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Providing an Integrated Model of Lean Six Sigma and Supply Chain Resilience and Analyzing Its Effects on Improving Flexibility in Industries

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ABSTRACT

The purpose of this study is to design and validate an integrated model of Lean Six Sigma and resilient supply chain management across various industries by evaluating the effects of lean tools on resilience indicators. The research employed an exploratory mixed-methods approach implemented in four stages: content analysis to identify key factors, interpretive structural modeling to develop the conceptual model, a fuzzy inference system to assess the effects, and design of experiments to validate the model. The statistical population consisted of twelve experts, including industrial engineering specialists and managers active in different industries, selected through purposive and snowball sampling. Data collection instruments included semi-structured interviews and NVivo version 11, MATLAB, and Minitab software. Content analysis resulted in the extraction of sixty-six open codes, twenty-four axial categories, and eleven selective categories, which led to identifying eight lean tools—including 5S, Poka-Yoke, QFD, SMED, FMEA, benchmarking, SIPOC, and BSC—and three resilience indicators: flexibility, capacity, and adaptability. Data saturation was achieved after the twelfth interview. Findings from interpretive structural modeling indicated that 5S and QFD serve as driving variables at lower levels and influence intermediate variables and resilience outcomes at higher levels. Results of the design of experiments using fractional factorial designs showed that 5S, with a coefficient of 15.3, had the greatest impact on flexibility and capacity, while QFD had the strongest effect on adaptability. The fuzzy inference system results further confirmed these findings. Periodic review of the supply chain using benchmarking at medium or high levels is recommended.

Keywords: *Lean Six Sigma, resilient supply chain, content analysis, fuzzy inference system, industrial management.*

1. Introduction

In today's increasingly volatile and competitive industrial landscape, organizations face unprecedented pressures to enhance performance, reduce operational waste, strengthen product quality, and build resilient supply chain infrastructures capable of adapting to rapid environmental changes. These challenges stem from globalization, technological disruptions, market uncertainty, and the complex structure of modern production networks, all of which demand integrated approaches for improving operational efficiency while simultaneously reinforcing organizational robustness. Lean Six Sigma has emerged as one of the most influential methodologies in this domain, offering a structured and data-driven framework for waste minimization, quality enhancement, and process optimization across industries (Asadi, 2019; Lorestani, 2018). As organizations increasingly strive for agility and responsiveness, Lean Six Sigma practices have expanded from traditional manufacturing settings to broader contexts such as logistics, healthcare, and food supply chains, highlighting the method's versatility and strategic relevance (Masini et al., 2017; Widiwati et al., 2024). Yet, with the rise of supply chain disruptions—ranging from global pandemics to geopolitical conflicts—the integration of Lean Six Sigma with resilience-oriented strategies has become essential.

Supply chain resilience is now considered a critical capability for sustaining operations and minimizing vulnerability to disruptions. Foundational research emphasizes that resilient supply chains possess enhanced adaptability, flexibility, redundancy, and recovery potential, enabling them to withstand shocks and restore performance levels efficiently (Christopher & Peck, 2023; Pettit et al., 2021; Tveiten, 2023). However, building resilience is not a passive outcome but rather a deliberate strategic process requiring coordination of structural, relational, and technological enablers (Hall et al., 2022; Jüttner & Maklan, 2022). Studies have demonstrated that organizations with integrated decision-making structures and effective communication pathways maintain a higher capacity to manage uncertainty and environmental complexity (Rana & Jani, 2023; Vachon & Klassen, 2022). As disruptions become persistent rather than episodic, the role of Lean Six Sigma as a strategic tool for reinforcing resilience becomes increasingly evident.

Recent research highlights a promising convergence between Lean Six Sigma principles and resilience-enhancing mechanisms. Lean tools such as 5S, SMED, and SIPOC contribute directly to strengthening process stability, reducing cycle times, and improving process transparency, while Six Sigma's statistical rigor supports data-driven risk management and defect prevention (Gomaa, 2022; Hamzeh Herandi, 2021; Hojjati & Mohsen Zarei, 2019). This alignment is especially significant in environments with high product variability and demand fluctuations, where waste reduction and precision become central to operational success (Sharafi et al., 2023; Tay & Aw, 2021). Furthermore, Lean Six Sigma fosters a culture of continuous improvement and cross-functional learning—key components of building organizational resilience—that enable firms to anticipate disruptions, mitigate risks, and rapidly adapt to external shocks (Khodaei, 2021; Sarlak, 2021). This cultural dimension underscores the necessity of integrating behavioral, managerial, and operational strategies within a unified performance framework.

Several empirical and conceptual studies point to the direct and indirect effects of Lean Six Sigma on overall supply chain resilience. For instance, Lean waste reduction practices lower operational fragility by minimizing inefficiencies and increasing available capacity, enabling firms to respond swiftly during crises (Hundal et al., 2022; Prajogo & Olhager, 2023). Likewise, QFD, FMEA, and Poka-Yoke facilitate error-proofing, early risk identification, and customer-driven improvements, fostering system stability and adaptability (Mohammadi & Shayannia, 2023; Rash et al., 2024). Research has also shown that Lean Six Sigma improves collaboration and information sharing across supply chain partners, which enhances responsiveness and alignment—two fundamental attributes of resilient networks (Kolawole et al., 2021; Kusumastuti et al., 2021). Aligning these capabilities with resilience-oriented supply chain design—such as network redesign, redundancy planning, and alliance formation—produces synergistic effects that amplify both operational efficiency and long-term stability (Bagherimanesh et al., 2019; Yavari & Aghalan, 2019).

