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A Structural Framework to Achieve Operational Excellence by Adopting Sustainable Lean Six Sigma and Industry 4.0 Technologies

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Abstract
It is widely accepted that achieving operational excellence remains a top priority for manufacturing industries, and in this aspect, Sustainable Lean Six Sigma (SLSS) emerged to be a promising approach for balancing flexibility, productivity, and customer demand. As SLSS gains traction, it becomes essential to identify key Sustainable Lean Six Sigma Enablers (SLSSEs) and prepare a comprehensive framework for its successful implementation. To address this, an in-depth literature review was conducted in this study, followed by the development of a structural framework using a hybrid methodology that combines the Robust Best Worst Method (RBWM) and Interpretive Structural Modelling (ISM), informed by expert insights. The ISM process involved analyzing the interrelationships between selected SLSSEs, while the fuzzy-MICMAC approach was employed to determine their driving and dependence powers. The study findings revealed that four low-intensity SLSSEs were removed in the framework's development process, however, the most critical enablers were identified as top management involvement, vision, and the government policies, research and sustainable product development initiatives, and funding for SLSS implementation. This is one of the unique studies that provides a holistic view of key enablers and serves as a valuable roadmap for researchers and practitioners to implement the SLSS strategies.

Keywords- Lean manufacturing, Six sigma, Sustainability, Multi-criteria decision-making, Enablers, Structural framework.

1. Introduction

The manufacturing sector is increasingly driven to adopt advanced quality improvement methodologies like Sustainable Lean Six Sigma (SLSS) to address evolving customer demands, and the complexities of international business, to stay competitive (Ali et al., 2020). SLSS is a dynamic system designed to enhance operational smoothness while ensuring the delivery of defect-free products. By eliminating non-value-added activities and upholding product quality, SLSS seamlessly integrates sustainability into its processes. Additionally, incorporating innovative approaches, such as sustainable product design and striving for a zero-defect production model, further minimizes reconfiguration costs and product defects, while enhancing overall quality (Chugani et al., 2017). At this juncture, it becomes crucial to understand the various phases of quality improvement strategies that integrate lean and Six Sigma principles, as these core concepts form the backbone of SLSS, which is essential for maintaining high standards of productivity and performance (Citybabu & Yamini, 2022).

It has been observed over the past decade that manufacturing concerns specifically encounter the ongoing challenge of meeting diverse and evolving customer demands. Eventually, SLSS plays a pivotal role in adapting to such dynamic conditions (Erdil et al., 2018). To address these shortcomings, several researchers across the globe have worked on developing the SLSS frameworks and their corresponding methodologies to facilitate their practical implementation. However, it is important to notice that despite their rigorous efforts, the results of these studies have often been inconclusive, indicating the need for further research to ensure the successful application of SLSS in various industries (Gholami et al., 2021). A crucial aspect of boosting the advantages of SLSS is identifying key Sustainable Lean Six Sigma Enablers (SLSSEs) and analysing the interaction among them. It is vital to determine the level of influence each enabler has on the SLSS implementation process. While several studies have discussed various enablers or core factors in the literature, few have thoroughly examined the impact of these enablers on the success of SLSS implementation (Hussain et al., 2023). The existing literature on sustainable Lean Six Sigma broadly reveals success stories of sustainable lean six sigma adoption across the manufacturing industries. But when it comes to its adoption across the automotive sector then its adoption rate is extremely low. This indicates the need for studies that could focus on the sustainable lean six sigma adoption across the automotive industries. Similarly, the literature projects several studies focussing on the identification of sustainable lean six sigma enablers but very few reveal the enabler intensity. In such situations, it becomes extremely difficult for the practitioners to adopt sustainable lean six sigma effectively. So, it is essential to identify the key sustainable lean six sigma enablers with their intensity of influence on the adoption. Additionally, a structural framework specifying the roadmap for its implementation will enhance the sustainable lean six sigma adoption rate. Furthermore, if the practitioners have the driving and dependence power of the enablers included in the framework then it will be much easier for them to plan the strategies for its effective implementation. This highlights the importance of investigating and identifying the most relevant SLSSEs and understanding their relationships. Additionally, there is a need for detailed, step-by-step guidance for SLSS implementers. Developing a framework that incorporates expert insights and represents SLSSEs in a structured format can significantly enhance the success and applicability of SLSS initiatives across industries.

The objectives of this research are as follows:
- To identify critical sustainable lean six sigma enablers, assess their influence, and create a structural framework.
- To calculate the driving and dependence power of sustainable lean six sigma enablers within the framework.

To accomplish these objectives, a comprehensive review of existing SLSS literature was undertaken, and the key SLSSEs were scrutinized. Further, a group of fifteen decision makers (details provided in later sections) was consulted for their insights on the applied decision-making process for SLSSEs. The decision-maker's feedback was gathered in two distinct stages. Initially, SLSSEs were selected according to their influence, captured through the robust best-worst method. Later, the interpretive structural modelling and fuzzy MICMAC (Matriced Impacts Croisés Multiplication Appliquée à un Classement) approach was utilised to prepare the required structural framework. This framework assists in computing the effect of the SLSSEs on its implementation. It is further reported that practitioners can prioritize the most critical enablers for SLSS implementation, enhancing the likelihood of success.

The article is structured into eight distinct sections, each covering a key aspect of the study. Section 2 provides an in-depth review of the existing literature on SLSS. Section 3 outlines the research methodology, focusing on the hybrid RBWM and ISM combined with the fuzzy MICMAC approach. Section 4 delves into the modelling of SLSSEs using ISM, while Section 5 presents the analysis using the fuzzy MICMAC technique. In Section 6, the findings of the study are discussed in detail, followed by an exploration of the study's implications in Section 7. Lastly, Section 8 offers a comprehensive summary, including the study's conclusions, limitations, and suggestions for future research directions.

2. Literature Review

The conducted literature review assists in capturing the factors associated with SLSS implementation as reported by several researchers in past studies. It will further help in investigating the most crucial factors that project long-lasting impacts on the new initiatives carried out in the SLSS domain. The present research work examines all peer-reviewed journal articles that include 'Sustainable Lean Six Sigma' in their titles or keywords. Similarly, from the methods perspective, a search over the different applications of RBWM and ISM-fuzzy MICMAC method was also conducted to better understand its applicability across different scenarios. Hence, this stage of the study attempts to select the SLSSEs through Scopus as the search database. During the search, the keywords 'Sustainable Lean Six Sigma,' and 'sustainable lean six sigma enablers' including across different book chapters, journal articles, review articles and conference proceedings were explored. However, the major focus has been on the journal articles and selected prominent conference articles. Accordingly, the details of the included SLSSEs are presented in the subsequent sub-sections.

