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Driving Operational Excellence: The Role of Technology-Organization-Environment Framework in Lean Six Sigma Integrated Industry 4.0 Adoption

Abstract: Adopting technological innovations is crucial for organizations to survive in dynamic and competitive market scenarios. Moreover, it is essential to understand the customer needs and respond accordingly. The presented research makes use of Technology-Organization-Environment (TOE) framework for Lean Six Sigma Integrated Industry 4.0 (LSSI) adoption. Scholarly literature shows that adopting LSSI drastically reduces waste and variations while facilitating real-time data analysis. However, empirical studies on LSSI adoption are limited and therefore, this study was conducted, with data collected from 287 respondents employed in various industries. Structural Equation Modelling (SEM) was used to analyse research model, and the results indicate that TOE dimensions significantly impact LSSI adoption, which in turn influences operational performance. Furthermore, strategic alignment towards sustainability initiatives partially mediates the relationship between LSSI and operational performance, and these results are highly useful for practitioners, managers, and researchers aiming to adopt LSSI.

Keywords: Lean Six Sigma, Industry 4.0, Lean six sigma integrated Industry 4.0 (LSSI), operational excellence.

1. Introduction

Changing market demands for getting high quality products and services at economic price urged the industries to adopt advanced technologies and stay competitive (Perera et al.,2021). In the last one decade, Lean Six Sigma Integrated Industry 4.0 (LSSI) have emerged as a proven approach to minimize the wastages, defects and product variations with the help of digital technologies (Samanta et al., 2024). Furthermore, digital technologies also facilitate the organizations in enhancing resilience, agility and prosper in completive marketplace (Han & Trimi, 2022). The key technologies under umbrella of Industry 4.0 includes Internet of Things (IoT), Additive Manufacturing, Digital Twin, Artificial Intelligence (AI) (Upadhyay et al., 2022), Machine Learning (ML), and Blockchain (Upadhyay, 2020). LSSI facilitates in real-time analysis, monitoring and control of equipment and help build dynamic capabilities (Abdirad & Krishnan, 2021). Adopting Lean Six Sigma radically enhances operational

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performance (Lameijer et al., 2021; Tetteh-Caesar et al., 2024). Also, Chiarini and Kumar (2021) made similar findings, highlighting the role of LSSI in Italian manufacturing industries and suggesting that LSSI facilitates horizontal and vertical integration.

Antony et al. (2023) examined the evolution of Lean Six Sigma 4.0 (LSS 4.0) from LSS 1.0. The mounting demand for varied products and services has led to growing competition among organizations (Tissir et al., 2023). Industry 4.0 has led to a paradigm shift in manufacturing operations (Kaswan et al., 2022), allowing organizations to analyse real-time data and make speedy decisions, thus increasing operational excellence, customization, and agility (Sony et al., 2021). Lean Six Sigma has become a key technique for continuous improvement, helping organizations accomplish operational excellence (Singh et al., 2021).

Vinodh & Shimray (2023) identified LSSI challenges such as lack of management support, insufficient resources, resistance to new technologies, lack of knowledge, organizational and process changes, inadequate skill sets, and insufficient regulations. Also, Zulfiqar et al. (2023) underlined further barriers, such as lack of real-time visualization capabilities, cyber-security issues, poor risk assessment, ineffective organizational policies, and inadequate automation and lack of intelligent monitoring of business operations. Instead of so many challenges, LSSI have numerous advantages. LSSI significantly improves organization's profitability, supports managers in making informed decisions, improves business operations efficiency, and promotes effective collaboration and co-ordination among stakeholders (Samanta et al., 2024). It also helps better decision-making, quickly identifies anomalies and bottlenecks, and enhances process optimization (Sordan et al., 2022).

Moreover, Gaikwad et al. (2020) highlighted the key strategies to tackle the mentioned barriers which includes effective management, cross-functional collaboration, adequate investments, accurate selection of LSS tools and techniques, robust supplier relationships, effective reward and recognition policies, strategic planning, and employee empowerment. Additionally, Singh et al. (2023) assessed solutions for adopting LSSI as strong Information Technology (IT) facilities, aligning business objectives with strategic goals, improved employee participation, robust project management skills, and a culture of continuous improvement.

Yadav et al. (2021) explored critical success factors for LSSI adoption, evaluated eighteen factors under following major categories: technological, commitment, engagement, communication, and quality management systems. Moreover, Skalli et al. (2023a) studied

factors affecting the adoption of circularity principles in LSSI, performed a qualitative evaluation in twelve Moroccan production industries and evaluated drivers related to operational and environmental performance. Similarly, Pongboonchai-Empl et al. (2024) proposed define, measure, analyse, improve and control (DMAIC 4.0) framework to deal with system complexity using contemporary technologies. Also, Kaswan et al. (2022) found that LSSI tools significantly reduce environmental degradation. Moreover, big data analytics helps assess variability from various sources such as equipment, human resources, customers, and vendors (Yadav et al., 2021). Likewise, Ibrahim & Kumar (2024) evaluated LSSI criteria, including cost, quality, delivery, flexibility, and developed causal relationship among them.

Interoperability and cloud computing are also significant enablers for seamless integration among equipment (Maheshwari & Devi, 2024). Moreover, Jagtap & Duong (2019) discussed the role of big data in manufacturing. Also, Pedone & Mezgár (2018) highlighted the critical role of cloud services. Singh et al. (2023) analyzed the challenges and solutions for LSSI adoption, concluded that management participation and a long-term vision are top solutions. More empirical studies on integrating Lean, Six Sigma and Industry 4.0 are essential (Rossini et al., 2022). Therefore, the research objectives are defined as follows:

RO1: To examine the Technological, Organizational, and Environmental (TOE) aspects of adopting LSSI

RO2: To evaluate the mediating role of strategic alignment of sustainability between LSSI and operational performance.