Furthermore, adopting Lean Six Sigma principles within digital and Industry 4.0 environments has created new opportunities for enhancing supply chain flexibility and reconfigurability. The increasing integration of advanced technologies such as artificial intelligence, automation, and IoT-enabled analytics has significantly broadened the scope of operational excellence initiatives. Recent studies demonstrate that AI-driven analytics can strengthen decision-making accuracy, improve demand forecasting, and enhance supply chain visibility, all of which contribute to disruption mitigation and organizational performance (Ma et al., 2025; Rahman et al., 2025). When aligned with Lean Six Sigma methodologies, these technologies enable organizations to implement predictive quality control, scenario-based planning, and real-time process monitoring. Consequently, digital transformation amplifies both the speed and precision of Lean Six Sigma interventions, facilitating continuous improvement cycles that reinforce resilience capabilities across multiple operational layers (Mohammadi & Shayannia, 2023; Mohapatra et al., 2023).

Despite these developments, existing literature highlights several challenges in implementing Lean Six Sigma within resilience-oriented frameworks. Resistance to change, lack of managerial commitment, limited employee engagement, and insufficient integration with organizational culture can undermine the success of Lean Six Sigma initiatives (Khajavi & Mohammadi, 2020; Sheikh Shoa'i, 2021). Supply chain complexity further compounds these barriers, as global networks require coordination among diverse stakeholders, each with varying levels of technological readiness and process maturity (Vachon & Klassen, 2022). Moreover, Lean's emphasis on minimal inventory and streamlined processes may conflict with resilience strategies such as redundancy and safety stock, necessitating careful alignment to avoid performance trade-offs (Mohapatra et al., 2023; Prajogo & Olhager, 2023). Understanding how these relationships interact is vital for designing balanced and context-appropriate models.

Scholars argue that combining Lean Six Sigma with resilience principles demands a multidimensional perspective that integrates operational, strategic, and technological components. Among the most influential frameworks are those that examine how human resource systems, quality management practices, and structural flexibility reinforce resilience outcomes (Hall et al., 2022; Tveiten, 2023). Other studies emphasize the strategic role of cross-functional collaboration and continuous learning in enhancing adaptability, especially in high-uncertainty industries such as food and manufacturing (Kolawole et al., 2021; Kusumastuti et al., 2021). As Lean Six Sigma expands to meet sustainability requirements, researchers highlight the emergence of Green Lean Six Sigma (GLSS), which integrates environmental considerations into process excellence frameworks (Sheikh Shoa'i, 2021). This evolution reflects the broader shift toward sustainable supply chain management, where economic efficiency, environmental performance, and operational resilience coalesce.

In addition, studies conducted in developing economies underscore the need for context-specific models that reflect local industrial conditions, resource limitations, and cultural characteristics (Rash et al., 2024; Sharafi et al., 2023). These contexts often require hybrid approaches that combine Lean Six Sigma with alternative operational improvement methodologies to overcome infrastructural constraints and managerial challenges. Such findings reinforce the importance of designing integrated frameworks tailored to industry-specific realities rather than relying solely on generic models.

Given these complexities, the present research addresses a critical gap by proposing a comprehensive integrated model that combines Lean Six Sigma tools with supply chain resilience indicators. Unlike previous studies that evaluate Lean Six Sigma or resilience separately, this study focuses on their synergistic relationship, emphasizing how specific Lean tools influence resilience outcomes such as flexibility, capacity, and adaptability. Furthermore, the study incorporates advanced analytical approaches—including content analysis, interpretive structural modeling (ISM), and fuzzy inference systems (FIS)—to identify key relationships and quantify the effects of Lean Six Sigma variables within a resilience-oriented supply chain structure. Integrating qualitative expert insight with quantitative modeling ensures both theoretical rigor and practical applicability, allowing for a more holistic understanding of how operational excellence initiatives can strengthen supply chain resilience across industries (Asadi, 2019; Hamzeh Herandi, 2021; Sarlak, 2021).

Ultimately, considering the rising frequency of disruptions, global supply chain interdependencies, and organizational pressures for quality improvement, developing an integrated Lean Six Sigma and resilience framework is not only beneficial but necessary for sustainable industrial performance. Drawing upon the extensive body of research in operations management, supply chain strategy, quality engineering, and organizational design (Bagherimanesh et al., 2019; Hojjati & Mohsen Zarei, 2019; Hundal et al., 2022; Mohapatra et al., 2023), this study advances a unified model that supports both theoretical progression and practical implementation.

The aim of this study is to design and validate an integrated Lean Six Sigma and resilient supply chain model to evaluate the effects of Lean tools on resilience indicators.

2. Methods and Materials

The present research is applied in purpose and exploratory mixed-methods (quantitative and qualitative) in nature, and in terms of implementation, it employs content analysis in the qualitative section and a survey method in the quantitative section. To achieve the research objectives, the research process was designed in four main stages: content analysis, interpretive structural modeling (ISM), and the fuzzy inference system (FIS). These stages were carried out systematically with the aim of addressing the four main objectives of the study (identifying factors, developing the conceptual model, assessing effects, and validating the model). The table below presents the research stages and their connection to the research objectives in a transparent manner.