2.1 Sustainable Lean Six Sigma Enablers

The concept of an 'enabler,' also referred to success factor, driver, or indicator, is regarded as a crucial element for the adoption of any methodology across the system. It is further reported by various researchers in literature mentioning notable contributions to SLSS when it comes to improving organisational productivity and performance improvement (Kaswan & Rathi, 2019). Given the high cost of SLSS implementation, it becomes significant to observe the factors associated with the adoption process. Consequently, the SLSSEs identified from the literature review are compiled and discussed with the decision-makers to pick the most critical factors linked its adoption. Hence, after thorough discussions and revisions with the involvement of decision-makers, the critical set of SLSSEs was developed.

It is noted through literature that Michael George and Robert Lawrence Jr. initially integrated the sustainability aspect with the lean six sigma concept to also reported that implementing SLSS effectively needs strong financial inputs on the project to develop strong infrastructure (Khanzode et al., 2023). Additionally, the higher authorities' engagement and their inclination towards the adoption of supportive policies emerge as the key step towards smooth SLSS implementation. It is further noticed in the literature that various researchers emphasise the focus on strategic planning, followed by the marking on product grouping and facility allocation within the system to promote SLSS adoption. Several researchers also noted that infrastructure and other facilities aid in strategic planning and can enhance SLSS performance (Kumar et al., 2016). Moreover, when employee empowerment is initiated, it helps in improving their productivity and further, it gets boosted by organised awareness and training programs that can improve their understanding towards the SLSS adoption as it was also essential for the adoption process. Recognising the performing employees and rewarding them boosts their morale and smoothens the adoption process. Even the focus on processes that promote green design and include environmental considerations supports sustainability in manufacturing processes (Mohan et al., 2024). Advanced machinery, such as automated material handling equipment, also benefits SLSS by increasing flexibility and performance. Few studies included advanced IT infrastructure and CAD/CAM technologies in the SWOT analysis for SLSS, along with government regulations and sustainable prototyping (Pandey et al., 2018).

Similarly, the removal of non-value-added activities also holds a critical role in reducing the production lead times and ensuring on-time deliveries to the end users (Gaikwad & Sunnapwar, 2020). The primary goal of SLSS development is to improve the agility of production resulting in the products as versatile, demonstrating the capability to manufacture diverse products using the same system (Shokri et al., 2022). Accordingly, before the SLSS adoption, it is extremely essential to capture the voice of the customer effectively, making the customer requirement analysis an essential SLSSE that may encompass quality and functionality requirements (Gholami et al., 2021). Metrics focusing on addressing the customer requirement might boost SLSS applicability. Additionally, managing manufacturing costs is important; optimizing resource use, including reconfiguration and underutilization costs, is preferred (Farrukh et al., 2024). Supplier integration is also critical for meeting customer demands efficiently and promptly (Singh & Rathi, 2022). The finalized list of SLSSEs is presented in **Table 1**.

Table 1. Sustainable lean six sigma enablers reported in the literature.

S. No.	SLSSE	Description	Literature support
1.	E-VSM process mapping	Digital process mapping for identifying waste and optimizing flow in SLSS implementation.	Parmar & Desai (2020)
2.	Enhanced satisfaction among customers	Increasing customer satisfaction by delivering high-quality, sustainable products.	Farrukh et al. (2024)
3.	Smart material requirement planning system	Automated systems for efficient material management to support Lean Six Sigma projects.	Kaswan & Rathi (2019)
4.	Collaboration & coordination within SLSS staff	Ensuring smooth collaboration between teams to improve workflow and process efficiency.	Kaswan & Rathi (2020)
5.	Systematic planning of SLSS adoption	Structured planning to ensure the smooth implementation and scalability of SLSS.	Khanzode et al. (2023)
6.	Penetration of government policies	Compliance with governmental policies to support sustainable and lean practices.	Pandey et al. (2018)
7.	Sustainable material processing like green design, green product development	Developing eco-friendly products and processes to align with sustainable goals.	Hussain et al. (2023)
8.	Employee motivation for SLSS adoption	Encouraging employees to engage with SLSS methodologies through motivation and rewards.	Yadav et al. (2023)
9.	Strong managerial support with defined strategies	Leadership commitment and clear strategies to drive the success of SLSS initiatives.	Raval et al. (2018)
10.	Testing facility & government approvals	Regulatory and testing frameworks to ensure SLSS compliance with industry standards.	Perez-Burgoin et al. (2024)
11.	Waste reduction	Minimizing waste in all forms is a core principle of Lean Six Sigma.	Singh & Rathi (2022)
12.	Effective resource utilization	Optimizing the use of resources to increase efficiency and reduce costs.	Hariyani & Mishra (2024)
13.	Effective monitoring of SLSS activities	Continuous tracking of SLSS projects to ensure they align with organizational goals.	Yadav & Desai (2017)
14.	Adoption of sustainable supportive practices	Integrating sustainability at every level to support long-term Lean Six Sigma goals.	Erdil et al. (2018)
15.	Smart prediction strategies for varied customer demands	Using advanced analytics to predict customer needs and adjust production processes.	Gholami et al. (2021)
16.	Penetration of smart technologies	Incorporating smart technologies for automating processes and improving efficiency.	Walter et al. (2023)
17.	Strong interdepartmental communication	Effective communication across departments to enhance collaboration and problem-solving.	Shokri et al. (2022)
18.	Reduction in lead time	Reducing the time between order and delivery to improve process efficiency.	Kumar et al. (2016)
19.	Coordination among suppliers	Streamlining communication and processes with suppliers to ensure seamless operations.	Dubey et al. (2016)
20.	Defined process-based analysis	A structured approach to analyze processes for better decision-making in SLSS.	Antony et al. (2018)
21.	Empowerment of employees	Empowering employees to take ownership of processes and contribute to SLSS's success.	Chugani et al. (2017)
22.	Smart manufacturing system	A technology-driven approach to automate and optimize manufacturing processes.	Gaikwad & Sunnpwar (2020)
23.	Sustainable work culture	Building a work environment that fosters sustainability and lean methodologies.	Swarnakar et al. (2021)
24.	Enhanced organisational performance	Overall performance improvement through effective SLSS implementation.	Mohan et al. (2024)
25.	Evaluation & rectification of customer feedback	Regular assessment of customer feedback to make improvements in SLSS processes.	Vinodh & Asokan (2018)

