

■ Capítulo 10 | Quality Evolution: Challenges and Opportunities in the Convergence of Lean Six Sigma and Quality 4.0 and future directions

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Abstract:

This study presents a literature review on the convergence of Lean Six Sigma (LSS) and Quality 4.0, focusing on the challenges, opportunities, and future directions. LSS, known for its emphasis on waste reduction and process optimization, is examined in the context of Industry 4.0 (I4.0) advanced digital technologies, such as the Internet of Things (IoT), big data analytics (BDA), artificial intelligence (AI), and robotics. The review identifies some key challenges including technological complexity, the need for skilled workforce, cultural suitability and financial plausibility. Opportunities highlighted include enhanced operational efficiency, real-time data-driven decision making, and improved customization and flexibility in production processes. Future directions are identified, emphasizing the need for developing robust frameworks for integration, interdisciplinary collaboration, and scalable solutions adaptable across various industries. The findings underscore the potential of convergence of LSS and Quality 4.0, paving the way for a more efficient, resilient, and adaptive organization environment.

Keywords: Challenges, Lean Six Sigma, Opportunities, Quality 4.0

10.1 Introduction

The quality evolution confirms the ongoing search for excellence in production, services, and management. This progress has been characterized by continuous development of tools and techniques to enhance efficiency, reduce waste, and improve customer satisfaction within some major paradigm shifts accompanied by a huge number of development steps with the establishment and unceasing improvement of innovative methods and tools for quality management (Weckenmann et al., 2015).

Earliest forms of quality assurance (QA) can be tracked back to the craftsmanship era, where crafts workers took pride in their labour, ensuring high-quality standards through accurate

attention to detail and tailored work to address customers' needs and expectations. With the arrival of mass production throughout the Industrial Revolution, quality inspection became essential where the inspectors were engaged to check finished products for defects, which was a reactive approach to quality control (Garvin, 1988). The introduction of Statistical Quality Control (SQC) in the 1920s by Walter A. Shewhart marked a significant shift and Shewhart's development of control charts was key for the monitoring of production processes to detect variations before they resulted in defects, adopting a preventive approach to Quality Control (QC) (Shewhart, 1931). The SQC was widely adopted during World War II as the need for reliable and high-quality military equipment pushed its use and development highlighting the relevance of statistical methods in QC (Duncan, 1986; Joseph Moses Juran, 1997). The post-world War II received important contributions from quality gurus such as W. Edwards Deming, Joseph Juran, and Philip Crosby, among others. Deming's 14 Points for Management, Juran's Quality Handbook (J M Juran & Godfrey, 1999) and Armand Feigenbaum's book Total Quality Control (TQC) were forerunners for the understanding of what would become Total Quality Management (TQM) (Feigenbaum, 1983). TQM emphasized a systematic and holistic approach to managing organizational quality with the integration of quality into all aspects of business operations and the term TQM began to be popularized in the second half of the 80s (Martínez-Lorente et al., 1998). Lean manufacturing was coined by Womack, Jones and Roos from the MIT in their book *The Machine that changed the world*, in which they compared Japanese and American companies highlighting the efficiency of Toyota Motor Company with its Toyota Production System (TPS) (Womack et al., 1990). Lean focuses on waste reduction and processes improvement with some tools including value stream mapping (VSM), 5S and kaizen which have been critical in rising efficiency and reducing costs. The main principles encompass the identification of value, the mapping of the value stream, the creation of flow, the establishment of a pull system and the strive for continuous improvement. The expression "lean thinking" was first used by Womack and Jones (2010) in the book with the same name. Lean thinking is a management framework aiming to help practitioners improve efficiency and the quality of work encouraging the whole organisation to banish waste and create wealth in the organization. The Six Sigma (SS) was developed by Motorola in the 1980s to reduce variations in Motorola's electronic manufacturing processes and was popularized by General Electric as a business methodology for quality improvement. The SS goal is the near perfect quality with the continuous reduction of processes variation using a data driven approach with the 5 step DMAIC (define, measure, analyse, improve and control) process and statistical analysis to identify and eliminate defects (Maguad, 2006). The concept Lean Six Sigma (LSS) was created in the 2000s with the book entitled *Leaning into Six*

Sigma: The Path to integration of Lean Enterprise and Six Sigma (Wheat et al., 2001). The LSS has the power of combining the strengths of both L and SS and has been widely adopted across various industries (Atmaca & Girenes, 2013). The adoption of LSS, as a continuous improvement approach has grown vastly in the manufacturing sector as well as some service sectors such as health care and higher education during the past decade (Patel & Patel, 2021).

In the current era of digital transformation, Quality 4.0 (Q4.0), a term introduced by Dan Jacob in 2017 is focused on integrating cyber and physical interfaces leveraging advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and Big Data analytics (BDA) to enhance quality management (QM) with Q4.0 emerging as a response to the industry 4.0 (I4.0) paradigm with the meaning of adapting quality management systems (QMS) to contemporary industrial advancements (Jacob, 2017). Predictive analytics, automated QC systems, and real time monitoring represent the path forward of modern quality tools. Q4.0 has recently become very popular and (Sader et al., 2022) performed a review of Q4.0 highlighting some of definitions and features of the Q4.0 with a focus in the digitalization of the TQM and the application of the technologies available in I4.0 with the goal of understanding which technologies could improve quality practices.