The remaining part of the research paper are structured as follows: Section 2 illustrates the theoretical background and hypotheses formulation, Section 3 presents the research methodology, followed by data analysis in Section 4. The penultimate section discusses the results and managerial implications. Lastly, the conclusion and scope for future research are revealed in Section 6.

2. Theoretical Background

2.1 Underpinning Theory

The research study is grounded in the TOE framework, which was introduced by Tornatzky and Fleischer (1990). TOE framework is generally used and focuses on industry-level attention rather than personal-level intentions (Kamble et al., 2021). For organizations to implement smart technologies and innovate gradually, they must have the necessary technological

infrastructure, effective organizational structure and policies, and a supportive external environment (Cezar et al., 2024). Scholarly literature discussed and analyzed variety of applications of TOE frameworks in various domains, like Enterprise Resource Planning (ERP) (Awa & Ojiabo, 2016), AI adoption (Chatterjee et al., 2021); Customer Relationship Management (CRM) acceptance (Cruz-Jesus et al., 2019), Halal Warehouse Adoption (Ngah et al., 2017), and ML in Supply Chain Management (SCM) (Kamble et al., 2021). Furthermore, Chittipaka et al. (2023) applied the TOE framework to investigate blockchain acceptance aspects and make supply chain efficient. Moreover, the authors (Kajla et al., 2024; Singh et al., 2024) assessed that TOE elements substantially influence blockchain technology adoption. While Ullah et al. (2021) analyzed smart city governance utilising a multilayered risk assessment framework.

2.2 Applications of Industry 4.0 technologies in achieving Lean Six Sigma

Scholarly literature discussed various applications of Industry 4.0 in distinct domains. Endrigo Sordan et al. (2024) examined the role of Augmented Reality (AR) in managing inventory, effectively handling warehouse operations. Jagtap et al. (2021a) reviewed the implementation of Augmented Reality (AR) in the food industry and proposed a framework for its application to enhance transparency and tackle industry issues. Maged et al. (2023) discussed the role of ML in achieving Six Sigma and enhancing productivity and performance, focussed on applying ML tools to various execution phases of the DMAIC process. Moreover, researchers examined the applications of IoT in enhancing resource efficiency (Jagtap et al., 2021b), productivity and ensuring safety protocols (Rane et al., 2023). Additionally, Maheshwari & Devi (2024) analyzed how integrating Digital Twin technology with Lean Six Sigma helps reduce defects, analyze data in real-time, optimize processes, and increase operational performance and customer satisfaction.

2.3 Hypotheses Development

The development of hypotheses is discussed as follows:

2.3.1 Technological aspects and LSSI adoption

Psomas & Deliou (2024) mentioned that the key technologies of LSSI includes cyber-physical system, cloud computing, IoT, big data analytics, AI, augmented reality. Belhadi et al. (2023) proposed a framework integrating Big Data Analytics, Lean Six Sigma (LSS) and green perspectives, discussing the application of cloud-based systems for effectively handling vast amounts of data. On similar lines, Lu and Xu (2019) discussed the role of connecting equipment

to cloud to track real-time data and information. Emerging technologies, such as IoT and AI, facilitate detection of variances and flaws in real-time, letting industries to take proactive actions rather than reactive (Escobar et al., 2022). Skall et al. (2023b) analyzed that emerging technologies have a positive impact on sustainable organizational performance. Implementing LSSI enables needed data and information instantly available, addressing considerable challenges (Yadav et al., 2020). As per research study conducted by Javaid et al. (2022), adopting technological innovations helps to enhance competitiveness, and achieving environmental sustainability. Another study by Rejikumar et al. (2020) analyzed the role of data-driven decision-making in effective LSS implementation. Moreover, the authors also determined the significant role of complexity perception as moderating variable in relationship between perceived usefulness and LSS adoption intention. Also, Maia et al. (2024) investigated the role of big data analytics in identifying anomalies, transforming traditional system, analysing predictive and descriptive statistics. Moreover, cybersecurity standards require serious consideration to avoid cyber-attacks (Samanta et al., 2024). Therefore, we hypothesize:

H1: Technological aspects have a relationship with LSSI adoption

2.3.2 Organizational aspects and LSSI adoption

Scholarly literature discusses the key role of Training and educational programs in LSSI adoption. Longo et al. (2017) evaluated Sophos-MS, a tool used for immersive training for both on-line and off-line. Likewise, Sordan et al. (2022) reviewed virtual training systems employing AR to improve on-site training. Another study by Bhat et al. (2021) emphasised the significance of cross-functional collaboration for increased organizational performance. Similarly, Tissir et al. (2023) observed that a continuous improvement culture, reinforced by smart technologies, builds the foundation for implementing LSSI. Besides, Ganjavi, & Fazlollahtabar (2021) considered combining continuous improvement with sustainable production to attain organizations goals. The authors further stated that continuous improvement is vital for achieving operational excellence and adopting technological advancements. Another study by Skalli et al. (2023b) discussed that organizational aspects such as organizational culture, teamwork, leadership plays crucial role and must be considered significantly.

