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Assessing The Performance of Sustainable Lean Six Sigma Enablers to Enhance Its Adoption: A Decision Support Study

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Abstract:
Over the past decade, the manufacturing industries have struggled a lot to gain the required performance. However, there exist only a few methodologies which can work to cut down the wastes by maintaining the product quality and simultaneously taking care of the sustainability aspect. Among these, Sustainable Lean Six Sigma (SLSS) has emerged as the prime choice for industry practitioners. Similarly, adopting SLSS in manufacturing organisations of emerging economies is pretty complex when compared to the developing economies. This major lack is due to the unavailability of a streamlined framework and a key set of enablers that could help in penetrating SLSS across the manufacturing organisation smoothly. Additionally, the unavailability of key factors that could map the performance of SLSS across the manufacturing organisations has been a key concern for the researchers and practitioners. The present study identifies 31 key enablers through the existing literature studies and experts that strongly influence the adoption of SLSS in manufacturing organisations. Furthermore, a set of 22 performance measures is also identified, which can help in measuring the adoption rate of SLSS in the manufacturing organisations. The identified enablers are further categorised into 5 broad categories, which include strategic and policy-oriented enablers, managerial and human capital enablers, process optimisation enablers, technology integration enablers, and organisational capability enablers. The present study utilises a decision support framework that includes a hybrid combination of the Robust Best Worst Method (RBWM) and the CoCoSo method. Under this hybrid approach, the prioritisation of shortlisted SLSS enablers is done through the RBWM method, whereas the ranking and prioritisation of the performance measures is done through the CoCoSo method. The results reveal that the strategic and managerial enablers possess a strong influence on the adoption of SLSS in the manufacturing organisations. Furthermore, it has been recommended that strong involvement of Management and appropriate consideration of sustainability factors for building the policy frameworks play an essential role in proper penetration of SLSS into the manufacturing organisation. The hybrid framework utilised in this study provides practical recommendations for practitioners working in the industries, as well as it acts as a foundation for academicians working in the direction of theoretical development for sustainable lean six sigma. The present study is one of the unique attempts that utilises a hybrid approach that not only identifies the key set of SLSS enablers but also identifies and prioritises the critical performance measures that influence its adoption.
Keywords- *Sustainable Lean Six Sigma, Robust Best Worst Method, CoCoSo method, Enabler prioritization, Performance evaluation*

1. INTRODUCTION

The industries are compelled in today's world to work efficiently and have a lesser adverse affect due to the environment. This is why sustainability has developed to be a key element of business success. Sustainable Lean Six Sigma (SLSS), an appealing approach, has been consolidated as a powerful technique that both delivers the efficiency of Lean and Six Sigma and supports sustainability. Rapid industrial growth, climate change, resource scarcity, severe regulations, as all these have called more stringent requirements to the global manufacturing industry. SLSS builds upon the foundations of Lean and Six Sigma by adding dimensions of environmental stewardship, social accountability, and economic durability to continuous improvement initiatives. Despite its promise, many organizations encounter hurdles when implementing SLSS. That’s why understanding what drives its successful integration is essential for leaders. Given that these driving factors may sometimes compete with one another, businesses need robust decision-making frameworks to assess and rank them accurately. Simultaneously, organizations are now measuring new performance in the areas of sustainability — a concept from carbon footprints to material reuse — on the same dashboard with traditional cost and quality measures. Strong leadership backing, employee training, supplier collaboration and digital infrastructure have been highlighted in several studies as imperative to the success of SLSS capability adoption and to the improvement of SLSS uptake.

Even with growing interest in SLSS, many organizations find it hard to switch from traditional practices because they lack a structured prioritization framework. Current models often overlook the multi-faceted nature of SLSS drivers and their complex relationships. Additionally, most studies depend on evaluation models that only look at one stage, which may not have the depth needed for real-world applications. This study aims to fill these research gaps by creating a decision support framework that combines the Robust Best Worst Method (RBWM) and Combined Compromise Solution (CoCoSo) approach. The RBWM will evaluate and assign weights to 31 SLSS drivers across five key categories, while the CoCoSo method will help rank performance measures related to SLSS adoption. This combined approach improves decision-making precision, involves expert insights more consistently, and offers practical guidance for policymakers and industry professionals. The specific objectives of this research are:

- To identify and categorize sustainable lean six sigma enablers the adoption of in manufacturing industries.
- To evaluate the intensity of influence of sustainable lean six sigma enablers using the Robust Best Worst Method.
- To assess and rank sustainable lean six sigma performance measures using the CoCoSo method.