Table 1 continued…

26.	Precise machining facilities	Advanced machining capabilities to support precise and efficient production.	Soti et al. (2010)
27.	Financial resources for SLSS adoption	Ensuring the availability of adequate financial backing for implementing SLSS.	Ali et al. (2020)
28.	SLSS rewards & recognition policies	Policies to reward employees for their contributions to SLSS initiatives.	Sony & Naik (2020)
29.	Effective sustainable manufacturing system	A manufacturing system that balances efficiency with sustainable practices.	Citybabu & Yamini (2022)
30.	Systematic customer capturing system	A structured approach to acquiring and retaining customers effectively.	Patel & Patel (2021)
31.	Diversified skill set of SLSS staff	A skilled workforce proficient in multiple areas of Lean Six Sigma and sustainability.	Antony et al. (2018)
32.	Lean and sustainable development initiatives	Initiatives aimed at integrating lean practices with sustainable development goals.	Valmohammadi & Dashti (2016)
33.	Strong quality inspection system	A robust system for ensuring that products meet quality and sustainability standards.	Walter et al. (2023)
34.	Allocation of sustainable resources as input	Ensuring the use of eco-friendly materials and resources in SLSS processes.	Shokri et al. (2022)
35.	Scheduled SLSS training sessions	Regular training programs to upskill staff in Lean Six Sigma and sustainability practices.	Kumar et al. (2016)

2.2 Multi-criteria Decision-Making Approaches

The inclusion of decision-supportive methods strongly depends on the nature of the selected problem and the expected outcomes of the researchers. There are several techniques observed in the literature that truly tend to capture the weights, prioritization, and structuring. Similarly, analytical hierarchy process, SWARA approach, weighted sum method, weighted product method etc. However, the majority of them used pairwise comparisons of the included criteria. However, in many cases, it holds certain biases that might affect the outcomes. Whereas, if an individual criterion is compared with best and worst among the same group then there are more likely chances to have optimum results. For such scenarios involving a large number of input variables, the RBWM is particularly effective (Kharola et al., 2022); it was utilized in this instance to determine the relative weights of selected SLSSEs (Soti et al., 2010). Unlike assigning a single value, RBWM incorporates multiple comparisons between pairs of SLSSEs, enhancing its relevance for the current application in the present study RBWM is utilised to compute the intensity of the shortlisted sustainable lean six sigma enablers.

It has been observed in the literature that there are several structural mapping approaches reported by various researchers which include analytical network process, decision-making trial and evaluation laboratory, fuzzy cognition maps etc. However, the majority of these approaches could not highlight the power of the selected criteria. In such situations, it becomes difficult for the practitioners to penetrate the structural framework and provide the process and production mapping advantages to the practitioners (Varchandi et al., 2024). This gap can be addressed through the ISM approach, projecting the structure involving the different selected criteria for the complex problems, while also capturing the complex interrelationships between factors (Vinodh & Asokan, 2018). This approach is beneficial in numerous scenarios. ISM is particularly useful for analysing indirect interdependencies among factor groups rather than focusing solely on the degree of interdependence. Initially, the Robust Best Worst Method was used for the analytical scrutiny of the sustainable lean six sigma enablers focusing the industry 4.0 technologies. Although, in the literature, there are several methods available for computing the weights and intensities; however, the RBWM approach has an edge over the traditional methods as it provides one comparison of each available criterion across the best and worst aspects. This ensures the authenticity of the intensities obtained for the selected criteria. Secondly, the article aims to develop a structural hierarchy by exploring the powers of the selected criteria. In that case, Interpretive Structural Modelling and Fuzzy MICMAC appear to be the most suitable method for the present research problem.

2.3 Research Gaps

Through an extensive literature review, several research gaps have been identified:

- While numerous studies in the SLSS field have focused on determining key characteristics, only a limited number have concentrated on identifying SLSSEs.
- Although some researchers have developed implementation plans based on SLSS characteristics, there remains a lack of comprehensive sets of SLSSEs that are useful for implementation.
- Few studies have provided frameworks for implementing SLSS using Multi-Criteria Decision-Making (MCDM) approaches, highlighting a need for a structured framework as revealed during this review.
- The incorporation of decision makers across different stages of the implementation is rarely observed which includes their involvement in the selection, computing and analysing stages as it helps in achieving more realistic results.
- There is a notable scarcity of research that considers real-world case scenarios and their routine challenges as the nature of the problem to be explored. This study addresses this gap.
- The literature also lacks input from academic experts in framework development. This study incorporates academic expertise to integrate theoretical insights from various fields.

The identified gaps in the literature underscore the necessity for a structured framework designed with input from both categories of decision-makers to effectively support the SLSS adoption in real-world scenarios. These gaps validate the objectives of the study.

3. Research Methodology

The process for structuring and analyzing interactions among SLSSEs is explored across different stages. Initially, most of the literature selected was from journal-based articles, and the SLSSEs identified were further refined with the help of decision-makers. Further, the calculation has been conducted for the relative weights of the chosen SLSSEs using the RBWM and removing those with low intensity. This was followed by structuring the remaining SLSSEs using the ISM technique and expert insights, which helped create a hierarchical framework from input to output. In the third stage, fuzzy MICMAC analysis was employed to explore the interactions among various SLSSEs, classifying each SLSSE within its respective cluster and evaluating its driving and dependence power. **Figure 1** illustrates the flowchart representing the entire process.