Moreover, employees must be motivated and encouraged to adopt innovative ideas and improve operational performance. Also, organizational support is crucial in shaping the vision

and mission for successful LSSI adoption (Kaswan et al., 2022). Top management must understand the strategic significance of LSSI adoption and be willing to invest in technological infrastructure and other necessary resources. Moreover, Raj & Jeyaraj (2023) also mentioned that top management support helps in mobilizing required resources for adopting advanced technologies. Change management strategies, which focus on helping employees embrace transitions and adapt to updated tools and techniques must be organized periodically (Samanta et al., 2024). Also, Macias-Aguayo et al. (2022) discussed the importance of employee empowerment for effective engagement and performance enhancement. Therefore, we hypothesize:

H2: Organizational aspects have a relationship with LSSI adoption

2.3.3 Environmental aspects and LSSI adoption

Evolving customer needs for customized products and services drive industries to focus on technological innovations. Industry 4.0 facilitates mass personalization by quickly reconfiguring the manufacturing setups based on customer requirements (Sony, 2020). Competition forces organizations to undergo digital transformations and adopt LSSI (Tissir et al., 2023). Vinodh & Shimray (2023) stated that a lack of stringent government policies, legal frameworks, and regulations impedes LSSI adoption. Li et al. (2023) discussed the positive impact of government subsidies on adopting technological innovations. In continuation of the same, Raj & Jeyaraj (2023) also mentioned that government policies and legal support helps in stimulating LSSI growth. Moreover, Choi & Siqin (2022) assessed ways to mitigate emissions using extended producer responsibility (EPR). Also, Zhong et al. (2024) noted that the availability of a digital business model acts as a catalyst, streamlining business operations. Additionally, Bag & Pretorius (2022) analyzed how mimetic pressure forces industries to acquire necessary resources and upgrade their manufacturing systems. Moreover, Skalli et al. (2023a) discussed regulations and standards as the key driving forces for LSSI adoption. Therefore, we hypothesize:

H3: Environmental aspects have a relationship with LSSI adoption

2.3.4 LSSI, Strategic Alignment for Sustainability and Operational Performance

Amjad et al. (2021) discussed how Industry 4.0 technologies help organizations achieve economic and environmental advantages, identifying lean as a precursor to agile and resilient

manufacturing systems. Nounou et al. (2022) integrated lean principles in designing Industry 4.0 architecture, proposing smart value stream mapping for real-time autonomous decision-making. Furthermore, Rüttimann & Stöckli (2016) highlighted Industry 4.0 technologies facilitates flexibility and agility in organizations. Although the roadmap to LSSI is complex, there are numerous advantages (Sanders et al., 2016). Skalli et al. (2023b) stated that Industry 4.0 helps achieve lean six sigma and sustainable operational performance. Moreover, Tissir et al. (2023) emphasized that LSS and Industry 4.0 share the common performance outcomes of quality and productivity enhancement.

"Strategic Alignment for Sustainability" is pivotal in explaining the relationship between LSSI and operational excellence. Javaid et al. (2022) discussed how Industry 4.0 technologies contribute to developing a sustainable environment, identifying twenty applications, including enhanced market efficiency, reduced waste, climate change mitigation, enhanced productivity, and reduced emissions and carbon footprint. Ciliberto et al. (2021) highlighted how Industry 4.0 bridges the gap between sustainable production and circular economy, integrating sustainability aspects across the supply chain. Ganjavi & Fazlollahtabar (2021) emphasized the need for a sustainable strategy to achieve a competitive advantage. Cherrafi et al. (2016) discussed the benefits of integrating LSS and sustainability, resulting in an eco-efficient system with enhanced quality of products, and services. Ghobakhloo (2020) investigated the impact of Industry 4.0 on enhancing sustainability, discussing functions such as supply chain digitization and integration, carbon emission reduction, employment creation, product personalization, and increased productivity. Also, Gandhi et al. (2018) highlighted the importance of green manufacturing planning for enhancing quality and productivity. Clancy et al. (2022) mentioned that Industry 4.0 facilitates intelligent planning and efficient control of business operations. Therefore, we hypothesize:

H4: LSSI has a relationship with operational excellence.

H5: Strategic Alignment for Sustainability mediates the relationship between LSSI and Operational Excellence

The various items under different constructs are shown in Exhibit 1.

Exhibit 1: Items included in various constructs

S.No	Construct	Items	References
1.	Technological Aspects	IoT enable real-time data collection for process optimization.	Skalli et al. (2023b); Li et al. (2024)
2.		Big Data Analytics uncover insights to drive LSSI improvements.	Belhadi et al. (2023); Maia et al. (2024); Ibrahim and Kumar (2024)
3.		Cloud Computing provides scalable storage and analysis of organization data.	Tay & Loh (2022)
4.		AI and Machine Learning automate data analysis and helps defect prevention.	Kaswan et al. (2023); Al Mamlook et al. (2024); Samanta et al. (2024)
5.		Cybersecurity helps in data safety and confidentiality that impacts LSSI adoption	Chiarini & Kumar (2021); Majumdar et al. (2021); Samanta et al. (2024)
6.	Organizational Aspects	LSSI training empowers employees with problem-solving skills.	Longo et al. (2017); Sordan et al. (2022)
7.		Cross-functional collaboration drives efficiency and process improvements.	Bhat et al. (2021); Gonzalez Santacruz et al. (2024)
8.		Continuous improvement culture fosters a mindset of innovation and growth	Vinodh et al. (2021); Ganjavi, & Fazlollahtabar (2021); Singh and Rathi (2022); Tissir et al. (2023)
9.		Organizational support drives successful adoption of LSSI	Kaswan et al. (2022); Vinodh & Shimray (2023)
10		Change management ensures smooth transition and acceptance of new practices	Samanta et al. (2024)
11	Environmental Aspects	Evolving customer needs urge the industries to improve their manufacturing processes and services	Sony (2020)
12		Industry competition forces organizations to undergo digital transformations	Tissir et al. (2023)
13		Government policies and support urges the industries to adopt LSSI	Kumar et al., (2023)
14		Availability of digital business models impact LSSI adoption	Zhong et al. (2024)
15		Regulations and standards impact LSSI adoption	Skalli et al. (2023a); Moreira et al. (2024)
16	Strategic Alignment for Sustainability	Organization do take initiatives to overcome sustainability-related risks	Bhattacharya (2021); Ozbiltekin-Pala et al. (2022)
17		Organization integrates sustainability aspects across various functions in organization	Ciliberto et al. (2021)
18		The objectives of sustainability strategy are clearly stated	Ganjavi & Fazlollahtabar (2021)
19		Stakeholders take proactive steps to include sustainability aspects in strategic planning process	Clancy et al. (2022)

