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Overview of the Theoretical Exploration and Application of Lean Six Sigma

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Abstract: In contemporary contexts, Lean Six Sigma (LSS) is extensively utilized and has evolved across various sectors due to its substantial benefits. This paper aims to explore the definition, origin, and development of LSS, as well as its key tools, methods, theoretical research, and future prospects. Furthermore, it analyzes the theoretical foundations and practical applications of LSS in-depth, with an emphasis on anticipating future development trends. The goal is to provide readers with a comprehensive overview of LSS and offer insights for enterprises seeking to implement LSS for process improvement and innovation.

Keywords: Lean Six Sigma; DMAIC process; Lean Production; Six Sigma

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1. Introduction

As global competition intensifies, market demands for product and service quality are increasing, compelling enterprises to enhance their competitiveness in response to market changes. Lean Six Sigma (LSS) has emerged as a systematic methodology that integrates the principles of lean production and Six Sigma management. It enables organizations to improve efficiency, reduce costs, enhance quality, and boost customer satisfaction, ultimately helping them achieve their strategic objectives. Due to its advantages, LSS has found extensive application across various sectors.

2. Overview of Lean Six Sigma

2.1. Definition

In the "Six Sigma Management Evaluation Criteria," LSS is defined as a systematic and structured approach to business improvement and innovation. Its primary objective is to achieve breakthrough improvements and design innovations in organizational processes through rigorous scientific methodologies. LSS aims to reduce variability, minimize waste, enhance quality and efficiency, and improve the satisfaction of customers and other stakeholders, thereby enabling the organization to reach its strategic goals [1].

2.2. Origins and development

The origins of Lean Production can be traced back to the Toyota Production System (TPS), established in the 1950s by Kiichiro Toyoda and Taiichi Ohno of Toyota Motor Corporation. The core principle of TPS is the elimination of waste, aimed at creating maximum value with minimal resources. Its two pillars are Just-In-Time (JIT) and automation (Jidoka).

Just-in-time emphasizes production based on demand, which prevents inventory buildup and minimizes waste. Automation focuses on automating the production process to improve efficiency and reduce defect rates. In 1988, Krafcik et al. officially introduced the term "Lean Production" in the article "The Winning Systems of Lean Production" [2]. In 1990, Womack *et al.* further elaborated on the concept in their book *Machines That Changed the World*, contributing to its widespread recognition [3]. The principles of Lean Production gradually expanded to encompass all areas of production, including product development, supply chain management, and enterprise management, leading to the concept of Lean Enterprises (LE).

In recent years, with increasing global competition, the principles of Lean Production have gained broader application and development. Researchers have focused on applying Lean Production in product development and enterprise management, proposing various frameworks and models tailored to different industries and contexts.

Six Sigma management originated in the 1980s at Motorola in the United States, as first proposed by the Motorola Research Center. It was initially defined as a data-driven process improvement method aimed at achieving stable and predictable process outcomes by reducing variations and defects. By the mid to late 1990s, Six Sigma gained traction due to successful applications in companies like Motorola and was subsequently adopted by other large enterprises, such as General Electric, evolving into a mainstream business strategy.

As these management models continued to develop and refine, practitioners began to recognize that their combination could yield greater advantages. Thus, in 2000, LSS emerged as a continuous improvement methodology that integrates Lean Production and Six Sigma management concepts [4].

3. Key tools and methods in LSS

Define, Measure, Analyze, Improve, Control (DMAIC) is a fundamental method in LSS, functioning as a cyclical process designed to improve processes, reduce defects, and enhance efficiency. The flow is illustrated in **Figure 1**. The process is structured as follows:

(1) Define phase: Clearly articulate improvement goals and processes, and identify key metrics, such as defect rates, cycle times, and costs.

(2) Measure phase: Assess current process performance, gather data, analyze the existing situation, and pinpoint significant problems and opportunities for improvement.

(3) Analyze phase: Examine the data to identify the root causes of issues using statistical tools, such as cause-and-effect diagrams and Pareto charts.

(4) Improve phase: Based on the analysis, propose and implement improvement measures, including process optimization, equipment upgrades, and personnel training.

(5) Control phase: Continuously monitor the improved process to ensure stable operation, establish a monitoring system, analyze data regularly, and promptly address any emerging issues.