One of the qualitative methods used in this study is content analysis, which was selected due to its particular strengths. Content analysis is a process for generalizing the results derived from a specific observation to a broader theory. Through this inductive method, theory is derived from everyday experiences, interactions, documents, literature, and observations. The researcher does not begin with a theory to prove; instead, the study starts from the field, allowing relevant concepts to emerge naturally. Thus, data collection, analysis, and theory are interrelated with a bidirectional relationship.

The statistical population of this study includes experts in the field of supply chain management whose opinions were used in the Delphi, ISM, and FIS stages—specifically the views of 12 experts. Characteristics of the statistical population include:

Complete mastery of the industrial field, especially from a practical perspective (minimum 10 years of work experience)

Full familiarity with challenges and strategies for developing private companies

Experts were selected from among chief executive officers, board members, deputy managers, research institute faculty members, and senior managers. Sampling was conducted through purposive and snowball techniques, such that each expert introduced additional specialists to the researcher. After analyzing each interview, ambiguities or weaknesses in the model and categories were identified, and the next expert was selected according to the needed expertise for addressing these gaps. The sample size was set at 12, because theoretical saturation was achieved after 12 interviews. Theoretical saturation occurred when no new codes emerged in later interviews and the data only confirmed previously identified concepts, indicating sufficient richness to develop the Lean Six Sigma and resilient supply chain model. The table below presents the experts' characteristics:

Table 1

Expert Characteristics

Expert No.	Specialization	Academic Degree	Work Experience (years)	Role in Research
1	Industrial Engineering	PhD	15	Analysis of Six Sigma tools
2	Supply Chain Management	PhD	12	Identification of flexibility factors
3	Food Industries	PhD	14	Quality assessment in food materials
4	Industrial Engineering	MSc	10	Supply chain risk assessment
5	Food Management	MSc	13	Production process analysis
6	Food Industries	PhD	11	Customer needs analysis
7	Industrial Engineering	PhD	16	Modeling relationships among factors
8	Supply Chain Management	MSc	12	Supply chain sustainability analysis
9	Food Industries	PhD	10	Quality standards assessment
10	Food Management	MSc	15	Operational analysis in food materials
11	Industrial Engineering	PhD	13	Validation of the proposed model
12	Food Industries	MSc	11	Supply chain performance analysis

The first step of data analysis is content analysis. The purpose of this stage is to identify the key factors and subfactors influencing Lean Six Sigma and the resilient supply chain. Through semi-structured interviews with experts (including specialists in industrial engineering, food industries, and managers in various industries), data were analyzed using NVivo software, and open, axial, and selective coding was conducted. The output of this stage includes key variables such as 5S, Poka-Yoke, QFD, SMED, FMEA, benchmarking, SIPOC, and BSC.

The second step of data analysis is interpretive structural modeling (ISM). This stage involves developing the conceptual model. The ISM method identifies causal and hierarchical relationships among the factors. ISM procedures include constructing the Structural Self-Interaction Matrix (SSIM), converting it into a reachability matrix, applying transitivity rules, and level partitioning of variables. This model provides a foundation for subsequent analyses.

The third step of data analysis involves the fuzzy inference system (FIS). This stage evaluates the effects of input variables (Lean Six Sigma tools) on output variables (flexibility, capacity, adaptability). Using fuzzy logic and the Mamdani model in MATLAB, complex nonlinear relationships between variables are analyzed. Fuzzy rules are developed based on the ISM model and expert judgments.

3. Findings and Results

Based on data analysis, 1 respondent (8.33%) was between 31–40 years old, 5 respondents (41.66%) were between 41–50 years old, and 6 respondents (50%) were aged 51 or older. Additionally, 5 respondents (41.66%) held a master's degree and 7 respondents (58.33%) held a PhD. Furthermore, 6 respondents (50%) had 16–20 years of work experience, and 6 respondents (50%) had 21 or more years of experience.

This section presents the qualitative content analysis results obtained from semi-structured interviews with the 12 experts in Lean Six Sigma and resilient supply chains. The content analysis process—conducted deductively and inductively using NVivo version 11—consisted of open, axial, and selective coding. The main purpose was to identify key factors influencing the design and implementation of Lean Six Sigma in the food supply chain and to develop a comprehensive framework for understanding relationships among these factors. Based on the systematic content analysis of the 12 interviews, a comprehensive conceptual framework for Lean Six Sigma and resilient supply chain modeling in the food industry was developed, forming the foundation for subsequent research stages.

Table 3 provides a statistical summary of the key findings from the content analysis. Of the 66 identified open codes, 38 codes (57.6%) directly relate to the eight main Lean Six Sigma tools, categorized as causal conditions, contextual factors, intervening conditions, and strategies. Five codes (7.6%) correspond to the three key outcomes (flexibility, capacity, adaptability). The remaining 28 codes (42.4%) relate to supporting axial categories that cover the organizational and managerial contexts necessary for model implementation, including senior management commitment, control over organizational flows, quality improvement, just-in-time production, productivity enhancement, and collaboration. This distribution demonstrates that the proposed model not only encompasses technical Lean Six Sigma tools but also integrates essential organizational and managerial factors. Additionally, the presence of 11 selective categories indicates a balanced and comprehensive model structure that covers all critical aspects without unnecessary complexity.

