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Improving Sustainable Lean Six Sigma Adoption by Assessment of its Barriers: An Emerging Economies Perspective

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Abstract
The manufacturing sector across the globe has faced strong issues to achieve the desired performances amidst escalating product complexity and evolving customer demands. The present research work aims to delve into the impediments hindering the sustainable lean six sigma (SLSS) adoption methodologies, by computing their intensity of influence. The comprehensive review carried out in this study identifies pivotal SLSS barriers prevalent in manufacturing organizations, especially in emerging economies. Employing a fuzzy-analytical hierarchy process (AHP), the research quantifies the intensity of these barriers, providing insights crucial for effective SLSS implementation. Categorizing the identified barriers into five distinct themes enhances their analytical clarity. The findings underscore considerable variations in the intensity of SLSS barriers, underscoring the imperative for practitioners to navigate these challenges adeptly. Moreover, this study offers a valuable resource for researchers and practitioners seeking deeper insights into SLSS dynamics. While extant literature has extensively documented SLSS barriers, scant attention has been paid to elucidating their intensity. The present study endeavours to address this gap, presenting a pioneering contribution to the SLSS domain, poised to enrich understanding and inform strategic decision-making in manufacturing contexts.

Keywords- Sustainable lean six sigma, Fuzzy set theory, Barriers, Decision support analysis, Analytical hierarchy process.

1. Introduction

Globally it has been observed that the manufacturing industries are struggling to achieve the required performance based on their shop floor operations and their entire organizational process line (Prasad et al., 2022). They have a strong need to adopt quality practices that can help improve their overall productivity and boost their confidence to sustain themselves in the global competition (Gholami et al., 2021). To maintain profit margins several manufacturing organizations are in the process of implementing different quality practices available across the industrial engineering domain (Tayaksi et al., 2020). However, when it comes to particularly manufacturing industries, it is important to note that these industries need to take care of their main concerns; namely, cost reduction, desired quality and green aspect consideration. Accordingly, lean takes care of cost reduction by removing the non-value-added wastes, six sigma manages the product quality as per the standards, whereas sustainability ensures the consideration of green aspects. Hence, various manufacturing industries are shifting towards the adoption of Sustainable Lean Six Sigma (SLSS) which can offer them tri-benefits as mentioned above (Tiwari et al., 2020).

Unlike other industries such as the service, and healthcare sectors, manufacturing industries have a very complex structure of execution. Especially in the automotive and related domains of manufacturing, extreme preciseness is required across the manufacturing operation (Psarommatis et al., 2022). So, SLSS emerges to be the most optimum option to achieve the desired results which are aligned with the organizational productivity. However, when it comes to the implementation of SLSS methodology, it becomes critical due to the complexity of the working environment. There exists a large number of barriers to implementing SLSS methodology (Kaswan & Rathi, 2019). Many practitioners attempt to implement SLSS methodology into the system without consideration of SLSS barriers and later experience failure across the SLSS adoption. Many case studies throughout the globe have addressed that they are not able to implement SLSS effectively into their system structure. The core reason behind the adoption failure is lack of the analysis of SLSS barriers (Rathi et al., 2022).

The literature reveals that many researchers throughout the world have identified various SLSS barriers in their study. However, it is essential to capture that the occurrence of SLSS barriers solely depends upon the nature of the organization where the SLSS methodology is implemented. The set of SLSS barriers which relevant to the service and healthcare section might not necessarily be correlated directly to the manufacturing concerns. Hence, depending upon the nature, environment and process scenario of the organization, the barriers have different sets of influence. Similarly, even if the set of common barriers for a particular sector is identified, then too it is at times difficult to predict their influence intensity. So, it is important to not only identify the unique set of the SLSS barriers but also identify the intensity of influence of each barrier. Accordingly, the following objectives are finalized to pursue the current work (Yadav et al., 2020).

- To identify and finalize a comprehensive set of barriers that hinder the adoption of sustainable lean six sigma in manufacturing industries.
- To quantify the impact and intensity of each identified sustainable lean six sigma barrier during the implementation process within manufacturing industries.

To achieve the above-defined objective, a decision-support study based on the fuzzy set theory is integrated with an analytical hierarchy process approach. In this study, the team of decision experts is constructed in a manufacturing organization and their inputs are captured in the above-mentioned decision support study. According to the results obtained from the decision support study, the intensity of the influence of each SLSS barrier is computed and accordingly, the managers and practitioners who are directly involved in SLSS implementation across the manufacturing industries can develop preventive strategies.

This research work is carried out in seven sections including this section. Section 2 projects the SLSS literature available related to its barriers. The section portrays the research methodology adopted for the study. Section 4 highlights the decision support method and its execution for analyzing the SLSS barriers. Section 5 portrays the discussion and findings of the study. Section 6 sheds light on the implications of the study. Whereas, the last section projects the study conclusions, followed by prospects based on the identified SLSS barriers.

2. Literature Review

2.1 Article Collection

Conducting a literature review before the initiation of research work is extremely essential. It is often observed that many researchers conduct extensive research work but do not take care of the prior published work, finally results in coming up with unpredictable outcomes which hold less reliability. In this context, before performing the decision support analysis of the SLSS barriers it is mandatory to move forward and explore the existing SLSS barrier literature reported by other researchers in the existing literature. To serve this purpose, the current study explores the existing SLSS literature that highlights the barriers, challenges, shortcomings and obstacles faced by the practitioners during SLSS implementation. For exploration purposes, the Scopus database was adopted by using the following keywords; “sustainable lean six sigma barriers", "sustainable lean six sigma challenges", "sustainable lean six sigma failure factors", "sustainable lean six sigma indicators". Only the journal articles were included and excluding all the types of articles. Later, the most critical SLSS barriers articles were shortlisted which specifically focused on SLSS barriers identification and its intensity computation.

