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ARTICLE

Green Lean Six Sigma for Smart and Sustainable Manufacturing: A Comprehensive Review and Strategic Framework in the Industry 4.0–5.0 Era

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Abstract

The transition toward smart, sustainable, and human-centric manufacturing is reshaping how organizations integrate operational excellence, environmental responsibility, and digital transformation. Green Lean Six Sigma (GLSS)—which synergizes Lean waste minimization, Six Sigma's data-driven methodology, and green manufacturing principles—has emerged as a robust approach for improving sustainability and operational performance. However, its strategic integration within the evolving Industry 4.0–5.0 landscape remains conceptually fragmented and insufficiently structured. This study presents a comprehensive review of GLSS and its convergence with advanced digital technologies, including the Internet of Things, cyber-physical systems, artificial intelligence, robotics, cloud computing, blockchain, additive manufacturing, and big data analytics. The review synthesizes key implementation drivers, performance impacts, organizational and technological challenges, and critical research gaps, with particular emphasis on sustainability integration, digital maturity, human–technology collaboration, and the progression toward resilient, circular, and human-centric manufacturing systems. Building on these insights, the study proposes an integrated strategic GLSS framework tailored to the Industry 4.0–5.0 context. The framework extends the traditional DMAIC methodology by embedding circular economy principles, sustainability-oriented performance metrics, digital intelligence, and human-centric innovation across all phases. Structured around five interrelated pillars—Technological Enablement, Human-Centric Management, Sustainable Materials and Processes, Policy and Governance Alignment, and Operational Integration—the framework provides a structured roadmap for deploying GLSS to achieve eco-efficient, socially responsible, and high-performance smart manufacturing systems.

Keywords: Green Lean Six Sigma (GLSS); Smart and Sustainable Manufacturing; Industry 4.0; Industry 5.0; Digital Transformation; Circular Economy; Sustainability; Operational Excellence.

1. INTRODUCTION

Modern manufacturing faces multifaceted pressures, including stringent environmental regulations, rising customer expectations, volatile markets, and global competition. Simultaneously, organizations must improve operational efficiency while achieving sustainability and social responsibility objectives. Addressing these interrelated demands requires integrated strategies that align operational excellence with environmental stewardship and human-centric principles. Consequently, sustainability has shifted from a compliance-driven obligation to a strategic imperative essential for long-term competitiveness, resilience, and industrial viability.

1.1. Green Lean Six Sigma as a Holistic Improvement Paradigm

Green Lean Six Sigma (GLSS) has emerged as a comprehensive framework that extends Lean Six Sigma by embedding sustainability into process optimization. By integrating Lean's waste elimination, Six Sigma's data-driven rigor, and environmental management principles, GLSS enables organizations to enhance efficiency, quality, and ecological performance simultaneously.

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Lean traditionally targets seven forms of operational waste—unnecessary motion, over-processing, overproduction, waiting, rework, excess inventory, and defects—but largely overlooks environmental impacts. Six Sigma excels in reducing variation and defects but does not inherently address ecological performance. GLSS bridges these gaps by identifying environmental hotspots alongside operational inefficiencies, fostering continuous improvement aligned with sustainability objectives [1-4].

GLSS is commonly implemented through the DMAIC (Define, Measure, Analyze, Improve, Control) methodology, supported by tools and enablers that align processes with sustainability objectives [5,6]. Evidence indicates that GLSS adoption delivers significant environmental, economic, and social benefits across manufacturing, food processing, construction, and public service sectors [5,7].

Despite these benefits, adoption is limited by skill gaps, resource constraints, cultural resistance, and challenges in aligning operational metrics with environmental goals. This underscores the need for structured, strategically aligned, and digitally enabled GLSS frameworks validated in industrial contexts [6,8].

1.2. Digital Transformation and Industry 4.0–5.0 Evolution

Manufacturing is undergoing a profound transformation driven by digital technologies, sustainability imperatives, and human-centric design. Industry 4.0 introduced smart, interconnected systems enabled by IoT, cyber-physical systems, AI, robotics, cloud computing, and big data analytics, emphasizing automation, efficiency, and flexibility.

Industry 5.0 extends this foundation by prioritizing human–machine collaboration, resilience, ethical responsibility, and sustainable value creation. It shifts the focus from purely technology-driven optimization to socially and environmentally responsible production, positioning humans at the center of digitally enabled systems.