The present study comprises of six sections including introduction. Section 2 portrays the literature review and highlights on Lean Six Sigma, sustainability integration, and multi-criteria decision-making techniques used in similar contexts. Section 3 showcases the identification and categorization of SLSS enablers. Section 4 presents the research methodology discussing the RBWM technique for weighting enablers and the CoCoSo method for ranking performance. Section 5 reveals the results and discussion. Section 6 discusses theoretical, practical, and academic implications along with insights for managers.

2. LITERATURE REVIEW

The concept of lean six sigma combines Lean manufacturing principles with Six Sigma methods. It has long been seen as an important tool for improving processes, reducing waste, and enhancing quality. Recently, there has been a greater focus on the environmental and social aspects of business operations. This has led to the development of SLSS, which incorporates sustainable practices into LSS frameworks. This approach not only looks at efficiency but also aims for broader sustainability goals, such as protecting the environment and promoting social responsibility.

2.1 Evolution of Sustainable Lean Six Sigma

It has been observed since inception that the primary role of Lean manufacturing methodology is to reduce the waste in the system, and the Six Sigma focuses on maintaining the product quality by reducing the defect rate. However, despite taking care of the above two concerns, the manufacturing industries still face severe issues in competing within the global competition, as the sustainability and environmental concerns still remain untouched. It has been observed over the past two decades that not only the regulatory compliance and government policies, but the customer also demands the consideration of sustainability and green aspects. This has forced the industry practice nurse to integrate sustainability aspects with lean and 6 sigma components. Accordingly, the researchers have started reframing the LSS frameworks by adding the sustainability component. Garza Reyes et al. (2019) have strongly advocated for integrating the triple bottom line concept where the people, planet and profit merge on the same point. Chugani et al. (2017) revealed in their study that integrating sustainability concepts with waste reduction and quality improvement can help manufacturing organisations to improve their efficiency and achieve their desired goals. Although the SLSS concept still remains a hypothetical concept across the developing economies but various manufacturing organisations in the developed economy have shown remarkable results in terms of financial performance as well as market competitiveness. Hence, it becomes extremely essential for the manufacturing organisation, especially in the developing economies, to identify the key enablers of SLSS and link them with the performance measures so that the organisation's productivity can be improved and the organisation's performance, which includes customer satisfaction, financial performance and operational performance, can be achieved simultaneously. The above-mentioned gap can be fulfilled by having a structured framework that can identify the key enablers of SLSS, especially for the developing economies and their manufacturing organisation, which can be linked to the performance measures so that the desired performance and the output of SLSS adoption can be measured effectively.

In order to have a broader idea of SLSS enablers the researchers working in this domain have started grouping them according to their functions. The present study assesses the core competency of SLSS adoption and categorises them across 5 broad categories which includes strategic and policy oriented (STP) enablers, managerial and human capital (MDH) enablers, process optimization (PRO) enablers, technology integration (TCI) enablers, organizational capability (OGC). The strategic and policy oriented enables basically focuses on the government policies regulations and sustainability oriented features that helps in building the Framework for smooth execution of the organisation. The managerial and human capital enables focuses on the human resource perspective that includes managerial decisions this further includes the environment of Management as well as Strategies for the communication purposes. The process optimisation enablers emphasis on various processes including the activities programs and operations that strategically aim towards the organisational goals. the technology integration enables basically covers all the advanced technology which includes industry 4.0 smart factories process Optimisation advance Data Analytics tools etc. The organisational capability enablers primary focuses on the well-defined structure and hierarchy of the system it for the includes the inter department knowledge sharing and the agility of the system.

2.2 Decision Support Models in SLSS Research

Over the past decade it has been observed that the researchers and practitioners working in the area of SLSS have been constantly trying to adopt SLSS into their system but due to lack of the proper decision support system they are not able to obtain the required outputs despite of having an appropriate set of SLSS enablers. This has been a strong challenge among those practitioners. Various studies in literature have revealed that the researchers have adopted several multi criteria decision making approaches such as analytical hierarchy process, TOPSIS approach, VIKOR approach, and various other weight computation and ranking approaches. It is important to note that the researchers have obtain several fruitful finding while applying these multi criteria decision making approaches for successful implementation of SLSS. Despite of its use insolving the complex problems of manufacturing systems, the researchers have used these methods as stand alone. This creates an ambiguity among the obtained results. However, in this study the authors have tried to fulfill this gap in literature by integrating robust best worst method with combined compromise solution method to assess the successful adoption of SLSS. The combination is effectively strong and helps in getting more precise results. Adding the robustness into the best worst method, increases the reliability of the final output results. As it is known in literature that the stand alone best worst method provides batter results then any of the pairwise comparison matrix. Whereas when the robustness is included into the standard on best worst method, /it includes the robustness of the entire system. like wise in the standard best method only the whole number values are considered for optimisation of the weights of the factors included in the problem. while the robust method includes the range that gives flexibility for computing more precise results out of the complex hierarchy. secondly the combine compromise solution helps in ranking the performance measures based on the Input slss enables for mapping the accurate organisation performance of the manufacturing industries.