20		Metrics used for measuring sustainability performance of organization is well conceptualized and documented	Contini et al. (2023)
21	Operational Performance	Optimize processes helps to attain competitive advantage	Amjad et al. (2021); Nounou et al. (2022)
22		Rigorous quality control mechanisms help ensure high product quality and services	Skalli et al. (2023b)
23		LSSI results in enhanced employee productivity and satisfaction	Yadav et al. (2020); Citybabu & Yamini (2024)
24		Data driven decision making help to make business operations efficient and effective	Frank et al. (2021)
25		LSSI results in enhanced flexibility and agility in the processes	Rüttimann & Stöckli (2016); Sanders et al. (2016)
26	Adoption of LSSI	Organization takes sufficient initiatives to adopt LSSI	Ghobakhloo, & Iranmanesh (2021)
27		Organization facilitates agile problem solving and critical thinking skills to effectively respond to the customers	Kumar et al. (2021); Sony et al. (2021)
28		Organization understands the strategic importance of LSSI adoption	Luthra and Mangla (2018)
29		Organization believe that incorporating smart technologies will help the organization in reducing defects and variations	Saxby et al. (2020); Shayganmehr et al. (2021); Virmani et al. (2023)
30		Organization focusses on scalable LSSI operations to enhance system robustness	Sony and Naik (2019)

Exhibit 2 presents the research model with various constructs.

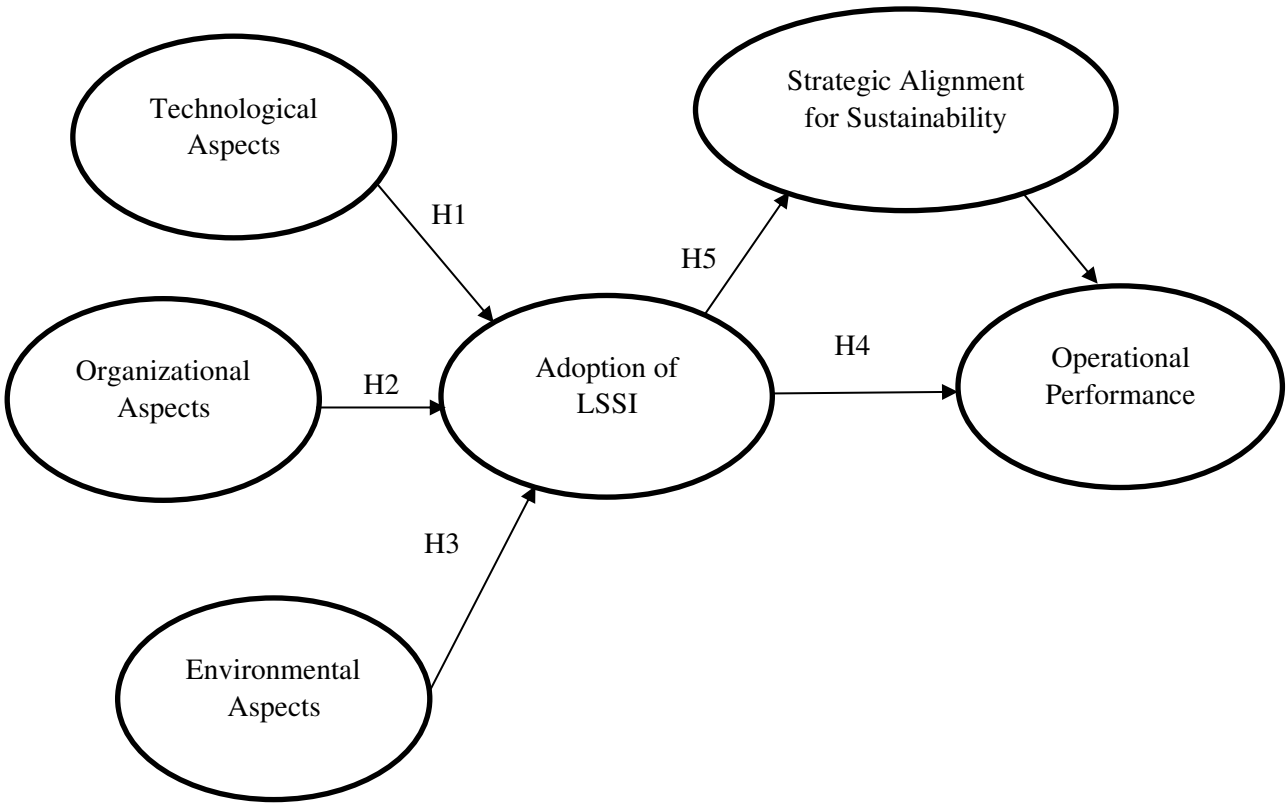


Exhibit 2: Proposed Research Model

3. Research Methodology

The research methodology is explained as follows:

3.1 Development of Survey Instrument & Data collection

The research design method as discussed by Skalli et al. (2023b) was adopted. In this study, survey instrument was used to collect primary data. A five-point Likert scale was employed, where 1 signifies “strongly disagree” and 5 signifies “strongly agree.” The questionnaire was developed in English language. To ensure the questionnaire was error-free and reliable, it was reviewed by area experts before data collection. The sample size was calculated as suggested by Kitchenham & Pfleeger (2002). After developing the questionnaire, twelve experts including academic and corporate professionals were asked to review it and provide feedback on its precision and completeness. The profile of experts at this initial stage included five university professors, three technological innovation experts, and four Chief Experience Officer's (CXO’s). Based on the expert’s feedback, the questionnaire was modified and revised for coverage, comprehensibility, and logical flow. Subsequently, a pilot study of the survey instrument was conducted with same twelve experts’ before final data collection. This step helped to identify and address any remaining flaws, ensuring validity and reliability of questionnaire. Once the data collected in the preliminary stage was satisfactory, we proceeded with the final data collection. The respondents were senior officials with adequate knowledge of business operations, Lean Six Sigma, Industry 4.0, sustainability, and circular economy aspects. Exhibit 3 presents research methodology.

