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Research Paper

A Scoping Review of Lean Six Sigma and Industry 4.0 Integration: Readiness Dimensions, Transformation Strategies, and Contextual Enablers in Manufacturing

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Abstract

Research on Lean Six Sigma (LSS) and Industry 4.0 (I4.0) integration in manufacturing has grown rapidly, yet remains fragmented between operational excellence and digital transformation streams. Existing studies predominantly employ cross-sectional designs that treat variables in isolation, while current readiness frameworks such as IMPULS, SIRI, and INDI 4.0 offer diagnostic assessment without prescriptive transformation guidance. This scoping review synthesizes 63 peer-reviewed studies (2020–2026) from the Scopus database, following the Arksey and O'Malley framework and PRISMA-ScR guidelines. Three research questions guide the inquiry: (RQ1) what LSS variables influence I4.0 readiness, (RQ2) what transformation strategies are employed and what outcomes they produce, and (RQ3) under what contextual conditions does integration yield effective results and what gaps remain. The review identifies 10 LSS variables and 7 transformation strategy dimensions. Technology Integration, Top Management Commitment, and Process Standardization are the most frequently reported variables across the reviewed studies, consistent with accounts suggesting that digital technologies cannot compensate for operational instability. The reviewed studies collectively describe the LSS–I4.0 relationship as bidirectional, with LSS providing the process foundation for digitalization while I4.0 technologies are reported to reciprocally enhance lean effectiveness through real-time analytics and predictive capabilities. Leadership and Change Management, Human Capital Development, and Phased Roadmap are the most frequently reported strategic dimensions, suggesting that the literature increasingly frames transformation as an organizational challenge rather than a technology procurement exercise. However, these insights are drawn from a geographically and sectorally concentrated evidence base dominated by Indian manufacturing contexts, with Southeast Asian economies and process industries such as food and beverages remaining largely unexamined, and systems thinking methodologies that could capture holistic interdependencies notably absent. To address these limitations, a conceptual framework integrating LSS variables, transformation strategies, and contextual moderators within a feedback-driven system is proposed to guide future research in underexplored contexts.

Keywords: *Lean Six Sigma, Industry 4.0, Scoping Review, Digital Transformation, Operational Excellence, Manufacturing Readiness*

INTRODUCTION

The manufacturing sector is undergoing a fundamental transformation driven by Industry 4.0 (I4.0) technologies—Cyber-Physical Systems, IoT, big data, and AI—toward intelligent, autonomous production (Kagermann et al., 2013; Hu et al., 2024; Radlbauer et al., 2025). Industry 5.0 (I5.0) further elevates human-centricity, resilience, and sustainability as co-equal priorities (Cimini et al., 2023; Hines et al., 2026; Fani et al., 2024), yet adoption remains uneven across developing economies constrained by infrastructure, human capital, and institutional gaps (Nafchi & Mohelská, 2020; Landín et al., 2023). In parallel, Lean Six Sigma (LSS) has established itself as the dominant operational excellence methodology (Womack et al., 1990; Pyzdek & Keller, 2014;

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George, 2002), with growing evidence of its synergy with I4.0 as a disciplined process foundation for digital layering (Ibrahim & Kumar, 2024; Tissir et al., 2024; Buer et al., 2021).

Despite this interest, a significant integration gap persists. The literature fragments into separate LSS and I4.0 readiness streams, with few studies examining how LSS variables collectively shape I4.0 readiness. Cross-sectional SEM and MCDM designs dominate, limiting insight into dynamic interactions (Sahoo et al., 2026; Virmani et al., 2025), while readiness models such as IMPULS, SIRI, Industry4WRD, and INDI 4.0 remain diagnostic snapshots without prescriptive roadmaps (Vance et al., 2023; Hasbullah et al., 2024). Coverage skews toward India and discrete manufacturing, underrepresenting Southeast Asia and process industries (Le & Le, 2025; Surindra et al., 2024), and systems thinking approaches—particularly SSM—remain virtually absent (Checkland, 1999; Tayaksi et al., 2020).

To address these gaps, this scoping review systematically synthesizes the literature on LSS and I4.0 integration in manufacturing. Following Arksey and O'Malley's (2005) framework and PRISMA-ScR guidelines (Tricco et al., 2018), the review examines 63 peer-reviewed studies published between 2020 and 2026 from the Scopus database. The scoping methodology is suited for this investigation as it enables exploration of a rapidly evolving field encompassing diverse study designs and implementation contexts (Levac et al., 2010). Three research questions structure the inquiry:

RQ1: What are the key Lean Six Sigma variables identified in the literature, and how do they influence Industry 4.0 readiness across manufacturing contexts?

RQ2: What transformation strategies are employed to integrate LSS and I4.0, and what outcomes do they produce?

RQ3: Under what contextual conditions (geographic, sectoral, and methodological) does LSS-I4.0 integration yield effective outcomes, and what research gaps remain?

The review contributes to the literature in three ways. First, it synthesizes 10 LSS variables and 7 transformation strategy dimensions across 63 studies, revealing their prevalence, interaction patterns, and contextual dependencies. Second, it identifies critical research gaps, including the underrepresentation of systems thinking approaches, food and beverage sectors, and Southeast Asian contexts. Third, it proposes a conceptual framework positioning LSS variables, transformation strategies, and I4.0 readiness within a contextually moderated relationship, providing a foundation for future investigations using holistic methodologies such as SSM integrated with multi-criteria decision analysis. These contributions respond to calls for research that moves beyond static maturity assessment toward dynamic, capability-based transformation logic for diverse economic environments (Silva et al., 2025; Gatell & Avella, 2024; Rana & Jani, 2025).