The progress from simple inspection techniques into the actual sophisticated digital solutions notably improve the efficiency of the processes, contribute to significantly lower the probability of defects and to improve and exceed customer satisfaction. The integration of digital technologies in Q4.0 presents great opportunities for growing quality management practices. The organizations that successfully pull these technologies can achieve unique levels of quality and efficiency.

LSS has evolved by combining I4.0 technologies such as IoT, BDA, AI, and robotics with the aim of enhancing processes, performing real-time monitoring, and improving decision-making capabilities. Skalli et al. (2023) developed a comprehensive framework for integrating LSS and I4.0 addressing theoretical elements and practical applications. The convergence of LSS and Q4.0 is a natural process that comes from the extension of I4.0 with a focus on QM encompassing real-time data collection, analysis, and feedback mechanisms, enabling organizations to make faster, more informed QC and QA decisions.

This paper attempts to explore the challenges and opportunities in the convergence of LSS and Q4.0 by reviewing the literature on the topic. The main research question is to understand how LSS has evolved to date, particularly by tracking the challenges and opportunities evolution over time and future directions.

10.2 Literature review

The review focuses on building through the understanding of LSS evolution particularly by looking at the evolution over time and understanding the new paradigm of LSS in the era of Q4.0 by examining research articles. The well-known Web of Science (WoS) was used with a search among all the searchable fields using one query “Lean Six Sigma” to easily find the search term in any field. A total of 2256 publications were selected from the WoS core collection. From the search for publication years, I could observe that the first publication addressing LSS dates to 1995, and since 2015 till the present the number of publications per year consistently exceed one hundred. While conducting this research from the selected publications I came across a total of 184 literature review papers, that were further investigated with the main goal of analyse the literature review papers to understand the focus of review that was conducted on those publications and be able to explore the challenges and opportunities in the convergence of LSS and Q4.0 by the analysis of the literature on the topic.

10.2.1 Outline of literature review on Lean Six Sigma

The first review paper dates to 2007 and since 2016 till the present the number of review papers consistently exceeds a dozen, with the year of 2021 presenting a total of 30 review papers, representing the year with the highest number of published review papers. The screening process consisted in the abstract reading of the 184 review papers to understand the purpose and the findings of each paper, and based on the screening a total a total of 45 review papers were selected for further reading and deeper analysis (Table 10.1).

#	Authors /Description of the Study
1	(Chugani et al., 2017) The study analyzed a sample of 70 papers published in the top operations and quality management journals to offer a discussion on environmental concerns related to Lean (L), Six Sigma (SS) and Lean Six Sigma (LSS). The study reveals that organizations can consider the adoption of L, SS and LSS to meet environmental regulations, save costs and meet quality management standards with the goal of contributing to help organizations to formulate more effective and inclusive strategies which do not only consider the quality and operational dimensions but also the environmental dimension.
2	(Psomas et al., 2022) This work identifies the practical implications of L, SS and LSS in the public administration sector showing that the application of L, SS and LSS in the public sector has not been widely reviewed. The study shows that the stream of literature focuses on limited issues such as critical success factors, benefits, challenges, etc. The study presents a comprehensive conceptual framework to the practical dimensions of L, SS and LSS that could serve as research avenues for academics.
3	(Raval et al., 2018) The goal of the study is to examine the field of LSS by reviewing the existing literature and detecting the research gap. Authors find a noticeable rise in the attention of LSS research, and the case study method scores the highest among all the research methods used in LSS. Manufacturing and health-care sectors have been the focus of LSS research but there is still a lack of standard in the LSS implementation framework.
4	(Panayiotou & Stergiou, 2021) The goal of this paper is to review LSS implementation in European organizations written by academics or practitioners from European institutions to extract useful conclusions about LSS adoption in European companies and the work presents a clear view about the application of LSS projects in European organization suggesting ways of how the literature could be enhanced to simplify the LSS implementation.