2.2 SLSS Barriers

SLSS has turned out to be a pivotal approach for enhancing efficiency, reducing waste, and promoting sustainability within manufacturing industries (Valamede & Akkari, 2020). By appropriate integration of lean and six sigma principles with sustainability practices, SLSS targets achieving operational excellence by minimizing the hazardous environmental impacts on society. Effective SLSS adoption strongly depends upon evaluating various critical factors that influence its adoption (de Freitas et al., 2017). The literature studies reveal that a robust interdepartmental IT linkage and communication system is important for smooth information flow across departments, resulting in fluent decision-making, and appropriate collaboration. Improved data analytics systems also assist this by providing valuable insights into the operational activities, exploring improvement areas, and resulting in effective decision-making. Furthermore, the inclusion of risk management practices is significant to assess the potential threats and accordingly prepare the mitigation strategies. Similarly, adopting industrial ecology initiatives involves the integration of eco-friendly practices among the system processes, that support resource efficiency, and eliminate waste (Alhuraish et al., 2017). Additionally, the awareness of government policies and schemes that provide financial subsidies, and training modules plays a vital role in the organizational structures for adopting green practices and giving financial support for improvement. These factors jointly result in developing a robust foundation for SLSS implementation, resulting in green adoption throughout the system (Singh et al., 2021a).

The appropriate SLSS adoption requires a systematic approach that focuses on strategic and operational planning, the involvement of stakeholders, and a strong awareness of sustainability principles (Kaswan et al., 2021). The effective junction of government-supportive schemes, manufacturers, customers, and suppliers is extremely important for managerial strategies that support sustainability objectives. Customer awareness within the different R's becomes essential because it creates the necessity for sustainable products and increases the possibility for responsible consumption. The management involvement and engagement across the sustainability initiatives assist them in refining and maximizing the SLSS efforts and help in building a strong sustainability culture within the organizational structure. The availability of an effective performance measurement system helps managers assess the progress towards sustainability goals and also explore the possible areas where more efforts are required. The financial planning acts as a guideline for SLSS adoption, ensuring that resources are allocated appropriately to meet the defined objectives. While the 6 R's assist in the resource efficiency and elimination of waste. Defined employee training and awareness programs boost manpower capabilities, ensuring that they are aware of the essentials of SLSS adoption. The above-stated factors help in developing a strategic SLSS framework that results in continuous improvement and achieving sustainability (Sagnak & Kazancoglu, 2016).

By incorporating digital technologies and advanced techniques within the SLSS adoption process, it becomes apparent to take a close watch on operational efficiency, data accuracy, and real-time monitoring of the activities (Shokri et al., 2022). The digitization of supply chain processes helps in improving the process transparency and real-time tracking of man, machine and materials. Supplier integration plays a vital role in establishing strong partnerships, to meet sustainability standards and boost the final desired output from the collaboration (Yadav & Gahlot, 2022). Similarly, the penetration of several demand and forecasting techniques streamlines the activities involved in the production planning stages finally reducing waste, and ensuring effective resource utilization. Green purchasing, manufacturing and packaging-related activities reduce the negative impact on the environment by promoting eco-friendly materials throughout the production processes. Regulatory compliance helps the system structures and managers to believe that they meet the environmental regulations and standards and will keep away from the legal penalties and maintain the brand value. Adoption of the rewards, recognition and incentive system across the SLSS adoption process motivates employees and stakeholders to actively participate in sustainability initiatives and leads to the performance improvement set across different benchmarks and standards. Integration of cyber-physical systems boosts process automation and tracking of the activities on real real-time basis which might strongly influence efficiency. The appropriate actions by the quality assurance team to address customer complaints enhance customer trust and loyalty (Walter et al., 2023). These technological advancements and digital innovations improve the SLSS adoption possibilities which results in deeper alignment with the sustainability goals (Walter et al., 2023).

The internal stakeholders are the strong pillars that result in effective SLSS adoption so it becomes essential to capture their capabilities, involvement, and motivation in the process structure. Effective skilled staff recruitment and later the effective utilization of a skilled workforce increases the chances of SLSS adoption (Walter et al., 2023). The defined employee training programs boost their capabilities and assist them to work at their maximum potential and also understand the SLSS tools and techniques effectively. A deeper knowledge of the environmental and social benefits of adopting SLSS will encourage them to better penetration of SLSS and achieve the objectives closely related to sustainability. Incorporating the circularity by preparing different channels to collect end-of-life (EOL) products penetrating the circular economy approach promoting recycling and waste minimization. The digital supply chain processes improve real-time tracking of materials reduce the chances of the production of defective products that might degrade the product quality and enhance the chances of rework.

Strategic planning and effective resource utilization become extremely essential to seamless SLSS adoption and achieving the aligned sustainability goals linked to the organizational objectives (Gholami et al., 2021). The smooth operational planning enhances the chances of execution of SLSS initiatives and also makes sure that there is appropriate allocation and optimization of resources associated with the SLSS adoption process. Green purchasing, manufacturing and packaging-related activities reduce the negative impact on the environment by promoting eco-friendly materials throughout the production processes and also improve customer satisfaction possibilities. Regulatory compliance motivates the management to take care of the environmental regulations and standards giving a base to handle the market competition and balance the legal aspects. Integration of cyber-physical systems with internal activities provides smoother tracking of processes and minimizes the margin of errors. Sustainable actions on product complaints build the repetitive customers and boost the sales accordingly. The developed infrastructure in the digital supply chain support assists in reducing production time and ensuring timely deliveries. The optimization of the 3M's balances the resources by reducing waste and boosting organizational productivity. This effective utilization requires the availability of a skilled workforce that can optimize material usage and reduce the environmental impact. Hence, through strategic planning and resource optimization, the managers can achieve sustainability goals, and enhance the organizational performance (Ozturkoglu et al., 2021).

