fishbone	Non-conformity reduced from 10% to 3%; precision; Scrap/rework/scratches: reduced Savings R1 million RMB over 3 years.	Automation-integrated replication studies.
2025	Wong, F.R., Ahmad, A., Azaki, M.F.A.N.	Improving the Manufacturing of Square Flange Gasket Through Lean Practices	Reduce waste, rework and lead time in gasket production.	PDCA, 5S, Pareto, Fishbone, 5Why	Movement decreased from 330 meters to 90 meters. The cycle time was reduced from 97 minutes to 71.5 minutes. Additionally, the weekly output increased from 25 units to 34 units.	Lean-digital supplier integration.

Year	Author/s	Study Title	Objective of the study / Problem faced	Applied LSS Tool/s	Outcome	Recommended Future Studies
2025	Lino Moreno, S.E., Navarro Ayola, B.L., Salas, R., Nallusamy, S.	Enhancement of Operational Efficiency in a Plastic Manufacturing Industry Through TPM, SMED and Machine Learning—Case Study	Reduce downtime and enhance operational efficiency.	TPM, SMED, OEE, Machine Learning	OEE improved from 61.87% to 80.86%. Availability improved from 84.64% to 90.66%, Quality increased from 93.22% to 97.42%, Set-up time decreased from 265.98 to 191.33 minutes. The defect rate dropped from 56% to 2.62% and runner waste decreased by 50%.	AI-TPM hybrid scalability.
2025	Sousa, S., Silva, M.M., Gaspar, P.D.	Implementation of SMED Workshops: A Strategic Approach in the Automotive Sector	Reduce changeover times affecting production flexibility.	SMED, Kaizen, 5S, PDCA	Machine D's setup time improved from 48 minutes and 30 seconds to 29 minutes and 41 seconds, resulting in a 38.8% reduction. Other machines also saw improvements of up to 53.66%.	Smart factory integration.
2025	Contreras Rios, V., Cortavarría Cruz, M., León Chavarri, C., Alvarez, J.C., Lepore, R.	Process Optimization through the Implementation of SLP, Kanban, Poka-Yoke and TPM to Improve Efficiency in a Metalworking SME	optimize efficiency in a metalworking SME by reducing process waste, minimizing defects, improving workflow	SLP, Fishbone, Fishbone, Pareto, TPM, Poka-Yoke, Kanban	Efficiency improved from 52.77% to 67.47%, cycle times decreased from 26.44 to 18.51 minutes; line balancing decreased by 30% and Kanban times decreased by 15%; the packaging defect rate decreased from 17.00% to 9.35%.	Implement the model in a larger, more complex production environment.
2025	Tejada, S., Valdez, S., Yildiz, O., Salas-Castro, R., Alvarez, J.C.	A Data-Driven Lean Manufacturing Framework for Enhancing Productivity in Textile Micro-Enterprises	Develop a data-driven lean framework for micro-enterprises.	VSM, 5S, OEE	Productivity increased from 0.085 to 0.10 units; rework was reduced by 50%. TPM improved, with MTBF increasing by 27% to 34% and MTTR cut by over 50%. The 5S audit scored 18/20 and dust levels stayed at or below 0.5 mg/m³.	Big data integration in micro-SMEs.
2025	Gonzales-Vera, R., Rodriguez-Barrientos, K., Castro-Rangel, P., Alvarez, J.C., Lepore, R.	Improvement Model of OEE in the Production Process of Cardboard Boxes Through SMED, TPM, Automation and IoT	Improve OEE by reducing downtime and setup losses.	OEE, SMED, TPM, IoT	Overall Equipment Effectiveness (OEE) improved from 64.27% to 82.70%; Setup time for die-cutting operations decreased by 30%. Wear on die-cutters reduced from 36.87% to 24.58%, capability index (Cpk) increased from 0.57 to 1.50.	Predictive OEE dashboards.
2025	Rathi, S.S., Sahu, M.K., Kumar, S.	Productivity Improvement of the Rolling Mill in the Steel Plant by Implementing Lean Manufacturing Tools	Reduce bottlenecks and improve throughput.	VSM, 5S, Kaizen, TPM, Pareto, OEE	Availability and productivity were improved by 10.64% and 23%, respectively.	Digital twin rolling simulations.
2024	Alarcón, F.J., Calero, M., Martín-Lara, M.Á., Pérez-Huertas, S.	An Integrated Lean and Six Sigma Framework for Improving Productivity Performance: A Case Study in a Spanish Chemicals Manufacturer	Improve productivity and reduce variability in chemical manufacturing.	DMAIC, VSM, SPC, SIPOC, Fishbone	50% reduction in product variability; setup time has been decreased by 42%; Costs associated with product losses have decreased by approximately 40%, while costs related to raw materials have decreased by around 54%.	Cross-sector framework validation.
2024	Rukmana, A.N., Nurrahman, A.A., Selamat, S., Abdillah, S.	Enhancing reliability in garment manufacturing through FMEA and FTA	Improve reliability and reduce failure risks in garment production.	FMEA, FTA, Pareto	Defect rate reduced from 3% to 1.25%.	Predictive risk analytics integration.
2024	Collao-Diaz, M.F., Saavedra-Cielo, M.V., Calderón, W.D., Reimer, D.	Optimizing fill Rate and Inventory Control in Peruvian Bakery SMEs through 5S and MRP Integration	Improve fill rate and inventory accuracy.	5S, MRP	Fill rate increased from 86% to 92%, closer to the target of 94%; Forecast error reduced from 27% to 9.5% stockout reduced from 14% to 8.8%; Inventory record accuracy (ARI) increased from 67% to 86%.	Smart inventory analytics integration.