5	(G. Yadav & Desai, 2016) The goal of the work is to clarify emerging aspects, trends and importance of LSS through reviewing the published literature. LSS research is growing rapidly, covering various domains with huge focus on LSS tools and techniques. Empirical research is prevalent with focus on case studies and research shows the growing gap between manufacturing- and service.
6	(Raval & Kant, 2017) This work investigates the literature about L, SS, and LSS frameworks. A huge number of frameworks were verified through survey, case study and simulation, but case study was found to be the most popular research design method for verification of frameworks but a coherent framework for LSS is still lacking. The study will assist to recognize the LSS filed trends and framework applicability.
7	(Pongboonchai-Empl et al., 2023) This review investigates which I4.0 technologies are proper for improving LSS tasks and the benefits of integrating I4.0 into improvement projects. The mapping of I4.0 related techniques to DMAIC phases and tools is presented in this work . The study refers to the fact that LSS practitioners are facing the challenges of growing complexity and data volumes and that they can benefit from the support of I4.0 technology into the DMAIC projects.
8	(Citybabu & Yamini, 2024) This paper investigates the research landscape of LSS 4.0 papers published in Scopus and Web of Science and a literature review was done to build a conceptual framework of integrated LSS and I4.0 (LSS 4.0) that encompasses operational, sustainability and human factors or ergonomics aspects. The conceptual framework and bibliometric analysis will be beneficial for those who are planning to apply and integrate techniques of LSS and technologies of I4.0 in their organizations and research.
9	(Huzu et al., 2018) The work provides information by the recent scientific literature on the impact of LSS on improved operational efficiency, higher profitability and quality of the processes in the medical sector and includes an analysis highlighting the advantages and disadvantages of the various LSS methods making recommendations on their application.
10	(Macias-Aguayo et al., 2022) A systematic literature review (SLR) of research on I4.0 and LSS integration was performed and as a result, 20 integration barriers and seventeen enablers were found. The article also discusses actions to facilitate I4.0 and LSS integration in practice, determined by connecting the identified enablers to their corresponding barriers.
11	(Trakulsunti et al., 2020) This work systematically review the literature on L, SS, LSS and its tools and techniques to reduce the medication errors in hospitals and some topics emerged in the context of medication errors, types of medication errors, LSS project selection, benefits, challenges and success factors.
12	(Tlapa, Tortorella, et al., 2022) This study aims to assess the effects of integrating L and SS with simulation modelling and provide a comprehensive understanding of their dynamics in healthcare settings. Most interventions focus on patient flow outcomes, reporting positive effects on outcomes related to access to service and utilization of services, including reductions in turnaround time, length of stay, waiting time, and turnover time. Notably, we found scarce outcomes regarding patient health, staff well-being, resource use, and savings.
13	(Alexander et al., 2019) This work explores the most common themes within LSS relating to SMEs within manufacturing organizations and the identification of research gaps within LSS so that practitioners can be fully aware of the benefits, limitations and impeding factors when implementing an LSS initiative. The paper provide insights to ensuring maximum value, is obtained from LSS implementation in SMEs
14	(Stankalla et al., 2018) This study addresses the critical success factors that condition the success of LSS and SS implementation in manufacturing SMEs to conclude that top management commitment and linking SS to business strategy are the top priority critical success factors, for both SMEs and large organizations. Additionally, for SMEs, it is necessary to develop a good communication plan and link SS to customers.
15	(Citybabu & Yamini, 2022) This work addresses LSS in the Indian context by reviewing the related literature for one decade based on various perspectives, such as author profile, year of publication, type of firm, type of methodology used, type of industry for which the research work is carried out and the key findings from the research., The authors have also identified the major contributions of researchers in various sectors during this period in India.
16	(Sreedharan & Raju, 2016) This study reviewed LSS literature and reported different definitions, demographics, methodologies and industries. Four significant LSS classifications were identified that deal with the spread of LSS in different industries followed by observation for classification. Various characteristics of LSS definitions and their theme were also reviewed.
17	(Abu Bakar et al., 2015) This paper review and gather critical success factors (CSFs) of LSS deployment and implementation into a comprehensive list of factors to conclude that most of the organizations were aware of the success story on LSS but did not scrutinize or consider its CSFs. CSFs similarities were clustered to provide the guidelines to industries/companies for successful deployment and implementation of LSS.
18	(Ahmad et al., 2023) This work explores the literature that integrates LSS with blockchain technology in different sectors for improved quality management and highlighted that prior blockchain-based solutions have neglected to leverage the benefits of LSS methodologies for effective quality management.
19	(Alnadi & McLaughlin, 2021) This paper provides a literature review on leadership behaviors that enable successful LSS implementation as thematic analysis in this field is scarce. Organizations and practitioners of LSS