Awareness of government incentives, financial subsidies, and training programs plays a vital role in encouraging organizations to adopt sustainable practices by providing financial support and enhancing workforce capabilities. These elements collectively contribute to creating a cohesive and strategic framework for SLSS, driving continuous improvement, and achieving long-term sustainability. By enhancing collaboration and stakeholder engagement, organizations can effectively implement SLSS initiatives, drive continuous improvement, and achieve sustainability goals (Gholami et al., 2021). **Table 1** represents the SLSS barriers reported in the literature.

Table 1. Sustainable lean six sigma barriers captured through literature.

S. No.	SLSS barrier	Barrier description	Source
1.	Implementation of risk management strategies	Developing comprehensive plans to identify, assess, and mitigate risks associated with SLSS initiatives, ensuring smooth operations and minimizing disruptions.	Kaswan & Rathi (2020a), Parmar & Desai (2020)
2.	Understanding of environmental and social benefits	Promoting awareness of the positive impacts of SLSS on environmental sustainability and social responsibility among all stakeholders.	Cherrafi et al. (2016, 2017)
3.	Enhanced data analytics capabilities	Utilizing advanced data analytics to drive decision-making, optimize processes, and monitor SLSS performance.	Kumar et al. (2016), Chugani et al. (2017)
4.	Integration of cyber-physical systems with operational activities	Implementing advanced technologies that integrate physical and digital systems to enhance efficiency and control within the supply chain.	Kaswan & Rathi (2019), Yadav et al. (2020), Psarommatis et al. (2022)
5.	Establishment of structured channels for collecting end-of-life (EOL) products	Creating efficient systems for retrieving, recycling, or repurposing products at the end of their life cycle to support circular economy principles.	Glasgow et al. (2010), Hussain et al. (2019)
6.	Sustainable practices in procurement, design, and packaging	Ensuring that procurement, product design, and packaging processes adhere to sustainability standards to reduce environmental impact.	de Freitas et al. (2017), Alhuraish et al. (2017), Singh et al. (2021a)
7.	Regular employee training programs	Providing ongoing training to employees on SLSS principles, tools, and practices to build a knowledgeable and skilled workforce.	Timans et al. (2016), Erdil et al. (2018)
8.	Adoption of the 6 R's principles	Implementing the six R's to minimize waste and enhance resource efficiency throughout the supply chain.	Ruben et al. (2018), Kaswan & Rathi (2020b), Swarnakar et al. (2020a)
9.	Optimization of the 3M's (man, machine, material)	Ensuring optimal use of human resources, machinery, and materials to improve efficiency and productivity in SLSS initiatives.	Tiwari et al. (2020), Bhat et al. (2021), Gholami et al. (2021), Rathi et al. (2022)
10.	Development of advanced infrastructure for smooth supply chain operations	Investing in infrastructure that supports seamless supply chain activities, including logistics, warehousing, and IT systems.	de Freitas & Costa (2017), Gaikwad & Sunnapwar (2020)
11.	Recruitment and effective utilization of a skilled workforce	Attracting and effectively deploying talented individuals who can drive SLSS projects and contribute to continuous improvement.	Sony & Naik (2020), Singh et al. (2021a)
12.	Active management participation in sustainability initiatives	Encouraging top management to lead and support sustainability efforts, ensuring alignment with organizational goals.	Swarnakar et al. (2020b), Tripathi et al. (2021)
13.	Raising customer awareness about recycling practices	Educating customers about the importance and benefits of recycling to foster a culture of sustainability.	Caiado et al. (2018), Klochkov et al. (2019)
14.	Promotion of industrial ecology practices	Implementing practices that mimic natural ecosystems to create more sustainable industrial processes and reduce waste.	Douglas et al. (2017), Kaswan et al. (2023a)
15.	Integration of supportive government policies with manufacturers, customers, and suppliers for effective product development	Collaborating with government bodies to align policies and incentives that support sustainable product development and supply chain management.	Sagnak & Kazancoglu (2016), Caiado et al. (2018), Kaswan et al. (2021)
16.	Implementation of sustainable performance measurement systems	Establishing metrics and tools to regularly assess and report on the sustainability performance of SLSS initiatives.	Shokri et al. (2021), Tripathi et al. (2021)
17.	Awareness of government incentives, financial support, and training programs	Leveraging available government programs to support SLSS implementation, including financial incentives and educational resources.	Douglas et al. (2017), Kaswan et al. (2023a)
18.	Robust interdepartmental IT connectivity and communication systems	Ensuring strong IT infrastructure and communication channels b/w departments to facilitate coordination & information sharing.	Kumar et al. (2016), Chugani et al. (2017)
19.	Utilization of advanced demand forecasting techniques	Applying sophisticated forecasting methods to predict demand accurately, reducing overproduction and waste.	Kaswan & Rathi (2019), Yadav et al. (2020)
20.	Digitization of supply chain processes	Adopting digital technologies to streamline supply chain operations, enhance visibility, and improve decision-making.	Bhat et al. (2021). Yadav et al. (2023)
21.	Strategic planning for operations and finances	Developing comprehensive plans that align operational and financial strategy goals to ensure long-term sustainability.	Sagnak & Kazancoglu (2016), Cherrafi et al. (2017)

Table 1 continued…

22.	Integration of suppliers and effective vendor management	Building strong relationships with suppliers and managing vendors effectively to ensure they adhere to sustainability standards.	de Freitas & Costa (2017), Gaikwad & Sunnapwar (2020)
23.	Sustainable management of product complaints and returns	Implementing systems to handle product complaints and returns in a way that minimizes environmental impact and recovers value.	Sony & Naik (2020), Singh et al. (2021b)
24.	Implementation of rewards and incentives for CSC activities	Establishing reward systems to encourage participation in circular supply chain activities & recognize green contributions.	Cherrafi et al. (2017), Psarommatis et al. (2022)
25.	Adherence to regulatory compliance	Ensuring all SLSS activities comply with relevant regulations and standards to avoid legal issues and promote sustainability.	Sagnak & Kazancoglu (2016), Cherrafi et al. (2017)
26.	Weak infrastructure	Insufficient infrastructural facilities to execute the SLSS strategies effectively	Douglas et al. (2017), Kaswan et al. (2023b)
27.	Improper assessment of SLSS adoption costs	The ineffective assessment of the entire SLSS adoption costs ie. Financial estimation of implementation	Bhat et al. (2021), Yadav et al. (2023)

2.3 SLSS Literature Gaps

Based on the above-mentioned SLSS barriers reported in the literature several gaps are identified.