LITERATURE REVIEW

The integration of Lean Six Sigma and Industry 4.0 in manufacturing is best understood as a bidirectional, multi-dimensional phenomenon rather than a sequential relationship. LSS provides the process stability, improvement culture, and organizational discipline upon which digital technologies can be layered, while I4.0 reciprocally enhances LSS through real-time analytics, predictive capabilities, and automated quality control (Buer et al., 2021; Frank et al., 2025; Elnadi et al., 2025). Neither paradigm can be optimized in isolation: digital tools on unstable processes amplify inefficiencies, while lean systems without digital augmentation struggle in data-intensive environments (Ding et al., 2023; Silva et al., 2025). This integration unfolds across three interconnected dimensions—operational variables (process, human, technological, organizational), strategic pathways for sequencing and resource allocation, and contextual moderators spanning geographic, sectoral, and institutional conditions (Tortorella et al., 2021;

Rana & Jani, 2025; Le & Le, 2025).

Existing readiness models such as IMPULS (Lichtblau et al., 2015), SIRI (EDB, 2017), Industry4WRD (MITI, 2018), and INDI 4.0 (2018) offer valuable diagnostic frameworks but provide static snapshots without prescriptive guidance for progressive capability-building (Vance et al., 2023; Hasbullah et al., 2024). This limitation is reinforced by variance-based approaches that isolate individual variables, overlooking the systemic interdependencies and feedback loops of socio-technical transformation (Bueno et al., 2023; Cimini et al., 2023), while systems thinking methodologies remain notably scarce in the LSS–I4.0 domain (Checkland, 1999; Tayaksi et al., 2020).

RESEARCH METHOD

A scoping review was conducted to systematically map the current state of knowledge on the integration of Lean Six Sigma and Industry 4.0 in manufacturing contexts. The scoping review methodology was selected over systematic review or meta-analysis because the LSS-I4.0 integration field encompasses heterogeneous study designs, diverse analytical approaches, and varied implementation contexts that preclude standardized effect-size comparison (Levac et al., 2010). The review followed Arksey and O'Malley's (2005) five-stage framework: (1) identifying the research questions, (2) identifying relevant studies, (3) study selection, (4) charting the data, and (5) collating, summarizing, and reporting results. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) was adopted to ensure transparency and reproducibility throughout the process (Tricco et al., 2018). The complete study selection process is illustrated in Figure 1, which presents the PRISMA flow diagram detailing the number of records identified, screened, and included at each stage.

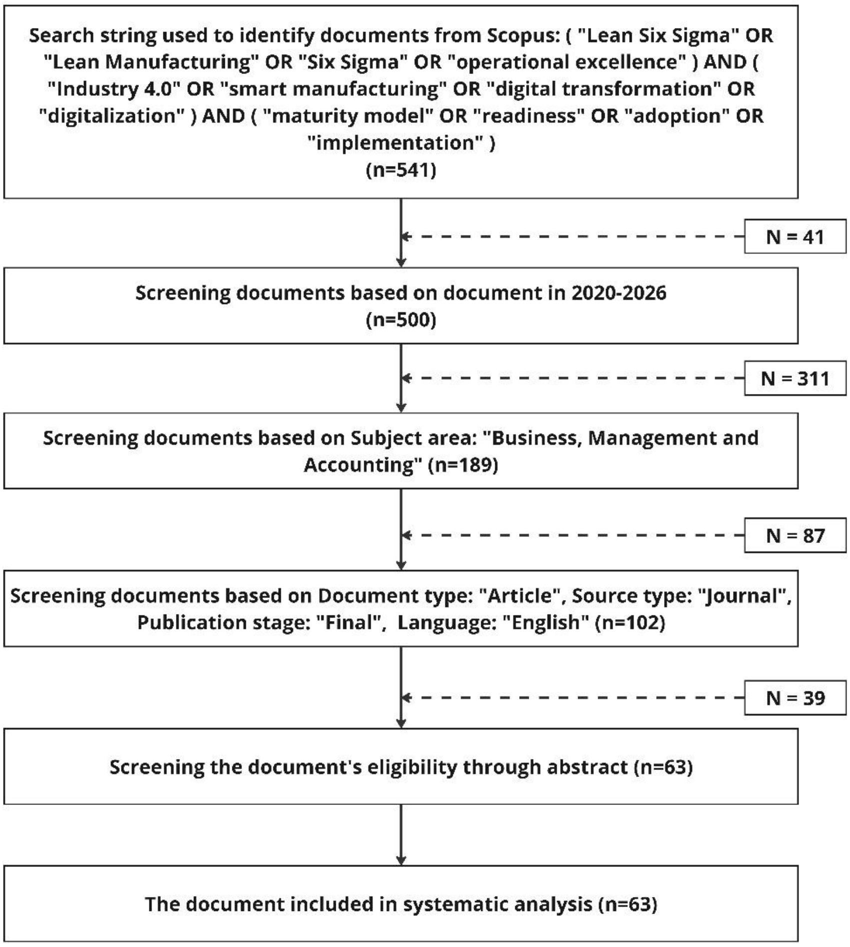

Figure 1. PRISMA Flow Diagram of Study Selection Process

A systematic search was conducted on the Scopus database on February 5, 2026, selected for its comprehensive coverage of peer-reviewed journals in engineering, business, and management disciplines (Mongeon & Paul-Hus, 2016; Burnham, 2006). A single comprehensive string combined three concept groups—operational excellence methodologies, digital transformation paradigms, and implementation-related constructs: ("Lean Six Sigma" OR "Lean Manufacturing" OR "Six Sigma" OR "operational excellence") AND ("Industry 4.0" OR "smart manufacturing" OR "digital transformation" OR "digitalization") AND ("maturity model" OR "readiness" OR "adoption" OR "implementation"). The initial search yielded 541 documents. Inclusion criteria restricted results to peer-reviewed journal articles in "Business, Management and Accounting," published between 2020 and 2026, in the final publication stage, and written in English. Conference papers, book chapters, review articles, and studies lacking explicit focus on LSS–I4.0 integration or manufacturing context were excluded. Filtering reduced the pool to 102 articles, after which three independent reviewers screened abstracts, excluding 39 studies for insufficient relevance, yielding a final sample of 63 articles (Figure 1).