	can take into consideration these behaviors as a key to the successful implementation of LSS and they can adjust their behaviors and know the behaviors that need to be developed amongst leaders.
20	(Shokri, 2017) This paper makes a hybrid analysis of three business improvement practices of L, SS and LSS within last two decades and identify the research gaps and focusses in more comprehensive and robust classification framework. Studies have been limited to a few industries, themes and countries. General manufacturing, healthcare, automotive and electronic industries as sectors; and tools and techniques, benefits and success factors as key themes have been mostly approached by LSS, SS and lean management articles
21	(Costa et al., 2018) A literature review was done to identify the appropriateness of L, SS and LSS initiatives for improvement in the food industry. The aim is to consolidate the existing knowledge about the application of LSS in the food industry, analyze the LSS evolution within the sector and identify the relevant aspects of implementation. The review suggests that LSS is effective in the food industry context and The application in the sector is still expanding.
22	(Rosa & Broday, 2018) This review of literature was made to identify the improvements acquired from the application of LSS in the industrial and service sectors in different countries. It has been found that LSS is a versatile tool that can be adapted and applied in any segment, allowing potential opportunities for new research and applications.
23	(Psarommatis et al., 2020) This literature review addresses the implementation of L, SS, LSS, TQM and Theory of Constraints, and their combination to improve quality of processes and products in a system. The study also covers the commonalities and differences with Zero Defect Manufacturing (ZDM) philosophy.
24	(V. Yadav et al., 2023) The study explores Green Lean Six Sigma (GLSS) approach, application status and potential benefits from a comprehensive review of the literature. It also provides a conceptual framework for GLSS and shows that GLSS implementation is increasing year by year, and it leads to considerable improvement in all dimensions of sustainability. Enablers, barriers, tools and potential benefits that foster the execution of GLSS in industrial organizations are also identified.
25	(McDermott et al., 2022) This study presents the challenges, critical success factors (CSFs), readiness factors and most common tools and techniques used for LSS deployment in healthcare. This work informs healthcare managers and professionals on the important factors for successful LSS deployment before embarking on the LSS journey and is a valuable resource to deploy LSS in the healthcare sector.
26	(Tampubolon & Purba, 2021) This review intends to identify how is the LSS implementation in many industries. The result shows that LSS is still being used and successfully help the organizations to improve their competitiveness, improve quality, reduce costs, increase customer satisfaction, increase productivity, and increase employee morale.
27	(Kaswan et al., 2024) This study investigates different facets of integrated GLSS and I4.0 approach in the context of COVID-19 for better healthcare management. Integrating GLSS and I4.0 has the potential to meet the modern demand of healthcare units and also leads to improving the quality of patient care with better safety, hygiene and real-time diagnoses. The study provides ways to comprehend the different facets of the integrated GLSS-I4.0 approach in different areas of COVID healthcare management.
28	(Prakash et al., 2022) This study presents an overview of leading research trends in the LSS domain published in the International Journal of Lean Six Sigma (IJLSS) since its inception and the findings informs about various qualitative research tools, applications and methods of implementing LSS tools in different industry sectors.
29	(Walter & Paladini, 2019) This work aims investigates LSS in the Brazilian context, and the results show that the most important critical success factor for integrating LSS in Brazil is top management support and commitment. LSS integration occurs predominantly in large industrial companies, being incipient in SMEs. In general, there is no structured way of applying LSS and a standard framework for LSS is still lacking. The study highlights several roadmaps for LSS implementation adopted by large and modern Brazilian automotive industries based on a robust technological base.
30	(Shokri et al., 2021) This work is a synthesis of literature published from 2010 to provide an understanding of the sustainable implementation of LSS projects in terms of project approaches rather than outcomes. The analysis shows that while studies have been conducted on LSS and green manufacturing integration, no studies have examined organizational culture or conducted readiness assessments on the sustainable implementation of LSS projects in the manufacturing sector.
31	(Muraliraj et al., 2018) This study addresses literature in LSS through multiple criterion for an enhanced understanding of the subject through summarizing its current trends, uncovering existing literature gaps and revealing opportunities for future research in the field.
32	(Nagadi, 2022) This review will help in sustainability and in the integration of various models for the improvement of the processes with GLSS as an approach to minimize emissions and carbon footprints while improving process efficiency. The successful integration of this GLS approach is dependent on different theoretical indicators and the model is developed based on DMAIC. Various tools, enablers and integration methods are employed for the GLS approach.

33	(Najafi et al., 2023) This review identified 58 articles that presented solutions for integrating AI or Blockchain in SS. The most widely used machine learning and deep learning algorithms in SS have been identified. Also, SS approaches that mostly use AI or Blockchain have been identified by the analysis of articles. Decision tree algorithms and artificial neural networks (ANN) are used in most DMAIC projects. By reviewing the articles, it was found that AI and Blockchain are mainly used as efficient tools in DMAIC and in this review 28 main gaps are presented as future works for future research.
34	(Patel & Patel, 2021) This work developed an understanding of the LSS since its inception and examined the few LSS dimensions as a research domain through a critical review of the literature. The adoption of LSS has grown in the manufacturing and few service sectors such as healthcare and higher education during the past decade. The study revealed that researchers came out with conceptual frameworks for the implementation of LSS, whereas the validation through case studies seems to be lacking. The integration of LSS and other approaches with a focus on sustainability has emerged as a research field.
35	(Saad et al., 2023) This study analyzed the current state of research to identify the link between Lean Manufacturing and I4.0 technologies to map out different research themes, to uncover research gaps and propose key recommendations. The integration will eventually bring many benefits and offers superior and long-term competitive advantages. There is the need for more analysis in real life and the promotion of operational changes to ensure enterprises run more sustainably.
36	(Franciscatto et al., 2023) A literature review was conducted, and findings show an increase in LSS applications in healthcare and higher education institutions. LSS is effectively applied in several areas and is continuously used in traditional industries. The main critical success factor identified was leadership and management involvement, project management and organizational infrastructure, as well as training and education and the main difficulties found are related to the organization's culture and developing communication with leaders and managers.
37	(Sunder et al., 2018) This paper reviewed the existing literature on LSS for services, constructed a morphological analysis (MA) framework and identify research gaps to point to future research possibilities and priorities. The MA framework constructed based on six dimensions, namely, organizational context of applications, desired outcomes, implementation systems, LSS tools and techniques, integration with other management philosophies and evaluation methods, involving 40 focused themes, has revealed 355 distinct research gaps as opportunities for future research.
38	(Laureani & Antony, 2019) This research goal was to consolidate the existing knowledge on leadership and LSS, providing a starting point for researchers and practitioners seeking to implement LSS in organizations.. The key findings of the review show that leadership is a requirement for successful LSS deployment in organizations, and LSS is an effective leadership development tool. Leadership is a critical factor for LSS success and there is the need to develop a new model of leadership that encompasses the leadership traits needed for LSS.
39	(Chugani et al., 2017) This work investigated, through a systematic review the environmental impact of using quality and operations improvement methods such as L, SS and LSS which includes the impact on energy saving and the usage of natural resources. The review indicates that both L and SS can be considered effective methods to support the conservation of resources, combat global warming and saving energy.
40	(Farrukh et al., 2020) This work explores the various constructs of GLSS that play an essential role in achieving environmental sustainability. For this purpose, a systematic review of available literature has been conducted to evaluate the drivers, enablers, and outcomes of a GLSS strategy as well as its critical success factors and barriers. Based on the analysis, an integrated GLSS framework is developed for environmental sustainability in addition to identifying vital research gaps and future directions.
41	(Sordan et al., 2022) This paper develops a conceptual framework of the implementation of the contact points (CPs) between LSS and I4.0 technologies. The conceptual framework involves 13 CPs between LSS practices and I4.0 technologies going through the technical requirements needed categorized as information technology (IT), automation and competence requirements, to finally present the main results reported in the literature. It is hoped that the framework can assist future research and operational excellence projects towards digitalization.
42	(Sharma & Singh, 2023) This study scrutinizes the constraints associated with initial quality control methods, underscoring the necessity for more all-encompassing and forward-looking models. The research advocates for the fusion of L, SS, and I4.0 (LSS 4.0) as a potent quality control paradigm for the Indian textile domain. The LSS 4.0 framework connects L and SS principles to optimize processes while incorporating I4.0 innovations for real-time monitoring, data analysis, and automation. The study sets a roadmap for industry stakeholders, delineating essential steps such as investing in technology, training, and transforming organizational culture to embrace and implement this integrated model.
43	(Citybabu & Yamini, 2023) This work conducts a literature review of LSS in the Indian context and related research publications and apply bibliometric analysis and the author's visualization to map research trends in this area. The results of the bibliometric analysis indicate that the LSS culture has widely spread in India.
44	(Tissir et al., 2023) This paper makes a review in the field of LSS4.0 to present the results of existing studies on the LSS and I4.0 integration, find the gaps in the literature, and provide directions for future studies. The paper