Table 2

Summary of Key Content Analysis Findings

Paradigmatic Dimension	Number of Selective Categories	Key Categories	Number of Open Codes	Percentage of Total Codes
Causal conditions	2	5S, Poka-Yoke	9	13.6%
Contextual factors	2	QFD, SMED	8	12.1%
Intervening conditions	2	FMEA, Benchmarking	8	12.1%
Strategies	2	SIPOC, BSC	8	12.1%
Outcomes	3	Flexibility, Capacity, Adaptability	5	7.6%
Other axial categories	–	Management commitment, flow control, quality improvement, etc.	28	42.4%
Total	11	11 main categories	66	100%

Based on the content analysis, qualitative relationships between the selective categories and model outcomes (flexibility, capacity, adaptability) were identified and quantified. These relationships form the basis for the ISM and FIS analyses. The results indicate that 5S has a strong effect on flexibility and capacity and a moderate effect on adaptability—confirmed in 11 interviews. QFD is the only tool with a strong effect on all three outcomes (confirmed in 10 sources), highlighting its comprehensive role in improving supply chain performance. SMED strongly influences flexibility and capacity, which is logical since reducing setup times directly increases flexibility and production capacity. FMEA mainly has a moderate effect on flexibility and adaptability but a weak effect on capacity. BSC has a strong effect on adaptability, suggesting that balanced performance assessment helps maintain stability and resilience. The "number of confirming sources" column indicates the reliability of each relationship, while the "overall relationship strength" column provides a qualitative evaluation of each tool's influence.

Table 3

Matrix of Relationships Between Selective Categories and Outcomes

Input Variable	Flexibility	Capacity	Adaptability	Confirming Sources	Overall Relationship Strength
5S	+++ (Strong)	+++ (Strong)	++ (Moderate)	11	Very Strong
Poka-Yoke	++ (Moderate)	++ (Moderate)	++ (Moderate)	9	Moderate
QFD	+++ (Strong)	+++ (Strong)	+++ (Strong)	10	Very Strong
SMED	+++ (Strong)	+++ (Strong)	++ (Moderate)	9	Strong
FMEA	++ (Moderate)	+ (Weak)	++ (Moderate)	8	Moderate
Benchmarking	+ (Weak)	+ (Weak)	++ (Moderate)	7	Moderate to Weak
SIPOC	++ (Moderate)	++ (Moderate)	++ (Moderate)	10	Moderate
BSC	++ (Moderate)	+ (Weak)	+++ (Strong)	9	Moderate

Based on the three stages of coding and validation, the final paradigmatic model for the "Lean Six Sigma and Resilient Supply Chain Model" was developed. This model visually and structurally presents the relationships between the various dimensions.

Figure 1

Paradigmatic Model of Lean Six Sigma and Resilient Supply Chain

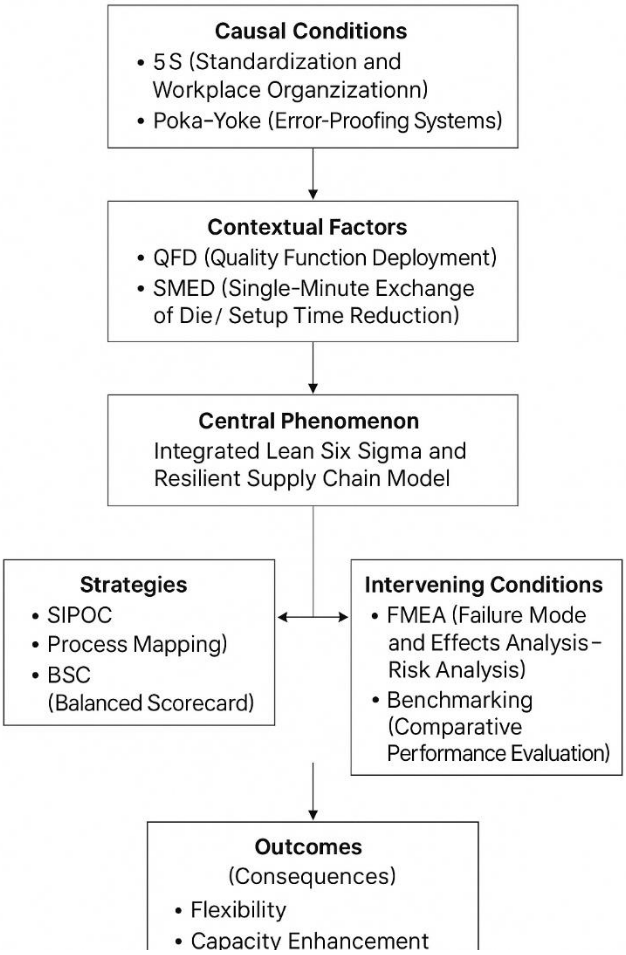


Figure 1 provides a visual and comprehensive summary of the paradigmatic model derived from content analysis. The model shows a causal flow from causal conditions (5S and Poka-Yoke) as foundational factors, to contextual factors (QFD and SMED) which create enabling conditions, and then to the central phenomenon (Lean Six Sigma and resilient supply chain model). Intervening conditions (FMEA and benchmarking) and strategies (SIPOC and BSC) appear on the sides as factors that can facilitate or direct the process. Finally, three key outcomes (flexibility, increased capacity, and adaptability) are shown at the bottom of the diagram as the results of implementing the model. One-directional arrows indicate the direction of influence, while the bidirectional arrows between intervening conditions, strategies, and the central phenomenon indicate mutual influence.