Year	Author/s	Study Title	Objective of the study / Problem faced	Applied LSS Tool/s	Outcome	Recommended Future Studies
2024	Aslan, N.S., Sazali, N., Junaidi, A.	The Effect of Lean Manufacturing on Production / Operation for the Small and Medium Enterprise in Malaysia	Examine the impact of lean practices on SME performance.	VSM, Kanban, 5S, Kaizen, OEE	Waiting time decreased by 66.59%, Lead time decreased from 6.5 to 4.5 days, OEE increased from 93.3% to 97.45% and the number of units per increased from 100 to 200.	Longitudinal SME studies.
2024	Islahudin, N., Jodanta, T.T., Yusianto, R.	Manufacturing Lead Time Using the Value Stream Mapping (VSM) Approach in the Oyster Mushroom Baglog Production Process	Reduce lead time using VSM	VSM, Fishbone	Mixing time decreased from 71.78 to 29.43 minutes by eliminating a non-value adding process Monthly lead time reduced from 28 to 26 days.	Application of digital VSM modelling.
2024	Alanya, B.S., Dextre, K.E., Nuñez, V.H., ... Alvarez, J.C., Hatakeyama, K.	Application of Lean Manufacturing to Improve Processes and Increase Productivity in the Textile Industry of Peru: Case Study	Improve productivity and eliminate waste in textile SME.	5S, VSM, Kaizen, SMED	Cutting time reduced from 3.40 to 1.12 days. Defect/rework rate: reduced from 13.12% to 4.23%. On-time/service level increased from 81.51% to 90.39%. Delayed deliveries decreased from 18.49% to 9.61%.	Sustainability integration studies.
2024	Florez-Cáceres, R.M., Huamán-Echevaría, C.E., Quiroz-Flores, J.C.	Improving Productivity in an SME in the Metalworking Sector Through Lean Manufacturing and TPM Tools: A Case Study in Peru	Improve productivity and reduce downtime.	TPM, 5S, VSM, SMED	Productivity increased by 10%; setup time decreased by 32.04%. Availability increased from 82% to 96%; OEE increased from 63.37% to 78.45%. MTBF increased from 324.57 to 438.17 minutes, MTTR reduced from 75.61 to 22.68 minutes.	Digital maintenance integration.
2024	Castañeda, S., Rodriguez, S., Yildiz, O., Aranda, D., Alvarez, J.C.	Increase of the Availability of Machinery in a Food Company Applying the TPM, SMED and RCM Methodologies	Increase equipment availability.	TPM, SMED, RCM	Availability increased from 79.06% to 89.37%. OEE increased from 70.48% to 85.02%, MTBF increased from 29.23 to 34.94 hours. SMED setup time decreased from 147.54 to 105.69 minutes. Failures & maintenance: failures reduced by 72%, process time reduced by 22.81%, Average stop-time reduced by 39%.	Predictive maintenance expansion.
2024	Zala, S.H., Jadeja, N.N., Chothani, H.G., ... Marsonia, D.J., Mehta, N.D.	Application of Lean Six Sigma Tools for Performance Improvement in an Automobile Sector SME	Improve performance by reducing defects and waste.	DMAIC, SPC, Pareto	Rejection rate reduced from 1.16% to 0.76%. Monthly rejection cost reduced from Rs 220 794 to Rs 142 966 Lead time reduced from 421.4 to 356.5 minutes; Cycle time reduced from 27.4 to 20.5 minutes.	Industry 4.0 integration.
2024	Rusli, M.H.M., Hassan, M.K., Muhamud-Kayat, S., Michael, E.	Development of IoT Kaizen System for Smart Lean Raw Material Inventory Management: A Case Study at an SME Factory in Malaysia	Develop an IoT-enabled Kaizen inventory system.	Kaizen, IoT	Warehouse space usage decreased 278 m² to 236 m² Ordering errors reduced from 2/month to 0, Stock-outs reduced from 2.5/month to 0, Inventory updates changed Manual counting to Real-time digital tracking, Transactions changed from Manual logs to 100% QR-based mobile capture.	AI-driven smart inventory systems.
2024	Sumasto, F., Safitri, I.N., Imansuri, F., ... Solih, E.S., Dzulfikar, A.	Enhancing Overall Equipment Effectiveness in Indonesian Automotive SMEs: A TPM Approach	Improve OEE through TPM implementation.	TPM, OEE, Pareto, Fishbone	OEE increased from 67.42% to 77. 80% Availability improved from 89.42% to 93.19% Reliability: MTTR reduced from 127.07 to 68.17 minutes while MTTF increased from 2,211 to 7,262 minutes.	Smart OEE dashboards.