	recommends a framework that classifies the findings into relationship, implementation, and impact on performance.
45	(Vashishth et al., 2019) This work explores the trend and most common topics about LSS application in the finance sector, and also to identify gaps in that may be avoiding organizations from recognizing benefits from their LSS strategy. This paper is based on a comprehensive literature review which allows LSS researchers to understand in depth some common topics about LSS.

Table 10.1 – Selected reviews on Lean Six Sigma

LSS, like many other scientific areas, has evolved, and new tools and best practices are continually being adopted and refined. Review papers from recent years reflect the advancements and offer insights. Looking at the results from Table I it is possible to understand the evolution within different criteria. The main criteria selected were to better understand the industry adoption and trends, the LSS framework, the response to global challenges and the technological integration.

10.2.2 Industry adoption and trends

Different industries adopt L, SS, and LSS practices at varying rates which leads to a corresponding increase in research. Huzu et al. (2018) evaluated the impact of LSS on improved operational efficiency, higher profitability and quality of processes in the medical sector. Also, Trakulsunti et al. (Trakulsunti et al., 2020) review the literature on L, SS and LSS intervention and its tools and techniques to reduce medication errors in hospitals. Tlapa et al. (2022) studied the dynamic of L, and LSS in healthcare settings and concluded that emergency departments and laboratories are the main settings. Shokri (2017) study reveals that outputs about L, SS and LSS have been mainly limited to a few industries such as general manufacturing, healthcare, automotive and electronic industries. Also, Raval et al. (2018) refer that manufacturing and health-care sectors have been the focus of LSS research but there is still a lack of standard in the LSS implementation framework. Huzu et al. (2018) provide information by the recent scientific literature on the impact of LSS on improved operational efficiency, higher profitability and quality of the processes in the medical sector. Alexander et al. (2019) explore the most common themes within LSS relating to SMEs within manufacturing organizations and provide insights to ensure that maximum value, is obtained from LSS implementation in SMEs. Other studies address the critical success factors that condition the success of LSS and SS implementation in manufacturing SMEs to conclude that top management commitment is the top priority critical success factor (Stankalla et al., 2018). Sreedharan and Raju (2016) highlighted that LSS research was mainly focused on the manufacturing sector, despite LSS was also spread to other type of

industries. However, the adoption of LSS in SMEs was not widespread due to implementation costs, uncertainty and lack of a clear roadmap for deployment.

Patel and Patel (2021) highlight that the adoption of LSS as a continuous improvement methodology has grown enormously in the manufacturing and few service sectors such as healthcare and higher education during the past decade. Costa et al. (2018) review suggest that L and SS are effective in the food industry context and their implementation in the sector is still growing. Psomas et al. (2022) study identifies the practical implications of L, SS and LSS in the public administration sector, showing that their application had not been widely reviewed with fewer studies in the public administrative sector. According to the authors, the practical implications of L, SS and LSS in the public sector reflect elements that should be adopted regarding organizational culture, employee education or commitment which can be explained by the service's distinctive characteristics as well as by the specific features of the public sector. Trakulsunti et al. (2020) made a systematic literature on L, SS, LSS and its tools and techniques to reduce the medication errors in hospitals. The authors refer that the extant literature does not provide a roadmap to guide practitioners to follow for the implementation of L, SS or LSS to reduce medication errors.