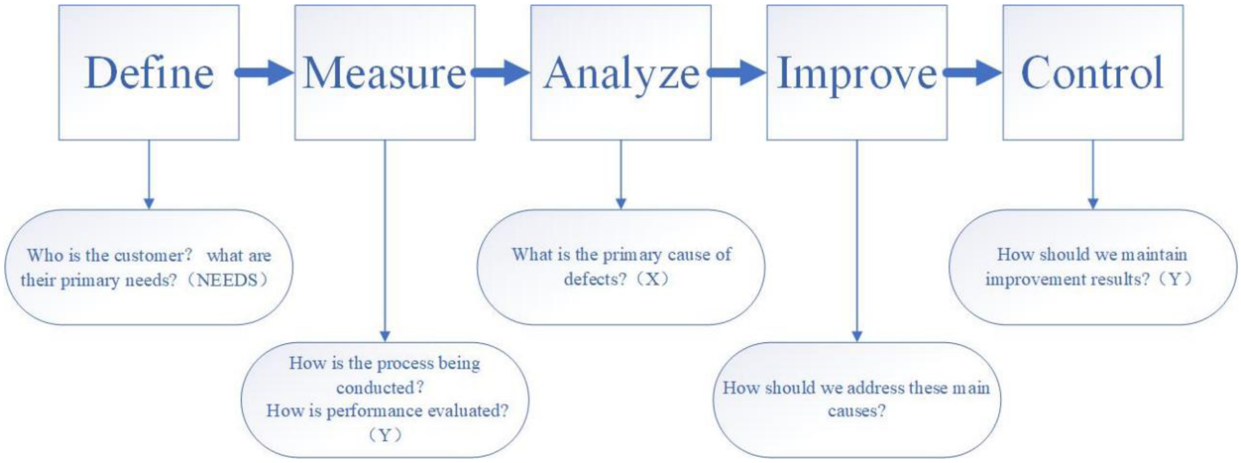

Figure 1. DMAIC

During the implementation of DMAIC, the tools selected at different stages are illustrated in **Figure 2** [5].