Data extraction used a standardized form capturing bibliographic details, geographical context, sample and unit of analysis, theoretical framework, methodology, LSS variables, transformation strategies, and key findings. Data charting followed a hybrid coding approach consistent with scoping review conventions (Arksey & O'Malley, 2005; Levac et al., 2010). The initial analytical structure was derived deductively from the three research questions and from foundational LSS literature (Womack et al., 1990; George, 2002; Pyzdek & Keller, 2014) together with established I4.0 readiness frameworks (Kagermann et al., 2013; Lichtblau et al., 2015), which oriented reviewers toward three broad charting domains: LSS-related variables (RQ1), transformation strategies (RQ2), and contextual conditions (RQ3). Within these domains, specific variable labels and strategy dimensions were not pre-specified but were developed inductively through iterative reading of the 63 included studies. This hybrid logic was adopted because the LSS–I4.0 integration literature draws on well-established operational excellence constructs yet continues to evolve through emerging themes such as sustainability integration and human-centric I4.0, which a purely deductive scheme would risk omitting.

To reduce interpretive subjectivity during charting, each construct was assigned a working operational definition derived inductively from recurring descriptions across the 63 reviewed studies. The definitions were not adopted from a single external source or imposed a priori; instead, they were consolidated through iterative reading, in which similar descriptions of variables and strategies across studies were compared, grouped, and refined until each definition reflected the shared meaning observed within the reviewed literature itself. These definitions served as shared reference points for the three reviewers during charting and were applied consistently to minimize inconsistent classification. Table 1 and Table 2 present the operational definitions applied to the ten LSS variables and the seven transformation strategy dimensions, respectively**.**

Table 1. Operational Definitions of LSS Variables

LSS Variable	Operational Definition
Technology Integration	Adoption or deployment of I4.0 digital technologies (IoT, AI, CPS, cloud, big data analytics) within manufacturing operations.
Top Management Commitment	Executive-level sponsorship, resource allocation, and strategic prioritization of LSS–I4.0 transformation.
Continuous Improvement	Institutionalized kaizen practices, PDCA cycles, and routine improvement activities.
Process Standardization	Documented, repeatable workflows established prior to digital layering.
Training and Skills	Structured capability development covering both lean and digital competencies.
Data Analytics	Use of data-driven decision-making tools and methods to guide operational improvement.
Waste Reduction	Identification and elimination of the seven lean wastes, including through digital monitoring.
Organizational Culture	Shared values, behaviors, and mindsets that support continuous improvement and technology adoption.
Employee Involvement	Shop-floor participation and engagement in improvement and digital initiatives.
Green / Sustainability	Integration of environmental and circular-economy objectives within LSS–I4.0 practice.

Building on the variable-level definitions above, Table 2 presents the operational definitions applied to the seven transformation strategy dimensions, similarly derived from the reviewed literature.

Table 2. Operational Definitions of Transformation Strategy Dimensions

Strategy Dimension	Operational Definition
Leadership and Change Management	Executive sponsorship, vision-setting, and organizational change readiness.
Human Capital Development	Reskilling, upskilling, and cross-functional talent development.
Process-First Approach	Stabilization of lean processes before the deployment of digital technology.
Technology Infrastructure Investment	Planned investment in IoT networks, cloud platforms, and analytics capabilities.
Phased Roadmap	Incremental, staged implementation logic for progressive capability building.
Sustainability Integration	Alignment of transformation pathways with circular and environmental performance goals.
Government Policy	Institutional support through policy, funding, and regulatory mechanisms.

These definitions functioned as working anchors during charting. Where studies used overlapping or ambiguous terminology, classification decisions were resolved through the consensus procedure described below. The charting procedure was conducted in three stages by the same three reviewers who performed abstract screening. Stage 1 (independent extraction): each reviewer independently charted the bibliographic, methodological, variable-level, strategy-level, and contextual information from an assigned share of the 63 studies into the standardized form. Stage 2 (iterative grouping): reviewers jointly compared charted constructs across studies, grouping semantically similar items into higher-order categories through constant comparison; this stage produced the final set of ten LSS variables and seven transformation strategy dimensions. Stage 3 (cross-validation and consensus): a 20% subsample of studies was re-charted across reviewers to verify consistency of category assignment, and remaining disagreements were resolved through discussion until consensus was reached. In line with scoping review guidance (Levac et al., 2010; Tricco et al., 2018), this consensus-based procedure was adopted to enhance transparency and limit individual bias, while acknowledging that scoping reviews prioritize breadth of mapping and do not typically report statistical inter-coder reliability metrics associated with meta-analytic designs. Following the charting stages described above, synthesis followed a narrative and tabular approach, aggregating quantitative patterns across variables, regions, sectors, and methodologies, while comparative analysis examined relationships between variable prevalence, strategic choices, and methodological approaches to identify knowledge gaps and evidence-based directions for future research on sustainable LSS–I4.0 integration.

FINDINGS AND DISCUSSION

Study Characteristics

The 63 included studies demonstrate a clear temporal acceleration in research attention toward LSS-I4.0 integration (Figure 2). Publications remained modest during 2020–2021 (approximately 10 studies), primarily exploring foundational synergies between Lean Manufacturing and I4.0 technologies (Buer et al., 2021; Ghobakhloo & Fathi, 2020; Tortorella et al., 2021). A noticeable shift occurred in 2022–2023, with studies increasingly focusing on barriers, critical success factors, and enablers using structured analytical methods (Kumar et al., 2023; Antony et al., 2023; Joshi et al., 2024). The most significant surge occurred in 2024–2026, where publications more than doubled as the field matured toward comprehensive implementation frameworks, human-centric models, and Industry 5.0 conceptualization (Skalli et al., 2025; Hines et al., 2026; Sahoo et al., 2026).