Panayiotou and Stergiou (2021) review the LSS implementation in European organizations and concluded that the proportion of papers produced by all European countries in total is too low in contrast with other countries from the rest of the world focusing areas such as higher education, healthcare or finance and public sector reflecting the positive impact of LSS on the society as a whole through the provided services by the public sector organizations. Nowadays sectors such as healthcare have grown substantially to improve patient care and reduce operational costs. Currently some educational institutions use LSS to streamline administrative processes and improve academic operations. Despite the lower number of studies in the public administrative sector, this is an area where the LSS have huge potential for governmental agencies and other public sectors in adopting LSS to improve public services and reduce bureaucratic inefficiencies.

10.2.3 LSS framework

Raval and Kant (2017) critically reviewed the LSS frameworks in the existing literature and were able to identify some discrepancies such as laxity of researcher in the utilization of existing frameworks as well as lack of participation of practitioners and consultants in the development of LSS frameworks with the case study founded to be the most popular research design method for verification of frameworks. According to the authors a coherent framework for LSS is still

lacking. Also, Yadav and Desai (2016) refer that empirical research is prevalent with focus on case studies.

More recently Citybabu and Yamini (2024) build a conceptual framework of integrated LSS and I4.0 which they named LSS 4.0 exploring how the conceptual framework helps professionals and researchers understand the significance and impact of integrating LSS and Industry 4.0 in the aspects of human factors/ergonomic, sustainability and operations. However, there is still missing a framework that is considered the standard and proved to be widely used by practitioners and managers. Developing a widely accepted framework that accommodates the convergence between LSS and Q4.0 would be extremely useful for practitioners and using Q4.0 in LSS allows organizations to position themselves consolidating LSS approach to promote sustained development towards stages of advanced technological integration.

10.2.4 Response to Global Challenges

The growing awareness of environmental issues mainly at the beginning of the new millennium led to the integration of sustainability into business processes with the rising emphasis on the adoption of LSS to push companies to look ways to improve efficiency and minimize costs. Green (G) LSS emerged as an approach combining LSS with environmental issues and so G-LSS as the goal on focusing not only on quality but also on reducing the environmental impacts, with G-LSS targeting emissions, energy usage and material resources to optimize the use of resources and minimize the environmental impact. Also, recent global challenges such as COVID 19 pandemic have forced organizations to rethink and improve their processes and LSS can help in this endeavour and be a valuable approach leading to an uptick in research. Chugani et al. (2017) refer that organizations can consider the adoption of L, SS and LSS to meet environmental regulations while saving costs and meeting quality management standards. The authors give some research questions that can be explored in the future including studies to understand if the implementation of LSS assists organizations to be more environmental sustainable, understand how environmental pressures may affect the choice of quality improvement programs and better understand what are the main challenges of G-LSS implementation

Shokri et al. (2021) study shows that despite research studies have been conducted on LSS and Green (G) manufacturing integration there is a lack of studies regarding the assessment on the sustainable implementation of LSS. Yadav et al. (2023) explored several aspects of GLSS and showed that G-LSS implementation is increasing year by year leading to considerable improvement in all dimensions of sustainability. Nagadi (2022) refers the value of GLSS as an approach to minimize emissions and carbon footprints while improving process efficiency as

GLSS includes green, Six Sigma and lean methodologies for high performance, sustainability, social development, economic progress and environmental protection. Chugani et al. (2017) investigated the environmental (green) impact of using quality and operations improvement methods such as L, SS and LSS. The review indicates that both L and LSS can be considered effective to support the conservation of resources and combat global warming as organizations should not only consider L and LSS to manage quality and improve operational performance but also meet environmental regulations. Farrukh et al. (2020) developed an integrated GLSS framework for environmental consideration. Kaswan et al. (2024) literature review investigated the integrated facets of G-LSS and Industry 4.0 (I4.0) to meet the demands of actual healthcare while providing different avenues to understand the different facets of the integrated GLSS-I4.0 in different areas of COVID healthcare management.

10.2.5 Technological integration

The integration of advanced technologies, such as AI, IoT, BDA, Data Mining (DM), Artificial Neural Networks (ANN) into LSS has been a significant trend in recent years. Review papers focus on how these technologies enhance LSS methodologies, making them more relevant to current industry needs. Pongboonchai-Empl et al. (2023) examined which Industry 4.0 (I4.0) technologies are suitable for improving LSS and mapped the I4.0 related techniques to DMAIC phases. The authors examined I4.0 solutions such as ANN, DM, BDA, and AI in conjunction with LSS tools, explored how I4.0 technologies can enhance LSS projects, and their study shows that there is much interest in exploring integration opportunities.

Citybabu and Yamini S. (2024) literature review was carried out to build a conceptual framework of integrated LSS and I4.0 that encompasses operational, sustainability and human factors or ergonomics aspects and their research is useful for professionals to incorporate all those factors while designing and applying the integrated framework (LSS4.0). Tlapa et al. (2022) assessed the effects of integrating L and SS with simulation modelling and provide a comprehensive understanding of their dynamics in healthcare settings and concluded that most interventions focus on patient flow outcomes, reporting positive effects on outcomes related to access to service and utilization of services, including reductions in turnaround time, length of stay, waiting time, and turnover time and scarce outcomes regarding patient health, and staff well-being.

Macias-Aguayo et al. (2022) made a systematic literature review of research on I4.0 and LSS to identify integration barriers as well as the main enablers and discuss actions to facilitate I4.0 and LSS integration by connecting the identified enablers to their corresponding barriers. A range

of I4.0 technologies enabling the integration was identified, with BDA, IoT, Cloud Computing (CC), and radio-Frequency Identification (RFID) referred as the most recurrent in the reviewed literature.