Environmental degradation, resource scarcity, and regulatory pressures have accelerated the adoption of sustainable manufacturing practices. Green Industrial Systems integrate sustainability principles, digital technologies, and strategic management to enhance environmental, economic, and social performance simultaneously. Sustainable manufacturing promotes cleaner production, optimized resource use, and waste minimization across product lifecycles, improving operational performance while reducing environmental impact [9-11].

Complementary practices such as eco-design, recycling, resource recovery, and circular product management further enhance efficiency, resilience, and competitiveness [12]. Empirical evidence confirms that sustainability strategies positively influence financial performance, operational efficiency, customer satisfaction, and innovation capacity [13].

1.3. Research objectives and Structure

Despite growing research on sustainable manufacturing, circular economy practices, and digital transformation, the literature remains fragmented. Most studies examine Lean Six Sigma, green practices, or digital technologies in isolation, offering limited insight into their integrated application. In particular, the potential of Industry 5.0 principles—human-centricity, resilience, and ethical value creation—to reinforce operational excellence frameworks such as GLSS is underexplored [14,15]

Critical success factors, implementation drivers, barriers, and performance implications of integrated GLSS frameworks in digitally enabled, human-centered manufacturing environments remain insufficiently understood, highlighting a significant research gap.

To address these gaps, this paper proposes a unified strategic Green Lean Six Sigma framework tailored for Industry 4.0 and 5.0 contexts. The framework integrates sustainability principles, human-centric design, and data-driven decision-making within a continuous improvement logic, providing a roadmap for eco-efficient, adaptive, and resilient manufacturing systems.

The study contributes theoretically by advancing the integration of GLSS with digital transformation and Industry 5.0 paradigms, and practically by offering actionable guidance for managers and practitioners implementing intelligent, sustainable, and human-centered industrial systems.

The remainder of the paper is organized as follows: Section 2 presents the literature review; Section 3 examines key challenges and opportunities; Section 4 introduces the proposed GLSS framework; Section 5 concludes with insights, managerial implications, and directions for future research.

2. Literature Review on Green Lean Six Sigma (GLSS)

A systematic literature review (SLR) covering 2015–2025 was conducted using Scopus, Web of Science, and ScienceDirect. Keywords included Green Lean Six Sigma (GLSS), Sustainable Smart Manufacturing, Industry 4.0, Industry 5.0, Sustainability, Digital Transformation, Green Industrial Systems (GIS), and Operational Excellence. The review focused on peer-reviewed, English-language studies that addressed GLSS, Lean Six Sigma, or sustainable manufacturing frameworks integrated with Industry 4.0/5.0 technologies.

Studies lacking discussion on operational excellence, sustainability, or digital integration, as well as duplicates and non-academic sources, were excluded. The final selection included theoretical foundations, practical implementations, and empirical evidence of GLSS. Thematic analysis identified key trends, enablers, challenges, and best practices, highlighting gaps in integrating GLSS with human-centric Industry 5.0 paradigms, advanced digital technologies, and comprehensive sustainability practices. These insights provide the basis for a unified strategic GLSS framework supporting eco-efficient, resilient, and adaptive manufacturing systems.

2.1. Fundamentals of Green Lean Six Sigma

Green technologies have become strategic enablers for reducing environmental impacts, improving resource efficiency, and enhancing process reliability [16]. GLSS integrates these technologies with Lean principles and Six Sigma's data-driven methodology to embed sustainability into manufacturing operations [17,15]. The approach emphasizes the 3Rs—Reduce, Reuse, Recycle—to minimize ecological footprints while enhancing operational efficiency and product quality [7].

Implementation is typically guided by the DMAIC cycle—Define, Measure, Analyze, Improve, Control—and employs tools such as Pareto charts, Statistical Process Control (SPC), Five Whys, and Failure Modes and Effects Analysis (FMEA). Incorporating sustainability into Lean Six Sigma has been shown to improve energy efficiency, reduce waste, and optimize resource utilization [18]. Advanced adaptations, such as Big Data Analytics–GLSS (BDA-GLSS), enable predictive analytics, real-time quality control, and proactive maintenance, further enhancing digital readiness, decision-making, and overall sustainability performance [15].

GLSS delivers substantial operational and strategic advantages, particularly for micro, small, and medium-sized enterprises (MSMEs). Key benefits include elimination of non-value-added activities, defect and waste reduction, enhanced operational efficiency, and decreased environmental impacts [19-21]. Frameworks emphasize continuous improvement, customer satisfaction, and the integration of Lean and Green practices to optimize performance across sectors such as healthcare and manufacturing [22,23].

