Integrating Green Lean Six Sigma and Industry 4.0 for Sustainable Supply Chains

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***Abstract*—This systematic literature review investigates the integration of Green Lean Six Sigma (GLSS) with Industry 4.0 (I4.0) to enhance sustainable supply chain management (SSCM). Using the PRISMA protocol, this review maps the academic landscape on synergies between GLSS and key I4.0 enablers. Our analysis reveals that emerging "LSS 4.0" frameworks are predominantly manufacturing-centric. The primary contribution of this paper is to address this limitation by integrating findings from the literature into a conceptual model for the entire supply chain. We identified a lack of validated and comprehensive frameworks, the need to quantify socio-environmental benefits, and limited research on digital traceability for lean logistics. The review consolidates core concepts and proposes a research agenda to guide the creation of sustainable, efficient, and resilient supply chains.**

***Index Terms*—Green Lean Six Sigma (GLSS), Industry 4.0, Sustainable Supply Chain Management (SSCM), Systematic Literature Review (SLR), Blockchain, Digital Transformation.**

I. Introduction

Modern supply chains are characterized by dynamic and highly competitive environments that require the integration of advanced concepts for organizational survival.The combined pressures of global competition, evolving customer requirements, and environmental standards now exceed the capabilities of many traditional operational improvement strategies. In this context, operational excellence methodologies, primarily Lean Six Sigma (LSS), have been critical for optimizing efficiency through waste elimination and variation reduction. [70]. Concurrently, the advent of Industry 4.0 (I4.0) has introduced digital technologies that are fundamentally reshaping manufacturing and supply chain operations [20].

A critical emerging trend is the integration of Lean Supply Chain Management (LSCM) with I4.0 [56]. This offers significant opportunities to enhance operational performance and decrease environmental impact. Furthermore, the evolution of these methodologies has led to **Green Lean Six Sigma (GLSS)**, an eco-friendly approach that explicitly advocates for high product quality while simultaneously reducing waste, defects, and environmental footprints to foster sustainable development and improve the triple bottom line [31], [32].

This systematic literature review surveys how digital technologies are being utilized alongside GLSS practices to reduce waste and emissions in supply chain operations. It maps existing studies and identifies which I4.0 tools are paired with them. While a body of literature exists on manufacturing-focused "LSS 4.0," a significant gap persists in applying these integrated concepts across the entire supply chain. **Therefore, the primary contribution of this review is the development of a conceptual model that addresses the limitation between these manufacturing-centric frameworks and the systemic needs of Sustainable Supply Chain Management (SSCM).** We identify critical missing links, such as the limited research on digital traceability for lean logistics, and propose an applicable research agenda to address them.

II. Methodology

This review follows a Systematic Literature Review (SLR) methodology, adhering to the PRISMA 2020 guidelines to ensure transparency and reproducibility. The stages of this process are depicted in the flowchart in Fig. 1. After screening and selection, the findings from the **75 included studies** were synthesized using **thematic analysis** to identify key features, recurring concepts, documented tools, and prominent research opportunities at the intersection of Lean, Six Sigma, and sustainability within the supply chain context [7]. An inductive approach was employed, allowing key themes and research gaps to emerge directly from the literature rather than being predefined.

III. Literature Review: Core Concepts and Interplay

A. The Evolution of GLSS for Sustainability

LSS integrates Lean's waste elimination focus with Six Sigma's data-driven approach to variation reduction, often using the DMAIC framework [2], [23], [70]. GLSS extends this framework by embedding sustainability as a core principle to improve the triple bottom line (TBL) performance [8], [21], [73]. This is crucial for SMEs, though implementation is hindered by a lack of generic frameworks and significant barriers [31], [32], [65]. The cumulative impact of GLSS, when combined with Big Data Analytics and sustainable supply chain practices, has been shown to positively affect the economic performance of manufacturing organizations [18].

B. Industry 4.0 as an Enabler for Lean Six Sigma

I4.0 represents the digitalization of production via technologies like IoT, CPS, and BDA [20]. The literature confirms a strong mutually beneficial relationship between Lean and I4.0, leading to concepts such as "LSS 4.0" [16], [62]. Digital technologies enhance traditional Lean methods; for example, I4.0 tools can be integrated into each phase of the DMAIC cycle