Year	Author/s	Study Title	Objective of the study / Problem faced	Applied LSS Tool/s	Outcome	Recommended Future Studies
2024	Farwaha, H.S., Singh, P., Kumar, M., Ranjan, N., Kaur, H.	Enhancing Sustainability in Manufacturing: A Case Study on Reducing Changeover Time through SMED and Risk Analysis	Reduce changeover time to enhance sustainability.	SMED, FMEA, OEE	Changeover time: reduced by 35.54% at Station A and by 49.94% at Station B; changeover time at the filling area reduced by 46.64%. OEE: improved to 89%.	Green-SMED integration research.
2024	Dahab, A., Younes, M.A., Backar, S.	Deployment of Lean Six Sigma Framework with Environmental Considerations in SMEs: A Case Study	Integrate environmental factors into the LSS framework.	DMAIC, VSM, 5S	Daily candle production increased by 32.2%; the wax waste decreased by 29.6%.	Circular economy alignment studies.
2024	Lago-Domínguez, E.M., Lago-Domínguez, M.F., Corzo-Chavez, J.A.	Improvement Design to Increase Productivity in the Finishing Area Through the Use of Poka Yoke, Value Stream Mapping and SMED in a Company of the Plastics Business	Identify challenges in finishing department, reduce costs and improve efficiency and productivity.	Poka-Yoke, VSM, SMED	Effective production time improved by 50.96%; profits increased by 10.3%.	More studies focusing on the application of Poka-Yoke, VSM and SMED

3.5 Lean Six Sigma Applications Across Manufacturing Industries

The reviewed studies demonstrate that Lean Six Sigma has been successfully implemented across a diverse range of manufacturing industries. Although the primary objective of most implementations is to improve operational performance, the specific challenges addressed vary with industry characteristics. Table 3 presents the industry-specific applications of Lean Six Sigma (LSS) in small and medium-sized enterprises (SMEs) in manufacturing. The reviewed studies demonstrate the widespread adoption of LSS methodologies across diverse manufacturing sectors, including tyre, textile, automotive, plastic, metalworking, food, chemical, steel, and bakery industries. Various LSS tools such as 5S, Kaizen, DMAIC, Total Productive Maintenance (TPM), Value Stream Mapping (VSM), and Single-Minute Exchange of Die (SMED) have been applied to address operational inefficiencies, reduce waste, improve quality, and enhance productivity. The table highlights the versatility of LSS as a continuous improvement approach that delivers measurable operational improvements across diverse manufacturing environments.

Table 3. Industry-Specific Applications of Lean Six Sigma in Manufacturing SMEs

Industry	Representative Studies	LSS Tools Applied	Major Outcomes
Tyre Manufacturing	Filho et al. (2025)	5S, Kaizen, Fishbone, Five Why's, SMED	Defect reduction from 3.0% to 1.4%; cycle-time reduction
Textile and Cloth Manufacturing	Ramasu & Kanakana-Katumba (2025); Alanya et al. (2024)	VSM, 5S, Kaizen, Line Balancing, SMED	Productivity improvement; workstation reduction; improved service levels
Automotive Manufacturing	Ren et al. (2025); Sumasto et al. (2024); Sousa et al. (2025)	DMAIC, TPM, SPC, SMED, FMEA	Reduced defects; increased OEE; reduced setup times
Plastic Manufacturing	Lino Moreno et al. (2025); Lago-Domínguez et al. (2024)	TPM, SMED, VSM, Poka-Yoke	Improved efficiency; reduced waste and downtime
Metalworking Industry	Contreras-Rios et al. (2025); Florez-Cáceres et al. (2024)	TPM, Kanban, Pareto, Fishbone, Poka-Yoke	Increased productivity and process efficiency
Food Manufacturing	Castañeda et al. (2024); Collao-Diaz et al. (2024)	TPM, SMED, MRP, 5S	Increased equipment availability and inventory accuracy
Chemical Manufacturing	Alarcón et al. (2024)	DMAIC, VSM, SPC, SIPOC	Reduced process variability and raw material costs
Steel Manufacturing	Rathi et al. (2025)	VSM, TPM, Kaizen, OEE	Productivity and availability improvements
Bakery Manufacturing	Collao-Diaz et al. (2024)	5S, MRP	Improved fill rate and inventory control