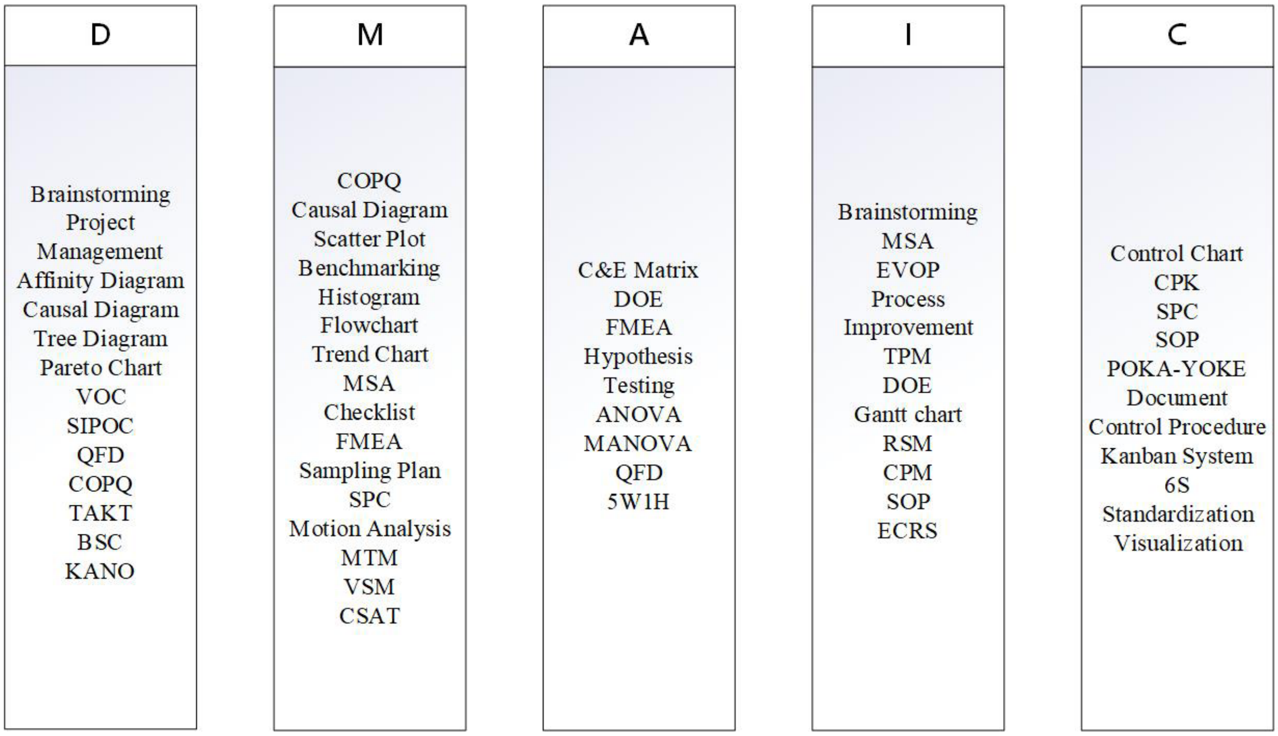

Figure 2. Diagram of DMAIC tools across various stages

4. Theoretical research on Lean Six Sigma

The keyword "Six Sigma" (including LSS) was used in the Web of Science database to conduct an exhaustive literature search of full-text articles, resulting in a total of 1,705 papers as of September 2024. According to the citation report provided by Web of Science (WOS), these papers collectively garnered 23,107 citations, with an average citation frequency of 13.55 per paper. **Figures 3** and **4** illustrate the number of papers published and their corresponding citations from 1997 to September 2024. As shown in **Figure 3**, academic research on LSS has steadily increased since 2015, exhibiting a rapid growth rate. **Figure 4** further indicates that the citation count for published papers in the LSS domain has consistently risen, reflecting significant growth over the years.

A review of the relevant literature reveals that LSS has been applied across various fields. The main research themes of LSS will be discussed in the following three areas: case application research, innovative integration research, and promotion application research.