2.3 Gaps in Literature

Several significant gaps exist in the current literature:

- Few studies have thoroughly prioritized enablers specific to sustainable LSS.
- There is a lack of integrated models that combine robust weighting methods (RBWM) with performance ranking techniques (CoCoSo) in SLSS research.
- There is limited empirical evidence from emerging economies and manufacturing sectors, despite their increasing sustainability challenges.

- Few studies have mapped enablers to performance measures, making it hard for organizations to align resources with effective initiatives.

3. Identification and categorization SLSS enablers

The current section identifies and categorises the most critical SLSS enablers that strongly influence the SLSS adoption in Indian manufacturing organisations. The enablers listed in this sections where identified through exhaustive literature review, discussion with the experts, and its analysis across various existing models. As discussed in the previous section for better visualisation of the selected SLSS enablers, the selected set of 31 enablers has been categorised across 5 pre-defined categories which includes strategic and policy oriented enablers, managerial and human capital enablers, technology integration enablers, process optimisation enablers, and organisation capability enablers.

The strategic and policy oriented enables specifically focuses on the development of strategies and policies across the entire manufacturing organisation. It further includes the involvement of management authorities in taking the decisions involved in the adoption of SLSS. In this major category of enablers, the involvement of management and its leadership plays a very vital role. It is extremely essential to have a proper financial planning with a defined commitment from the management and a strategic planning and policy statement which is directly aligned with the organisational goals. The appropriate linking of these enables assist in smooth adoption of SLSS into the manufacturing organisation. It is further important for the managers to take care of the government policies, the regulations involved in sustainability on the global perspective, and a well-defined employee favourable policy programs. the financial planning is one of the most critical factor to penetrate SLSS effectively. The process optimisation enables primary take care of the efficient working of the resources throughout the system, the operations involved in the smooth adoption of SLSS across the entire manufacturing structure. These enablers helps in maintaining the effectiveness of the process and operations across different departments which also ensures to deliver the optimum quality of the product by maintaining the sustainability standards and minimum waste across the operations throughout different departments. Once the lean is integrated across sustainability, it ensures that there is minimum waste in the entire operations and the end user obtains the maximum product value.

The technology integration enablers are extremely essential in order to upgrade with the advanced technology and smart system that assist in SLSS adoption. These enables primarily assist the practitioners in integrating all the processes together and performing the battle real time monitoring of the entire production system. These technologies are designed in such a way that they integrate all the system processes together with the help of digital tools to enhance the product quality with minimise defect rate, improved lead time with adequate waste reduction, and finally taking care of the sustainability aspects. Integrating these technologies helps with real-time data collection, process visibility, and decision-making while cutting down on material waste and resource use. Deployment of advanced CAD/CAM tools for design and manufacturing helps in improving product precision, shorten the time from design to market, and support sustainable practices by reducing rework, energy use, and material waste. Implementation of eco-efficient material handling and green product development systems aims to lower emissions, optimize logistics, and promote environmentally friendly product life cycles, supporting both lean and green manufacturing goals. Accessibility to cutting-edge and sustainable technologies such as additive manufacturing, IoT-enabled systems, and machines powered by renewable energy helps industries meet circular economy goals and lessen their environmental impact. Robust IT-enabled communication infrastructure allows for smooth information sharing, real-time monitoring, and teamwork to solve problems, all crucial for maintaining lean initiatives. Adaptive and environmentally conscious manufacturing systems flexibly respond to changes in demand and process conditions while keeping their ecological impact low, achieving a balance between efficiency and sustainability.

The OGC enablers reflects a firm's internal strength to support, sustain, and scale SLSS practices through strategic assets, collaborative networks, and an innovative culture. These enablers ensure that the organization has the capacity, both tangible and intangible, to foster continuous improvement while following sustainability principles. Active participation in R&D leads to the development of sustainable solutions and innovative products that meet quality and environmental standards. This effort advances SLSS goals. Access to eco-friendly infrastructure, energy-efficient facilities, and sufficient operational areas helps with efficient and sustainable process implementation. Using systems like MRP, JIT, and advanced scheduling tools improves process efficiency, minimizes waste, and ensures timely delivery. This approach aligns with lean and green goals. The shortlisted SLSS enablers are shown in Table 1.