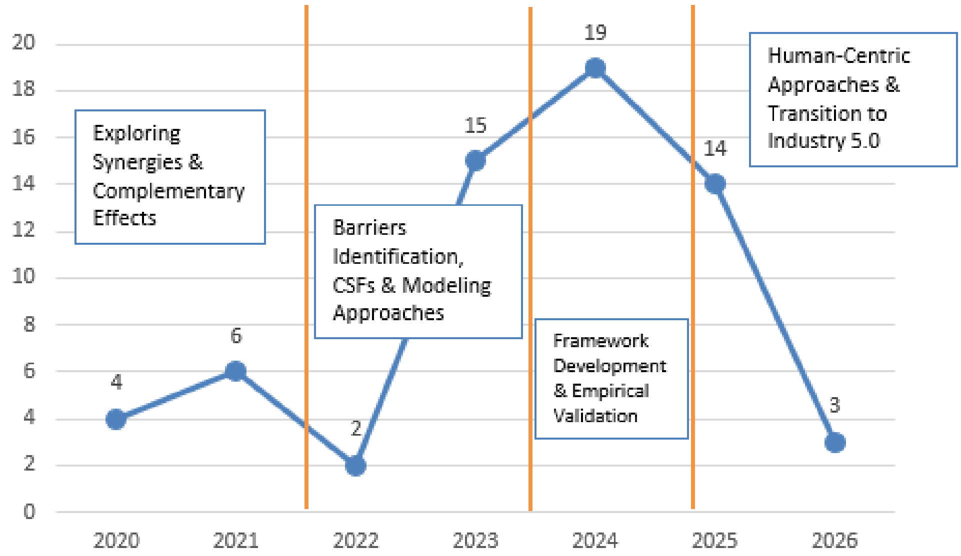

Figure 2. Temporal Distribution of Publications

Geographically, the literature reveals a pronounced concentration in Asian countries, which collectively account for 65% of total studies. India alone contributes approximately 33% (21 studies), with researchers extensively focusing on barrier identification, structural modeling, and SME contexts. Morocco (5 studies, 8%) has emerged as a notable contributor through LSS 4.0 and Digital Green Lean frameworks. Brazil accounts for 6% (4 studies), emphasizing strategic roadmap development. European studies comprise only 8%, with a distinct orientation toward human-centric approaches and Industry 5.0 transitions (Hines et al., 2026; Fani et al., 2024; Buer et al., 2021). Multi-country and global studies represent 21%, providing cross-cultural comparisons and expert-based insights (Table 3).

Table 3. Geographic Distribution of Studies

Region/ Country	Count	Research Trend
Asia	**41**	
India	21	Dominates with barriers identification, CSFs analysis, ISM/DEMATEL modeling, SME-focused studies, and framework development for LSS-I4.0 integration (Kumar et al., 2023; Kumar et al., 2024; Virmani & Salve, 2023; Virmani et al., 2023; Vinodh & Shimray, 2023; Yadav et al., 2021; Bhadu et al., 2025; Rana & Jani, 2025; Vimal et al., 2025; Citybabu & Yamini, 2025; Kumar et al., 2025; Khanzode et al., 2023; Joshi et al., 2024; Daniel et al., 2024; Upadhyay et al., 2023; Dixit et al., 2022; Koteswarapavan & Pattanaik, 2024; Kumar et al., 2021; Samanta et al., 2024; Tortorella et al., 2021b)
Morocco	5	Focus on LSS 4.0 framework development, CLSS 4.0, Digital Green Lean, and sustainability integration through case studies in automotive and manufacturing sectors (Skalli et al., 2024a; Skalli et al., 2024b; Skalli et al., 2025; Tissir et al., 2024; El Affaki et al., 2024)

Region/ Country	Count	Research Trend
Saudi Arabia	1	Examining the interplay of I4.0, lean, agile, and circular manufacturing on sustainability performance (Elnadi et al., 2025)
Vietnam	1	Smart manufacturing technologies and sustainable corporate performance in food industry SMEs (Le & Le, 2025)
Malaysia	1	Moderating effect of I4.0 technologies on lean production and sustainable organizational performance (Ooi et al., 2023)
Pakistan	1	Maturity model development (LM4I4.0) for assessing I4.0 readiness in a developing country context (Sajjad et al., 2024)
Turkey	2	Leanness assessment framework and LSS integration with RAMI 4.0 lifecycle in high-tech electronics (Tayaksi et al., 2020; Özkan-Özen et al., 2024)
Iran	1	Lean-digitized manufacturing for corporate survival in SMEs (Ghobakhloo & Fathi, 2020)
Australia	1	Lean-centric readiness model development through systematic literature review (Silva et al., 2025)
Czech Republic	1	Readiness assessment model for LSS and I4.0 conjunction implementation (Efimova & Briš, 2022)
Colombia	1	Maturity model for operational excellence in emerging countries (Henríquez-Machado et al., 2023)
Greece	1	Lean automation plan with AGV/IoT integration using socio-technical systems approach (Vlachos et al., 2023)
Ireland	1	Pharma Industry 4.0 deployment and readiness assessment (McDermott et al., 2024)
Europe	**5**	
Italy	2	Lean 5.0 human-centric paradigm in the fashion industry; comparative studies with emerging economies (Fani et al., 2024; Tortorella et al., 2021c)
Norway	1	Complementary effect of lean manufacturing and digitalization on operational performance (Buer et al., 2021)
Spain	1	Human-centered model for Lean Industry 5.0 in the automotive sector (Hines et al., 2026)
South America	**4**	
Brazil	4	Strategic roadmaps, Lean 4.0 implementation frameworks, technology prioritization using network theory, and pathways to high-performing lean automation (Dos Santos et al., 2025; Vargas et al., 2024; Bueno et al., 2023; Utiyama et al., 2025)
Multi-country/ Global	**13**	Cross-cultural comparisons (developed vs developing economies), global expert interviews on Quality 4.0, systematic literature reviews, Design Science Research for DMAIC 4.0, and large-scale surveys examining LSS-I4.0 relationships (Sahoo et al., 2026; Pongboonchai-Empl et al., 2026; Wankhede et al., 2025; Virmani et al., 2025; Frank et al., 2025; Zulfiqar et al., 2024; Pansare et al., 2024; Sunder M & Prashar, 2024; Gatell & Avella, 2024a; Gatell & Avella, 2024b; Komkowski et al., 2023a; Komkowski et al., 2023b; Antony et al., 2023; Ding et al., 2023;

Region/ Country	Count	Research Trend
		Fortuny-Santos et al., 2020; Kumar et al., 2020; Cimini et al., 2023; Tortorella et al., 2021a)

Methodologically, quantitative approaches dominate the literature. Structural equation modeling (SEM/PLS-SEM) is the most frequently employed technique (18 studies), followed by multi-criteria decision-making methods including ISM-MICMAC (8), Fuzzy AHP/AHP (6), and Fuzzy DEMATEL (4). Qualitative approaches account for a substantial portion through systematic literature reviews (14 studies) and single or multiple case studies (14 studies). Mixed-method designs remain relatively scarce, indicating an opportunity for methodological advancement. Table 4 summarizes the methodological distribution.