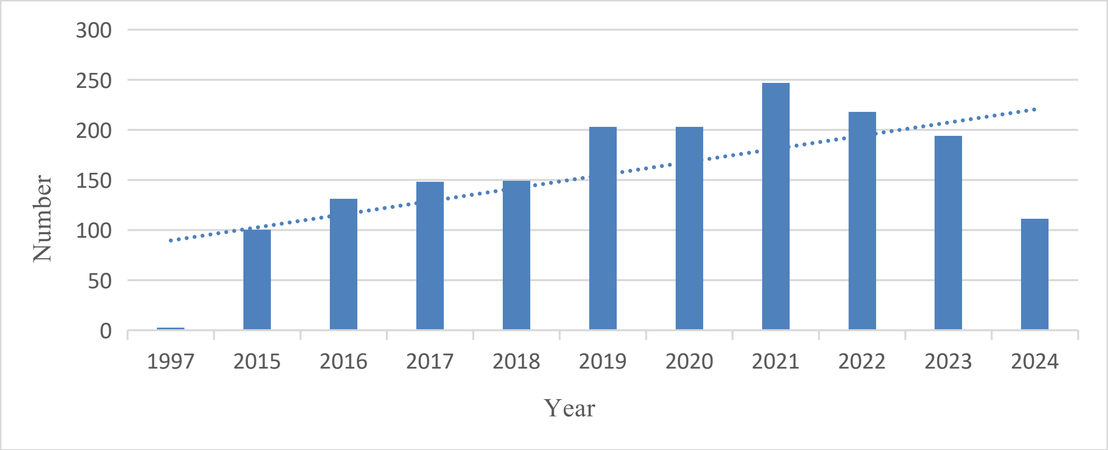

Figure 3. The number of published papers

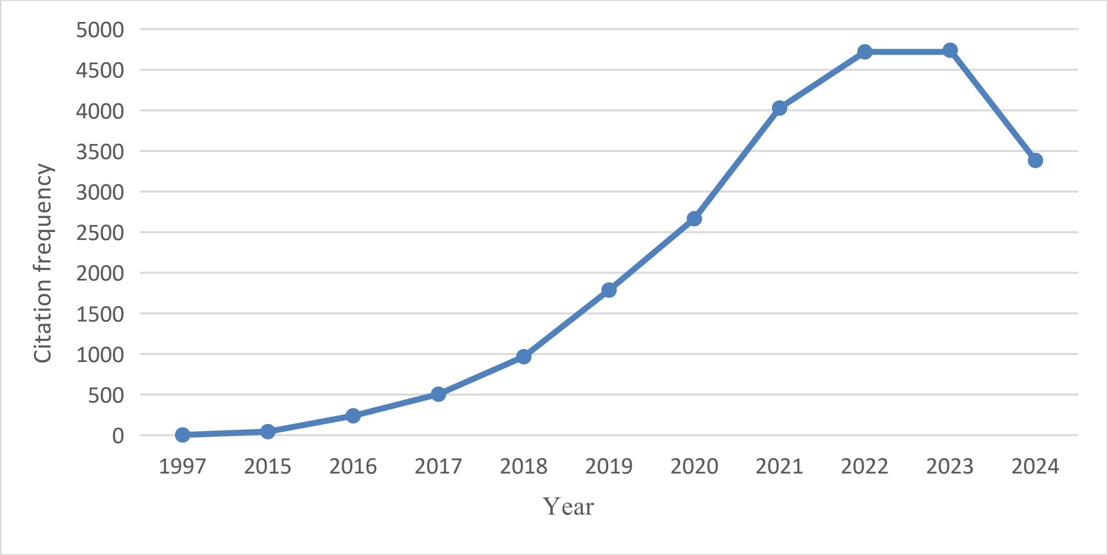

Figure 4. Citation volume of published papers

4.1. Research on the case application of Lean Six Sigma

This area of LSS research focuses on the technical bottlenecks and management challenges encountered by specific enterprises, revealing that they skillfully employed the DMAIC and Design for Six Sigma (DFSS) methodologies to analyze and resolve these issues.

For instance, Francia *et al.* applied the DFSS method to design a new E-class hybrid electric vehicle, featuring innovations such as a full hybrid powertrain, an aluminum alloy tubular frame, low fuel consumption, high comfort, and affordability [6]. Similarly, Frizziero *et al.* utilized the DFSS method to design an environmentally friendly motorcycle, achieving notable success during the conceptual design phase [7]. Chen *et al.* optimized production parameters and processes through the DMAIC method, successfully elevating the quality level of the eccentricity of transistor gaskets to Six Sigma standards [8]. Additionally, Mittal *et al.* implemented the Six Sigma DMAIC method within a rubber seal manufacturing company in India, effectively reducing the repair rate of rubber seals, enhancing operational efficiency, and increasing customer satisfaction. The company's sigma level improved from 3.9 to 4.45 [9].

Through an in-depth analysis of these cases, it is evident that LSS is extensively applied within the manufacturing industry, yielding remarkable results. The flexible application of DMAIC and DFSS methodologies has effectively addressed specific technical bottlenecks and management challenges, fostering improvements in product quality and customer satisfaction.

4.2. Research on the innovative integration of Lean Six Sigma

With the evolution of contemporary society, particularly during the Industry 4.0 era, LSS, as an integrated management system, faces unprecedented opportunities and challenges. To maintain competitiveness and effectiveness, LSS must be innovatively integrated to align with emerging trends in digitalization, intelligence, automation, and connectivity.

Yang *et al.* argue that traditional Six Sigma has shortcomings in the product design phase, which can lead to increased costs and quality issues. To address this, they propose an improved DFSS process called Define, Identify, Measure, Design, Optimize, Verify (DIMDOV). The study uses MTM, a motor manufacturing company in Taiwan, as a case study to demonstrate the effectiveness of DFSS in enhancing product quality, reducing customer complaints, and increasing corporate profits [10].

Nedra *et al.* analyzed the limitations of the conventional Lean Six Sigma approach, particularly the logical and practical deficiencies of the DMAIC framework when applied to PDCA implementations. In response, they propose a novel method—PDCA-applied-to-DMAIC—that integrates the PDCA cycle into each step of DMAIC to facilitate continuous improvement. In the case of an ISO 9001-certified Tunisian garment SME, this approach effectively improved product quality, reduced defect rates, shortened production cycles, and enhanced customer satisfaction [11].

Peruchi *et al.* identified the limitations of traditional DMAIC when addressing multiple related Critical to Quality (CTQ) characteristics. They advocate for the use of multivariate statistical methods to enhance the efficiency of analysis and optimization, proposing an improved Six Sigma DMAIC method called Multivariate DMAIC (MDMAIC). Using the AISI 52100 hardening steel turning process as an example, their research demonstrated that the MDMAIC method significantly improved the quality and efficiency of the turning process while notably reducing defect rates [12].

Guo *et al.* introduced a new model that integrates Value Stream Analysis (VSM) with the DMAIC problem-solving framework, incorporating a production problem set and sequencing mechanism to achieve simultaneous improvements across multiple production challenges. Application of this model to an air conditioning assembly line indicated significant improvements in production line balance, reduced work-in-process inventory, shortened supply delays, and enhanced economic benefits [13].

4.3. Research on the promotion and application of Lean Six Sigma

To date, LSS continues to gain momentum, with applications extending beyond the manufacturing sector into software and information technology, finance, transportation, healthcare, education, and other service industries.

Shahin *et al.* utilized the GPT-3.5 Turbo model to extract Voice of the Customer (VOC) data from Twitter customer support, innovatively correlating it with LSS to demonstrate how the model enhances customer-centric strategies in the era of Industry 4.0. This technological innovation provides real-time insights into customer needs, drives data-oriented customer service strategies, and offers robust data support for product iteration and process optimization [14].