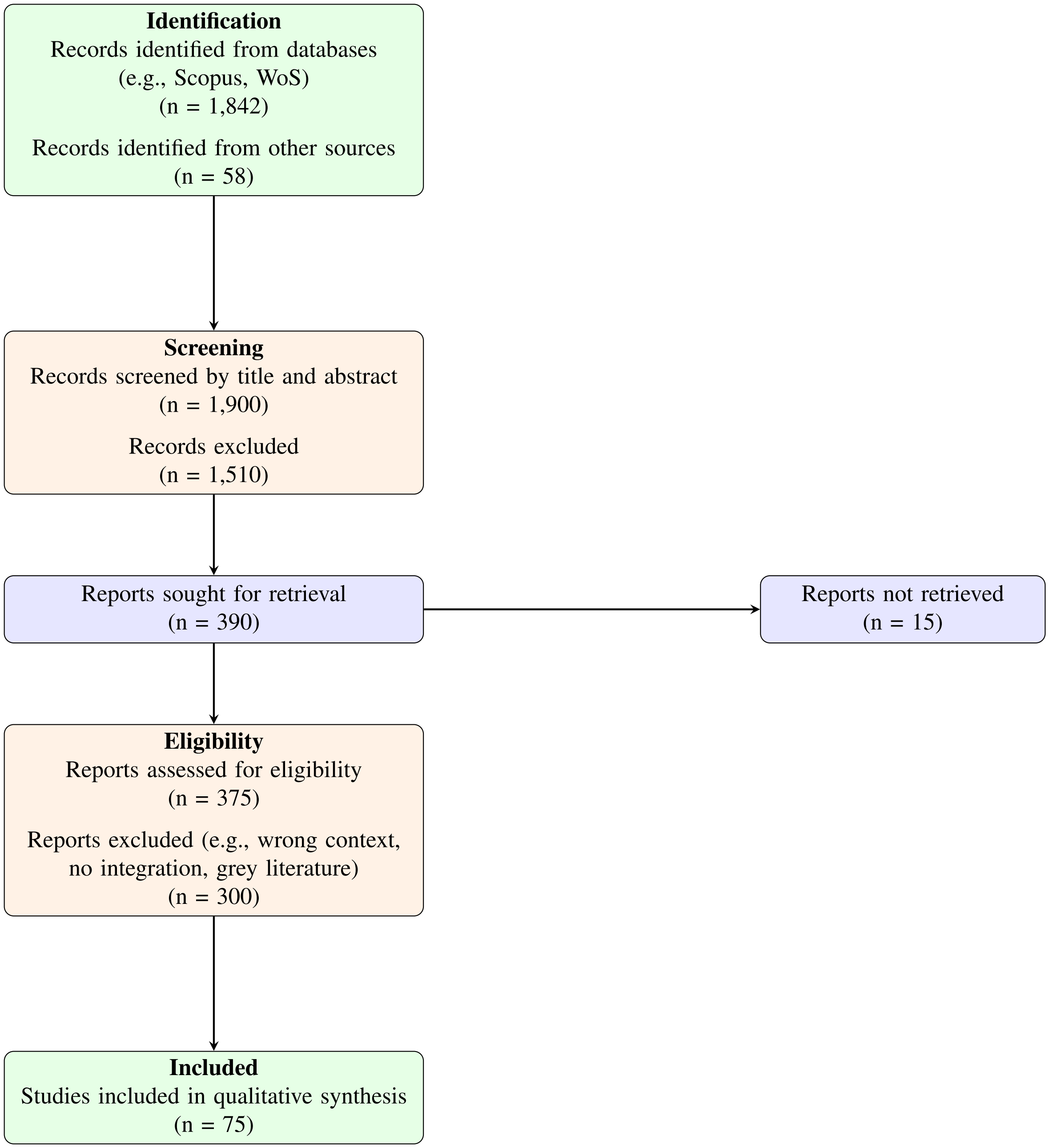

Fig. 1. PRISMA 2020 Flow Diagram for the Systematic Literature Review Process

to improve data collection, analysis, and control [16], [50]. A notable application is the LSS 4.0 project for improving spare parts (MRO) inventory management, a critical supply chain function [68].

C. Implementation: Barriers and Enablers

The successful deployment of GLSS requires addressing and leveraging key enablers. Multiple empirical studies, particularly focusing on MSMEs, have identified and categorized these factors.

- **Barriers**: Consistently cited barriers include a **lack of top management commitment**, **financial constraints**, a **lack of knowledge and skills**, and a general **resistance to change** [29], [35], [37], [42], [55], [60].
- **Enablers**: Conversely, the most critical enablers are the mirror image of the barriers. **Top management commitment**, **organizational readiness**, developing **competence for green products and processes**, and clearly **linking GLSS to business objectives** are essential for success [30].

D. Digital Technologies in Sustainable Supply Chains

The application of I4.0 technologies is critical for advancing sustainable and resilient supply chains. This includes the development of sustainable production value measurement models based on Lean and Six Sigma in an I4.0 context [22].