Table 4. Distribution of Research Methodologies

Category	Data Analysis Method	Count	Representative Reference
Quantitative	SEM/PLS-SEM	18	Sahoo et al. (2026), Elnadi et al. (2025), Virmani et al. (2025), Skalli et al. (2024), Dixit et al. (2022)
	ISM + MICMAC	8	Rana & Jani (2025), Kumar et al. (2024), Joshi et al. (2024)
	Fuzzy AHP/AHP	6	Dos Santos et al. (2025), Daniel et al. (2024), Kumar et al. (2023)
	Fuzzy DEMATEL	4	Samanta et al. (2024), Khanzode et al. (2023), Tayaksi et al. (2020)
	TOPSIS/Fuzzy TOPSIS	3	Upadhyay et al. (2023), Pansare et al. (2024)
	Hierarchical Regression	2	Buer et al. (2021), Tortorella et al. (2021c)
	Delphi Method	4	Pongboonchai-Empl et al. (2026), Vimal et al. (2025)
	BWM/RBWM	2	Rana & Jani (2025), Daniel et al. (2024)
	Other MCDM (SWARA-WASPAS, PROMETHEE, GTMA)	4	Pansare et al. (2024), Dos Santos et al. (2025), Virmani et al. (2023)
Qualitative	Thematic/Content Analysis	12	Hines et al. (2026), Skalli et al. (2024b), Fani et al. (2024), McDermott et al. (2024), Antony et al. (2023)
Systematic Literature Review (SLR)		14	Silva et al. (2025), Komkowski et al. (2023a, 2023b), Gatell & Avella (2024b), Ding et al. (2023)
Single/Multiple Case Study		14	Bhadu et al. (2025), Vlachos et al. (2023), Ghobakhloo & Fathi (2020)
MIXED	SEM + ANN	1	Citybabu & Yamini (2025)

Category	Data Analysis Method	Count	Representative Reference
	Delphi + TISM	1	Vimal et al. (2025)
	SLR + Case Study	5	Utiyama et al. (2025), Bueno et al. (2023), Vargas et al. (2024)
	Survey + Interview	3	Pongboonchai-Empl et al. (2026), Skalli et al. (2025)

The underlying theoretical frameworks employed across studies exhibit considerable diversity. The Triple Bottom Line (TBL) theory is the most frequently adopted lens (15 studies), followed by Systems Theory (10 studies), Socio-Technical Systems theory (6 studies), and Dynamic Capabilities (4 studies). The Technology-Organization-Environment (TOE) framework appears in 3 studies, while Contingency Theory has been applied in only 1 study despite its relevance to context-dependent transformation outcomes.

Sectorally, general manufacturing studies dominate (28 studies, 44%), followed by discrete manufacturing (14 studies, 22%) concentrated in automotive, metal-mechanical, and electronics industries. Process industries including pharmaceutical, ceramic, food, and mining account for only 5 studies (8%), while SME-focused cross-sector studies represent 8 studies (13%). This distribution reveals a notable underrepresentation of process industries and food and beverages specifically, with only one study (Le & Le, 2025) examining the food industry in a developing economy context (Table 5).

Table 5. Sectoral Distribution of Studies

Sector Category	Industries Included	Count	Sector Characteristics	LSS and I4.0 Readiness Context	References
General Manufacturing	Cross-industry manufacturing studies, multi-sector surveys	28	Diverse production systems; varying automation maturity; heterogeneous organizational sizes; broad supply chain networks	Early-to-intermediate I4.0 adoption stages. Readiness focuses on organizational culture, top management commitment, and workforce skills. Lean practices serve as foundational enablers for digital transformation.	Buer et al., 2021; Frank et al., 2025; Sahoo et al., 2026; Tortorella et al., 2021a; Tortorella et al., 2021b; Komkowski et al., 2023a; Antony et al., 2023; Ding et al., 2023; Yadav et al., 2022; Ooi et al., 2023

Sector Category	Industries Included	Count	Sector Characteristics	LSS and I4.0 Readiness Context	References
Discrete Manufacturing	Automotive, metal-mechanical, electronics, plastics, fashion/leather	14	Assembly-oriented with countable units; established QMS (IATF 16949); high customization demands; capital-intensive; strong competitive pressures	Higher I4.0 readiness due to established lean culture. Automotive leads with DMAIC 4.0 and Lean 5.0 models. Tangible improvements: 10-27% defect reduction, enhanced equipment effectiveness.	Hines et al., 2026; Tissir et al., 2024; El Affaki et al., 2024; Skalli et al., 2025; Vlachos et al., 2023; Dos Santos et al., 2025; Utiyama et al., 2025; Vinodh & Shimray, 2023
Process Industries	Pharmaceutical, ceramic, food, mining, sugar	5	Continuous/ batch production; stringent regulatory compliance; resource-intensive; complex process control needs	Sector-specific readiness influenced by regulations. Pharma shows late adopter behavior; ceramic achieves 10-27% efficiency gains; mining validates 20% energy efficiency improvement.	McDermott et al., 2024; Bhadu et al., 2025; Le & Le, 2025; Skalli et al., 2025; Bueno et al., 2023
SMEs (Cross-sector)	Small-medium enterprises, MSMEs	8	Limited resources; flat structures; constrained infrastructure; owner-driven decisions; localized supply chains	Nascent I4.0 adoption, classified as "immature" in maturity assessments. Key barriers: limited finance, skill gaps, and inadequate infrastructure. Phased implementation with lean as mediator is recommended.	Ghobakhloo & Fathi, 2020; Kumar et al., 2025; Joshi et al., 2024; Upadhyay et al., 2023; Henríquez-Machado et al., 2023; Vargas et al., 2024; Efimova & Briš, 2022; Sajjad et al., 2024

LSS Variables and Their Influence on I4.0 Readiness (RQ1)

The systematic analysis of 63 studies reveals 10 distinct LSS variables with varying prevalence and influence patterns on I4.0 transformation. Table 6 presents the frequency distribution of each variable alongside its primary role in the integration process.