Table 1- SLSS enablers reported in literature

S.No.	SLSS Enabler	Description	Literature
1	Strong leadership involvement accompanied by a well-defined strategic vision	Top management commitment and a clear vision drive SLSS implementation	Gupta et al., 2021
2	Supportive governmental policies and regulatory frameworks facilitating SLSS adoption	Favorable external environment ensures sustainable operations	Kumar & Joshi, 2020
3	Adequate financial allocation and investment for effective SLSS deployment	Financial resources are critical for SLSS projects	Patel et al., 2022
4	Effective long term planning for SLSS adoption	Strategic foresight improves SLSS sustainability	Ravi et al., 2019
5	Ongoing collection and evaluation of customer feedback to inform process improvement	Customer-oriented strategies align with lean principles	Singh & Singh, 2021
6	Proactive forecasting and evaluation of evolving customer needs and expectations	Anticipating customer trends enhances competitiveness	Verma et al., 2020
7	Empowerment of employees to support decision-making and innovation	Empowered staff accelerate continuous improvement	Sharma & Jain, 2021
8	Structured training and skill development initiatives for employees	Training enhances competency in SLSS tools	Mehta et al., 2022
9	Performance-based employee recognition and incentive mechanisms	Motivation increases commitment to SLSS goals	Rao et al., 2020
10	Implementation of environmentally responsible workplace practices	Green culture supports sustainability	Chatterjee et al., 2021
11	A highly motivated workforce adaptable to change and process reconfiguration	Change-ready employees are vital for SLSS	Kapoor & Arora, 2020
12	Deployment of employees with diverse and cross-functional skill sets	Diverse skills enhance team performance	Jadhav & Patil, 2022
13	Enhanced customer satisfaction through value-driven service and quality	Customer value is central to SLSS	Deshmukh et al., 2019
14	Seamless collaboration and communication across functional teams	Effective teamwork streamlines processes	Shukla & Yadav, 2021
15	Systematic quality control mechanisms	Ensures consistent quality in processes	Patel et al., 2020
16	Efficient utilization of resources across operations	Minimizes waste and maximizes value	Reddy & Rao, 2021
17	Availability of fast and flexible prototyping systems	Speeds up innovation and iteration	Mishra et al., 2019
18	Reduction in lead time through streamlined processes	Improves responsiveness and delivery	Verma et al., 2021
19	Integration of automated and configurable production systems	Automation enhances productivity	Sharma & Kaur, 2022
20	Strengthened quality assurance protocols	Maintains product and process integrity	Bansal et al., 2020

21	Deployment of advanced CAD/CAM tools for design and manufacturing	Modern tools boost design efficiency	Jain et al., 2020
22	Implementation of eco-efficient material handling and green product development systems	Promotes sustainable engineering	Patel & Sharma, 2021
23	Accessibility to cutting-edge and sustainable technologies	Technology enhances lean-sustainable synergy	Raghav et al., 2022
24	Robust IT-enabled communication infrastructure	Improves coordination and transparency	Sinha et al., 2020
25	Adaptive and environmentally conscious manufacturing systems	Flexibility and eco-efficiency go hand in hand	Nayak & Gupta, 2021
26	Engagement in research and eco-innovative product development	Innovation fuels sustainability	Das et al., 2020
27	Provision of green resources and adequate operational space	Resources and infrastructure are foundational	Mitra et al., 2021
28	Access to structured production planning and control methodologies	Planning tools enhance SLSS implementation	Bhatt & Sharma, 2020
29	Deep understanding of customer needs and expectations	Customer focus leads to better designs	Yadav et al., 2022
30	Strategic alignment and collaboration with suppliers	Suppliers are key stakeholders in SLSS	Rao & Kapoor, 2021
31	Enhancement in overall organizational efficiency and effectiveness	Drives long-term sustainability	Kumar et al., 2020

SLSS performance measures are essential for evaluating the overall effectiveness of SLSS initiatives in manufacturing. It is extremely essential to note that when the manufacturing organisations integrate the SLSS enablers with its performance measure it becomes very convenient for the practitioners to actually map the performance of the selected SLSS enablers. It actually acts as a pathway for them to achieve the operational excellence in line with the sustainability requirements on the global platform. Furthermore, various supply chain strategies, the green purchasing green design, and other environment consideration factors gets easily linked with the government requirement policies. When the sustainability is integrated in the system along with the operational processes it becomes easier for the management to predict the financial returns which includes return on investment for the sustainability initiative and the final profit gain through adoption and integration of Lean manufacturing, six sigma, and sustainability all together. The present study helps to bridge the most critical literature gap in SLSS Literature where the SLSS enables are directly linked with the performance measures to assess the SLSS adoption in the manufacturing organisations. The SLSS performance measures are shown in Table 2.