The findings presented in Table 3 indicate that Lean Six Sigma has been successfully implemented across a wide range of manufacturing SMEs, generating significant improvements in operational performance. Commonly applied tools such as TPM, VSM, 5S, Kaizen, SMED, and DMAIC contributed to reductions in defects, downtime, process variability, and setup times, while improving productivity, equipment effectiveness, inventory control, and service levels. The automotive, textile, and food manufacturing sectors reported substantial gains in efficiency and quality, whereas tyre, plastic, and chemical industries achieved notable reductions in waste and process variation. Overall, the evidence suggests that Lean Six Sigma provides a flexible and effective framework for enhancing competitiveness, operational excellence, and sustainability within manufacturing SMEs.

Table 4 presents the classification of Industry 4.0 technologies applied in Lean Six Sigma studies and the operational benefits. The findings indicate that Industry 4.0 technologies are increasingly being employed to strengthen different phases of the LSS methodology, particularly in data collection, process monitoring, root cause analysis, predictive maintenance, process optimization, and decision-making. The integration of these digital technologies enhances the effectiveness of continuous improvement initiatives by enabling real-time visibility, advanced analytics, and automated process control.

Table 4. Classification of Industry 4.0 Technologies Applied in Lean Six Sigma Studies

Industry 4.0 Technology	**Lean Six Sigma Function Supported**	**Example Study**	**Operational Benefits**
Internet of Things (IoT)	Real-time monitoring and measurement	Gonzales-Vera *et al.* (2025); Rusli *et al.* (2024)	Improved OEE, reduced downtime, real-time inventory visibility
Machine Learning	Root cause analysis, predictive maintenance	Lino Moreno *et al.* (2025)	Defect reduction, predictive failure detection
Digital Twin	Process simulation and optimization	Aldouri (2025)	Reduced inventory, shorter lead times, improved scheduling
Artificial Intelligence	Predictive analytics and decision support	Aldouri (2025)	Enhanced operational decision-making
Big Data Analytics	DMAIC data analysis and performance monitoring	Pongboonchai-Empl *et al*. (2024)	Improved analytical capability and process optimization
Cyber-Physical Systems (CPS)	Process automation and real-time control	Pongboonchai-Empl *et al*. (2024)	Improved process visibility and responsiveness
Cloud Computing	Data integration and collaboration	Pongboonchai-Empl *et al*. (2024)	Centralized performance monitoring
Smart Sensors	Continuous equipment monitoring	Filho *et al.* (2025)	Predictive maintenance and process stability
QR-Based Mobile Systems	Inventory management and traceability	Rusli *et al.* (2024)	Elimination of inventory recording errors
Predictive Maintenance Platforms	Control phase support	Gonzales-Vera *et al.* (2025); Lino Moreno *et al.* (2025)	Reduced downtime and maintenance costs

The evidence presented in Table 4 demonstrates that IoT, machine learning and digital twin technologies are the most frequently adopted Industry 4.0 technologies in Lean Six Sigma applications. These technologies primarily support the Measure, Analyze and Control phases of DMAIC by enabling real-time data acquisition, predictive analytics and automated performance monitoring. The findings indicate a gradual shift from traditional Lean Six Sigma implementations towards digitally enabled continuous improvement systems that enhance operational visibility, process reliability and predictive decision-making.

4. Discussion

The findings of this systematic literature review provide compelling evidence regarding the evolving role and impact of Lean Six Sigma (LSS) methodologies in small and medium-sized manufacturing enterprises (SMEs). By synthesizing bibliometric trends, keyword co-occurrence patterns and empirical case evidence, the study reveals several critical insights into the contemporary application of LSS within manufacturing environments. The discussion of results will focus on (i) Bibliometric discussion and followed by (ii) Futuristic conceptual framework for integrating Lean Six Sigma and Industry 4.0 towards smart and sustainable manufacturing

4.1 Bibliometric discussion

The bibliometric analysis indicates that research on LSS implementation in manufacturing SMEs has experienced moderate growth between 2021 and 2025, with a noticeable peak in publication output during 2023. This trend reflects increasing scholarly and industrial interest in structured operational improvement methodologies capable of addressing productivity challenges and operational inefficiencies within SMEs. The decline observed in 2024 suggests a potential shift in research focus on adjacent domains such as Industry 4.0, digital transformation and smart manufacturing. The overlay visualization confirms this interpretation, as emerging keywords such as Industry 4.0 and digitally enabled manufacturing frameworks appear increasingly prominent in recent studies. This observation suggests that contemporary evolution in Lean Six Sigma research is increasingly converging with digital manufacturing paradigms.