Table 6. Distribution of LSS Variables Across Studies

LSS Variable	Count	%	Primary Role in I4.0 Integration
Technology Integration	53	84%	Technical backbone of I4.0; IoT, AI, CPS, cloud computing deployment
Top Management Commitment	41	65%	Strategic direction, resource allocation, sponsorship of transformation
Continuous Improvement	34	54%	Philosophical alignment between kaizen orientation and digital feedback loops
Process Standardization	32	51%	Stable operational baseline upon which digital technologies operate
Training and Skills	32	51%	Bridging capability gaps in digital literacy and cross-functional competence
Data Analytics	27	43%	Critical bridge connecting lean's data-driven approach with I4.0 computation
Waste Reduction	21	33%	Enhanced precision through I4.0 technologies; real-time monitoring
Organizational Culture	21	33%	Foundational mindset for embracing technological change
Employee Involvement	17	27%	Shop-floor acceptance and participatory engagement in digital initiatives
Green / Sustainability	12	19%	Emerging stream integrating environmental objectives into the LSS-I4.0 nexus

Technology Integration (84%) and Top Management Commitment (65%) are the most frequently reported variables across the reviewed studies, while process-oriented practices—Continuous Improvement (54%), Process Standardization (51%), and Waste Reduction (33%)—are commonly described as prerequisite foundations for effective digitalization in the reviewed literature (Ding et al., 2023; Fortuny-Santos et al., 2020). Human capital variables (27–51%) are frequently positioned as mediating links between technological capabilities and realized outcomes (Citybabu & Yamini, 2025; Hines et al., 2026), whereas Green/Sustainability (19%) appears less frequently but is reported as a rapidly growing theme (Sahoo et al., 2026). Several studies in the sample describe the LSS–I4.0 relationship as bidirectional: Buer et al. (2021) report complementary effects between lean and digitalization, while Frank et al. (2025) and Silva et al. (2025) describe reinforcing feedback loops when the two paradigms are properly sequenced. It should be noted that these patterns reflect how often themes are discussed in the reviewed literature rather than measures of empirical effect size or causal direction, which this scoping review does not assess.

Transformation Strategies and Outcomes (RQ2)

The analysis reveals seven distinct strategic dimensions through which organizations translate LSS variables into actionable I4.0 transformation pathways. Table 7 presents the prevalence and key characteristics of each strategy dimension.

Table 7. Transformation Strategy Dimensions Across Studies

Strategy Dimension	Count	%	Strategic Focus
Leadership and Change Management	28	44%	Executive sponsorship, change readiness, vision alignment
Human Capital Development	17	27%	Digital literacy, cross-functional skills,

			workforce transformation
Process-First Approach	16	25%	Stabilize lean processes before digital technology deployment
Technology Infrastructure Investment	13	21%	IoT networks, cloud platforms, analytics capabilities
Phased Roadmap	17	27%	Incremental implementation, progressive capability building
Sustainability Integration	10	16%	Circular economy, environmental performance alignment
Government Policy	4	6%	Institutional support, funding mechanisms, regulatory frameworks

Leadership and Change Management (44%) is the most frequently reported strategic dimension, followed by Human Capital Development (27%) and Phased Roadmap (27%), covering executive sponsorship, workforce transformation, and incremental implementation (Kumar et al., 2024; Gatell & Avella, 2024). The Process-First Approach (25%) positions lean stability before digital deployment (Vargas et al., 2024), while Technology Infrastructure Investment (21%), Sustainability Integration (16%), and Government Policy (6%) appear less frequently in the reviewed literature. Reported outcomes include 10–27% reductions in processing time, waiting time, and defects (Bhadu et al., 2025), and 20% energy efficiency gains (Skalli et al., 2025), with phased approaches associated with gradual capability accumulation compared to comprehensive overhauls.

Contextual Conditions and Research Gaps (RQ3)

The synthesis of contextual factors across 63 studies reveals systematic patterns in the conditions under which LSS-I4.0 integration yields effective outcomes, alongside critical gaps constraining the generalizability of existing findings. Table 6 compares the four major national I4.0 readiness frameworks identified in the literature, highlighting their strengths, limitations, and applicability to different economic contexts.

Table 8. Comparison of Major Industry 4.0 Readiness Frameworks

Criteria	IMPULS (Germany)	SIRI (Singapore)	4WRD RA (Malaysia	INDI 4.0 (Indonesia)
Year Introduced	2015	2017	2018	2018
Institutional Origin	Developed by IMPULS Foundation based on German mechanical and plant engineering survey data	Developed by Singapore Economic Development Board in collaboration with McKinsey & ARTC	Developed under Malaysia's Ministry of International Trade and Industry (MITI)	Developed by Indonesia's Ministry of Industry under Making Indonesia 4.0
Primary Purpose	Benchmarking and maturity assessment	Structured diagnostic and prioritization tool	Readiness assessment linked to national	National readiness benchmarking aligned with