Design strategies have also been proposed to optimize both environmental and economic outcomes [26]. However, MSMEs often face adoption barriers, including financial constraints and limited technical expertise. Mohan et al. [27] provide guidance on overcoming these barriers by analyzing enablers, challenges, and toolsets for effective GLSS implementation.

2.2. Integration with Industry 4.0 and 5.0 Technologies

GLSS shows strong synergy with Industry 4.0 and 5.0 technologies. Artificial intelligence, collaborative robotics, digital twins, predictive analytics, and automation enhance operational performance, innovation, and sustainability, supporting Lean 5.0 practices [28-30]. Industry 4.0 facilitates resource optimization, energy efficiency, and quality improvement, while Industry 5.0 introduces human-centric, ethical, and collaborative dimensions, ensuring that technological innovations generate societal value and workforce well-being [31-33].

Integrating GLSS with these technologies allows real-time monitoring, predictive maintenance, and data-driven decision-making, reinforcing operational efficiency, resource optimization, and ecological responsibility. Applications in healthcare, manufacturing, and plywood industries demonstrate improvements in resource utilization, delivery times, and industrial waste recycling [34,35].

Green Industrial Systems (GIS) provide a comprehensive framework integrating technological, operational, and strategic dimensions to drive sustainable industrial transformation. GIS combines advanced digital technologies, circular economy principles, human-centric approaches, and supportive policies to improve environmental performance, resource efficiency, and socio-economic resilience

[9,10]. Operational practices include lean production, circular processes, eco-efficient interventions, and advanced materials. Smart factories leverage CPS, IoT, AI, and machine learning for autonomous, energy-efficient operations [10,36,37]. Empirical evidence shows GIS enhances energy savings, emissions reduction, and resource utilization, further supported by policy incentives and sustainability standards [38,39].

2.3. Challenges and Adoption Barriers

Despite clear benefits, GLSS and GIS adoption faces multiple challenges. Technological barriers include interoperability limitations, cybersecurity risks, fragmented data, and limited scalability. Organizational challenges involve skill gaps, insufficient training, and limited expertise in life-cycle assessment. Operational limitations include high costs, restricted availability of sustainable materials, and complex supply chains. Policy and regulatory barriers encompass inconsistent regulations, overlapping standards, and fragmented sustainability metrics. Limited cross-sector collaboration further constrains adoption and knowledge sharing [40-47,36]. Overcoming these challenges requires coordinated integration of digital technologies, human-centric practices, sustainable materials, strategic management, regulatory harmonization, workforce development, and cross-sector collaboration.

The literature confirms that GLSS and GIS are critical frameworks for enabling sustainable smart manufacturing. Nevertheless, systematic integration of Industry 5.0 technologies, human-centric approaches, and advanced sustainability metrics remains limited. Addressing these gaps is essential for developing resilient, adaptive, and eco-efficient industrial systems that combine operational excellence with environmental and societal value.

3. Challenges and Research Gaps in Implementing Green Lean Six Sigma (GLSS)

The implementation of Green Lean Six Sigma (GLSS) and Green Industrial Systems (GIS) faces multifaceted challenges across technological, human, material, policy, and operational dimensions. Addressing these barriers is critical for achieving sustainable, efficient, and resilient manufacturing systems.

3.1. Technological Challenges

Technological barriers include interoperability issues among AI, IoT, blockchain, and cyber-physical systems (CPS), cybersecurity vulnerabilities, energy efficiency constraints, and limited scalability. Fragmented or inconsistent data, coupled with limited expertise in Life Cycle Assessment (LCA), restricts accurate environmental monitoring, predictive analytics, and performance optimization.

Key research gaps exist in integrating Industry 5.0 technologies with GLSS and establishing standardized sustainability protocols and benchmarking metrics. Mitigation strategies involve implementing interoperable, energy-efficient infrastructures, standardized communication protocols, AI-assisted LCA tools, and digital twins for real-time monitoring and predictive decision-making [41-43,37,48].

3.2. Human and Organizational Challenges

Human and organizational factors strongly influence GLSS adoption. Workforce skill gaps, insufficient training, low organizational readiness, resistance to change, and fragmented integration of sustainability with Industry 4.0/5.0 practices hinder effective implementation.

Current literature indicates limited exploration of human-centric strategies and workforce development within GLSS adoption. Addressing these barriers requires targeted upskilling programs, participatory management, stakeholder engagement, and sustainability-focused change management to foster a culture of continuous improvement, environmental stewardship, and innovation [40-43].