Responses were collected from experts working in industries located in the National Capital Region (NCR) region of India, which is renowned industrial hub (ET, 2024). Data was collected from various industry types including, automobile, Fast-Moving Consumer Goods (FMCG), electronics. Reputed industry databases, such as the Centre for Monitoring India Economy (CMIE) and India Brand Equity Foundation (IBEF), were used to gather industry data. Given the technical nature of LSSI, profiles of production managers, design managers, general managers, CXOs, and quality professionals were deemed most suitable. The questionnaire was sent to 600 respondents using online surveys, and cross-sectional data was collected. We used random sampling techniques to select the respondents from pool of area experts. Moreover, Zhu et al. (2008) mentioned that random sampling helps to triangulate the data quality, resulting in enhanced reliability and accuracy. Data was collected from 287 respondents, yielding a response rate of 47.83 %, which is sufficient for further analysis. Peng

& Lai (2012) mentioned that as a thumb rule, sample size must be approximately ten times per measuring item. In scholarly literature, Kottala & Herbert (2019) applied supply chain operations reference (SCOR) model to investigate supply chain performance, 17 measuring items were considered and data was collected from 155 respondents. Another study by Jamil et al. (2024) collected data from 342 respondents for 37 measuring items related to Industry 4.0 integration in supply chain management. Therefore, our sample size was also found adequate, as we had 30 items. The details of the respondents are presented in Exhibit 4.