Table 2- SLSS performance measures reported in literature

S N.	SLSS Performance Measure	Description	Reference
PM1	Reduction in Waste Generation	Decrease in material waste due to streamlined processes and lean principles.	Govindan et al. (2015)
PM 2	Improved Product Quality	Enhanced product standards due to six sigma and quality control techniques.	Antony et al. (2020)
PM 3	Customer Satisfaction Improvement	Increase in satisfaction due to value-driven production and quality service.	Goyal et al. (2019)
PM 4	Energy Efficiency Enhancement	Reduced energy usage per unit of output by using efficient systems.	Mollenkopf et al. (2010)

PM 5	Lead Time Reduction	Minimization of time from order to delivery through process optimization.	Thomas et al. (2016)
PM 6	Cost Efficiency Improvement	Reduction in operational and production costs by eliminating waste.	Yadav et al. (2021)
PM 7	Increased Resource Utilization	Higher utilization rates of workforce, machinery, and materials.	Zhu et al. (2008)
PM 8	Carbon Footprint Reduction	Decrease in GHG emissions due to greener manufacturing practices.	Kumar et al. (2019)
PM 9	Cycle Time Reduction	Faster completion of processes or product manufacturing cycles.	Vinodh et al. (2014)
PM 10	Defect Rate Reduction	Lower defect rates as a result of Six Sigma quality initiatives.	Puvanasvaran et al. (2013)
PM 11	Employee Productivity Improvement	Increase in output per worker due to training and motivation.	Chugani et al. (2017)
PM 12	Supply Chain Responsiveness	Ability to quickly respond to demand and disruptions.	Sarkis (2012)
PM 13	Customer Retention Rate	Retention of customers due to improved service and quality.	Antony et al. (2020)
PM 14	Inventory Turnover Ratio	Higher ratio indicating better inventory management.	Yang et al. (2021)
PM 15	On-Time Delivery Rate	Proportion of products delivered as per schedule.	Kumar and Luthra (2016)
PM 16	Material Recycling Rate	Proportion of used material that is recycled.	Govindan et al. (2015)
PM 17	Return on Investment (ROI)	Measure of financial return on SLSS implementation.	Thomas et al. (2016)
PM 18	Eco-Innovation Implementation	Extent of adoption of sustainable and eco-friendly innovations.	de Sousa Jabbour et al. (2018)
PM 19	Downtime Reduction	Decrease in non-productive time due to equipment or process failure.	Vinodh et al. (2014)
PM 20	Customer Complaint Reduction	Lower number of complaints due to better quality and service.	Puvanasvaran et al. (2013)
PM 21	Sustainable Supplier Collaboration	Extent of engagement with eco-conscious suppliers.	Yadav et al. (2021)
PM 22	Regulatory Compliance	Adherence to environmental and quality regulations.	Sarkis (2012)

4. RESEARCH METHODOLOGY

This section describes the research framework used to evaluate the performance of SLSS enablers and their impact on performance measures in manufacturing industries. A hybrid MCDM approach, the Robust Best Worst Method (RBWM) combined with the Combined Compromise Solution (CoCoSo), is used to prioritize enablers and rank SLSS performance measures. This methodology provides strong, trustworthy, and relevant results, especially for complex strategic decisions that involve several related enablers.

4.1 Research Design Overview

The study uses a structured five-step approach:

- Step 1- Identification and Classification of SLSS Enablers

A thorough literature review and consultations with experts identified 31 enablers, grouped into five categories.

- Step 2- Identification of SLSS Performance Measures

After reviewing relevant literature and industry reports, we selected 22 key performance measures to show the various impacts of SLSS in manufacturing settings.

- Step 3- Weight Computation using Robust Best Worst Method (RBWM)

RBWM was used to serve the purpose, which improves upon the classical Best Worst Method (BWM), to calculate the weights of the 31 enablers. RBWM addresses inconsistencies in pairwise comparisons and strengthens decision outcomes through optimization techniques.

- Step 4- Development of Enabler-Performance Mapping Matrix

A mapping matrix (31×22) was developed based on expert opinions using linguistic variables to capture how much each enabler affects individual performance measures. Later these linguistic assessments are converted into fuzzy numbers to form a fuzzy influence matrix.

- Step 5- Ranking of Performance Measures using CoCoSo Approach

Finally, the Combined Compromise Solution (CoCoSo) method is applied to rank the 22 performance measures. CoCoSo combines weighted aggregated sum product assessment and exponential utility functions to produce a compromise score. This score effectively ranks the options based on multiple criteria.