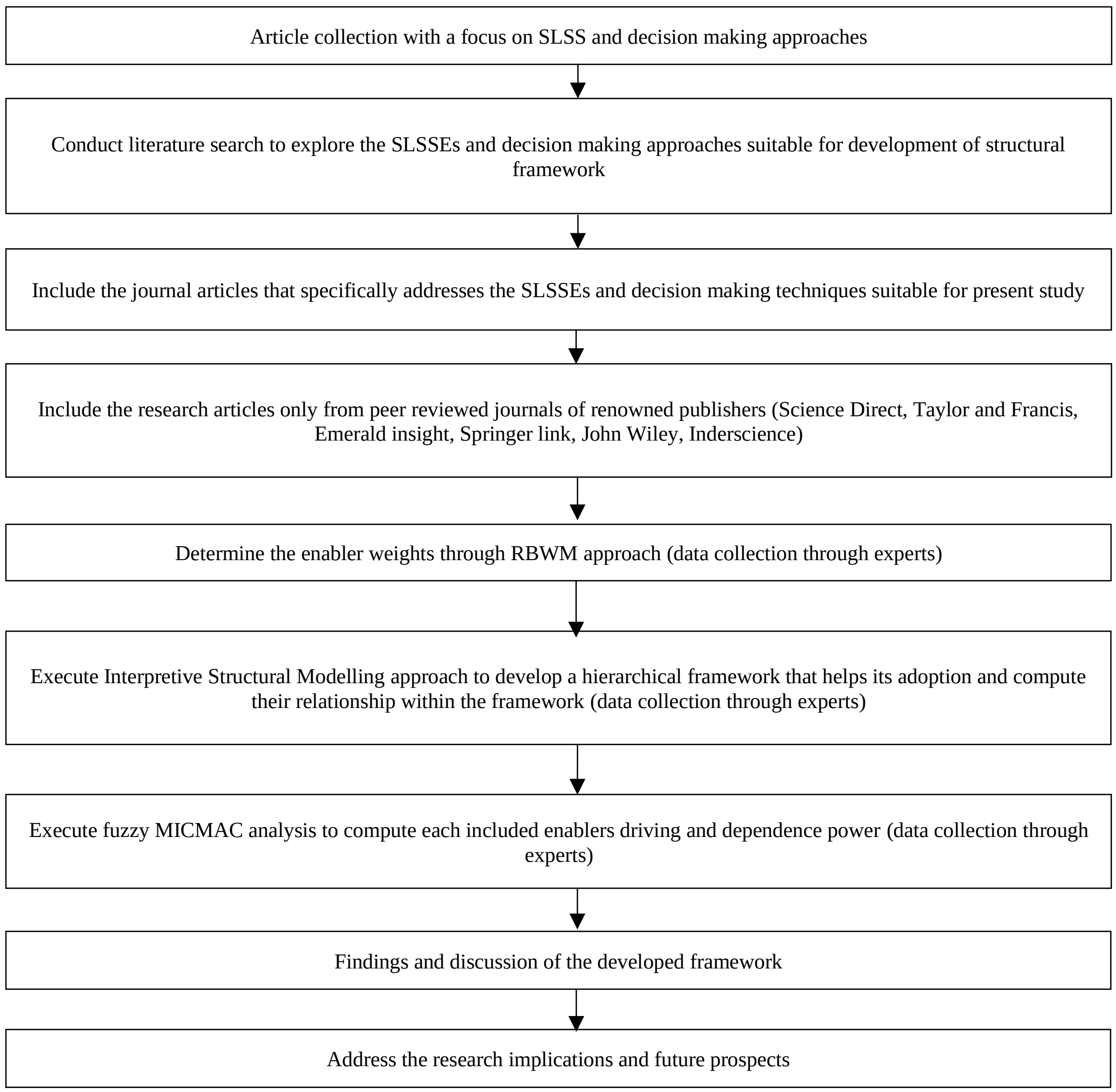

Figure 1. Research methodology.

4. SLSS Structural Hierarchy Development

ISM emerged as the best option when the structural framework between various factors is to be established. The execution of the adoption research method is shown below.

4.1 Problem Discussion

The present study opted to address a specific case study by identifying an organization facing the relevant issues. They consulted prior research of a similar nature to find a suitable candidate. The 'ABC organisation was selected in this research work due to its proximity to the central region in India and its production of various control valves, including its inclusion in various related manufacturing organisations. These valves are supplied to numerous related process industries within India and also hold international clients. The company employs 70 staff members across technical and non-technical roles.

The organization has long struggled with challenges such as sustaining on the wider platforms, product customisation, delivery delays, and ensuring the desired product quality, which has impacted its market sustainability. To address these issues, a techno-managerial solution was needed to enhance performance. The organization sought to adopt a new manufacturing strategy to expand its product range and improve operational efficiency. The authors engaged with various officials to gather relevant information and planned to execute the decision-support approaches to address the issues encountered. The management, recognizing the ongoing manufacturing challenges and enhancing their organisational performance, agreed to participate in the research. They believed that the study could offer valuable solutions and provide support in data collection.

Before constructing the expert panel, the authors discussed with the management to ensure that the provided experts have their expertise and experience in the areas of sustainability, lean manufacturing and six sigma. Hence, the management agreed to this point and provided only those experts who had earlier exposure to the related domain. Accordingly, an expert panel was formed, consisting of fifteen members. The members from academia selected for this study hold strong expertise in the sustainability and lean six sigma domain to ensure the validity of the study findings. The industry experts included professionals from various sections that are directly involved in the production stages. The decision-makers were highly qualified, with four holding PhD degrees, four having postgraduate qualifications, seven being undergraduate engineers, and eight possessing experience in SLSS implementation. After extensive brainstorming sessions, 31 SLSSEs were finalized and the decision-making approach was applied to prepare the framework that can help the practitioners execute the structural framework and also assess the powers of all the factors that are included in the framework.

4.2 Robust Best Worst Method Execution

A total of 35 SLSSEs were selected for this study and subsequently divided into five categories following the recommendations of the expert panel, as depicted in **Table 2**. This classification was carried out to assess their intensity using the RBWM method.

The process of conducting RBWM involves the following steps (Kharola et al., 2022):

Step 1: Identify and finalize the criteria to be used, denoted as R_1, R_2, R_3, ….. R_n.

Step 2: Assign 'best-worst criteria' in all the developed groups and subgroups. This results in the following vectors:

$C_B = (c_{b1}, c_{b2}, c_{b3}, \ldots\ldots c_{bn})$,

$C_W = (c_{w1}, c_{w2}, c_{w3}, \ldots\ldots c_{wn})$.

Step 3: Perform pairwise comparisons, utilizing a defined range of the corresponding robust set value say 4.5 and 5.5 as shown in **Table 3**.

Step 4: Identify the optimal solution (Nigam et al., 2024).

To obtain the SLSSE weights, the same approach has been captured as projected in **Table 4**.

The traditional RBWM approach is followed to assess the weight as depicted in **Table 5**, whereas later to project the SLSSE power the cluster analysis is utilised, as presented in **Table 7**.

Out of the 35 SLSSEs identified, 13 were classified as strongly influencing, 18 as moderately influencing, and 4 as low influencing according to the intensity cluster diagram. The low-intensity enablers- 'Testing facility & government approvals,' 'Defined process-based analysis,' 'Effective monitoring of SLSS activities,' and 'Waste reduction'-were recommended by the expert panel to be excluded from the framework's development. Thus, 31 enablers were retained for further analysis. During discussions, the experts reasoned that implementing 'Government policies and regulations' would naturally address 'Testing facility & government approvals.' Additionally, 'Defined process-based analysis' was considered already accounted for under the 'Availability of advanced technologies' enabler. The panel also pointed out that 'Effective monitoring of SLSS activities' is a fundamental requirement in any manufacturing process, and 'Waste reduction' is part of the broader quality control and assurance measures already included in other SLSSEs. Based on these evaluations, 31 critical enablers were ultimately chosen for inclusion in the structural framework development.

Table 2. Categorisation of SLSSEs.