In this study, a two-round Delphi method was used to identify the key and influential variables. The Delphi method is one of the structured qualitative techniques that utilizes the collective judgment of experts to identify and select the research variables. Due to its interactive and iterative nature, this method makes it possible to achieve theoretical consensus among specialists. Based on the data analysis from the Delphi procedure, the 8 final research variables with the highest level of expert agreement are presented in the table below.

The results of this section showed that the Delphi process, as a scientific and structured method, plays an effective role in selecting and reaching consensus on the research variables. All final confirmed variables are consistent with the research objectives and are positioned within the conceptual model of the study. Therefore, in the following stages, these 8 variables will be used as the main variables for quantitative analyses and statistical modeling to examine their impact on quality management and the supply chain. This stage helped the researchers, by incorporating expert opinions, to increase the accuracy and scientific validity of the study and to select the research variables based on industrial and managerial realities.

Table 4

Final Variables Confirmed in the Delphi Process

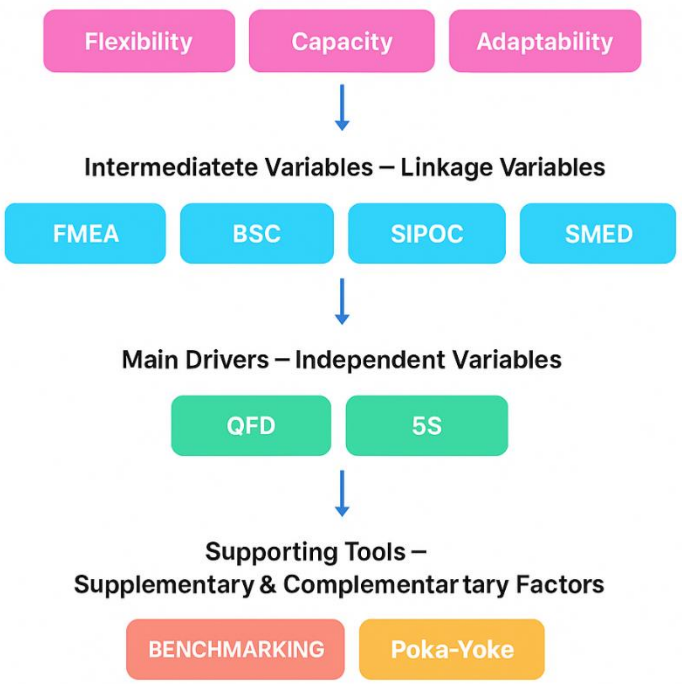
No.	Final Research Variable	Final Mean Score
1	5S (Total Quality Management)	4.8
2	POKA-YOKE (Six Sigma Methodology)	4.7
3	QFD (Quality Function Deployment)	4.6
4	SMED (Reduction of Changeover Time in Processes)	4.5
5	FMEA (Failure Modes and Effects Analysis)	4.6
6	BENCHMARKING (Competitive Benchmarking)	4.4
7	SIPOC (Organizational Process Modeling)	4.5
8	BSC (Balanced Scorecard)	4.3

After identifying the key factors using content analysis, interpretive structural modeling (ISM) was employed to develop the conceptual model. This method specified the causal and hierarchical relationships between the input variables, including Lean Six Sigma tools, and the output variables (flexibility, capacity, adaptability). The ISM implementation steps included constructing the Structural Self-Interaction Matrix (SSIM), converting it into the initial reachability matrix, applying the transitivity rule, and level partitioning of variables. The final ISM model showed that 5S and QFD act as driving variables, while flexibility, capacity, and adaptability act as dependent outcomes. This model provided a coherent framework for subsequent analyses in the fuzzy inference system (FIS), facilitating detailed examination of the effects of Lean Six Sigma tools on supply chain resilience indicators. Excel and MATLAB were used for matrix computations.

The final ISM model demonstrated that 5S and QFD, as the main driving variables, are located at the lower levels and influence intermediate variables such as SMED and SIPOC, which in turn affect the dependent outcomes of flexibility, capacity, and adaptability at higher levels. For example, 5S, by focusing on workplace organization and reducing wasted time, strengthens supply chain flexibility, whereas QFD, by translating customer needs into technical specifications, improves adaptability. The tools used, including Excel and MATLAB for matrix calculations, enhanced the accuracy of the analyses.

Figure 2

Interpretive Structural Model (ISM) of Lean Six Sigma and Resilient Supply Chain



Fuzzy if–then rules were developed based on the opinions of 12 experts (specialists in industrial engineering, food industries, and industrial managers) and the conceptual model derived from interpretive structural modeling (ISM) to determine the relationships between the input variables (5S, POKA-YOKE, QFD, SMED, FMEA, BENCHMARKING, SIPOC, BSC) and the output variables (flexibility, capacity, adaptability). The input and output variables were defined at three levels (low, medium, high), aligned with triangular membership functions (low: 0, 0, 0.4 or 0.5; medium: 0.2, 0.4, 0.6 or 0.3, 0.5, 0.7; high: 0.4, 1, 1 or 0.5, 1, 1). The table below presents a sample of the fuzzy rules that specify the effects of different combinations of input variables on the output variables.

Table 5

Sample Fuzzy Rules

5S	POKA-YOKE	QFD	SMED	FMEA	BENCHMARKING	SIPOC	BSC	Flexibility	Capacity	Adaptability
Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Medium	Low	Low	Low	Medium	Medium	Low	Low	Medium	Medium	Medium
Medium	Medium	Medium	Medium	High	Medium	Medium	Medium	High	High	Medium
High	Medium	Medium	High	High	High	High	Medium	High	High	High
High	High	High	High	High	High	High	High	High	High	High

Next, based on the above rules, the fuzzy inference system is designed separately for each of the three output variables.