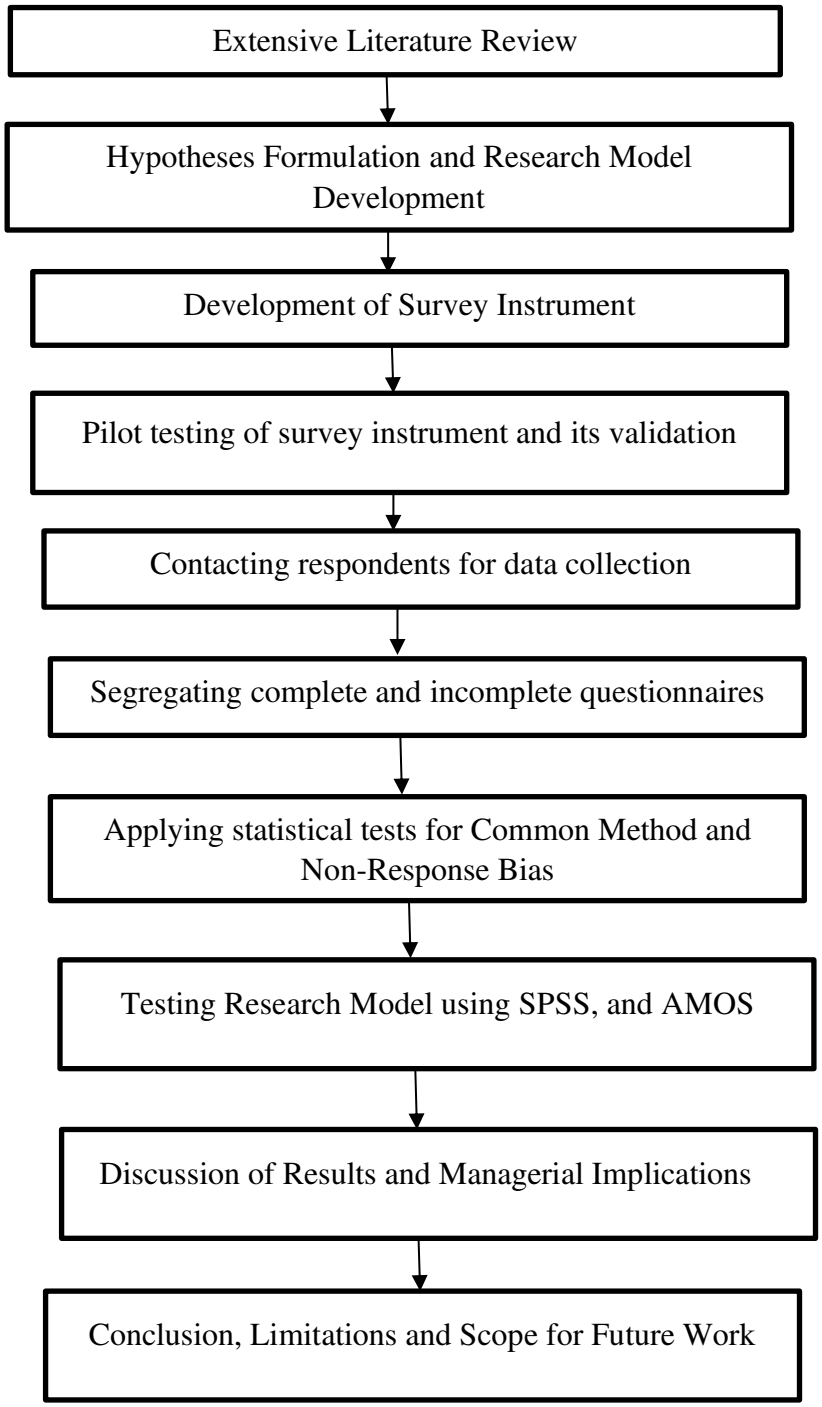


Exhibit 3: Research Methodology

3.2 Common Method & Non-Response Bias

We conducted common method bias using Harmon single factor test. The results indicated that variance obtained by any of the factor is less than threshold value, which is 50%, which indicates the absence of common method bias (Yaseen et al., 2023). Also, the questionnaire was developed with utmost care to ensure ease of understanding by each respondent. Causes of non-response bias, such as incorrect length, double-barrelled questions, and improper question sequence, were avoided (Hashem & Aboelmaged, 2023). Following standard protocols, a statistical t-test was conducted on binary sample trials from the same population to ensure absence of non-response bias. Samples from the first eighty and the last eighty respondents were compared. The test results showed no significant differences, indicating that the results are free from non-response bias.

Exhibit 4: Respondents Profile

Attribute	Sub-Attribute	Frequency	%
Demographics Parameters			
Gender	Male	178	62.02
	Female	109	37.98
Age (in years)	41-45	54	18.82
	46-50	68	23.69
	51-55	72	25.09
	> 55	93	32.40
Education Level	Bachelor	198	68.99
	Master	67	23.34
	Doctorate	22	7.67
Organization's Parameters			
Turnover (in billion $)	10-15	69	24.04
	16-20	53	18.47
	21-25	87	30.31
	> 25	78	27.18
Number of employees	01-200	89	31.01
	201-400	74	25.78
	401-600	65	22.65
	> 600	59	20.56
Years of Establishment (years)	< 5	47	16.38
	05-10	59	20.56
	11-15	68	23.69
	> 15	113	39.37
Industry Type	Automobile	124	43.20
	FMCG	87	30.31
	Electronics	76	26.49

4. Measurement Model and Model Fit

The intent of the measurement model is to test the relationship among identified constructs and the corresponding latent variables. The strength of the constructs having reflective measures is calculated using reliability of different items, discriminant validity and internal consistency.

4.1 Check for Unidimensionality and Internal Consistency

A test for unidimensionality was carried out which confirms that individual measuring items are strongly linked and represent a construct (Vikas et al., 2022). Principal Component Analysis (PCA), Cronbach's alpha was used for this objective. Different methods were applied to test the validity of identified construct measures. Firstly, content validity was ensured to confirm that the items selected in the survey questionnaire suitably expressed the concept. Questionnaire was developed after thorough investigation of literature review to ensure content validity (Gachanja et al., 2020).

Furthermore, Cronbach's alpha was computed to verify internal consistency of the survey instrument. Based on the results, all values were found to be greater than 0.7, which verifies the reliability and validity of the survey instrument. Also, a communality check was done to confirm that the items characterised the anticipated latent variables. As per the standards, the threshold value is 0.60 (Kumar & Rahman, 2016). Moreover, our research results demonstrate that all values are well above the threshold, validating that all constructs are reliable.

4.2 Convergent Validity (CV)

Confirmatory Factor Analysis (CFA) was performed to get factor loadings. CV is usually assessed using Average Variance Extracted (AVE) and Composite Reliability (CR), where AVE was assessed using the mean of the square of factor loadings of a given construct. Also, it enumerates the variance intensity given by construct items in contrast with the variance intensity specified by measurement error (Kumar & Rahman, 2016). The value of AVE should be greater than or equal to 0.5 (Wamba et al., 2017), and in this analysis, all values are found to be more than 0.5. Also, the values of CR were calculated for all constructs, and found adequate (greater than 0.7), thus validating CV. Exhibit 5 depicts the CV analysis.

Exhibit 5: Convergent validity Analysis

S. No.	Construct	Item Code	Factor Loading	Average Variance Extracted (AVE)	Composite Reliability (CR)
1.	Technological Aspects (T)	T1	0.790	0.588	0.875
2.		T2	0.618		
3.		T3	0.686		
4.		T4	0.956		
5.		T5	0.741		
6.	Organizational Aspects (O)	O1	0.976	0.634	0.894
7.		O2	0.704		
8.		O3	0.657		
9.		O4	0.860		
10.		O5	0.742		
11.	Environmental Aspects (E)	E1	0.720	0.616	0.888
12.		E2	0.949		
13.		E3	0.752		
14.		E4	0.667		
15.		E5	0.806		
16.	Lean Six Sigma Integrated Industry 4.0 (LSSI)	LSSI 1	0.801	0.623	0.890
17.		LSSI 2	0.967		
18.		LSSI 3	0.682		
19.		LSSI 4	0.712		
20.		LSSI 5	0.751		
21.	Strategic Alignment for Sustainability (SAS)	SAS 1	0.800	0.659	0.906
22.		SAS 2	0.878		
23.		SAS 3	0.732		
24.		SAS 4	0.886		
25.		SAS 5	0.752		
26.	Operational Performance (OP)	OP1	0.802	0.563	0.865
27.		OP2	0.834		

28.		OP3	0.697		
29.		OP4	0.707		
30.		OP5	0.701		

4.3 Discriminant Validity

The discriminant validity indicates how well the identified constructs differentiate from each other (Kumar & Rahman, 2016). The individual variance of identified constructs with its own measuring items must be greater than that of the remaining identified constructs (Fornell & Larcker, 1981). To ensure discriminant validity, diagonal values must be represented as the square root of AVE, and these values must be greater than the correlation value between the constructs. The research results reveal that constructs are strongly related to their own measuring items but not to the remaining constructs, confirming that the presented research model is accurate and reliable. Exhibit 6 shows the discriminant validity.