Major category SLSSEs	**Sub-category SLSSEs**
Process-based Enablers (PEN)	Strong quality inspection system (PEN1)
	Effective resource utilization (PEN2)
	Waste reduction (PEN3)
	Precise machining facilities (PEN4)
	Reduction in production lead time (PEN5)
	Smart manufacturing system (PEN6)
	Defined process-based analysis (PEN7)
	Enhanced sustainability supportive practices (PEN8)
Technology-based Enablers (TEN)	Effective monitoring of SLSS activities (TEN1)
	E-VSM process mapping (TEN2)
	Sustainable material processing like green design, green PD (TEN3)
	Penetration of smart technologies (TEN4)
	Strong interdepartmental communication (TEN5)
	Effective sustainable manufacturing system (TEN6)
Strategy-based Enablers (SEN)	Strong managerial support with defined strategies (SEN1)
	Penetration of government policies (SEN2)
	Financial resources for SLSS adoption (SEN3)
	Smart prediction strategies of varied customer demands (SEN4)
	Testing facility & government approvals (SEN5)
	Evaluation & rectification of customer feedback (SEN6)
	Systematic planning of SLSS adoption (SEN7)
Organisation-based Enablers (OEN)	Lean and sustainable development initiatives (OEN1)
	Allocation of sustainable resources as input (OEN2)
	Smart material requirement planning system (OEN3)
	Systematic customer capturing system (OEN4)
	Coordination among suppliers (OEN5)
	Enhanced organizational performance (OEN6)
Managerial-based Enablers (MEN)	Empowerment of employees (MEN1)
	Scheduled SLSS training sessions (MEN2)
	SLSS rewards & recognition policies (MEN3)
	Sustainable work culture (MEN4)
	Employee motivation for SLSS adoption (MEN5)
	Diversified skill set of SLSS staff (MEN6)
	Enhanced satisfaction among customers (MEN7)
	Collaboration & coordination within SLSS staff (MEN8)

Table 3. Robust set values of the defined range.

S. No.	**Range**	**Robust set value**
1.	0.5-1.5	RSV1
2.	1.5-2.5	RSV2
3.	2.5-3.5	RSV3
4.	3.5-4.5	RSV4
5.	4.5-5.5	RSV5
6.	5.5-6.5	RSV6
7.	6.5-7.5	RSV7
8.	7.5-8.5	RSV8
9.	8.5-9.5	RSV9

Table 4. Robust set values for major criteria.

Decision exp. no.	Input set	PEN	TEN	SEN	OEN	MEN	ξ
DE1	C_B C_W	RSV6 RSV1	RSV4 RSV2	RSV3 RSV3	RSV2 RSV4	RSV1 RSV6	0.03
DE2	C_B C_W	RSV2 RSV4	RSV3 RSV3	RSV1 RSV5	RSV4 RSV2	RSV5 RSV1	0.05
DE3	C_B C_W	RSV2 RSV5	RSV6 RSV1	RSV1 RSV6	RSV5 RSV2	RSV4 RSV4	0.09
DE4	C_B C_W	RSV6 RSV1	RSV2 RSV4	RSV4 RSV2	RSV3 RSV3	RSV1 RSV6	0.03
DE5	C_B C_W	RSV6 RSV1	RSV2 RSV5	RSV6 RSV3	RSV3 RSV3	RSV1 RSV6	0.06
DE6	C_B C_W	RSV1 RSV5	RSV3 RSV2	RSV5 RSV1	RSV3 RSV3	RSV2 RSV3	0.05
DE7	C_B C_W	RSV2 RSV5	RSV1 RSV6	RSV5 RSV2	RSV3 RSV3	RSV6 RSV1	0.06
DE8	C_B C_W	RSV1 RSV5	RSV3 RSV2	RSV5 RSV1	RSV3 RSV3	RSV2 RSV3	0.05
DE9	C_B C_W	RSV3 RSV5	RSV5 RSV1	RSV1 RSV5	RSV3 RSV3	RSV4 RSV3	0.10
DE10	C_B C_W	RSV5 RSV1	RSV4 RSV2	RSV2 RSV4	RSV3 RSV3	RSV1 RSV5	0.05
DE11	C_B C_W	RSV4 RSV3	RSV1 RSV5	RSV3 RSV4	RSV5 RSV1	RSV4 RSV4	0.12
DE12	C_B C_W	RSV2 RSV5	RSV1 RSV6	RSV5 RSV2	RSV3 RSV3	RSV6 RSV1	0.06
DE13	C_B C_W	RSV5 RSV1	RSV2 RSV5	RSV1 RSV6	RSV4 RSV3	RSV5 RSV2	0.08
DE14	C_B C_W	RSV3 RSV2	RSV2 RSV2	RSV1 RSV4	RSV4 RSV1	RSV2 RSV3	0.04
DE15	C_B C_W	RSV2 RSV4	RSV3 RSV3	RSV1 RSV5	RSV4 RSV2	RSV5 RSV1	0.05

Table 5. Sub-criteria weights.

Main criteria	Sub criteria	Code	Weights	Status
PEN	Strong quality inspection system	PEN1	0.03345	Included
	Effective resource utilization	PEN2	0.03489	Included
	Waste reduction	PEN3	0.00607	Excluded
	Precise machining facilities	PEN4	0.03624	Included
	Reduction in production lead time	PEN5	0.01852	Included
	Smart manufacturing system	PEN6	0.02871	Included
	Defined process-based analysis	PEN7	0.00811	Excluded
	Enhanced sustainability supportive practices	PEN8	0.02362	Included
TEN	Effective monitoring of SLSS activities	TEN1	0.01252	Excluded
	E-VSM process mapping	TEN2	0.04923	Included
	Sustainable material processing like green design, GPD	TEN3	0.04041	Included
	Penetration of smart technologies	TEN4	0.05178	Included
	Strong interdepartmental communication	TEN5	0.02749	Included
	Effective sustainable manufacturing system	TEN6	0.03427	Included
SEN	Strong managerial support with defined strategies	SEN1	0.05158	Included
	Penetration of government policies	SEN2	0.04317	Included
	Financial resources for SLSS adoption	SEN3	0.03338	Included
	Smart prediction strategies for varied customer demands	SEN4	0.04366	Included
	Testing facility & government approvals	SEN5	0.00665	Excluded
	Evaluation & rectification of customer feedback	SEN6	0.03391	Included
	Systematic planning of SLSS adoption	SEN7	0.03032	Included
OEN	Lean and sustainable development initiatives	OEN1	0.02121	Included
	Allocation of sustainable resources as input	OEN2	0.02688	Included
	Smart material requirement planning system	OEN3	0.02400	Included

Table 5 continued…

	Systematic customer capturing system	OEN4	0.03021	Included
	Coordination among suppliers	OEN5	0.02273	Included
	Enhanced organizational performance	OEN6	0.01862	Included
MEN	Empowerment of employees	MEN1	0.02591	Included
	Scheduled SLSS training sessions	MEN2	0.02789	Included
	SLSS rewards & recognition policies	MEN3	0.02891	Included
	Sustainable work culture	MEN4	0.02976	Included
	Employee motivation for SLSS adoption	MEN5	0.02678	Included
	Diversified skill set of SLSS staff	MEN6	0.02762	Included
	Enhanced satisfaction among customers	MEN7	0.02421	Included
	Collaboration & coordination within SLSS staff	MEN8	0.01932	Included

4.3 Interpretive Structural Modelling Execution

The execution of the ISM approach is outlined below (Panghal et al., 2022):

(i) The first step involves identifying the interrelationships among the shortlisted SLSSEs. These comparisons are then organized into a Structural Self-Interaction Matrix (SSIM). The following notations are used to represent the relationships:

V: SLSSE i helps achieve SLSSE j
A: SLSSE j helps achieve SLSSE i
X: SLSSE i and j support each other
O: SLSSE i and j have no relationship

(ii) After completing the VAXO analysis, the Initial Reachability Matrix (IRM) is computed for further analysis which projects the reachability of each included SLSSE.