Figure 3

Fuzzy Inference System for Flexibility

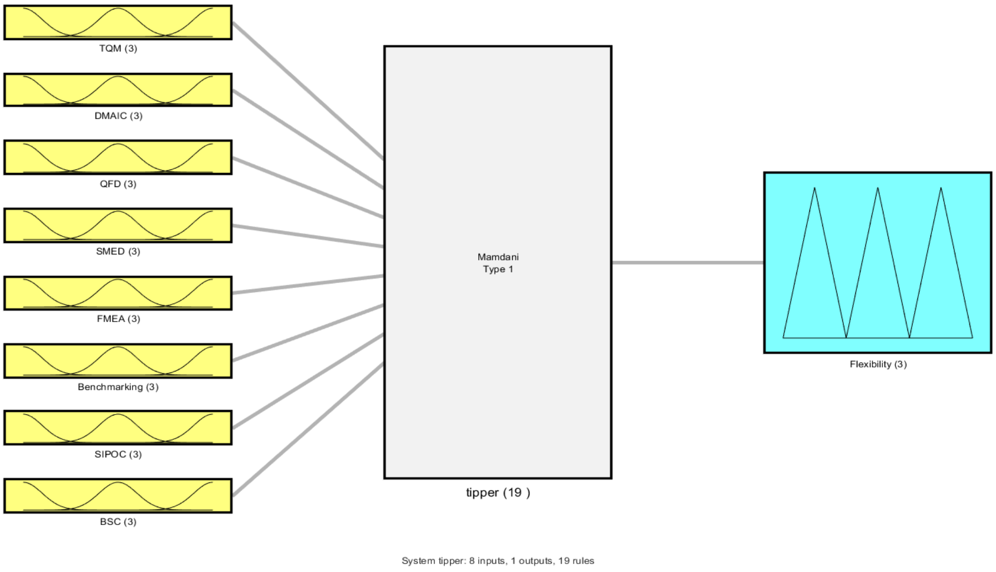
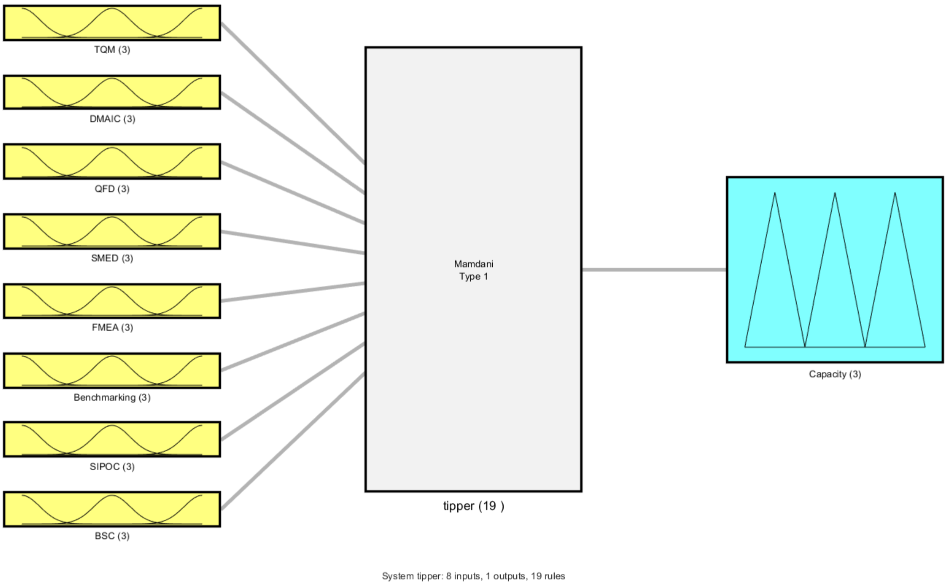


Figure 4

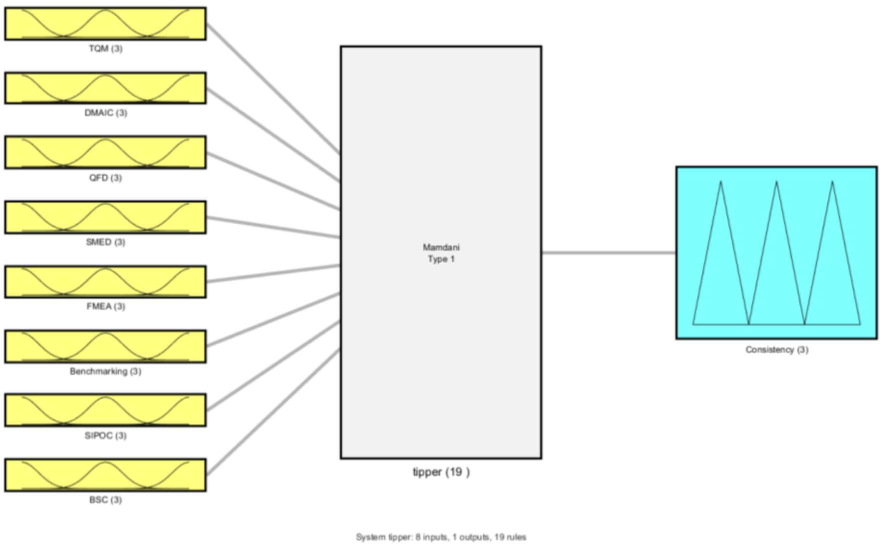
Fuzzy Inference System for Capacity



After examining the influencing variables on the output variable of flexibility, in this section the fuzzy inference system for capacity is plotted, and as can be seen, 8 input variables and one output variable are considered. In the following figure, the fuzzy inference system for adaptability is drawn, taking into account 8 input variables and one output variable (adaptability).