3.3. Material and Process Constraints

Material and process-related challenges include high implementation costs, limited scalability of sustainable materials, complex supply chains, and difficulties adopting circular processes. Empirical evidence on scalable sustainable materials and circular manufacturing practices is limited, representing a critical research gap.

Mitigation strategies include phased technology adoption, investment in scalable sustainable materials, circular process optimization, IoT- and blockchain-enabled supply chains, and adaptive production systems supported by predictive analytics and scenario planning. These measures improve resource efficiency, reduce waste, and maintain operational flexibility while supporting sustainability objectives [45,36,46,49-51].

3.4. Policy, Regulatory, and Market Barriers

Policy, regulatory, and market factors significantly impact GLSS and GIS adoption. Challenges include regulatory inconsistencies, fragmented policies, overlapping environmental standards, limited harmonized sustainability metrics, and insufficient cross-sector collaboration.

Research gaps include the lack of longitudinal and multi-sector studies assessing policy effectiveness, sustainability metrics, and GLSS/GIS outcomes. Mitigation strategies require regulatory harmonization, targeted incentives, standardized KPIs, and strengthened collaboration among industry, academia, and government, supported by continuous monitoring of adoption and performance trends [36,46,47,52,53].

3.5. Operational Challenges

Operational challenges arise from the complexity of integrating Lean, Six Sigma, sustainability, and digital technologies into a unified framework. Real-time monitoring of energy consumption, waste generation, emissions, and resource utilization adds further complexity. Current research shows a scarcity of frameworks linking operational efficiency with human-centric and sustainability objectives.

Mitigation strategies include developing unified GLSS frameworks that incorporate digital enablers, Industry 5.0 principles, and continuous improvement practices. Tools such as real-time dashboards, predictive maintenance systems, and data-driven decision-making platforms enhance the integration of operational excellence, sustainability, and human-centric design, supporting resilient and adaptive industrial systems [15,21,28,32].

3.6. Summary

Table 1 presents a structured overview of challenges, research gaps, and mitigation strategies across the five dimensions of GLSS and GIS implementation. It provides a concise reference for researchers, managers, and practitioners seeking to understand barriers to sustainable smart manufacturing and to develop integrated frameworks that align operational excellence with environmental sustainability and digital transformation objectives.

In conclusion, successful adoption of GLSS and GIS requires a coordinated, multidimensional approach addressing technological, human, material, policy, and operational barriers. Integrating advanced digital technologies, circular and sustainable practices, human-centric workforce strategies, and evidence-based policy frameworks enables eco-efficient, resilient, and future-ready industrial systems. This integrated approach enhances productivity, product quality, and environmental performance while delivering broader social, economic, and ecological benefits, providing a solid foundation for sustainable smart manufacturing in the Industry 4.0 and 5.0 eras.

Table 1. Challenges, Research Gaps, and Mitigation Strategies for GLSS Implementation.

Category	Challenges	Research Gaps	Mitigation Strategies	References
Technological	Interoperability issues among AI, IoT, blockchain, and CPS; cybersecurity risks; energy efficiency and scalability constraints; fragmented data; limited LCA expertise	Lack of standardized sustainability protocols; limited integration of Industry 5.0 technologies; insufficient frameworks linking digital tools with GLSS	Develop interoperable and energy-efficient infrastructures; adopt standardized data and communication protocols; use AI-assisted LCA tools; leverage predictive analytics and digital twins	Horváth & Szabó, 2018; Stock et al., 2018; Braccini & Margherita, 2019; Cui et al., 2019; Phuyal et al., 2020

Table 1(Continued). Challenges, Research Gaps, and Mitigation Strategies for GLSS Implementation.