Ahmad et al. (2023) studied and analysed the literature that integrates LSS approach with blockchain technology (BT) in different sectors for improved quality management. Kaswan et al. (2024) systematic review provides different avenues to comprehend the different facets of the integrated GLSS-I4.0 approach in different areas of COVID health-care management. Saad et al. (2023) analysed the current state of research to identify the link between Lean Manufacturing (LM) and I4.0 technologies to map out different research themes, to uncover research gaps and propose key recommendations for future research, including lessons to be learnt from the integration of L and I4.0. Sordan et al. (2022) developed a conceptual framework of the implementation of the contact points (CPs) between LSS practices and I 4.0 technologies. Sharma and Singh (2023) research advocated for the fusion of LSS, and I4.0 (LSS 4.0) as a potent quality control paradigm for the Indian textile domain. Tissir et al. (2023) did a review to present the results of existing studies on the LSS and I4.0 integration. According to Panayiotou and Stergiou (2021) the role of technological advancements such as I4.0 should be further analysed in future studies, as it can act as important enabler in the implementation of improvement initiatives based on the LSS principles.

10.3 Convergence of Lean Six Sigma and Quality 4.0

Industry 4.0 encompasses the integration of digital technologies into manufacturing and industrial processes including technologies such as the IoT, AI, robotics, BDA, and cyber-physical systems. Quality 4.0 represents the application of Industry 4.0 technologies to quality management aiming to enhance traditional quality practices through digital transformation, improving the accuracy, speed, and effectiveness of quality control and assurance processes. The convergence of Lean Six Sigma and Quality 4.0 will allow enhanced data collection and analysis as Quality 4.0 with IoT and advanced analytics provide real time, and comprehensive data improving the ability of LSS to focuses on reducing waste and inefficiency, and minimize defects and variations in processes in a combined approach used to streamline operations, improve quality, and rise organizational efficiency. The convergence also has a strong role in predictive and preventive quality as AI and machine learning can predict issues before they occurring allowing for proactive interventions within LSS to better understand process behaviour and implement preventive measures. The convergence will also contribute to the use of automated

processes as Q4.0 automation and digital systems can implement LSS improvements more consistently, with a reduction in human errors and enhanced reliability. The utilization of IoT sensors and BDA will provide continuous monitoring allowing rapid feedback and adjustments conducting to real time quality monitoring. The dynamic process improvement is a benefit as Q4.0 implements improvements using real time and predictive analytics to continuously optimize processes assuring that the processes will be kept effective and efficient over time. The convergence of LSS and Quality 4.0 creates a robust framework for achieving operational excellence in the digital age and organizations can enhance efficiency, reduce waste, and improve quality, positioning themselves for success in a rapidly evolving market.

10.3.1 Challenges and opportunities

The convergence of LSS and quality 4.0 offers numerous opportunities but also presents several challenges. One of the main challenges can be cultural resistance as it can be difficult to change management and get employees keen to adopt new I4.0 technologies and moreover to merge the traditional LSS and quality 4.0. To make the convergence easier the skill gap between traditional manufacturing practices and digital technologies must be overcome. The technological complexity is a challenge with issues of interoperability to ensure that different systems and technologies can work together, or issues regarding data management with the questions raised by I4.0 with the handling, storing and analysis of large volumes of data, as well as data privacy to ensure compliance with data protection regulations. Cybersecurity is also a challenge with the need to protect critical manufacturing data from cyber threats. The convergence of LSS and Q4.0 can also pose challenges related to the process integration and how to incorporate new technologies with existing systems without disrupting existing systems and operations. Despite the challenges there are excellent opportunities related to the enhancement of efficiency and productivity posed by the convergence of LSS and quality 4.0. First, the possibility to implement real time data monitoring and analytics to rapidly identify and address process nonconformities or inefficiencies, and the possibility to use IoT and AI to promote the automation of repetitive tasks also contributing to the increase of efficiency as well as to the reduction of human errors, giving the employees the opportunity to perform more creative tasks. Another huge opportunity is related to the QC improvement with the utilization of machine learning to predict equipment failures reducing downtime and the utilization of advanced analytics to identify defects and improve product and process quality and using LSS principles to improve processes based on data driven actions and using big data analytics to data driven decision making. The convergence of LSS with quality 4.0 will lead to great flexibility with smart manufacturing techniques allowing

to quick and efficient adaptations in the production requirements aligning it with changes in customers' needs and delivering products faster that are aligned with customers' needs and lead to increasing customer satisfaction. The convergence of LSS and quality 4.0 also brings opportunities related to sustainability with the use of smart energy and resource management systems.