Figure 5

Fuzzy Inference System for Adaptability



4. Discussion and Conclusion

The results of the present study, which aimed at designing and validating an integrated Lean Six Sigma and resilient supply chain model, revealed that eight key Lean Six Sigma tools—5S, Poka-Yoke, QFD, SMED, FMEA, Benchmarking, SIPOC, and BSC—play significant but differentiated roles in strengthening resilience indicators, namely flexibility, capacity, and adaptability. The findings demonstrated that 5S and QFD function as the most powerful driving variables within the ISM hierarchy, exerting substantial influence on intermediate variables and ultimately on resilience outcomes. This is consistent with the broader literature, which positions foundational Lean tools as essential enablers of robust operational systems capable of withstanding unexpected disruptions. The strong role of 5S identified in this study aligns with prior research emphasizing that workplace organization, waste elimination, and improved process clarity enhance overall system responsiveness and capacity to adjust efficiently under uncertainty (Widiwati et al., 2024). Likewise, the prominent effect of QFD on all three resilience indicators reflects its centrality as a customer-driven planning tool, enabling firms to translate external requirements into operational specifications that support adaptability and performance stability (Rash et al., 2024). These findings reinforce longstanding arguments that Lean Six Sigma's effectiveness lies in its structured, data-driven approach to harmonizing process control with strategic responsiveness (Tveiten, 2023).

The study further showed that SMED and SIPOC occupy middle layers within the ISM model, demonstrating meaningful indirect impacts on resilience. SMED's strong influence on flexibility and capacity can be explained by its direct contribution to reducing setup times and increasing throughput, thereby enabling firms to respond quickly to fluctuating demand and production contingencies. This supports earlier studies highlighting SMED's capacity-enhancing value, particularly in industries facing volatile operating environments (Sharafi et al., 2023). Similarly, the role of SIPOC in mapping high-level processes contributes to improved visibility, coordination, and standardization—structural attributes associated with resilient supply chains. Prior empirical research affirms that transparent process architecture facilitates rapid reconfiguration and information flow, both of which are essential for minimizing disruption impacts (Rana & Jani, 2023). These findings confirm that resilience is not solely the outcome of redundancy or flexibility but is also deeply rooted in the clarity, standardization, and transparency of internal operations.

A further insight demonstrated through fuzzy inference analysis is that the strength of each Lean Six Sigma tool varies across different resilience dimensions. For example, FMEA showed a moderate effect on flexibility and adaptability but only a weak effect on capacity, reflecting its primary role in risk identification rather than throughput enhancement. This is consistent with published studies, where FMEA is positioned as a proactive failure prevention method that enhances system reliability and adaptability, particularly in early design or continuous improvement contexts (Prajogo & Olhager, 2023). Benchmarking, on the other hand, yielded weaker associations with the resilience outcomes, particularly flexibility and capacity. While its strategic relevance in evaluating external best practices is well documented, its indirect nature and dependence on interpretive managerial action may explain its lower operational-level effect. Nevertheless, literature suggests that Benchmarking remains vital for long-term resilience building, providing strategic orientation and learning opportunities that contribute to continuous renewal (Mohapatra et al., 2023).

The findings also underscored the strong effect of BSC on adaptability, highlighting the importance of integrated performance measurement systems in guiding organizational resilience strategies. Balanced Scorecard frameworks help align objectives, monitor systemic signals, and reinforce learning-based organizational cultures—elements seen as essential for adaptive capabilities in dynamic environments (Mohammadi & Shayannia, 2023). This corresponds to earlier works emphasizing that resilience is not merely structural but behavioral, built through systematic reflection and strategic alignment across performance dimensions (Christopher & Peck, 2023). The study's results thus extend this understanding by positioning BSC as an essential strategic complement to operational Lean tools.

Beyond tool-specific findings, this study confirmed that Lean Six Sigma, when integrated through a systematic structural framework such as ISM and operationalized via FIS, offers significant potential to enhance supply chain resilience. As complexity and variability increase across global networks, organizations require models that not only improve operational efficiency but also build foundational capacities for dealing with emergent disruptions. Prior studies have argued that traditional Lean principles must evolve to accommodate resilience goals, particularly as minimal inventory and streamlined processes can contradict redundancy-based resilience strategies (Vachon & Klassen, 2022). However, our findings suggest that Lean and resilience are not inherently conflicting; instead, strategic integration, facilitated by proper modeling and tool alignment, yields synergistic outcomes. This supports contemporary arguments that hybrid Lean-resilience frameworks enable organizations to maintain both high efficiency and high adaptability (Jüttner & Maklan, 2022).