The keyword co-occurrence analysis reveals strong conceptual linkages between Lean Six Sigma tools and key operational performance indicators. Central keywords such as Lean manufacturing, Six Sigma, 5S, TPM, SMED and Lean Six Sigma dominate the network visualization map, indicating their foundational importance within the operational improvement literature. Importantly, these tools exhibit strong associations with performance indicators, including efficiency, cycle time, inventory control, lead time, order fulfilment and quality control. Such patterns confirm that LSS tools are not implemented in isolation but rather function as integrated mechanisms that simultaneously improve multiple dimensions of manufacturing performance.

The co-occurrence between TPM and operational efficiency highlights the critical role of proactive maintenance strategies in improving equipment reliability and reducing production downtime. The association between Kanban and inventory management reflects the contribution of pull-based production systems in improving supply chain responsiveness and reducing work-in-progress inventory. The linkage between DMAIC and sustainability further indicates that structured improvement methodologies are increasingly being applied to support environmentally responsible production practices. These findings align with the broader literature, which positions Lean Six Sigma as a holistic operational excellence framework capable of integrating quality management, operational efficiency and sustainability outcomes.

The empirical synthesis presented in Table 2 provides strong quantitative evidence demonstrating the effectiveness of LSS tools in improving manufacturing performance. Across the reviewed studies, the implementation of Lean Six Sigma practices consistently led to measurable operational improvements, particularly in defect reduction, productivity, process efficiency and equipment performance. Several case studies reported substantial reductions in defect rates, including improvements from 3.0% to 1.4%, from 3% to 1.25% and from 10% to 3%, demonstrating the effectiveness of root-cause analysis and statistical process control techniques in addressing process variability.

Productivity and workflow efficiency improvements were frequently observed following the application of Lean tools such as Value Stream Mapping, Kaizen and 5S. Studies reported productivity improvements exceeding 20% and increases in production efficiency from 29.17% to 87.5% following process redesign and waste elimination initiatives. These results confirm that Lean practices remain highly effective in improving operational flow and eliminating non-value-adding activities in SME production environments.

Another critical insight emerging from the reviewed studies concerns the role of maintenance-oriented improvement strategies in enhancing manufacturing performance. The integration of Total Productive Maintenance (TPM), Single Minute Exchange of Die (SMED) and Overall Equipment Effectiveness (OEE) monitoring resulted in substantial improvements in machine availability, reliability and operational performance. Several studies reported OEE improvements exceeding 15-20%, alongside reductions in equipment downtime, setup time and operational disruptions. Such findings highlight the importance of equipment reliability and preventive maintenance as fundamental drivers of operational excellence in SME manufacturing systems.

The evidence indicates that Lean Six Sigma is highly adaptable across manufacturing sectors. While quality improvement and defect reduction dominate applications in automotive, tyre and chemical manufacturing, productivity improvement and waste elimination are more prominent within textile and metalworking industries. Furthermore, TPM and OEE-based approaches are particularly prevalent in equipment-intensive sectors such as automotive, steel and food manufacturing. These findings suggest that Lean Six Sigma provides a flexible operational improvement framework capable of addressing industry-specific challenges while maintaining consistent performance benefits.

The results reveal an emerging trend toward integrating Lean Six Sigma with Industry 4.0 digital technologies. Several studies reported the application of digital twin technologies, Internet of Things (IoT) platforms, machine learning algorithms and real-time data analytics to enhance Lean process optimization. These digital integrations contributed to improved production visibility, predictive maintenance capabilities and enhanced decision-making within manufacturing environments. The convergence between Lean Six Sigma and digital manufacturing technologies suggests that the next generation of operational excellence frameworks will increasingly rely on data-driven, digitally enabled improvement systems. The findings confirm that Lean Six Sigma remains a robust and adaptable framework for improving operational performance in manufacturing SMEs. However, the results also indicate that the future evolution of LSS is likely to be strongly influenced by digital transformation, advanced analytics and sustainability considerations.