4.4 Model Fit

SPSS AMOS 24.0 version was used to check the model fit. The parameters were reported as CMIN/DF=1.897, GFI= 0.907, NFI =0.954, TLI = 0.913, CFI = 0.921, RMSEA=0.024. All the hypotheses were tested at 95% confidence interval.

Exhibit 6**:** Discriminant validity

Construct	AVE	CR	T	O	E	LSSI	SAS	OP
T	0.588	0.875	**0.766**					
O	0.634	0.894	0.024	**0.796**				
E	0.616	0.888	0.101	0.323	**0.785**			
LSSI	0.623	0.890	0.067	0.112	0..337	**0.789**		
SAS	0.659	0.906	0.040	0.020	0.334	0.247	**0.812**	
OP	0.563	0.865	0.015	0.017	0.082	0.075	0.097	**0.750**

Hypotheses results are revealed in Exhibit 7. Also, Exhibit 8 and Exhibit 9 shows the direct and indirect effects of mediation respectively.

Exhibit 7: Inferences of hypothesis testing

Hypothesis	Structural Path	Beta	p-value	Supported (Yes/No)

H1	Technological Aspects ⟶ LSSI	0.265	0.032	Yes
H2	Organizational Aspects ⟶ LSSI	0.324	0.015	Yes
H3	Environmental Aspects ⟶ LSSI	0.398	0.001	Yes

Exhibit 8: Test for mediation (Direct Effect)

	LSSI ⟶ SAS ⟶ OP					
	Beta	**Se**	**T**	**P**	**LLCI**	**ULCI**
Direct Effect	0.159	0.020	7.95	0.024	0.1182	0.1990

Exhibit 9: Test for mediation (Indirect Effect)

Relationship	**Effect**	**Se**	**LLCI**	**ULCI**
LSSI ⟶ SAS ⟶ OP	0.14	0.01	0.1178	0.1602

5. Results

The research results show that Hypothesis H1 is supported (β=0.265, p=0.032), indicating that Technological aspects significantly impact LSSI adoption. IoT technology enables industry managers to access real-time data continuously, facilitating timely decision-making. Big data analytics (BDA) capabilities help derive insights from large data sets and draw meaningful conclusions. Similar findings were reported by Belhadi et al. (2019), who noted that BDA enhances transparency, performance, decision-making capabilities, and knowledge creation. BDA also helps identify root causes of problems and supports continuous improvement in business operations (Sahoo, 2022). Furthermore, AI & ML applications in manufacturing automate processes significantly and enable proactive flaw detection, allowing necessary preemptive steps. These results are consistent with Zeba et al. (2021). Enhanced connectivity among equipment raises concerns about strengthening cybersecurity norms to protect sensitive data and intellectual property. Also, adopting advanced technologies helps the employees to engage in productive tasks rather than monotonous and repetitive work, therefore enabling them to explore innovative solutions (Psomas & Deliou, 2024). Also, LSSI is quite helpful in obtaining process robustness, which otherwise is difficult to attain using traditional tools and techniques (Pongboonchai-Empl et al., 2024).

Organizational aspects positively impact LSSI adoption as hypothesis H2 is supported (β=0.324, p=0.015). As LSSI is a relatively new concept, initially, organizations may face

hurdles. Managers should embrace change management strategies and foster cross-functional collaboration. Leadership commitment is crucial in adopting LSSI by establishing a clear vision and mission. Top managers must recognize the strategic importance of digital technologies and make concerted efforts to achieve organizational success. Raj & Jeyaraj (2023) also highlighted the role of top management commitment, absorptive capacity, trust, and expertise in adopting Industry 4.0. Since LSSI adoption is complex and dynamic, sustained effort is vital. Involving every employee in kaizen activities for continuous improvement is equally important. Tissir et al. (2023) observed similar results. Also, smart technologies aid in enhancing supply chain optimization by increasing transparency and visibility, thus improving efficiency and effectiveness. Employee intentions also significantly contribute to the overall picture of LSSI adoption. These results align with Javaid et al. (2022), who highlighted that a positive mindset towards Industry 4.0 and sustainability boosts employee engagement, resulting in improved operational excellence.

Environmental aspects also positively influence LSSI adoption as hypothesis H3 is supported (β=0.398, p=0.001). Conducting regular assessments to recognize the organization's condition is compulsory. Moreover, competitive analysis facilitates assessing organization readiness towards adopting LSSI. It is equally important to have supportive government policies, rules and regulations that have momentous impact on encouraging industries towards adopting technological innovations. Also, digital business models allow optimal resource utilization, helps in better control over business operations and hence achieve higher operational performance. Furthermore, synchronization among functional areas helps in seamless business operations, and attainment of organization's objectives. Also, applications of advanced data analytic tools help to minimize lead time, scraps and wastages, thereby enhancing customer satisfaction.

Also, Hypothesis H4, adoption of LSSI significantly impacts organizational performance is supported. Adopting LSSI helps to optimize the business operations and reduce costs significantly. Furthermore, it helps in achieving high quality products and services in the minimum possible time, thereby reducing lead time and enhancing customer satisfaction. Moreover, LSSI helps to make processes effective and efficient. Also, Hypothesis H5, strategic alignment concerning sustainability perspectives partially mediates the association between LSSI and operational performance as both direct and indirect paths are significant (Exhibit 8 & Exhibit 9). Organizations must assess anticipated business operations challenges and adopt mitigation strategies to obtain a sustainable competitive advantage. Cross-functional

collaborations are equally essential for implementing sustainable practices across various functional areas. Moreover, incorporating sustainability aspects in strategic planning facilitates formulation of robust organizational strategies. Also, developing sustainability metrics supports organizations by evaluating their readiness. Citybabu & Yamini (2024) reported similar results and further discussed the benefits of adopting LSSI include increased productivity, flexibility, efficient utilization of resources, higher quality, profitability, enhancing capability to handle complex problems.