Existing research has broadly identified barriers to SLSS adoption, yet there exists a significant lack of understanding of barriers that are dedicatedly shaped by the unique characteristics and contexts of individual organizations. It is imperative to investigate how organizational dynamics influence the manifestation and severity of SLSS barriers. There is a notable scarcity of comprehensive frameworks proposed for the effective implementation of SLSS in manufacturing industries. Future research should prioritize the development of structured frameworks that offer clear guidelines and methodologies to bolster SLSS adoption and address implementation hurdles. While some studies have pinpointed organization-specific SLSS barriers, there is a distinct gap in assessing the intensity or severity of these barriers. Understanding the relative impact of different barriers can enable organizations to allocate resources strategically and devise tailored mitigation strategies.

The literature lacks sufficient research employing decision support tools, optimization techniques, or mathematical modelling to quantitatively analyze SLSS barriers' intensities. Incorporating these analytical approaches can provide a more rigorous assessment of barriers' impacts and enhance decision-making processes. Despite SLSS aiming to integrate sustainability principles into lean and six sigma practices, there is a need for research focusing on incorporating specific sustainability metrics into SLSS frameworks. This integration can facilitate a comprehensive evaluation of environmental and social impacts throughout the SLSS implementation lifecycle. Several studies reported in the literature offer snapshot insights into SLSS barriers, but longitudinal research that tracks the evolution of barriers over time is scarce. More longitudinal studies with a focus on SLSS challenges and the enhancing effectiveness of long-term mitigation strategies will strengthen the SLSS domain. Although SLSS barriers have been explored across various industries, still there is a dearth of in-depth, industry-specific analysis. More rigorous work dedicated to some industry sectors such as core manufacturing, services, healthcare, or processing and chemical segments can uncover sector-specific challenges and opportunities for tailored SLSS implementation strategies.

3. Research Methodology

3.1 Research Flow

The current study aims to explore the intensity of SLSS barriers through expert inputs and case analysis by executing a fuzzy analytical hierarchy process. The methodology followed in this study can be understood in **Figure 1**. It indicated the study flow for obtaining the intensity of the influence of SLSS barriers.

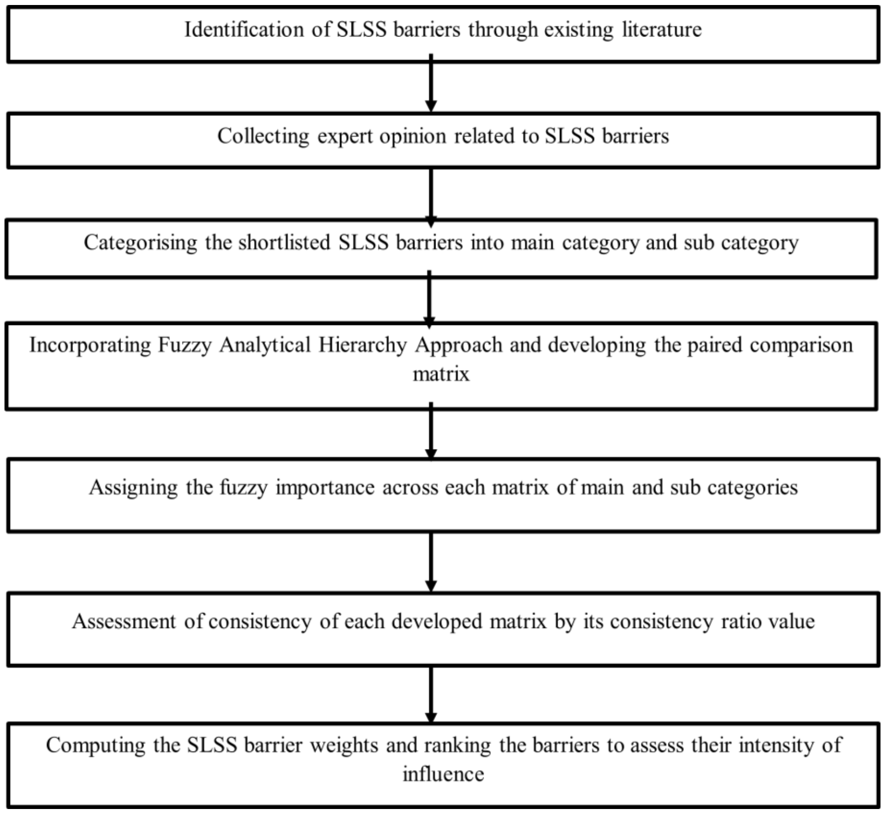

Figure 1. Research flow adopted for the study.

3.2 Fuzzy Analytical Hierarchy Process

The current study helps in identifying the SLSS barriers and computing their influence intensity to achieve the desired results that can help managers and practitioners implement SLSS effectively in manufacturing organizations. For computing the weights and intensity of influence of the related factors, it is observed that the Analytical Hierarchy Process (AHP) has been utilized by researchers across the globe. However, to boost the outcomes of AHP it is always suggested that if it is integrated with some other methodologies then the effectiveness among the outcomes tends to give more accurate and precise results. Considering these criteria, this research work merges fuzzy set theory and AHP to compute the intensity of influence of SLSS barriers. The fuzzy approach is included in this research work because AHP utilizes decision experts' inputs to perform the analysis. Hence, there is likely the chance to have biases among the decision experts' judgements. So, to overcome such situations, fuzzy set theory appears to be the most appropriate choice.