4.1.1 Research gaps and future directions

The review identifies several important research gaps that warrant future investigation. (i) Although Industry 4.0 technologies are increasingly integrated with Lean Six Sigma, most existing studies remain limited to single-case implementations, thereby restricting the generalizability of findings across manufacturing sectors. Future studies should conduct multi-industry and cross-country investigations to evaluate the scalability of Industry 4.0-enabled Lean Six Sigma frameworks. (ii) The majority of studies focus on operational outcomes such as productivity, quality improvement and equipment effectiveness, while relatively limited attention has been given to financial performance, organizational resilience and sustainability outcomes. Future research should therefore investigate the long-term economic, environmental, and social impacts of the integration of Lean Six Sigma and Industry 4.0. (iii) While technologies such as IoT and machine learning are increasingly reported in the literature, emerging technologies, including generative artificial intelligence, blockchain, augmented reality and autonomous manufacturing systems, remain underexplored within Lean Six Sigma applications. Future studies should examine how these advanced technologies can support DMAIC activities and continuous improvement initiatives.

Finally, manufacturing SMEs face unique implementation challenges related to financial constraints, digital maturity, workforce capabilities and technology adoption readiness. Additional research is required to develop SME-specific implementation frameworks that support successful Lean Six Sigma digital transformation.

4.2 Conceptual framework integrating Lean Six Sigma and Industry 4.0 for smart, sustainable manufacturing

The conceptual framework in Figure 8 illustrates how Lean Six Sigma (LSS) can be integrated with Industry 4.0 technologies to enable smart and sustainable manufacturing systems. The framework positions the DMAIC improvement cycle as the central operational improvement methodology, while Industry 4.0 technologies act as digital enablers that enhance data visibility, predictive capabilities and real-time decision-making.

In the framework, the Define phase is supported by big data analytics and cloud platforms that integrate information from production systems, supply chains and customer interfaces. These technologies enable organizations to identify operational problems more accurately and prioritize improvement opportunities based on real-time performance insights. During the Measure phase, Internet of Things (IoT) sensors and cyber-physical systems (CPS) enable continuous monitoring of equipment performance, production throughput, energy consumption and environmental emissions. These technologies significantly improve the reliability of performance measurement and provide the real-time operational data required for evidence-based process evaluation. The Analyze phase benefits from the application of artificial intelligence (AI) and machine learning algorithms that identify patterns in production data and detect root causes of defects, equipment failures and process variability. These analytical capabilities strengthen traditional LSS analytical tools such as statistical process control, root cause analysis and failure mode and effects analysis. In the Improve phase, digital twin technologies and smart automation systems allow organizations to simulate process improvements before implementation. Virtual modelling of production systems enables organizations to evaluate alternative improvement scenarios, optimize production parameters and reduce implementation risks. The Control phase is strengthened through intelligent monitoring systems, predictive maintenance platforms and blockchain-based traceability systems. These technologies enable continuous process monitoring, early detection of deviations and improved supply chain transparency, ensuring that improvement gains are sustained over time.

Beyond operational efficiency, integrating Lean Six Sigma with Industry 4.0 technologies also contributes to the broader objectives of sustainable manufacturing. Digital monitoring systems allow organizations to track resource utilization, energy consumption and environmental emissions in real time. This capability supports the integration of Lean–Green manufacturing principles by enabling data-driven optimization of resource efficiency, waste reduction and carbon footprint management. The integration illustrated in this framework demonstrates that Lean Six Sigma and Industry 4.0 are not competing paradigms but rather complementary approaches. Lean Six Sigma provides the structured improvement methodology, while Industry 4.0 technologies provide the digital capabilities necessary for real-time optimization and predictive decision-making. The synergy between these approaches enables manufacturing organizations to transition from traditional continuous improvement practices towards data-driven, intelligent and environmentally sustainable production systems.