(iii) In this stage, the SSIM is converted into a reachability matrix, and the concept of transitivity is applied. The general assumption of transitivity across the ISM process indicates that if SLSSE i is related to SLSSE j, and SLSSE j is related to SLSSE k, then SLSSE i is related to SLSSE k. Hence, transitivity removal is essential to achieve the desired levels.

(iv) The next step involves the level partitioning of the reachability matrix, also known as the canonical matrix. Three sets are created: the reachability set, the antecedent set, and the intersection set.

(v) A directed graph (digraph) is then created based on the reachability matrix, with transitive links being removed.

(vi) Finally, the framework is developed by substituting the SLSSE factors in the digraph with the corresponding SLSSE that were shortlisted for this research work. The complete hierarchy as projected in **Figure 2** indicates the framework that can be adopted by the researchers for its smooth penetration across the manufacturing organisations.

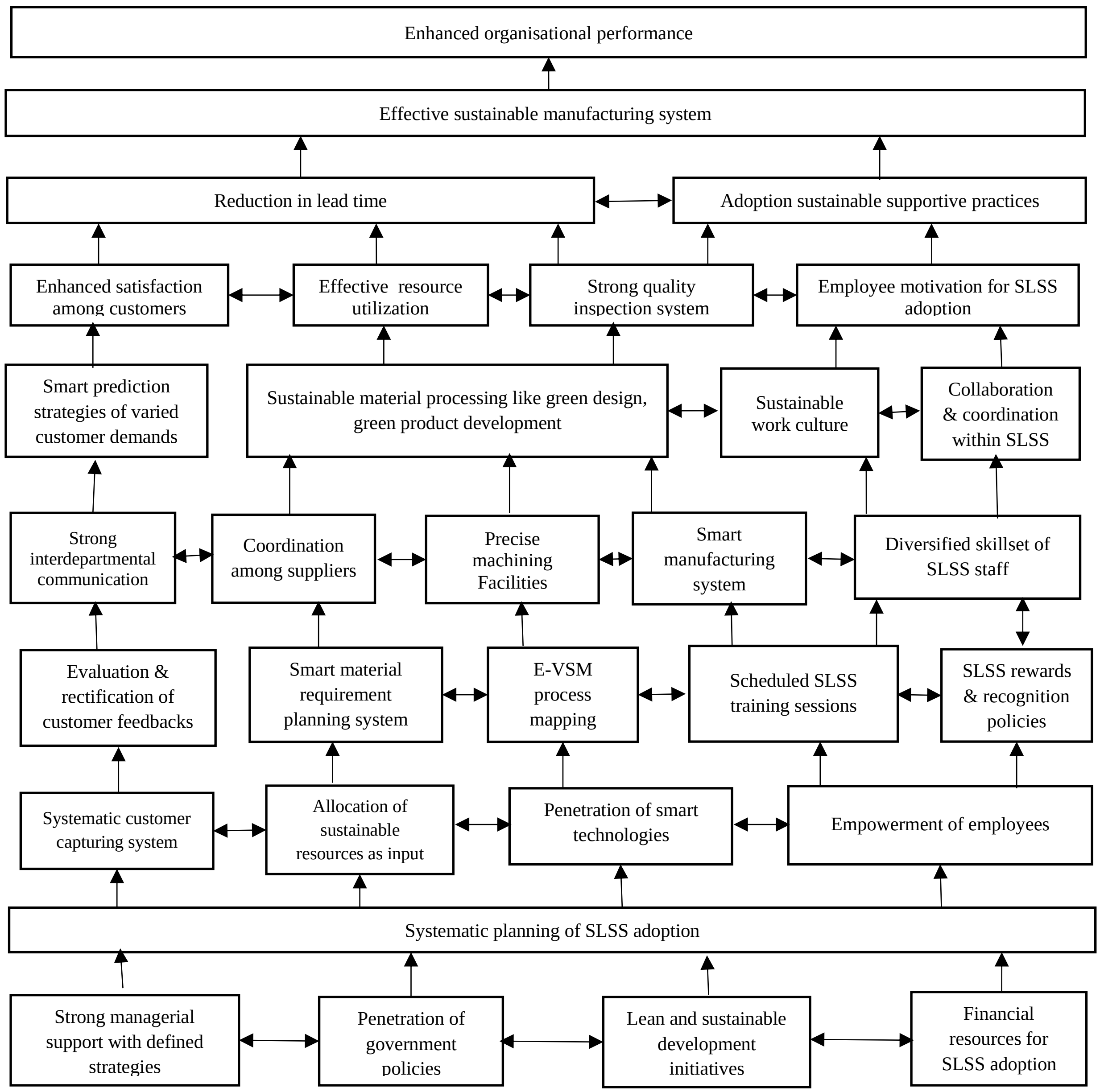

Figure 2. Structural framework for SLSSEs.

At this point in the structuring process, the power of the SLSSEs has not yet been determined, which is a crucial factor for successful SLSS implementation. To address this gap, fuzzy MICMAC analysis can be applied alongside the ISM method, offering an optimized outcome. This approach is detailed in the subsequent section.

5. Fuzzy MICMAC Analysis

In the process of creating the complete implementation framework, the relationships among the SLSSEs are indicated using binary values of 0 and 1. This means that if a relationship exists between two SLSSEs, it is represented by a 1, while a lack of relationship is shown as a 0. However, this binary approach does not account for the varying degrees of relationships that may exist; some SLSSEs may have a close connection, while others may be only loosely related, yet both would still be recorded as 1. Accordingly, MICMAC analysis incorporates fuzzy set theory to solve this issue. This helps in removing the biases among the judgments made by the experts. The usage of binary number restriction has been overcome in this method. Here, the actual interaction among the 2 SLSSEs is mapped between the 0 & 1 range to obtain the exact driving and dependence power of the selected SLSSEs. The steps for implementing this approach are outlined in subsequent subsections.

5.1 Binary Direct Reachability Matrix (BDRM)

The influences among the SLSSEs are used to derive the Binary Dependency Reachability Matrix (BDRM), following the ISM methodology. In this step, all the diagonal entries in the matrix are replaced by zero, which is referred to as the BDRM, which will subsequently serve as the foundation for the Fuzzy Dependency Reachability Matrix (FDRM). Following this, the expert panel was requested to utilize fuzzy numbers to compare the SLSSEs to construct the FDRM, as further elaborated in the next subsection.