Category	Challenges	Research Gaps	Mitigation Strategies	References
Human / Organizational	Workforce skill gaps; inadequate training; low organizational readiness; resistance to change; fragmented sustainability adoption	Limited research on human-centric strategies and workforce development for GLSS	Implement targeted upskilling and training programs; foster participatory management; engage stakeholders; embed sustainability-focused change management practices	Xu et al., 2021; Horváth & Szabó, 2018; Stock et al., 2018; Braccini & Margherita, 2019
Material / Process	High implementation costs; limited scalability of sustainable materials; complex supply chains; challenges in adopting circular processes	Few empirical studies on scalable sustainable materials and circular manufacturing	Phased adoption of technology; invest in scalable sustainable materials; optimize circular processes; enable IoT- and blockchain-enabled supply chains; implement adaptive production systems with predictive analytics	Moshood et al., 2021; Kirchherr et al., 2017; Garrison et al., 2016; Pickering et al., 2016; Antelava et al., 2019; Sun et al., 2022
Policy / Market	Regulatory inconsistencies; fragmented policies; overlapping environmental standards; lack of harmonized sustainability metrics; limited cross-sector collaboration	Limited longitudinal and multi-sector studies evaluating policy effectiveness and GLSS/GIS outcomes	Harmonize regulations; provide targeted incentives; standardize sustainability KPIs; enhance collaboration among industry, academia, and government; conduct longitudinal monitoring studies	Kirchherr et al., 2017; Bonilla et al., 2018; Garrison et al., 2016; Klemm et al., 2011; Idumah et al., 2016
Operational	Complexity of integrating Lean, Six Sigma, sustainability, and digital technologies; real-time monitoring of energy, emissions, and waste	Limited frameworks linking operational efficiency, sustainability, and human-centric objectives	Develop unified GLSS frameworks; integrate Industry 5.0 principles; implement real-time dashboards and data-driven decision-making tools; embed continuous improvement practices	Bhamu & Sangwan, 2016; Belhadi et al., 2023; Kaswan & Rathi, 2020; Rahardjo et al., 2023; Maddikunta et al., 2022

4. Strategic Framework for Green Lean Six Sigma (GLSS)

The effective deployment of Green Lean Six Sigma (GLSS) requires a comprehensive strategic framework that integrates operational excellence, sustainability, and advanced digital technologies. This framework provides a structured roadmap for planning, executing, monitoring, and continuously improving GLSS initiatives, ensuring alignment with environmental, economic, and social objectives. It addresses multidimensional challenges—technological, human, material, policy, and operational—by linking enabling capabilities, digital tools, workforce development, and performance measurement into a coherent system.

4.1. Strategic Framework for GLSS Implementation

Implementing GLSS in smart and sustainable manufacturing requires a structured, integrative approach that aligns operational efficiency, environmental stewardship, and digital transformation. While GLSS enhances efficiency, quality, and sustainability, its application in Industry 4.0 and 5.0 contexts demands a holistic framework addressing technological, human, material, policy, and operational dimensions simultaneously. Table 2 presents a strategic framework organized around five interrelated pillars:

1) Technological Enablement – Leverages IoT, AI, digital twins, blockchain, and CPS for real-time monitoring, predictive maintenance, and data-driven decision-making. Emphasizes interoperable, energy-efficient infrastructures and AI-assisted Life Cycle Assessment (LCA) tools to optimize performance.

2) Human-Centric Management – Develops a skilled, adaptive workforce through training, participatory management, and sustainability-focused change initiatives, fostering continuous improvement, innovation, and collaboration.

3) Sustainable Materials and Processes – Applies circular economy principles to maximize resource efficiency via modular design, recyclable materials, remanufacturing, and energy-optimized operations. IoT-enabled supply chains and adaptive production systems enhance flexibility while reducing environmental impact.

4) Policy and Governance Alignment – Ensures regulatory compliance and strategic alignment with sustainability objectives. Promotes harmonized policies, standardized KPIs, multi-stakeholder collaboration, and evidence-based governance reinforced by incentive mechanisms.

5) Operational Integration and Performance Measurement – Integrates Lean, Six Sigma, sustainability, and digital technologies into a unified operational framework. Real-time dashboards, predictive analytics, and continuous improvement cycles enhance efficiency, quality, and environmental performance, linking operational metrics to sustainability goals.

This framework is inherently iterative, emphasizing continuous feedback, adaptive learning, and data-driven optimization, positioning GLSS as a dynamic, resilient system for eco-efficient and high-performance manufacturing operations.

Table 2. Strategic Framework for GLSS Implementation.