1) Blockchain in Supply Chain Management: Blockchain technology offers a decentralized and immutable ledger, providing unprecedented transparency and traceability [52]. It can be used to develop collaborative frameworks, with smart contracts automating and enforcing agreements in areas like Vendor Managed Inventory (VMI) [46], [75]. This is particularly relevant for automating procurement in complex supply chains like healthcare [47] and agriculture [15].

IV. Research Gaps and Future Directions

This review confirms several critical gaps. To move the field forward, we translate these gaps into testable research propositions for future investigation.

- **From Manufacturing-Centric Models to Systemic Supply Chain Frameworks:** The current LSS 4.0 models are predominantly focused on the factory floor. Future research should aim to develop and empirically validate a multi-level framework that maps specific I4.0 technologies (e.g., IoT sensors for in-transit monitoring, blockchain for traceability) to distinct supply chain tiers (e.g., Tier 2 raw material suppliers, OEMs, third-party logistics providers) and their respective GLSS objectives (e.g., waste reduction, emissions monitoring, ethical sourcing verification).
- **Beyond Operational Metrics to Integrated TBL Quantification:** Many proposed models are theoretical, lacking empirical validation of their sustainability claims. We propose that future quantitative case studies should move beyond traditional operational metrics (e.g., cycle time, defect rates) and employ a holistic performance measurement system. This should incorporate metrics such as **Total Cost of Ownership (TCO)**, **lifecycle assessment (LCA)** data for environmental impact, and **Social Return on Investment (SROI)** to rigorously quantify the triple-bottom-line impact of GLSS-I4.0 integration.
- **From Barrier Identification to Actionable Mitigation Strategies:** While barriers to GLSS are well-documented [29], [37], [55], research must now progress beyond identification. Future studies should focus on developing and testing practical, context-specific strategies for overcoming these hurdles, particularly in SMEs where resource constraints are most acute.
- **Integrating Blockchain for Automated Process Control:** The integration of Blockchain with LSS is not yet well - developed. A precise research question to guide future work is: **"How can smart contracts on a permissioned blockchain platform be designed to automate the monitoring and verification steps of the DMAIC 'Control' phase for critical-to-quality (CTQ) parameters across a multi-echelon, geographically dispersed supply chain?"** This moves the focus from simple traceability to automated, decentralized quality assurance.

V. Conclusion

The integration of Green Lean Six Sigma and Industry 4.0 offers a powerful pathway toward creating sustainable, resilient, and highly efficient supply chains. Our analysis confirms that while foundational concepts are well-established, their integrated applications across the supply chain are not yet well developed. **This review's primary contribution is to conceptually develop a unifying framework between manufacturing-focused 'LSS 4.0' frameworks and the systemic needs of SSCM**, synthesizing disparate research streams to highlight a clear trajectory forward. By addressing the identified gaps with a concrete research agenda—focusing on empirical TBL validation, barrier mitigation, and advanced digital integration—future work can provide practitioners with concrete roadmaps for their green and digital transformations. **Furthermore, the societal implications of this integration are significant; digital traceability, for example, can enhance food safety via farm-to-fork tracking, combat counterfeit pharmaceuticals, and provide consumers with verifiable proof of ethically sourced materials.** Ultimately, this synthesis aims to accelerate the development of the truly sustainable, transparent, and socially responsible supply chains of the future.

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TABLE I: Annotated Summary of Key Literature (Characteristics of Included Studies)

Reference	Study Objective	Methodology/Type	Key Contribution to this Review
Category A: Systematic Literature Reviews (SLRs) and Scoping Reviews			
Barbosa et al. (2023) [7]	To analyze the literature on the practical application of LSS in the context of the supply chain.	Systematic Literature Review (SLR)	Critically identifies a major gap: ”no studies referring to the main tools used by green lean six sigma methods in the supply chain,” which directly motivates our review's focus.
Skalli et al. (2023) [62]	To review the integration of LSS and I4.0 in manufacturing and propose an integrated framework.	SLR & Framework Development	A key source that proposes a comprehensive ”LSS 4.0” framework and explicitly states that literature combining LSS with I4.0 components is scarce, reinforcing a core premise of this paper.
Yadav et al. (2023) [73]	To conduct a systematic review of GLSS for sustainability improvement and propose a future research agenda.	SLR	Outlines the current status of GLSS research and provides a detailed future research agenda, which heavily informs this review's ”Gaps and Future Directions” section.
Gaikwad & Sunnapwar (2020) [21]	To systematically review integrated Lean, Green, and Six Sigma strategies and provide directions for future research.	SLR	Confirms the need for more integrated studies and frameworks and provides a foundational overview of the combined methodologies, supporting the rationale for this review.
Pongboonchai-Empl et al. (2023) [50]	To systematically review the integration of I4.0 technologies into the LSS DMAIC cycle.	SLR	Provides a detailed look at how digitalization enhances each phase of an LSS project, offering a granular perspective on the LSS 4.0 concept.
Mian et al. (2024) [40]	To conduct a scoping review on integrating LSS with Blockchain for quality management.	Scoping Review	Highlights current trends and future prospects for a specific, high-impact technology pairing, directly informing the technology-specific gap analysis.
Category B: Frameworks & Conceptual Models			
Kolberg et al. (2021) [33]	To propose a new holistic approach for the integration of Lean Manufacturing and I4.0.	Conceptual Framework (”Lean 4.0”)	Defines specific principles for the ”Lean 4.0” paradigm, providing a structured conceptual model for the integration that informs the theoretical basis of this review.