Moreover, fuzzy AHP supports the development of structured decision-making frameworks tailored to address SLSS barriers effectively (Papic et al., 2017). It facilitates the prioritization of mitigation strategies and resource allocation based on the dynamically changing importance of barriers (Yadav & Desai, 2017). This adaptive capability enhances the feasibility and sustainability of SLSS implementations by ensuring that decision-making processes align with evolving organizational needs and environmental goals. Therefore, fuzzy AHP emerges as a powerful tool in advancing the understanding and implementation of sustainable lean six sigma practices across manufacturing and service sectors.

4. Case Analysis

4.1 Company Information and Problem Identification

The ABC manufacturing organization was encountering numerous challenges due to escalating competition and evolving customer demands. It is situated in the western region of Madhya Pradesh (India) and deals in pump manufacturing. It holds an employee strength of 80, working in 2 shifts and an annual turnover of ₹90 crores. Consequently, there was an urgent need for quality-oriented solutions to enhance efficiency by reducing lead time, cutting manufacturing costs, and leveraging other advantages. The model developed in this research requires unwavering commitment from top management, as training and resources are critical for successful implementation. The company faced mounting challenges as its competitors began adopting various advanced technologies such as lean production, quality control systems, Six Sigma, green practices, smart factories, and more. Recognizing the necessity for a robust framework, the management, demonstrating considerable maturity, was eager to implement a SLSS approach due to the constantly evolving nature of their products.

Accordingly, after appropriate discussions with the management in the organization, the core benefits of SLSS were explained and they deeply understood the desired outcomes which can be achieved through its adoption. These benefits further boosted their requirements as during the recent time they failed to deliver the orders timely and also struggled in some quality related issues. Finally, they realized the SLSS adoption would definitely improve their performance and can lead to financial gains. Hence, the managers agreed to adopt the SLSS framework across their organization to gain the said benefits. This initiative of SLSS framework was best suited for the said company requirements and their inputs to develop this framework would definitely assist in generating the desired outcomes which can act as a benchmark for similar kind of organizations. Accordingly, the identification of the said barriers will definitely assist in developing the framework to benefit the manufacturing organizations. This strategic move reflects their commitment to continuous improvement and their proactive approach to overcoming industry challenges, ultimately striving for operational excellence and sustainability in their manufacturing processes.

4.2 Construction of Decision Panel

During the initial phase of the meeting, the managers strongly agreed to adopt the SLSS methodology into their system to improve organizational productivity. Consequently, they assisted the authors by developing a decision expert panel having rich experience in the operations and shop floor activities. It was also evident that a few experts selected in the decision panel had significant experience with SLSS systems, which led to constructive inputs in reaching out to fruitful outcomes. To ensure a thorough understanding, the authors shared a comprehensive list of SLSS barriers, meticulously extracted from extensive literature, with the decision experts. This list was intended to help them grasp the potential challenges and their implications. The management's proactive approach underscored their genuine interest in developing a robust hybrid model that incorporates multi-criteria decision-making strategies. Their engagement and maturity in handling the SLSS implementation process were instrumental in driving the study forward. This collaborative effort facilitated a deeper understanding of the SLSS barriers and contributed to the creation of a more effective and practical model. The active involvement of the company's management, coupled with the expertise of the decision panel, played a pivotal role in the study, ensuring that the SLSS model could be tailored to meet the organization's specific needs and challenges. This strategic approach not only demonstrated the management's commitment to continuous improvement but also underscored the importance of involving knowledgeable stakeholders in the decision-making process. Overall, the management's readiness to embrace and support the SLSS model significantly enhanced the study's outcomes, paving the way for successful implementation and tangible benefits in operational efficiency and productivity. The complete details of the selected decision experts are shown in **Table 2**.

Table 2. Expert panel information.

Decision expert	Qualification	Designation	Department	Total experience (Years)
D-1	Ph. D.	President	Management	35
D-2	Graduate	Vice President	Management	15
D-3	Postgraduate	General Manager	Administration	24
D-4	Postgraduate	Dy. Manager	Administration	08
D-5	Graduate	Design Engineer	R&D	14
D-6	Graduate	IT Head	Administration	18
D-7	Ph. D.	Section Head	Production	21
D-8	Postgraduate	Senior Engineer	Production	07
D-9	Graduate	Junior Manager	R&D	16
D-10	Postgraduate	Logistics Manager	Administration	22

4.3 Fuzzy Analytical Hierarchy Process Analysis

The steps to execute the fuzzy-AHP for computing the intensity of influence of SLSS barriers in presented below.

1) Criteria definition: The initial step involves delineating the specific SLSS barriers that impede successful implementation. These criteria are carefully selected based on their impact within manufacturing contexts.
2) Defining problem structure: Following the identification of SLSS barriers, a hierarchical structure is formulated. This structure outlines the primary problem statement, followed by a delineation of various criteria and associated strategies. Additionally, all criteria are categorized under overarching themes.
3) Formation of the expert panel: Subsequently, decision experts are engaged to assign weights to each main criterion and its related sub-criteria. This allocation occurs on a scale ranging from 0 to 1, signifying increasing influence.
4) Defining the type of fuzzy set: With intensity specifications in place, the subsequent step involves finalizing fuzzy sets for analysis. Triangular fuzzy numbers are employed in this study for analysis purposes. These fuzzy numbers represent varying degrees of uncertainty and are instrumental in capturing the nuanced nature of SLSS barrier influence (Sun, 2010) (Refer to **Table 3**).
5) Analysis of weights:
   Following the determination of fuzzy sets for decision support analysis, the relative significance of each SLSS barrier is computed. This computation encompasses all SLSS barrier groups. Inputs are solicited from individual decision experts, and subsequently amalgamated to consolidate their judgments. Each comparison undergoes rigorous consistency testing utilizing the RI scale, as delineated in **Table 4**.
6) Computation of the global weights/alternative scores:
   Once the computation of each main criteria and sub-criteria weight is done then the next step is to compute the global weights which is also known as alternative scores. This is obtained by multiplying each SLSS sub-criteria weight with its main criteria weight. After multiplication, the final obtained value is the alternative score of each SLSS barrier.
7) Ranking of SLSS barriers:
   The final step involves ranking the SLSS barriers and determining their intensity of influence in the SLSS implementation. This process entails arranging all the alternative scores of SLSS barriers in descending order. SLSS barriers attaining higher rankings are deemed of greater importance, while those with lower rankings signify a diminished intensity of influence during the SLSS implementation process.