Criteria	IMPULS (Germany)	SIRI (Singapore)	4WRD RA (Malaysia intervention programs	INDI 4.0 (Indonesia) industrial transformation
Core Dimensions	6 Dimensions: Strategy & Organization; Smart Factory; Smart Operations; Smart Products; Data-Driven Services; Employees	3 Pillars (Process, Technology, Organization), 8 Dimensions, 16 Categories	Multi-dimensional (Technology, Process, People, Governance) integrated within policy ecosystem	5 Dimensions: Management & Organization; People & Culture; Products & Services; Technology; Factory Operations
Assessment Mechanism	Six-level maturity scale; online self-assessment tool	Structured scoring system + Prioritization Matrix	Readiness scoring connected to government support schemes	Scoring system classifying firms from Beginner to Expert
Orientation	Primarily diagnostic benchmarking	Diagnostic + prioritization guidance	Diagnostic + policy-driven intervention	Diagnostic with sector prioritization
Strengths	Simple and practice-oriented; clear maturity scale; internationally referenced	Holistic scope; integrates organizational & talent readiness; globally recognized; decision-support prioritization matrix	Strong policy alignment; linked to incentives and capability-building programs; SME-focused	Context-sensitive to emerging economy; aligned with national development agenda; relevant to priority sectors (e.g., F&B)
Limitations	Developed from German sectoral data; limited contextual adaptability; static snapshot; lacks Industry 5.0 integration	Singapore-centric design; resource-intensive implementation; requires contextual adaptation in less developed economies	Limited global comparability; more diagnostic than roadmap; implementation challenges for firms with resource constraints	Uneven implementation; risk of self-assessment bias; limited external validation; largely diagnostic
Geographical Transferability	Adopted beyond Germany (e.g., Portugal, Middle East), but requires contextual adaptation	Widely adopted internationally; adaptable but infrastructure-dependent	Primarily Malaysia-focused	Primarily Indonesia-focused

Criteria	IMPULS (Germany)	SIRI (Singapore)	4WRD RA (Malaysia	INDI 4.0 (Indonesia)
Policy Integration	Moderate	Moderate to High	Very High	Very High
Prescriptive Roadmap Capability	Limited (benchmarking emphasis)	Moderate (via prioritization matrix)	Limited–Moderate (through policy linkage)	Limited (focus on assessment)
Industry 5.0 Consideration	Not explicitly integrated	Not explicitly integrated	Limited integration	Limited integration
Suitability for Emerging Economies	Requires strong adaptation	Adaptable but infrastructure-sensitive	Designed for emerging context	Designed for emerging context

Conditions favoring effective integration outcomes cluster around three factors. First, organizations with established LSS maturity demonstrate significantly higher I4.0 readiness, as pre-existing process stability, improvement culture, and data-driven practices provide the absorptive capacity necessary for digital technology adoption (Elnadi et al., 2025; Ding et al., 2023). Second, larger firms with dedicated resources and structured management systems tend to progress further in integration compared to SMEs facing resource constraints and capability gaps (Joshi et al., 2024; Ghobakhloo & Fathi, 2020). Third, supportive institutional environments, including policy alignment, funding availability, and regulatory frameworks, significantly enhance adoption trajectories, particularly in emerging economies (Rana & Jani, 2025; Le & Le, 2025).

Conversely, conditions associated with limited effectiveness include low organizational maturity, resource-constrained SME environments, absence of clear policy support, and purely technology-driven approaches that neglect human capital and cultural readiness (Virmani et al., 2023; Upadhyay et al., 2023; Sajjad et al., 2024). The analysis identifies five critical research gaps summarized in Table 9.

Table 9. Summary of Research Gaps and Opportunities

Dimension	Current State	Gap / Opportunity
Theoretical	Variance-based frameworks predominate (TBL: 15, Systems Theory: 10); systems-based holistic approaches limited	Application of Soft Systems Methodology to analyze systemic interdependencies from multiple stakeholder perspectives
Methodological	Cross-sectional designs prevalent (SEM: 18, MCDM: 27); variables treated in isolation	Integration of SSM with AHP enabling holistic problem structuring complemented by rigorous prioritization
Geographic	Concentration in India (33%) and multi-country studies (21%); Southeast Asian emerging economies underrepresented	Investigation within Indonesian context, given the INDI 4.0 national initiative
Sectoral	General manufacturing (44%) and discrete manufacturing (22%) dominant; process industries underexamined	Food and beverages sector, given its distinctive regulatory environment and supply chain complexity
Integration	Individual LSS variables well-	Unified model examining systemic

Dimension	Current State	Gap / Opportunity
	documented; comprehensive integration across all variables and strategies less common	interactions among multiple LSS variables and transformation strategies

The geographic gap is particularly pronounced. While India and multi-country studies together account for over 54% of the literature, Southeast Asian manufacturing economies, including Indonesia, are virtually absent despite active national I4.0 policy implementation. The sectoral gap is equally significant: the food and beverages industry, which constitutes a national priority sector in Indonesia's Making Indonesia 4.0 roadmap and the largest contributor to manufacturing GDP, has received almost no attention in the LSS-I4.0 integration literature, with only one study examining food industry SMEs in Vietnam (Le & Le, 2025). Methodologically, the absence of systems thinking approaches capable of capturing holistic problem situations from multiple stakeholder perspectives, combined with the static diagnostic nature of existing readiness models, constrains the field's ability to generate prescriptive and context-sensitive transformation guidance.

Discussion

The synthesis of 63 studies suggests that, across the reviewed literature, LSS–I4.0 integration is described in terms of the interplay of operational readiness, strategic sequencing, and contextual conditions. The high reporting frequency of Technology Integration (84%), Process Standardization (51%), and Continuous Improvement (54%) is consistent with narratives in the reviewed studies that position lean process stability as a foundational layer for digital adoption, with multiple authors reporting that digital technologies deployed on unstable processes tend to amplify rather than resolve inefficiencies (Ding et al., 2023; Fortuny-Santos et al., 2020; Silva et al., 2025). This pattern is consistent with Socio-Technical Systems theory, which holds that optimizing the technical subsystem in isolation from organizational and human elements yields suboptimal outcomes (Trist & Bamforth, 1951; Cherns, 1976). The evidence also points to bidirectional reinforcement, where lean practices enable digitalization while digital technologies enhance lean effectiveness (Buer et al., 2021; Frank et al., 2025).

At the methodological level, the dominance of SEM (18 studies) and MCDM approaches (27 studies) has supported variable identification more than systemic analysis of how factors interact within specific organizational contexts. Systems thinking methodologies such as Soft Systems Methodology (SSM) remain largely absent from the LSS–I4.0 literature, despite SSM being designed for complex, ill-structured problem situations involving multiple stakeholder perspectives (Checkland, 1999). A hybrid SSM–AHP approach represents one option for addressing this gap. On the strategic side, Leadership and Change Management (44%), Human Capital Development (27%), and Phased Roadmap (27%) appear most frequently, while Government Policy (6%) is underexamined—indicating limited attention to institutional factors relevant in emerging economies (Rana & Jani, 2025; Le & Le, 2025).