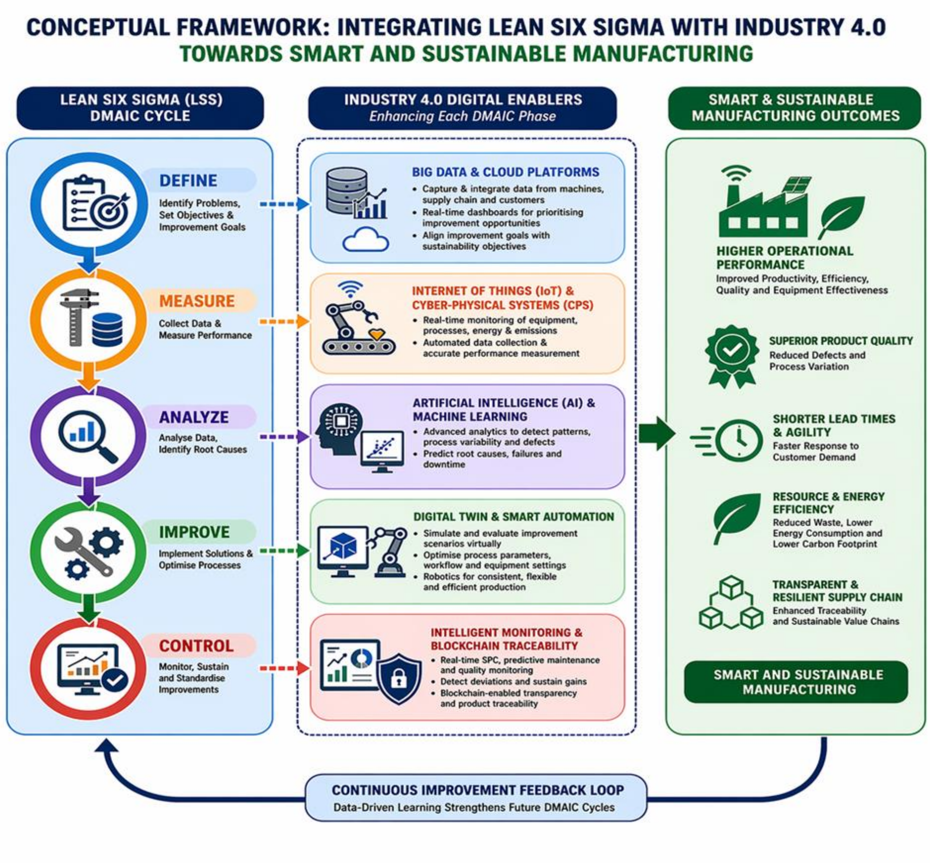

Figure 8. Conceptual framework: Integrating LSS with Industry 4.0 technologies towards smart and sustainable manufacturing

5. Managerial Implications

The findings offer several practical insights for managers in manufacturing SMEs seeking to enhance operational efficiency and competitiveness. Lean Six Sigma should be adopted as a strategic operational excellence framework rather than a set of isolated improvement tools. Managers should institutionalize the DMAIC methodology to guide continuous improvement initiatives and systematically apply tools such as Value Stream Mapping, root cause analysis, statistical process control, Kaizen and 5S to eliminate waste, improve process stability and enhance production efficiency.

The results emphasize the importance of equipment reliability and proactive maintenance in achieving operational excellence. Managers should prioritize strategies such as Total Productive Maintenance (TPM), predictive maintenance and Overall Equipment Effectiveness (OEE) monitoring to reduce machine downtime, improve equipment utilization and stabilize production performance. Process optimization and workflow management are essential for improving operational responsiveness. Lean practices such as Kanban systems, line balancing and pull-based production enable SMEs to improve inventory control, reduce lead times and enhance customer responsiveness while maintaining cost efficiency.

The findings highlight the increasing importance of digital transformation in strengthening Lean Six Sigma initiatives. Managers should progressively integrate Industry 4.0 technologies, including Internet of Things (IoT) sensors, digital twins, and machine-learning analytics, to enhance operational visibility, support data-driven decision-making, and sustain improvement outcomes. Successful Lean Six Sigma implementation requires strong leadership commitment and the development of organizational capability. Managers should invest in employee training, establish cross-functional improvement teams and foster a culture of continuous improvement to ensure that operational gains are sustained over time.

The industry-specific evidence presented in this review demonstrates that managers should tailor Lean Six Sigma implementation strategies according to sector-specific operational challenges. TPM and OEE monitoring may yield greater benefits in equipment-intensive industries, whereas Value Stream Mapping, line balancing and inventory optimization may be more suitable in labour-intensive manufacturing environments.

Managers should recognize that the future competitiveness of manufacturing SMEs will increasingly depend on their ability to combine traditional operational excellence methodologies with digital technologies. Rather than viewing Industry 4.0 as a standalone technological initiative, organizations should align digital investments with Lean Six Sigma improvement objectives. Strategic investments in IoT-enabled monitoring systems, predictive maintenance platforms, digital twins and AI-driven analytics can significantly enhance the effectiveness of DMAIC projects while providing real-time operational intelligence. Furthermore, managers should develop digital competencies among employees and establish data-driven decision-making cultures to maximize the benefits of Industry 4.0-enabled Lean Six Sigma initiatives.