The judgements from all the experts are taken into consideration for the analysis purpose. The inputs received from Decision Expert-1 for the SLSS barrier category are shown in **Table 5** below.

Table 3. Triangular fuzzy scale.

Linguistic variable	Fuzzy variable	Function
Same preference	N1	(1,1,3)
Weak preference	N2	(1,3,5)
Moderate preference	N3	(3,5,7)
Strong preference	N4	(5,7,9)
Extremely strong preference	N5	(7,9,11)

Table 4. Random index scale.

Size (n)	1	2	3	4	5	6	7	8
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40

Table 5. Major criteria comparison through Expert-1.

SLSS Barrier	CT1	CT2	CT3	CT4	CT5
CT1	N1	N7	N3	N7	N5
CT2	1/N7	N1	N3	N7	N3
CT3	1/N3	1/N3	N1	1/N5	N5
CT4	1/N7	1/N7	N5	N1	N7
CT5	1/N5	1/N3	1/N5	1/N7	N1

As shown in **Table 5**, a similar process is carried out to collect the inputs from all the decision experts and according to the defined decision support procedure, the analysis is done to compute the final intensity of influence of SLSS barriers. The details are presented in **Table 6**.

Table 6. Analysis of selected SLSS barriers.

Major category	Major category value	Sub-category	CR-value	Internal value	Final value
Managerial & policy barriers	0.392	MPB1	0.078	0.1321	0.0518
		MPB2		0.0895	0.0351
		MPB3		0.0957	0.0375
		MPB4		0.0885	0.0347
		MPB5		0.4256	0.1670
		MPB6		0.0739	0.0290
		MPB7		0.0947	0.0371
Communication &technology barriers	0.213	CTB1	0.062	0.0974	0.0207
		CTB2		0.4935	0.1051
		CTB3		0.1176	0.0250
		CTB4		0.1228	0.0261
		CTB5		0.1687	0.0359
Behavioral-cultural barriers	0.145	BCB1	0.054	0.1704	0.0247
		BCB2		0.0879	0.0127
		BCB3		0.1785	0.0258
		BCB4		0.5632	0.0816
Infrastructural & organizational barriers	0.177	IOB1	0.066	0.1672	0.0295
		IOB2		0.0976	0.0172
		IOB3		0.1091	0.0193
		IOB4		0.1127	0.0199
		IOB5		0.1160	0.0205
		IOB6		0.3974	0.0703
Individual barriers	0.072	IVB1	0.071	0.1231	0.0089
		IVB2		0.0734	0.0053
		IVB3		0.1526	0.0110
		IVB4		0.5142	0.0372
		IVB5		0.1367	0.0099

4.4 Sensitivity Analysis

In this research, sensitivity analysis was conducted to assess the stability and reliability of the developed framework for implementing SLSS in manufacturing industries. The analysis involved systematically varying key input parameters within specified ranges to evaluate their impact on the framework's output results. Key input parameters, such as management involvement, sustainable practices adoption, workforce training, and the integration of advanced technologies were adjusted within realistic limits to simulate various real-world conditions. This multiple-scenario analysis portraying the different outcomes along with the proposed solutions evaluates the framework's robustness by comparing the solution rankings across different simulated conditions. Accordingly, the sensitivity analysis demonstrated that variations of up to 10% in input values did not substantially change the rankings of the solutions considered for the SLSS barriers in this study. It further highlights the framework's resilience to uncertainties and its behaviour across different scenarios and conditions. A total of 15 experiments were run across the different scenarios to check the robustness of the framework shown in this study.

Accordingly, the study outcomes indicate that the framework proposed in this research work is completely robust and well-executable in the given environmental conditions. The robustness shown in the sensitivity analysis indicates the model's applicability. Hence, the sensitivity analysis shown in this research confirms that the proposed framework can tackle the typical situations, changes and uncertainties, across manufacturing organizations and hence the researchers and practitioners working under similar environmental conditions could be benefitted. **Figure 2** represents the sensitivity analysis conducted for SLSS barriers.

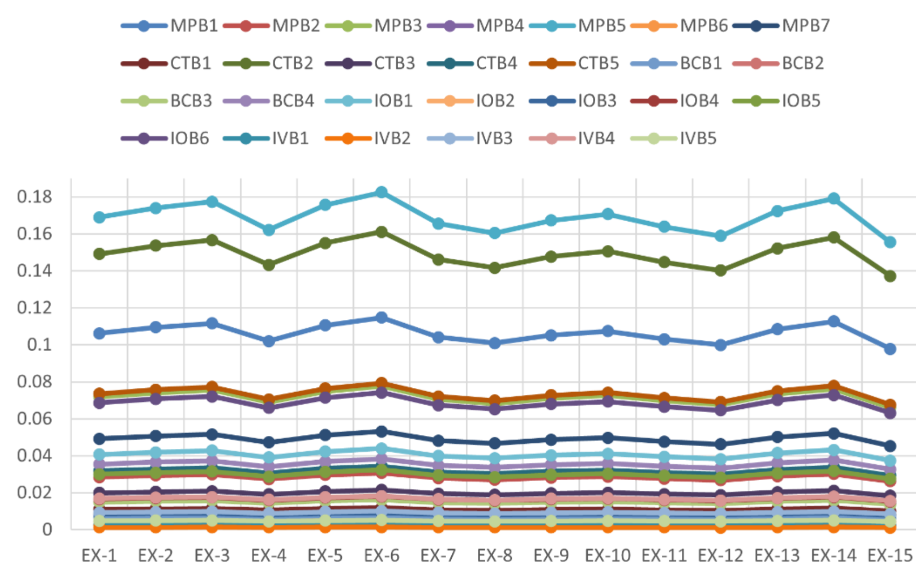

Figure 2. Sensitivity analysis of SLSS barriers.