TABLE I – continued from previous page

Reference	Study Objective	Methodology/Type	Key Contribution to this Review
Kaswan & Rathi (2020) [31]	To propose an integration and framework for GLSS for sustainable development.	Framework Development	Proposes a foundational GLSS framework and explicitly notes the lack of generic models applicable across different organizational types, highlighting a key research gap.
Caiado et al. (2021) [12]	To propose a framework for integrating LSS and I4.0 and identify its critical success factors (CSFs).	Framework & Expert Survey (Fuzzy-AHP)	Provides an integrated framework and, importantly, uses an expert-based method to identify and prioritize CSFs for its implementation.
Ganjavi & Fazlollahtabar (2023) [22]	To develop a measurement model for integrated sustainable production value based on LSS and I4.0.	Mathematical Modeling	Offers a quantitative approach to assessing the performance of integrated systems, addressing the gap related to performance measurement.
de Sousa et al. (2023) [16]	To propose an innovative "DMAIC 4.0" framework that integrates I4.0 technologies into the LSS methodology.	Framework Development	Provides a practical roadmap for digitally enhanced LSS projects by mapping specific I4.0 technologies to each of the five DMAIC phases.
Category C: Case Studies & Empirical Applications			
Vazquez Hernandez & Elizondo Rojas (2024) [68]	To improve spare parts (MRO) inventory management policies using an LSS 4.0 approach.	Case Study	Presents a practical LSS 4.0 project in a highly relevant supply chain context (MRO inventory), demonstrating the application of these concepts beyond production.
Jamwal et al. (2021) [28]	To leverage LSS to reduce defects and rejections in a filter manufacturing industry.	Case Study (DMAIC)	A practical case study showing quantifiable improvements in quality metrics (PPM reduction, sigma level increase) through a standard LSS project.
Bela et al. (2023) [8]	To analyze the impacts of Lean, Green, and Six Sigma on Triple Bottom Line (TBL) performance.	Conceptual with Empirical Links	Provides evidence for the effectiveness of GLSS in achieving holistic sustainability by explicitly linking the methodologies to TBL performance indicators.
Ahmed (2019) [2]	To provide a framework for implementing LSS in the healthcare sector.	Framework/Application	Offers an example of applying LSS principles in a service-oriented supply chain (healthcare), supporting the call to expand research beyond manufacturing.
Category D: Technology-Specific Studies			

TABLE I – continued from previous page

Reference	Study Objective	Methodology/Type	Key Contribution to this Review
Zhang et al. (2020) [75]	To demonstrate a blockchain-based framework using smart contracts for supply chain collaboration.	Framework Demonstration	Provides a practical example of how blockchain and smart contracts can be implemented to improve collaboration and transparency in the supply chain.
Omar et al. (2021) [47]	To automate procurement contracts in the healthcare supply chain using blockchain smart contracts.	Application Case Study	A specific case study showing the use of blockchain in a complex, regulated supply chain, highlighting its potential for reducing administrative waste and errors.
Category E: Barrier & Enabler Studies			
Kaswan & Rathi (2020) [29]	To investigate and prioritize barriers to GLSS implementation in the manufacturing sector.	Empirical Study (DEMATEL, BWM)	Empirically finds that management-related barriers are the most critical, providing robust, quantitative evidence for the ”Research Gaps” section.
Rathi et al. (2023) [55]	To evaluate critical failure factors for implementing a sustainable LSS framework.	Empirical Study (MCDM)	Uses a robust methodology to rank failure factors, providing actionable insights for managers on what to prioritize to avoid project failure.
Macias-Aguayo et al. (2022) [37]	To systematically review the barriers and enablers of LSS and I4.0 integration.	Systematic Literature Review (SLR)	Directly informs the ”Research Gaps” section by synthesizing the known challenges and success factors for implementing LSS 4.0.
Laureani & Antony (2017) [35]	To systematically review the role of leadership in LSS implementation.	SLR	Confirms through a literature review that leadership is a critical enabler for the successful deployment of any LSS initiative, a foundational concept for implementation studies.