5.1 Theoretical Implications

The TOE framework assists managers evaluate both soft and hard aspects of LSSI adoption, offering a broad perspective to focus on anticipated challenges and devising strategies for successful implementation. Integrating advanced technologies to adopt lean six sigma helps to lay a foundation for advancing current theories and optimizing processes. Moreover, the TOE framework helps the organizations to adopt a holistic approach for overcoming LSSI roadblocks. Furthermore, it can help the organizations to develop performance frameworks by means of which tracking organizations readiness become observable. Moreover, this study also offers insights to business managers to understand the nitty-gritty of adopting LSSI. It is highly imperative for the top officials to enlist key enablers so that necessary initiatives can be taken accordingly. In addition, organizations must understand the strategic importance of LSSI implementation so that required information and knowledge can be disseminated across team members. Rather than working in silos, managers from various functional areas must come forward to collaborate and cooperate for effective LSSI implementation. As LSSI adoption requires organizational and process changes, most of the business operations require revamping, therefore it becomes crucial to adopt change management models. Moreover, employees should have contemporary skill sets; to feel comfortable working with smart technologies, organizations must conduct training and educational programs. It will help them to increase employee awareness and confidence towards utilizing LSSI tools and techniques, enabling quick implementation, and plummeting resistance. Furthermore, Government must make supportive policies which act as facilitators for adopting smart technologies, as discussed by Mishra & Pathak (2024), who applied extended TOE and total interpretive structural modelling (TISM) technique to analyze Industry 4.0 adoption. Bhuiyan (2024) also discussed similar findings, who listed supportive government policies, investing in digital technologies, collaborations, training and educational programs and public-private partnerships plays crucial role in Industry 4.0 adoption.

5.2 Practical Implications

Integrating sustainability into LSSI can help drive long-term growth and operational excellence. Real-time data analytics capabilities help to minimize machine breakdowns, thereby enhancing resource utilization and operational performance. However, investigating risks and adopting risk mitigation strategies is highly crucial for successful LSSI implementation. Initiatives towards data governance and cybersecurity measures are also crucial to safeguarding data and ensuring privacy and security. Also, LSSI cannot be implemented overnight, and it may take a few years, therefore continuous improvement is required to make the system robust and ease implementation process. As the concept of LSSI is emerging, managers should analyze various anticipated risks including operational, environmental, human resource, and technological. LSSI minimizes risks and maximizes return on investment (ROI). Moreover, organizations must use key performance indicators (KPIs) to monitor their performance and maturity level. Also, adopting feedback mechanisms is essential to compare achieved operational performance against set targets, and take suitable actions in case of any deviation. Additionally, the organizations must develop strategic vision and mission for enhancing efficiency, performance, and sustainability, so that organizational goals are well aligned. Moreover, insights from value stream mapping can help to identify the loopholes, which further helps the production team to take necessary actions. Besides this, adopting advanced technologies like digital twin facilitates simulating the entire process and therefore helps in optimizing processes before actual implementation.

6. Conclusion and Scope for future Work

The research evaluated TOE aspects impacting LSSI adoption, offering valuable insights for industries and ultimately affect operational performance. In a developing country like India, LSSI adoption is still at its growing stage, but both organizations and government are putting stringent efforts for its effective implementation. Due to the complexity of LSSI adoption, it is vital for organizations to recognize its challenges, drivers, and KPI’s so that they can evaluate themselves and take suitable initiatives. LSSI focuses on reducing wastages and variations, enhancing real-time data analytics capabilities, achieving operational excellence, and achieving sustainable development goals. Organizations must provide sufficient funds for

smart technology adoption. In small and medium-scale industries, employees may still feel hesitate towards LSSI adoption due to challenges. Therefore, motivating employees and using effective change management strategies is essential to overcome employee resistance.

Like other studies, this research has some limitations. It only considered TOE aspects for analysing LSSI adoption, other significant factors like human resources and change management aspects can be explored to assess their impact on operational performance. Also, the presented results are based on cross-sectional data; longitudinal studies can further evaluate LSSI role in achieving operational excellence. Therefore, future research can explore these areas, providing opportunities for budding managers, researchers and practitioners.

Additionally, this study was conducted in India, and results may vary across different geographical areas, similar research can be analyzed in other regions. Furthermore, more empirical evidence focusing on the behavioral adoption of LSSI are needed. Research studies could assess employees' intentions using behavioral techniques like Theory of Planned Behavior and Behavioral Reasoning Theory. Case studies in different industrial sectors, including manufacturing, construction, and pharmaceuticals, can further explore LSSI adoption patterns. Developing a conceptual framework with standardized procedures and working protocols can also enhance understanding of LSSI. More points for the scope of future work are discussed in Exhibit 10.

Exhibit 10: Scope for future work

Key Research Aspects	Research Questions
Integration Framework and Methodologies	- How the integration framework can be standardized facilitating seamless collaboration and process optimization?
	- What are the guidelines, policies and procedures required to develop LSSI and facilitate effective managerial decision making?
Data Analytics and Artificial Intelligence	- How the emerging technologies augment LSSI to help with precise predictive maintenance and achieve operational excellence?
	- What are the pivotal techniques to leverage AI based algorithms for real-time tracking, monitoring, and analysis in LSSI?
Human-Robot Collaboration	- How the collaboration among human and robot can be enhanced to improve workforce efficiency, reduce accidents, and enhance employee satisfaction

	-What are the key human centred design aspects to be taken care of while designing smart equipment?
Supply Chain Optimization	How smart technologies can help in effective supply chain management, precisely forecast demands, reduce costs, and optimum utilization of resources?

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Driving operational excellence: the role of technology-organization-environment framework in Lean Six Sigma Integrated Industry 4.0 adoption

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