5. Discussion and Study Findings

The present research work utilizes the combination of fuzzy set theory and the AHP approach to compute the SLSS barriers shortlisted from the literature. The main reason behind the selection of the AHP approach is its uniqueness in handling the complexity among the number of criteria in the uncertain manufacturing environment. Unlike traditional AHP methods that assume fixed weights for criteria, fuzzy AHP gives the flexibility of variation under different complex industry scenarios. This flexibility is crucial in evaluating the SLSS implementations, where the barriers might have different influences in the adoption scenarios depending on the situations and type of environment. By utilizing fuzzy AHP, the present research work assists in computing the nuanced differences in the impact and significance of SLSS barriers. The methodological approach includes the mapping of inputs from the decision panel to establish fuzzy sets that represent the varying degrees of importance across the set of SLSS barriers selected for this research work. These fuzzy sets enable a more robust analysis of SLSS barriers by considering the different scenarios applicable under the lean, six sigma, and sustainability environment.

The present research work assesses the SLSS barriers across the manufacturing environment to process improvement that considers the broader, long-term implications of decisions. The multi-criteria decision-making approach utilized in this research focuses on identifying and evaluating SLSS barriers. The complete set of SLSS barriers is divided into major and minor sets and better evaluation purposes. The weights or alternative scores assigned to these categories reflect their significance in obstructing SLSS implementation. Additionally, a consistency check is conducted to ensure the reliability and precision of judgments made by decision experts, thereby enhancing the accuracy of the findings. This approach not only aids in understanding the critical barriers that impede SLSS adoption but also provides a structured method for prioritizing efforts to overcome these obstacles effectively. By categorizing barriers and assessing their impact through a rigorous decision-support process, organizations can better allocate resources and develop targeted strategies to enhance the sustainability and efficiency of their operations through SLSS practices. The consistency check serves as a quality assurance step, affirming the robustness of the analysis and ensuring that the insights gained are dependable for guiding practical implementation strategies.

The final findings and discussion section of this research on SLSS presents an in-depth analysis of the critical barriers to SLSS implementation. The main criteria scores derived from the fuzzy AHP analysis are as follows: managerial & policy barriers scored 0.392, ranking first; communication & technology barriers scored 0.213, ranking second; infrastructural & organization barriers scored 0.177, ranking third; behavioral-cultural barriers scored 0.145, ranking fourth; and Individual barriers scored 0.072, ranking fifth. This analysis assesses the sustainability of lean six sigma initiatives by evaluating the relative importance of various SLSS barrier criteria. The consistency index for each category and sub-criterion was calculated using a standardized procedure for weighting SLSS barrier criteria. This index was then multiplied by the rank of the corresponding criteria to determine the overall score for each category. The high value of an SLSS barrier score indicates its criticality to the sustainability of lean six sigma initiatives.

The results indicate that managerial & policy-related SLSS barriers are the most critical for successful SLSS adoption and further portray the strategic alignment and vision in sustainability concerns taken up by the manufacturing organizations. Communication & Technology-related barriers project the importance of the adoption and integration of advanced technologies to support SLSS processes. Infrastructural & Organization-related barriers hold the third position and showcase the need for structural and cultural alignment within the organization. Behavioural-cultural barriers hold the fourth position and highlight the impact of societal and cultural factors on SLSS adoption. Lastly, individual SLSS barriers, which may include external factors or isolated issues, rank fifth, indicating a lesser but still significant impact on SLSS implementation. Among the sub-criteria, "Lack of top management attitude, commitment, and involvement" (MPB 5) emerged as the most significant barrier. It showcases the importance of top management in understanding and championing SLSS initiatives so that a streamlined pathway can be created to develop smooth SLSS adoption. Accordingly, any lack of commitment might result in the SLSS efforts towards adoption failure. The second most significant barrier is the lack of SLSS project training and education. Training is vital to equip employees with the necessary skills and knowledge to implement

SLSS effectively. Ensuring that the workforce is adequately trained helps in overcoming resistance and ensures smoother implementation.

The third key barrier is the lack of strategic planning (MPB 1). Effective SLSS implementation requires clear objectives and a cohesive vision. Without strategic planning, efforts to improve productivity and achieve sustainability goals can be disjointed and ineffective. This finding highlights the necessity of a well-defined strategy that aligns with the organization's overall goals and ensures coordinated efforts across various departments. These findings highlight the complex interplay of various barriers that organizations face in implementing SLSS initiatives. The critical importance of strategic alignment, top management support, and training and education is evident. Organizations aiming to adopt SLSS must prioritize these areas to overcome the barriers and achieve successful implementation. Moreover, the results emphasize the need for a holistic approach that considers technological advancements, organizational structure, and cultural factors.

In conclusion, the fuzzy AHP analysis provides valuable insights into the critical barriers to SLSS implementation. The high scores of strategy-related and technology-related barriers indicate their pivotal role in the sustainability of lean six sigma initiatives. Addressing these barriers through top management commitment, strategic planning, and employee training is essential for successful SLSS implementation. Additionally, the analysis highlights the importance of considering organizational and social-cultural factors in developing comprehensive SLSS strategies. The findings from this study offer practical guidance for researchers, practitioners, and policymakers in enhancing the adoption and effectiveness of SLSS in manufacturing organizations. By addressing the identified barriers, organizations can improve their productivity, sustainability, and overall performance, thereby gaining a competitive edge in the industry.