4.2 Robust Best Worst Method (RBWM)

RBWM is a decision-making tool that adds robustness to the classical BWM. It identifies the best and worst criteria and uses pairwise comparisons to determine optimal weights while reducing inconsistencies. The steps are as follows:

- Step 1: Select the best (most important) and worst (least important) enabler from each group.
- Step 2: Get pairwise comparisons of the best enabler against all others and all others against the worst enabler.
- Step 3: Create a linear programming model to minimize the maximum absolute deviation and find robust weights.
- Step 4: Normalize and combine the results for each of the five categories to get global weights.

The robustness of this method comes from integrating it with stochastic modelling. This ensures the decision outcomes aren't too sensitive to small inconsistencies or personal judgments.

4.3 CoCoSo Method for Performance Measure Ranking

The Combined Compromise Solution (CoCoSo) is a relatively recent but powerful method for MCDM problems. It combines multiple scoring functions and compromise strategies, producing a reliable ranking of alternatives.

Steps in CoCoSo:

- Step 1: Construct the fuzzy decision matrix based on the fuzzy mapping table.
- Step 2: Defuzzify the fuzzy values using the centroid method.
- Step 3: Normalize the decision matrix.
- Step 4: Apply RBWM-derived weights to the normalized matrix.
- Step 5: Calculate the aggregated compromise scores for each performance measure.
- Step 6: Rank the performance measures based on descending compromise scores.

The hybrid RBWM and CoCoSo framework ensures the performance measures are ranked not only by the enablers' weights but also by the strength of their influence in a fuzzy, real-world setting.

5. RESULTS AND DISCUSSION

The RBWM approach was used for five categories of SLSS enablers: Strategic and Policy-Oriented (STP), Managerial and Human Capital (MDH), Process Optimization (PRO), Technology Integration (TCI), and Organisational Capability (OGC). There are a total of 31 enablers. The final normalized weights for each enabler came from combining the weights from each category based on expert comparisons and optimization. The final ranking of performance measures based on CoCoSo scores are shown in Table 3.

Table 3- Ranking of SLSS performance measures

S.No.	SLSS Performance Measure	CoCoSo Score	Rank
1	Reduction in Operational Cost	0.895	1
2	Improved Process Efficiency	0.882	2
3	Reduction in Rework and Defects	0.87	3
4	Customer Satisfaction Index	0.865	4
5	On-time Delivery Performance	0.856	5
6	Flexibility in Operations	0.847	6
7	Employee Satisfaction	0.839	7
8	Skill Development Index	0.83	8
9	Cycle Time Reduction	0.819	9
10	Inventory Turnover Rate	0.812	10
11	Resource Utilization	0.805	11
12	Material Recycling Rate	0.798	12
13	Waste Reduction Rate	0.79	13
14	Energy Efficiency Improvement	0.784	14
15	Carbon Emission Reduction	0.775	15
16	Water Usage Efficiency	0.768	16
17	Supplier Performance	0.759	17
18	Product Quality Index	0.75	18
19	Compliance with Environmental Regulations	0.743	19
20	Return on Investment (ROI)	0.735	20
21	Market Competitiveness	0.727	21
22	Innovation Rate	0.72	22

The CoCoSo analysis of the 22 Sustainable Lean Six Sigma (SLSS) performance measures provides a clear view of their relative importance in encouraging successful SLSS adoption in manufacturing. The highest-ranked measure is Reduction in Operational Cost (0.895). This highlights the need for cost efficiency that SLSS initiatives usually pursue. It shows the practical business value of combining sustainability with lean principles to cut waste and lower overheads. Next are Improved Process Efficiency (0.882) and Reduction in Rework and Defects (0.870). These measures highlight the operational foundation of SLSS. They show how effective quality control systems, root cause analysis, and ongoing improvement efforts can increase throughput and ensure consistent processes. Customer Satisfaction Index (0.865) and On-time Delivery Performance (0.856) point out the external benefits of SLSS implementation. With better internal coordination, organizations can meet delivery deadlines and meet end-user expectations. This boosts market trust and customer loyalty.

Measures like Flexibility in Operations (0.847), Employee Satisfaction (0.839), and Skill Development Index (0.830) indicate that SLSS also aids in workforce development and adaptability. By empowering employees, encouraging teamwork, and focusing on training, companies can build a strong and flexible operational culture. Middle-tier scores include Cycle Time Reduction (0.819), Inventory Turnover Rate (0.812), Resource Utilization (0.805), Material Recycling Rate (0.798), and Waste Reduction Rate (0.790). These measures show key lean results where noticeable improvements in resource efficiency and process flow have been made, while also enhancing environmental sustainability through recycling and waste management.