Vashishth *et al.* reviewed relevant studies on LSS in the financial services industry since 2005, noting a positive development trend in LSS applications but also identifying areas for improvement, such as the need for a sustainability framework and a professional training and certification system for LSS [15].

Mitchell *et al.* conducted a case study on a shipping service company, designing a new information-sharing process using the DFSS method. The research team gathered user needs through interviews, surveys, and other methods, ultimately determining the final solution through affinity diagramming and option analysis. This enabled effective communication of cargo transportation information across all levels of the supply chain [16].

Similarly, Adeodu *et al.* examined a third-party logistics company's warehouse, employing the DMAIC method to enhance warehouse processes. Their efforts resulted in a significant improvement in production efficiency, with process cycle efficiency increasing by approximately 30% and non-value-added time reduced by 30% [17].

Additionally, Garza-Reyes *et al.* proposed an LSS framework for reducing ship loading commercial time, building on the traditional DMAIC approach. They clearly defined the specific activities and tools at each stage and demonstrated the framework's effectiveness using a large iron ore producer as an example, reducing loading times by over 30% and yielding substantial economic benefits for the business. These studies collectively highlight the effective application of Lean Six Sigma in the transportation industry, showcasing its potential to enhance efficiency, improve processes, and facilitate communication [18].

Trakulsunti *et al.* applied the LSS method to the drug dispensing process in the inpatient pharmacy of a large public hospital in Thailand. Their case study demonstrated that the LSS method is both effective and feasible in reducing drug dispensing errors [19].

Teeling *et al.* discussed the application of the LSS method in optimizing surgical processes, covering everything from patient referral to postoperative rehabilitation. In this context, the LSS method proved its value by shortening patient waiting times, standardizing procedures, and enhancing operating room efficiency as well as postoperative care [20].

Suman *et al.* investigated the use of LSS in the medical field in India, finding that while it is still in the early stages of implementation, it holds significant potential. Hospitals that adopt LSS show improvements in quality and practice; however, they face challenges such as costs, knowledge gaps, and difficulties in data collection and analysis. Overall, LSS plays a crucial role in enhancing the quality and efficiency of care, although its implementation requires overcoming several challenges [21].

Gupta *et al.* utilized LSS to address the dropout problem among middle school students in educational institutions, effectively resolving three key obstacles: unclear causes, insufficient controls, and weak awareness.

Their efforts helped colleges and universities reduce dropout rates [22].

5. Future prospects of Lean Six Sigma

In the context of Industry 4.0 and "Made in China 2025," integrating LSS with advanced technologies offers promising development prospects.

(1) Data-driven improvements in accuracy and efficiency: The vast amount of data produced by Industry 4.0 serves as a valuable resource for LSS. Through data analysis, organizations can more accurately identify issues and their root causes, enabling the development of scientific and effective solutions.

(2) Collaborative optimization to enhance overall efficiency: Integrating LSS with Industry 4.0 technologies facilitates collaborative optimization across departments and processes. For instance, smart devices provide real-time feedback on production data, allowing LSS projects to perform precise measurements and analyses. Moreover, industrial internet platforms can integrate data from various stages, improving process management efficiency.

(3) Human-machine collaboration to unleash human potential: Combining LSS with smart manufacturing enables employees to shift from repetitive tasks to higher-value activities. For example, intelligent robots can handle dangerous and mundane operations, freeing employees to focus on problem-solving and enhancing productivity.

(4) Predictive maintenance to reduce operational costs: By integrating LSS with sensors and big data analytics, predictive maintenance of equipment can be achieved. Early detection of equipment failures minimizes downtime, reduces production losses, and improves equipment utilization.

(5) Promoting digital transformation and supporting enterprise upgrades: The digital transformation of LSS helps enterprises build a robust quality management system, enhance production efficiency, and reduce costs. This, in turn, strengthens overall competitiveness and supports the strategic objectives outlined in "Made in China 2025."

6. Summary

In recent years, there has been increasing emphasis on the research and application of LSS. This paper provides a systematic review of the origins and development of LSS, discusses its theoretical framework, and considers its future prospects. Research shows that LSS can be effectively applied across various sectors, including manufacturing, services, healthcare, and education, yielding significant results. With the continued advancements in Industry 4.0 and digital transformation, LSS is expected to integrate with advanced technologies, presenting broader development opportunities. Moving forward, LSS will focus increasingly on data-driven methodologies, collaborative optimization, human-machine collaboration, predictive maintenance, and digital transformation to create greater value for enterprises.

Disclosure statement

The author declares no conflict of interest.

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