6. Study Implications

6.1 Theoretical Implications

This research work theoretically assists the researchers by providing a systematic framework to assess SLSS barriers. It enhances the understanding of different barriers and their impact on SLSS adoption. The integration of fuzzy set theory and AHP provides the theoretical understanding of decision support tools to analyze the SLSS barriers. It further provides a deeper understanding of overcoming biases captured during the decision-making processes. The theoretical framework proposed in this research work helps in understanding and mitigating SLSS barriers. It helps in proposing structured guidelines for practitioners to develop effective strategies according to the organizational requirements. The present research work computes the SLSS barrier intensities longitudinally to assess its dynamic nature across manufacturing organizations. It assists in interpreting the SLSS barriers and their behaviors across changing organizational and environmental contexts.

The benchmarking of SLSS implementation practices across industries provides a comparative analysis by identifying best practices and identifying the industry-specific challenges faced during the SLSS adoption. This research work reveals the alignment of SLSS with sustainability goals through the close examination of SLSS barriers as it gives guidelines to organizations to integrate sustainable practices within quality methodologies. The theoretical outcomes of this research work act as a foundation for the policymakers to develop industry-favoring policies that boost SLSS adoption. It includes awareness of supportive regulatory environments and benefits that might motivate industry practitioners to adopt SLSS and move ahead in the pathway to sustainability. The present research work advances theoretical knowledge by defining the advantages of merging fuzzy set theory with the analytical hierarchy process for evaluating the intensity of SLSS barriers. This sets a foundation for future research in applying sophisticated decision-support methodologies that help in tackling complex industry problems.

6.2 Practical Implications

The industry practitioners can directly utilize the analyzed SLSS barriers intensities and plan their work and resources accordingly. It further assists them in focusing on the high-impact barriers primarily, which can later result in successful SLSS adoption. The most critical SLSS barriers revealed in this study assist managers and practitioners in developing appropriate strategies to pathway smooth SLSS adoption through the analysis of root causes and intensities of barriers, boosting the possible success in adoption as well as effective operational contexts. The Amalgam of fuzzy set theory and AHP equips decision-makers with robust tools to reach the optimized decisions. It further facilitates effective objective decision-making processes in selecting SLSS strategies. The practical outcomes of this research work will help the policymakers to formulate supportive policies which can promote a positive environment for SLSS adoption across manufacturing sectors, and align them together with the sustainability aspects planned by the organization.

Appropriate strategies to handle the SLSS barriers can help the practitioners improve their resilience against challenges related to sustainability and internal process structure. The present research work showcases the significance of workforce training and awareness in SLSS practices. The practitioners associated with the SLSS adoption process can schedule training programs to motivate the workforce towards SLSS adoption and assist in implementing sustainability initiatives. The strong involvement of industry experts and their response collection helps practitioners broaden their view towards the obstacles encountered during the SLSS adoption process. It penetrates the execution of best practices and industry-specific insights, leading towards successful SLSS adoption. The smooth SLSS practices execution based on identified barriers might assist in improving organizational productivity and operational efficiency. This provides the managers and practitioners a competitive advantage by reducing waste, reducing defects and improving quality parameters associated with the product.

7. Conclusion and Prospects

The present research work provides a strong contribution to the field of SLSS. Addressing identified research gaps, there exists an immediate need to measure the impact and intensity of SLSS barriers reported by different studies in published SLSS research. To fulfil this need, the present study undergoes a comprehensive literature review to identify a unique SLSS barrier set that strongly influences manufacturing organizations. Subsequently, the selected SLSS barriers were processed through different decision-making tools to compute their intensity of influence towards the SLSS adoption. The methodology utilizes the integration of fuzzy set theory with AHP, a robust approach that can tackle decision-making scenarios with multiple criteria and biases among the decision-makers. The integration of fuzzy set theory with AHP focused on deriving optimal scores to obtain the precise score of influence of SLSS barriers and their impact on the regular manufacturing settings. Furthermore, this research work undergoes another check for consistency to ensure reliability among the judgments provided by the expert panel included in this research work. The above process resulted in eliminating the potential biases that could strongly affect the credibility of the findings obtained in terms of the SLSS barrier intensities.

Hence, the present research work bridges the critical literature gap by systematically analyzing and quantifying SLSS barriers and computing their intensities. It further provides valuable insights for practitioners and decision-makers who have faced difficulty in adopting SLSS in manufacturing environments. The outcomes of the present research work will assist in making strategic decisions, resource allocations, and policy formulations to tackle SLSS adoption barriers and spreading awareness of sustainable practices to improve operational performance. The final alternative scores of SLSS barriers are invaluable for researchers and practitioners engaged in SLSS implementation. The obtained results would help the managers and practitioners devise proactive strategies in handling the SLSS barriers with significant intensities, thereby taking real-time actions to improve SLSS penetration. The comprehensive compilation of SLSS barriers will assist the young researchers working in the domain of SLSS with deeper insights. Although, the present research work includes the involvement of ten experts from a single organization which can be considered as the limitation of the study the future research work can include multi-organizations with a greater number of experts to strengthen the study findings. The researchers can leverage these scores to conduct multi-method analyses and include more criteria and other methods for more precise results. Similarly, conducting a large-scale survey involving industry experts will help in including more essential SLSS barriers, enriching the study's scope and achieving deeper findings.

The present research work outcomes benefit not only researchers and practitioners but also assist the government policymakers who are involved in industrial policy development. These policymakers can derive valuable insights from the present research work and develop fruitful policies that are aimed at enhancing operational performance and SLSS adoption. With a deeper understanding of identified SLSS barriers, policymakers can create an environment which is supportive of sustainable improvement initiatives. This research work bridges the gap between academia, industry, and government and ensures that SLSS adoption efforts are well-supported sustainability goals. In conclusion, the present research work acts as a cornerstone for advancing SLSS adoption and framework with assistive guidelines to overcome SLSS barriers and enhance the green environment. By promoting evidence-based decision-making and fostering collaboration across sectors, the present research work is a strong contribution to the domain of lean, six sigma and sustainability goals aligned in the manufacturing context.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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