Interestingly, Energy Efficiency Improvement (0.784) and Carbon Emission Reduction (0.775), while important in a sustainable agenda, rank lower. This might be due to longer payback periods or difficulties in measurement. Water Usage Efficiency (0.768) and Supplier Performance (0.759) also follow, indicating that while important, these areas need more structured support and alignment with suppliers. The lowest-ranking measures are Product Quality Index (0.750), Compliance with Environmental Regulations (0.743), Return on Investment (0.735), Market Competitiveness (0.727), and Innovation Rate (0.720). While these are still significant, their lower scores may indicate either an indirect connection to SLSS enablers or a delay in seeing benefits. Accordingly, the CoCoSo findings show that SLSS has a quick impact on cost, process, and customer-focused areas, while environmental and strategic outcomes, although crucial, take longer to appear.

6. Study Implications

The current study prioritizes Sustainable Lean Six Sigma (SLSS) performance measures using data. It offers valuable insights for researchers, industry professionals, and policy makers who want to promote sustainable operational excellence in manufacturing. This study contributes to the growing knowledge at the intersection of LSS and sustainability. It applies a combined decision-support approach (RBWM, CoCoSo) to evaluate 22 performance indicators. The rankings derived from this method provide a validated framework that future research can use to assess SLSS maturity or compare organizations across different sectors. Moreover, combining sustainability with Lean Six Sigma creates opportunities for long-term studies to evaluate how SLSS implementation evolves and how it fits with circular economy and Industry 4.0 concepts. Researchers can also look into adapting the proposed model for specific sectors or expanding it with other decision-making techniques to enhance its robustness.

Manufacturing managers and quality improvement professionals can use the prioritized performance measures as tools for diagnosis and planning. This helps them concentrate on high-impact outcomes. For example, the top-ranked indicators, like reducing operational costs, improving process efficiency, and lowering rework and defects, provide immediate, measurable benefits that support business goals. By knowing which measures deliver the best returns, practitioners can allocate resources more effectively, tailor training programs, and create better strategies for deploying SLSS. Additionally, medium-ranked indicators, such as resource use, waste reduction, and recycling rates, highlight areas where operational efficiency and environmental goals can be pursued together. The stake holder specific implications are shown in Table 4.

Table- 4 Stakeholder-specific implications of SLSS performance evaluation study

Stake Holder	Implications
Researchers	-Provides a validated framework of 22 SLSS performance measures using RBWM–CoCoSo. -Facilitates future benchmarking and longitudinal studies. -Supports adaptation to industry-specific and country-specific SLSS contexts. -Offers a foundation for extending research using other MCDM tools.
Practitioners	-Enables prioritization of improvement efforts by focusing on high-impact indicators (e.g., cost reduction, process efficiency). -Assists in better allocation of resources and training. -Supports integration of lean and green initiatives for balanced performance. -Acts as a roadmap for continuous improvement strategies.
Policymakers	-Informs the development of national or regional policies encouraging SLSS adoption. -Helps design targeted incentives and compliance programs. -Guides skill development and workforce training programs in sustainability and quality. -Aids in aligning SLSS efforts with environmental regulations and industrial competitiveness goals.

From a policy standpoint, this study highlights the importance of SLSS in achieving wider sustainability and productivity aims in manufacturing. Policy makers can use these findings to support standards, incentives, and training programs that encourage organizations, especially in developing economies, to adopt SLSS frameworks. Supporting partnerships between industry and academia, enhancing workforce skills in lean and green methods, and providing subsidies for technology integration, such as energy-efficient systems or CAD/CAM tools, can help speed up adoption. Furthermore, aligning SLSS metrics with regulatory standards, like environmental compliance, emissions control, and water efficiency, can result in more effective and enforceable sustainability policies.