6. Conclusion and Recommendation

This study systematically reviewed the application of Lean Six Sigma (LSS) in manufacturing small and medium-sized enterprises (SMEs) and assessed its contribution to operational performance improvement between 2021 and 2025. The findings confirm that Lean Six Sigma remains a highly effective operational excellence methodology capable of improving productivity, quality, process efficiency, equipment reliability, inventory management and overall organizational performance. The bibliometric analysis revealed growing scholarly interest in Lean Six Sigma implementation within manufacturing SMEs, while the keyword co-occurrence analysis demonstrated strong relationships between LSS tools and critical performance indicators such as productivity, efficiency, lead-time reduction, quality improvement, inventory optimization and sustainability. The review further confirms that Lean Six Sigma tools, including DMAIC, Value Stream Mapping (VSM), 5S, Kaizen, Total Productive Maintenance (TPM), Single Minute Exchange of Die (SMED), Statistical Process Control (SPC), Failure Mode and Effects Analysis (FMEA) and Poka-Yoke, consistently generate measurable operational improvements across diverse manufacturing sectors. Reported benefits include substantial reductions in defect rates, process variability, downtime and setup times, together with significant improvements in productivity, Overall Equipment Effectiveness (OEE), workflow efficiency and customer service performance. These findings demonstrate that Lean Six Sigma provides manufacturing SMEs with a comprehensive and adaptable framework for achieving sustainable operational excellence.

A significant contribution of this review is the identification of the increasing convergence between Lean Six Sigma and Industry 4.0 technologies. The findings indicate that digital technologies such as the Internet of Things (IoT), machine learning, artificial intelligence, digital twins, cyber-physical systems, and predictive maintenance platforms are increasingly integrated into Lean Six Sigma initiatives to enhance real-time monitoring, predictive analytics, process visibility, and data-driven decision-making. The proposed conceptual framework demonstrates that Industry 4.0 technologies serve as strategic enablers of the DMAIC methodology by enhancing measurement accuracy, analytical capability, process optimization, and control mechanisms. Consequently, Lean Six Sigma is evolving from a traditional continuous improvement methodology into a digitally enabled operational excellence system capable of supporting intelligent, predictive and responsive manufacturing environments. Furthermore, the findings reveal that integrating Lean Six Sigma with Industry 4.0 technologies contributes not only to operational performance but also to broader sustainability objectives by improving resource utilization, reducing waste, enhancing energy efficiency, and strengthening environmental performance.

Based on these findings, manufacturing SMEs should adopt Lean Six Sigma as an organization-wide strategic improvement framework rather than implementing isolated improvement tools. Organizations should institutionalize the DMAIC methodology as a structured approach to continuous improvement and align operational excellence initiatives with digital transformation strategies. Manufacturing managers should prioritize investments in Industry 4.0 technologies such as IoT-enabled monitoring systems, machine-learning analytics, digital twins and predictive maintenance platforms to enhance operational visibility, equipment reliability and decision-making capabilities. Equally important is the development of organizational capabilities through employee training, cross-functional improvement teams and the establishment of data-driven cultures that support continuous learning and innovation. In addition, sustainability considerations should be embedded within Lean Six Sigma initiatives to ensure that productivity improvements are achieved alongside environmental and social performance objectives.

The study also highlights the important role of policymakers, industry associations and SME support agencies in facilitating the adoption of Industry 4.0-enabled Lean Six Sigma systems. Support mechanisms such as digital transformation programmes, technical assistance, skills development initiatives and funding incentives may help overcome resource constraints that frequently limit technology adoption within SMEs. Future research should focus on longitudinal evaluations of Lean Six Sigma implementation outcomes, cross-industry and cross-country comparative studies, and the exploration of emerging technologies such as generative artificial intelligence, blockchain, augmented reality and autonomous manufacturing systems within Lean Six Sigma environments.

Overall, the study concludes that the future competitiveness and sustainability of manufacturing SMEs will increasingly depend on their ability to integrate Lean Six Sigma principles with advanced digital technologies and sustainable manufacturing practices. Organizations that successfully combine continuous improvement methodologies with Industry 4.0 capabilities will be better positioned to achieve operational excellence, enhance organizational resilience and secure a sustainable competitive advantage in an increasingly complex and technology-driven manufacturing landscape.

Author Contributions

Conceptualisation, T.M; methodology, R.L.S.; software, R.L.S.; validation, T.M., R.L.S. and O.M.; formal analysis, T.M.; investigation, T.M. and O.M.; data curation, R.L.S.; writing—original draft preparation, T.M.; writing—review and editing, T.M., R.L.S. and O.M. All authors have read and agreed to the published version of the manuscript.

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The authors avoided data fabrication, falsification, and plagiarism, and any form of misconduct.

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Conflict of interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Co-Pilot to improve Figure 1 and Figure 8. After using this generative AI tool, the author(s) reviewed the content as needed and take full responsibility for the content of the manuscript.

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