5.2 Construction of Fuzzy Direct Reachability Matrix (FDRM)

This step primarily focuses on binary relationships among the chosen variables, which restricts the flexibility of decision-making by experts. To strengthen the sensitivity of the MICMAC analysis, this study employs fuzzy sets. In fuzzy MICMAC, there is an inherent supernumerary stimulation of the potential interactions between SLSSEs. The interaction matrix incorporates a range of values on percentages ranging from 0% to 100% that includes it from no reach to the total reach. **Table 6** illustrates the scale utilized in this analysis.

Table 6. Intensity of influence.

Case of interaction	Code	Influence percentage
No reach	NR	0
Extremely low reach	ELR	10%
Low reach	LR	30%
Moderate reach	MR	50%
Strong reach	SR	70%
Extremely strong reach	ESR	90%
Total reach	TR	100%

5.3 Fuzzy MICMAC Stabilized Matrix

At this stage, the stabilization of SLSSE power is accomplished through the sequential product of the matrices. Accordingly, the fuzzy set operations rule of products is applied for this matrix multiplication. This process essentially simplifies the multiplication of Boolean matrices. According to fuzzy set theory, the product of two fuzzy matrices will always yield another fuzzy matrix. The following outlines the rules for multiplying two matrices:

$$P = Q.R = \max n[\min(Q_{in}, R_{nj})]$$

where, $Q = Q_{in}$ and $R = R_{nj}$.

The driving power is calculated by summing the entries in each row, while the entries in each column reflect the dependence power of the SLSSEs. The resulting sums provide insights into the influence of each SLSSE on the effective implementation of SLSS, thereby aiding practitioners in making critical decisions.

6. Results and Discussion

The hierarchical model developed in this study with the aid ISM approach is spread across 10 different levels specifying their applicability at various stages to facilitate the adoption of SLSS. Each level in this hierarchical model is critical, forming a robust pathway that ultimately leads to enhanced organizational performance. At the foundational level, strong managerial support is essential. This entails not only the commitment of top management but also the establishment of clear, actionable strategies for SLSS adoption (Ozturkoglu et al., 2021). Once the government policies are executed strategically, the aim to streamline the operational, financial and sustainability goals can be achieved effectively. It is often observed that financial resources play a crucial part in SLSS adoption because they enable the penetration of lean and further integrate it with sustainable aspects very easily. Hence, the SLSSEs included in the framework eventually create a strong base for the upper-level enablers, making its roots strengthen and better adaptability (Papic et al., 2017).

Similarly, as the base structure gets ready, then the systematic planning for the other SLSSEs gets much easier for penetration. This level involves the development of appropriate plans that assist in the proper adoption of SLSS across the system. Accordingly, strong and focused planning reduces the failure risks and enhances the success possibility, by getting ensured that they can handle all the complexities among the system and promote sustainability across the upcoming levels. At level 3, it is expected to include the customer as one of the most significant factors and explore their required insights properly. With an appropriate focus on the allocation of sustainable resources, the penetration of smart technologies, and employee empowerment, this stage analyses and works on the changing customer requirements and addresses the raised queries. Empowered employees play a critical role by driving innovation and developing solutions that align equally with the varied customer expectations and organisational defined sustainability goals. At level 4 effective evaluation of customer feedback is essential for continuous improvement. Among this level, advanced methodologies such as e-VSM process mapping and smart material requirement planning systems to enhance operational efficiency hold a strong role. By scheduling SLSS training sessions and employing the reward policies a culture of recognition, and motivating employees emerge strongly as critical SLSS initiatives to strengthen the implementation. This cyclical feedback process ensures that customer needs are consistently met and that improvements are properly aligned with the system.

At level 5, the focus shifts to the enhancement of communication across departments. Effective coordination among suppliers and precise machining facilities supports a smart manufacturing system. A diversified skill set among SLSS staff is crucial for fostering innovation and addressing diverse challenges. This integrated approach ensures that all departments work collaboratively towards common sustainability goals. As organizations advance, the need for smart prediction strategies becomes critical. Understanding customer demand fluctuations allows for the development of sustainable material processing methods, such as green design and product development which is obtained at level 6. A sustainable work culture is essential at this stage, as it promotes collaboration and coordination among SLSS staff, enabling more responsive and agile operations. The impact of the initiatives from previous levels culminates in enhanced customer satisfaction is noticed at level 7. Effective resource utilization and a robust quality inspection system contribute to this outcome, while employee motivation for SLSS adoption plays a pivotal role. Satisfied customers are more likely to be loyal, providing valuable feedback that can further drive improvement. A significant outcome of successful SLSS adoption is the reduction in lead times can be observed at level 8. By adopting sustainable supportive practices, organizations can streamline processes, resulting in faster delivery times and improved service levels. This efficiency is vital in maintaining competitiveness in an ever-evolving market.

This performance boost not only benefits the organization but also contributes positively to the broader community and environment. The ISM framework effectively illustrates the interconnectedness of various SLSS enablers and highlights the structured pathway organizations can follow to achieve sustainable manufacturing practices. Each level builds upon the previous one, ensuring a comprehensive approach to SLSS adoption that is both strategic and responsive to the dynamic needs of the industry. By understanding and applying this framework, practitioners can make informed decisions that propel their organizations towards successful sustainable initiatives.

However, the initial scrutiny of the SLSSEs is carried out through the RBWM approach. This method was specifically utilized to shortlist the most influencing SLSSEs that hold a strong impact on the SLSS implementation. **Figure 3** clearly illustrates the intensity of each SLSSE selected for this study. Although the exclusion of the enabler doesn't indicate that it does not contribute to SLSS implementation it states that its influence on the structural framework for smooth SLSS implementation is low.