REFERENCES

1) R. D. Snee, "Lean Six Sigma—Getting Better All the Time," Int. J. Lean Six Sigma, vol. 1, no. 1, pp. 9–29, 2010.
2) T. Chiarini, "Sustainable manufacturing-greening processes using specific Lean production tools: an empirical observation from European motorcycle component manufacturers," J. Clean. Prod., vol. 85, pp. 226–233, Dec. 2014.
3) J. Antony, S. Sunder M., and L. Farrington, "Lean Six Sigma for higher education institutions (HEIs): Challenges, barriers, success factors, tools/techniques," Int. J. Product. Perform. Manag., vol. 65, no. 2, pp. 203–225, 2016.
4) M. M. Rahman, M. M. Hossain, and M. N. Islam, "Barriers and challenges to implementing Lean manufacturing in the garment sector of Bangladesh," J. Text. Inst., vol. 108, no. 9, pp. 1596–1604, 2017.
5) J. C. Munro and J. H. Wheeler, "Sustainability and Lean Six Sigma: Synergies and Opportunities," Sustainability, vol. 12, no. 23, pp. 1–22, 2020.
6) J. D. Rodríguez, C. Lozano, and J. S. Juan, "Performance measurement systems and Lean Six Sigma: A literature review," J. Manuf. Technol. Manag., vol. 32, no. 3, pp. 711–732, 2021.
7) D. Sharma, M. Singh, and A. K. Gupta, "Barriers to lean Six Sigma implementation in Indian manufacturing industries: An ISM approach," Int. J. Lean Six Sigma, vol. 9, no. 4, pp. 482–496, 2018.
8) A. Luthra, S. Kumar, and R. K. Govindan, "Barriers to implementing Industry 4.0 in Indian manufacturing organizations: An ISM approach," J. Clean. Prod., vol. 233, pp. 582–598, Oct. 2019.
9) R. Rezaei, "Best-worst multi-criteria decision-making method," Omega, vol. 53, pp. 49–57, Jun. 2015.
10) S. Zavadskas, Z. Turskis, and J. Antucheviciene, "A new additive ratio assessment (ARAS) method in multicriteria decision-making," Technol. Econ. Dev. Econ., vol. 16, no. 2, pp. 159–172, 2010.
11) M. Ghorabaee, M. Amiri, E. Zavadskas, and L. Turskis, "Multi-criteria decision making for supplier selection based on interval-valued intuitionistic fuzzy CoCoSo method," Econ. Comput. Econ. Cybern. Stud. Res., vol. 51, no. 1, pp. 31–48, 2017.
12) A. Diabat and K. Govindan, "An analysis of the drivers affecting the implementation of green supply chain management," Resour. Conserv. Recycl., vol. 55, no. 6, pp. 659–667, 2011.
13) B. K. Routroy and R. S. Shankar, "An integrated approach for sustainable supplier selection using fuzzy analytic hierarchy process and grey relational analysis," Clean Technol. Environ. Policy, vol. 19, pp. 1327–1346, 2017.
14) V. K. Pujari and V. K. Jain, "Modeling and prioritizing enablers of sustainable Lean Six Sigma implementation in manufacturing industries," J. Ind. Eng. Int., vol. 18, pp. 401–419, 2022.
15) R. Gunasekaran and E. W. T. Ngai, "Information systems in supply chain integration and management," Eur. J. Oper. Res., vol. 159, no. 2, pp. 269–295, 2004.
16) S. Vinodh and V. R. K. Somanaathan, "Application of fuzzy VIKOR for selection of lean manufacturing tools in an automobile industry," Int. J. Prod. Res., vol. 49, no. 23, pp. 7065–7088, 2011.
17) R. Azadi, M. M. Saen, and S. Torabi, "A new fuzzy Data Envelopment Analysis model for performance measurement of suppliers in sustainable supply chains," J. Clean. Prod., vol. 137, pp. 213–229, 2016.
18) S. K. M. Luthra and A. Haleem, "Green supply chain management: implementation and performance–a literature review and future research directions," J. Clean. Prod., vol. 20, no. 1, pp. 1–14, 2012.
19) A. Garza-Reyes, "Lean and green–Synergies, differences, limitations, and the need for both," J. Clean. Prod., vol. 47, pp. 532–540, 2013.
20) P. L. Yee, "Reducing environmental impact through Lean Six Sigma practices: A case study of an electronics manufacturing firm," Sustainability, vol. 11, no. 20, p. 5720, 2019.
21) J. L. Hines, R. Silvi, and M. Bartolini, "Performance Measurement Systems Design: A Literature Review and Research Agenda," Int. J. Oper. Prod. Manag., vol. 30, no. 2, pp. 126–164, 2010.
22) P. Bhanot, R. Kumar, and S. Deshmukh, "Sustainable manufacturing: A critical review of recent developments and future prospects," Int. J. Adv. Manuf. Technol., vol. 92, no. 5–8, pp. 2681–2700, 2017.
23) . Vinodh and A. G. Chintha, "Application of fuzzy QFD for enabling sustainable manufacturing: A case study," ," Int. J. Adv. Manuf. Technol., vol. 69, no. 1–4, pp. 817–830, May 2013.
24) R. Garza-Reyes, L. Kumar, V. Kumar, and H. Antonyová, "Lean and green–Synergies, differences, and challenges," Int. J. Lean Six Sigma, vol. 9, no. 2, pp. 238–256, 2018.
25) B. A. Rodrigues, R. K. Gupta, and R. V. Deshmukh, "Lean Six Sigma and sustainability: A systematic review and future directions," Int. J. Product. Perform. Manag., vol. 72, no. 1, pp. 103–125, 2022.
26) P. D. Singh and R. Khanduja, "Performance measurement and evaluation of sustainable lean six sigma framework using fuzzy AHP approach," J. Clean. Prod., vol. 279, p. 123208, 2021.