The study also reveals that the integration of Lean Six Sigma and resilience capabilities cannot occur without strong organizational infrastructure and human capital development. Expert interviews highlighted the importance of management commitment, cross-functional collaboration, capability-building initiatives, and cultural readiness. This is in line with human resource and organizational development literature, which suggests that resilient systems are cultivated through leadership involvement, employee empowerment, and strategic learning mechanisms (Hall et al., 2022; Hundal et al., 2022). Moreover, behavioral factors such as error management, involvement in improvement initiatives, and quality-oriented mindsets play a significant role in operationalizing Lean Six Sigma tools effectively (Gomaa, 2022). These findings reinforce the argument that resilience is not solely a technical characteristic but a socio-technical capability embedded in people, processes, and technology.

Another important dimension emerging from the findings is the increasing role of digital technologies in strengthening the synergy between Lean Six Sigma and supply chain resilience. AI-driven decision-support systems, automation, and data analytics offer real-time insights that enhance responsiveness and reduce decision-making uncertainty. This supports recent literature demonstrating that digital transformation amplifies Lean Six Sigma's benefits by increasing visibility, prediction accuracy, and system flexibility (Sheikh Shoa'i, 2021; Tay & Aw, 2021). Furthermore, the integration of digital intelligence enhances process control, error detection, demand forecasting, and capacity planning, thereby supporting agile and resilient supply chain configurations (Sarlak, 2021). Parallel studies also show that AI enhances supply chain flexibility and performance by enabling rapid reconfiguration and dynamic optimization, consistent with our findings regarding the importance of adaptable, technology-enabled infrastructures (Ma et al., 2025). This validates the conclusion that operational excellence in the contemporary era must incorporate digital capabilities alongside Lean Six Sigma methodologies to fully realize resilience potential.

Additionally, the empirical findings reaffirm previous work emphasizing the interconnected nature of resilience dimensions. Flexibility, capacity, and adaptability, while conceptually distinct, are operationally interdependent. Improvements in flexibility often translate into increased capacity, and both contribute to adaptability in uncertain environments. This resonates with earlier conceptual frameworks describing resilience as a multidimensional construct encompassing readiness, response, and recovery capabilities (Pettit et al., 2021). Our results demonstrate how Lean Six Sigma tools contribute differentially to these dimensions, providing a clearer practical roadmap for industries seeking to build resilience strategically.

The study also advances prior research by providing a detailed hierarchical model outlining the causal and structural relationships among Lean Six Sigma tools, which prior studies have often examined independently or descriptively. For example, while earlier studies noted the importance of integrating continuous improvement methods with resilience strategies (Kolawole et al., 2021; Kusumastuti et al., 2021), few provided systematic structural modeling to clarify interaction pathways. Our ISM and FIS analyses contribute significantly to the operationalization of these concepts, enabling practitioners to understand not only which tools matter most but how they exert influence within multi-layered organizational systems. This contributes to both theoretical refinement and practical applicability.

Furthermore, this study supports findings from strategic operations research, which view supply chain network redesign, collaboration, and alliance formation as essential for resilience outcomes. The identified importance of flexibility and capacity mirrors prior studies showing that organizations capable of rapid resource reallocation and process realignment recover faster from disruptions (Yavari & Aghalan, 2019). The role of collaboration highlighted by the study's expert inputs aligns closely with research advocating alliance-building as a strategy for strengthening supply chain resilience and competitiveness (Bagherimanesh et al., 2019). The integration of Lean Six Sigma tools into such collaborations further strengthens shared learning, information flow, and performance consistency across partners.

Overall, the findings reaffirm that Lean Six Sigma—when structured, prioritized, and strategically aligned—serves as a powerful enabler of supply chain resilience. This study advances the field by offering a validated integrated model supported by empirical evidence, structural modeling, and expert insights. Consistent with earlier works in both operational excellence and resilience theory, it demonstrates that durability in contemporary supply chains depends on proactive process optimization, risk-based decision-making, information integration, and cultural adaptability (Asadi, 2019; Lorestani, 2018; Mohapatra et al., 2023; Rahman et al., 2025). It also builds on research emphasizing that excellence frameworks must be adapted to new global realities, where resilience is not merely desirable but essential for sustainability, competitiveness, and performance continuity (Khajavi & Mohammadi, 2020; Madhani, 2020; Masini et al., 2017).

This study, while comprehensive in design and analytical approach, was limited by its reliance on expert-based qualitative judgments and a relatively small expert sample. Fuzzy inference outcomes are dependent on the subjective evaluations of experts, which may introduce bias despite structured protocols. Additionally, the research focused on generic industrial contexts, and domain-specific differences across industries such as automotive, food, and logistics were not separately analyzed. Finally, the study's modeling approach, though rigorous, does not account for temporal dynamics or real-time disruption scenarios that may alter tool effectiveness under different conditions.

Future studies should expand empirical validation by applying the proposed model across multiple industries with larger sample sizes to examine contextual variations. Incorporating real-time data analytics and simulation-based stress testing could enhance understanding of how Lean Six Sigma tools perform under different disruption scenarios. Additionally, future research may integrate sustainability metrics, digital maturity assessments, and behavioral factors to create a more holistic framework. Longitudinal studies could further explore how Lean-driven resilience capabilities evolve over time.

Organizations seeking to strengthen supply chain resilience should prioritize foundational Lean tools such as 5S and QFD while building structured pathways for integrating SMED, SIPOC, and FMEA into daily operations. Managers should invest in digital transformation initiatives that complement Lean Six Sigma practices, promote cross-functional training, and foster a culture of continuous improvement. Establishing strategic partnerships, benchmarking networks, and robust performance measurement systems will further support the operationalization of resilience strategies across the supply chain.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

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Declaration of Interest

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Ethics Considerations

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