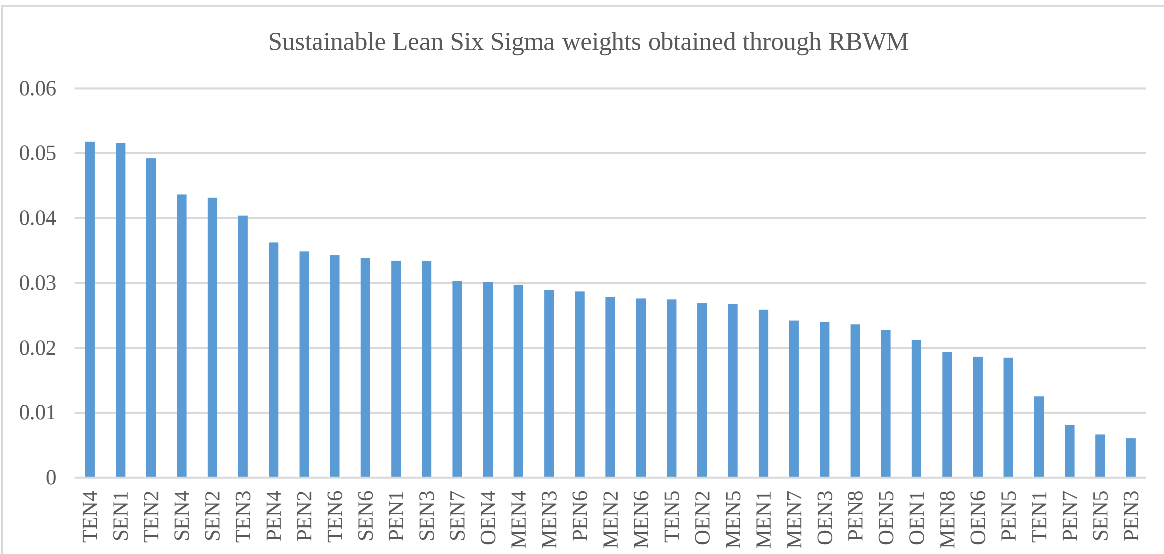

Figure 3. SLSSEs intensity obtained through RBWM approach.

The Fuzzy MICMAC analysis classifies the SLSSEs into four clusters based on their driving and dependence power. Notably, no enablers fall into the autonomous cluster, indicating that all enablers are either strongly connected or highly influential. The dependent cluster includes enablers such as smart prediction strategies for varied customer demands, sustainable material processing, collaboration within SLSS staff, and enhanced customer satisfaction, which exhibit high dependence but low driving power, meaning they are outcomes reliant on stronger enablers. The linkage cluster, consisting of enablers like systematic customer capturing systems, smart material requirement planning, E-VSM process mapping, and strong interdepartmental communication, shows high driving and dependence power, indicating these factors are highly interconnected and subject to influencing or being influenced by other enablers. Lastly, the driving cluster contains critical enablers such as strong managerial support, government policy penetration, lean and sustainable development initiatives, and systematic planning, which possess high driving power and serve as the foundation for the successful adoption and implementation of SLSS, making them essential priorities in the SLSS framework.

Table 7. Cluster analysis for SLSSEs.

Cluster	SLSSEs	Significance
Autonomous cluster	No enablers.	As no SLSS enabler falls in this cluster, it indicates the stability of the developed framework.
Dependent cluster	Smart prediction strategies for varied customer demands, Sustainable material processing like green design, green product development, Collaboration & coordination within SLSS staff, Enhanced satisfaction among customers, Effective resource utilization, Strong quality inspection system, Employee motivation for SLSS, Reduction in lead time, Adoption sustainable supportive practices, Effective sustainable manufacturing system, Enhanced organisational performance.	These enablers possess high dependent power and indicate their existence depending on the effective execution of other enablers in the system.
Linkage cluster	Systematic customer capturing system, Smart material requirement planning system, E-VSM process mapping, Scheduled SLSS training sessions, SLSS rewards & recognition policies, Strong interdepartmental communication, Coordination among suppliers, Precise machining Facilities, Smart manufacturing system, Diversified skillset of SLSS staff.	These enablers act as a bridge between the driving and dependence enablers. They possess strong driving and a strong dependence power.
Driving cluster	Strong managerial support with defined strategies, Penetration of government policies, Lean and sustainable development initiatives, financial resources for SLSS adoption, Systematic planning of SLSS adoption, Allocation of sustainable resources as input, Penetration of smart technologies, Empowerment of employees, Evaluation & rectification of customer feedbacks.	These enablers are often termed as initiators of the framework. Their execution is very important to execute the linkage and dependent cluster enablers. They possess strong driving power.

7. Implications for Practitioners and Academicians

The findings of this research provide significant implications for both industry practitioners and academics:

- Practitioners can prioritize high-intensity enablers identified by the Robust Best Worst Method for effective SLSS implementation.
- The framework highlights Research and Sustainable Product Development as a key enabler, guiding organizations facing development challenges.
- High-driving power enablers like funding, government policies, and top management commitment should be closely monitored for project success.
- Enablers in the linkage cluster show high interdependence, requiring careful management to prevent performance issues.
- Minimized lead time and improved quality assurance are critical to enhancing organizational performance.
- Inclination towards automated and production systems can drive success across multiple SLSS enablers.
- Employee training, rewards, and recognition should be prioritized as they impact other enablers with high dependence.
- The framework enables proactive risk management by identifying vulnerable enablers and suggesting corrective actions.
- Academically, the hybrid decision-making method applied in this research work offers a robust methodology for future research on complex interrelated enablers in various domains.

8. Conclusions, Limitations, and Future Scope

This research provides a robust framework for improving the adoption of SLSS in manufacturing industries by identifying and structuring key SLSSEs. Through an extensive literature review, the study utilized the RBWM to compute the intensity and importance of 31 SLSSEs. Based on expert recommendations, four enablers with lower intensity were excluded, and the remaining were organized using the ISM approach. This framework helps clarify the causal-effect interactions among the enablers, enabling decision-makers to prioritize and systematically address the most influential factors in SLSS implementation. To further enhance the ISM results, Fuzzy MICMAC analysis was applied, allowing for the evaluation of driving and dependence powers among the enablers. This hybrid approach-combining RBWM, ISM, and Fuzzy MICMAC-provides a comprehensive view of the interdependencies and relative significance of each enabler. The analysis identified key enablers with high driving power, which are critical inputs to the system and require special focus. These include factors such as managerial support, financial resources, government policies, and the systematic planning of SLSS adoption. On the other hand, enablers with high dependence power, such as enhanced organizational performance, are positioned as key outcomes in the framework.

This study offers a practical guide for manufacturing managers and decision-makers, helping them create actionable strategies to focus on high-driving enablers that significantly impact SLSS success. The structural framework not only aids in pre-implementation planning but also helps avoid costly and time-consuming post-implementation corrections. Moreover, the findings contribute to academic research by laying a solid foundation for further investigation into SLSS adoption strategies, offering insights for both large organizations and small and medium enterprises. While expert judgment was critical in assessing the enablers, potential biases could influence outcomes. The sustainable lean six sigma enablers selected for this study are explored through the existing literature. However, the researchers working in a similar domain can further conduct a large-scale survey to explore a more exhaustive list of sustainable lean six sigma enablers followed by the empirical analysis. The researchers can further conduct a multi-method comparison of the sustainable lean six sigma enablers' intensity of influence on the framework. Applying the structural equation modelling would help in achieving a broader perspective on the relationships of the sustainable lean six sigma enablers. The present study outcomes can also be tested across the sub-domains of manufacturing which include chemical industries, electronics industries, metal industries etc. Additionally, if applied to service and healthcare sectors, then such study outcomes will improve its applicability in a global context.

Conflict of Interest
The authors declare no potential conflict of interest.

AI Disclosure
The author(s) declare that no assistance is taken from generative AI to write this article.

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