Macias-Aguayo et al. (2022) made a systematic literature review (SLR) of research on the integration of I4.0 and LSS discussing actions to facilitate I4.0 and LSS integration in practice and identified opportunities and challenges of the integration. One of the main opportunities that was identified is the collaborative culture. A collaborative culture within a business can significantly enhance its chances of success conducting to enhanced innovation as a collaborative culture promote the sharing of ideas and perspectives sparking creative solutions. Collaboration brings diverse viewpoints and lead to better decision-making. A collaborative culture also encourages knowledge sharing contributing to learning and development and increased efficiency as when teams work together effectively, they streamline processes and reduce redundancies. Businesses can also respond more flexibly to market changes and innovate better through strong collaboration among the stakeholders. The strategic orientation is also an opportunity that cannot be missed. Investing in staff training, IT infrastructure, and work to the mature understanding of intelligent digital technologies and its integration in manufacturing and industrial processes and leveraging the technology with people to improve the quality of an organization makes part of the strategy. Another opportunity is to work in the simplification and standardization of processes as they are key to make the operations more efficient. Also do not miss the opportunity to interconnect IT systems as interoperability will increase flexibility and contribute to better integrate Q4.0 and LSS. In addition, Macias-Aguayo et al. (2022) also identified supporting technologies studied in the context of integration with LSS. The main enabling technologies were big data, internet of things (IoT), cloud computing, radiofrequency identification (RFID), digital twins/simulation, robots/automation, enterprise resource planning (ERP), augmented reality (AR), digital automation/sensors, artificial intelligence (IA), virtual reality (VR), blockchain and wireless sensor networks (WSNs).

The main challenges identified by Macias-Aguayo et al. (2022) in their SLR were cultural suitability, financial plausibility, operational viability and technological feasibility. Cultural suitability in the contexts of supporting technologies refers to the alignment of organizational culture with the principles and practices associated with the fourth industrial revolution and the main obstacles can be the resistance to change, lack of management support, lack of strategic company goals to integrate technologies and LSS, low employee involvement and lack of

communication. The financial barrier can occur due to high implementation costs or long implementation time. The operational viability can also be an issue, and the long learning curve can be a significant obstacle, as well as problems with non-standardized processes or poorly structured processes and insufficient data privacy or data security and data loss issues. The technological feasibility was also an identified barrier with obstacles such as the technology incompatibility, insufficient IT design and infrastructure, or the matching and integration between different data sources, the massive volume of data to be managed or even the lack of common communication protocols.

By addressing the challenges and leveraging the opportunities, organizations can significantly enhance their operational efficiency, product quality, and overall competitiveness through the convergence of LSS and Q4.0.

10.4 Future directions

LSS will continue to evolve with technological advancements and organizations that include these trends will likely see improvements in efficiency, and overall competitiveness. Despite the lower number of studies in certain sectors the LSS promise to drive significant benefits through the integration of cutting-edge technologies, responding to global challenges and widening the scope of application within industry sectors and geographical areas. This work highlights the need of developing a robust framework that accommodates the convergence between LSS and Q4.0 consolidating the LSS approach to support LSS through the integration of technology. The flexibility and customization will also emerge as a trend with scalable solutions adaptable across various industries, with flexible production systems that can quickly adapt to changes in production schedules, fluctuations in product demand or new product designs. The findings underscore the potential of convergence of LSS and Quality 4.0, paving the way for a more efficient, resilient, and adaptive organization environment. However, when organizations are still looking to implement the best practices highlighted by LSS and Quality 4.0, there are whispers and murmurs of Quality 5.0 and all the changes that it is going to bring to the world of QM. From the literature review carried out in this study, no review article on LSS and industry 5.0 (I5.0) was identified which shows that this is still a very recent topic and that there is room to explore the role that LSS can have within the scope of industry 5.0 and in the convergence towards Quality 5.0.

The European Commission offers some interesting views on I5.0 highlighting that Industry 5.0 complements and extends the features of I4.0 by emphasizing aspects that will be deciding

factors in placing industry in future European society (*Industry 5.0 - Towards a Sustainable, Human-Centric and Resilient European Industry - European Commission, n.d.*). These factors are not just economic or technological in nature, but also have important environmental and social dimensions.

The industry of the future should focus on the well-being of each individual and the impact of the goods produced on society. It should also consider the impact of manufacturing processes on the environment seeking to use energy-efficient production practices that reduce the carbon footprint. A balanced approach incorporating both technological advancements and sustainable and human-centric practices, is essential for sustaining and enhancing quality in the future.

LSS can offer a robust framework for continuous improvement and effective excellence, which can be substantially intensified by the advanced, sustainable and human-centric practices advocated by I5.0. The LSS focus on workers engagement where workers are empowered to contribute with ideas to innovation which leads to increased job satisfaction and productivity aligning with the human-centric approach of the I5.0. LSS also encourages skills development, encouraging training and development preparing the workforce to better collaborate with advanced technologies such as AI and robotics in I5.0. Lean principles aim to eliminate waste in processes which becomes even more effective when combined with I5.0 technologies, such as IoT sensors and AI, which can provide real-time data and predictive analytics to identify and mitigate inefficiencies. LSS emphasis on the efficient use of resources, with the minimization of environmental impacts, reducing wastes and enhancing energy efficiency aligning with I5.0 sustainability goals. The integration of LSS with I5.0 and the convergence towards Q5.0 can lead to more sustainable manufacturing processes and a better alignment with the circular economy model. LSS can help organizations to better adapt to changes in market demand, with a focus on flexibility as well as a rigorous approach to QC, combined with real-time monitoring and predictive maintenance facilitated by technologies, which can drastically reduce defects and improve product and service quality. LSS encourages a culture of continuous improvement and problem-solving, which can be enhanced by I5.0 emphasis on human creativity and the integration of advanced technologies and the synergy between humans and machines in I5.0 can drive innovative solutions that LSS teams can implement to further refine and enhance processes.

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