Geographic and sectoral coverage shows notable concentration in India (33%), with limited representation of Southeast Asia, Indonesia, and the food and beverages sector, despite Indonesia's active INDI 4.0 framework. Existing readiness models (IMPULS, SIRI, Industry4WRD, INDI 4.0) offer diagnostic value but provide limited prescriptive guidance on sequencing transformation investments (Vance et al., 2023; Hasbullah et al., 2024). These patterns point toward a framework integrating LSS variables as operational enablers, transformation strategies as implementation pathways, and contextual factors as moderators, connected through feedback mechanisms and operationalizable via SSM complemented by AHP (Figure 2).

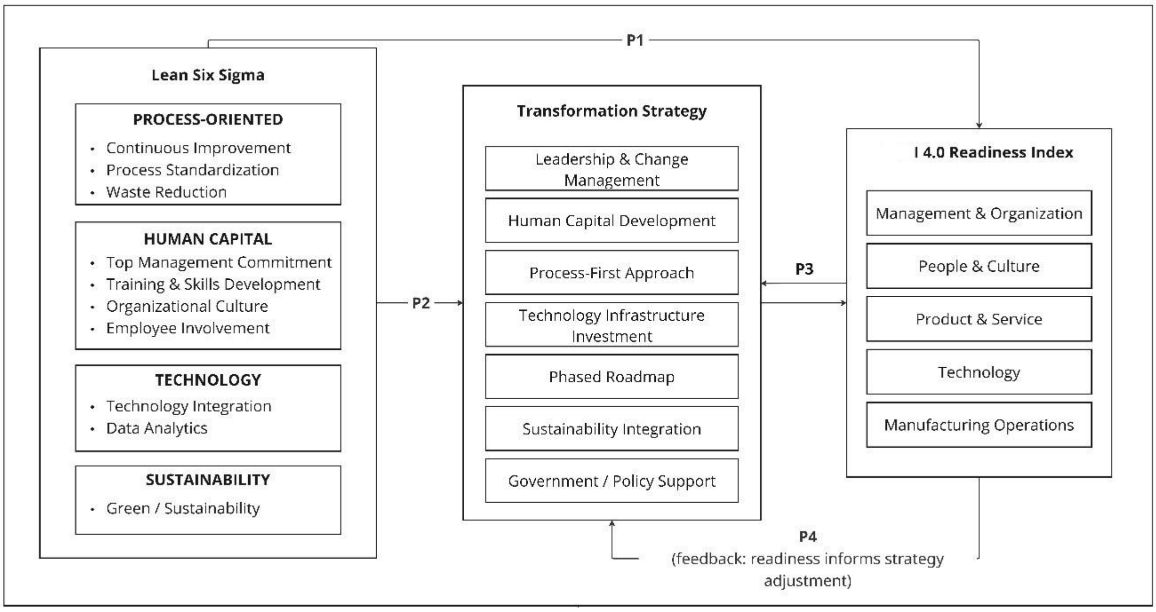

Figure 2. Proposed Conceptual Framework for LSS-I4.0 Integration

CONCLUSIONS

This scoping review systematically synthesized 63 peer-reviewed studies published between 2020 and 2026, identifying 10 LSS variables and 7 transformation strategy dimensions, and examining their prevalence, interaction patterns, and contextual conditions. Three core insights emerge. First, the reviewed literature predominantly characterizes LSS as a foundational layer for I4.0 adoption rather than an optional complement, with Technology Integration (84%), Top Management Commitment (65%), Continuous Improvement (54%), and Process Standardization (51%) emerging as the most frequently reported enablers; several studies in the sample further describe the relationship as bidirectional, with each paradigm reinforcing the other through feedback loops when properly sequenced. Second, transformation is increasingly framed as an organizational rather than purely technological challenge, with Leadership and Change Management (44%), Human Capital Development (27%), and Phased Roadmap (27%) as the most prevalent strategies, while Government Policy (6%) remains underexamined despite its relevance in emerging economies.

Third, the evidence base shows notable concentration in India (33%), general manufacturing (44%), and cross-sectional designs (SEM: 18; MCDM: 27), with Southeast Asia, the food and beverages sector, and systems thinking methodologies largely absent. Existing readiness frameworks (IMPULS, SIRI, Industry4WRD, INDI 4.0) offer diagnostic value but limited prescriptive guidance. The proposed framework positions LSS variables as operational enablers, transformation strategies as implementation pathways, and contextual factors as moderators within an iterative system, offering a foundation for future empirical work employing Soft Systems Methodology combined with AHP to bridge the diagnostic–prescriptive gap.

LIMITATION & FURTHER RESEARCH

This review has several limitations. The exclusive reliance on Scopus may have excluded relevant studies indexed elsewhere, while the restriction to English-language journal articles within Business, Management and Accounting subject areas may have filtered out technically oriented or non-Anglophone contributions. The temporal scope (2020–2026), though capturing the most active publication period, introduces recency bias and limits the availability of longitudinal evidence. Additionally, the heterogeneity of methods and metrics across 63 studies precluded meta-analysis, and the frequency-based synthesis captures variable prevalence rather than causal effect sizes.

These limitations point to five future research directions: (1) geographic expansion into Southeast Asia, particularly Indonesia given its active INDI 4.0 policy; (2) sector-specific investigation of food and beverages manufacturing with its distinctive regulatory and supply chain characteristics; (3) adoption of systems thinking methodologies, particularly SSM integrated with AHP, to enable holistic problem structuring with rigorous prioritization; (4) longitudinal and action research designs tracking transformation outcomes across complete implementation cycles; and (5) examination of how the Industry 5.0 transition toward human-centricity, resilience, and sustainability reshapes LSS's integrating role in manufacturing transformation.

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