Pillar	**Objectives**	**Key Components**	**Enabling Technologies**	**References**
Technological Enablement	Enhance operational efficiency, sustainability, and data-driven decision-making	Interoperability, real-time monitoring, predictive analytics, energy optimization	IoT, AI, Digital Twins, Blockchain, CPS, AI-assisted LCA tools	Horváth & Szabó, 2018; Belhadi et al., 2023; Phuyal et al., 2020
Human-Centric Management	Develop skilled, adaptive workforce and foster continuous improvement	Workforce training, participatory management, sustainability-focused change management	Industry 5.0 human-centric principles, collaborative problem-solving, leadership development	Xu et al., 2021; Rahardjo et al., 2023
Sustainable Materials and Processes	Optimize resource efficiency, circularity, and environmentally responsible production	Scalable sustainable materials, circular process design, modularity, recyclability	Circular economy practices, IoT-enabled supply chains, adaptive production systems	Moshood et al., 2021; Kirchherr et al., 2017; Sun et al., 2022
Policy and Governance Alignment	Ensure regulatory compliance, strategic alignment, and cross-sector collaboration	Harmonized regulations, sustainability KPIs, incentive programs, evidence-based governance	Policy frameworks, standardized reporting, multi-stakeholder partnerships	Kirchherr et al., 2017; Bonilla et al., 2018
Operational Integration and Performance Measurement	Integrate Lean, Six Sigma, sustainability, and digital technologies for continuous improvement	Real-time dashboards, operational KPIs, continuous improvement cycles, energy/resource monitoring	DMAIC methodology, predictive analytics, digital performance dashboards	Bhamu & Sangwan, 2016; Kaswan & Rathi, 2020; Maddikunta et al., 2022

4.2. GLSS Framework: Integrated DMAIC Approach

GLSS extends traditional Lean Six Sigma by embedding sustainability, circular economy principles, digital transformation, and human-centric innovation across all DMAIC phases. This structured approach enables operational excellence, reduced environmental impact, and socio-economic value creation. Table 3 illustrates the DMAIC methodology within GLSS for Industry 4.0/5.0 contexts, aligning each phase with objectives, key activities, digital technologies, sustainability, and human-centric integration.

1) Define: Sets operational, sustainability, and social goals. Activities include identifying critical processes, stakeholders, and KPIs. Tools such as ERP, MES, and dashboards align initiatives with strategy.

2) Measure: Quantifies baseline performance on energy, materials, emissions, and waste. IoT sensors, digital twins, and AI analytics provide real-time precision. Workforce engagement ensures transparency and data-driven decisions.

3) Analyze: Detects inefficiencies, risks, and improvement opportunities using root cause analysis, simulations, and scenario modeling. AI/ML and process mining enhance insight, embedding sustainability by identifying environmental hotspots, while human–machine collaboration fosters innovative solutions.

4) Improve: Implements enhancements through Lean redesign, Six Sigma defect reduction, and circular practices. AI optimization, automation, AR/VR guidance support cleaner production, modular/recyclable design, and resource recovery, with workforce engagement promoting practical innovation.

5) Control: Maintains improvements via monitoring, feedback loops, and compliance. Real-time dashboards, predictive maintenance, and automated alerts ensure operational and environmental performance, supporting resilience and continuous learning.

In conclusion, by integrating sustainability, circularity, digital technologies, and human-centric principles into the DMAIC cycle, the GLSS framework transforms Lean Six Sigma into a dynamic, resilient, and eco-efficient system. It empowers organizations to achieve continuous improvement, operational excellence, and environmental responsibility concurrently, while fostering innovation, workforce engagement, and adaptability, effectively supporting the goals of Industry 4.0 and 5.0 smart manufacturing systems.

Table 3. GLSS Framework: DMAIC Integration.

Phase	Objectives	Key Activities	Industry 4.0/5.0 Enablers	Sustainability & Circularity	Human-Centric Integration
Define	Set operational, sustainability, and social goals	Identify critical processes, stakeholders, KPIs	ERP, MES, digital dashboards	Energy efficiency, emission reduction, circular material flows	Align with strategy, regulations, stakeholder priorities
Measure	Quantify baseline performance	Collect data on energy, materials, emissions, waste	IoT sensors, digital twins, AI analytics	Resource utilization, waste, and carbon footprint	Support data-driven decision-making, workforce engagement
Analyze	Identify inefficiencies, risks, and opportunities	Root cause analysis, process simulations, scenario modeling	AI/ML, process mining, predictive analytics	Detect environmental hotspots, material inefficiencies	Support human–machine collaboration, co-created solutions
Improve	Implement operational and sustainability enhancements	Lean redesign, Six Sigma defect reduction, circular practices	AI optimization, automation, AR/VR guidance	Cleaner production, modular/recyclable design, resource recovery	Foster engagement, innovation, and practical solutions
Control	Sustain improvements, enable continuous optimization	Monitor performance, feedback loops, and compliance	Dashboards, predictive maintenance, automated alerts	Maintain circularity, eco-efficiency, and energy optimization	Promote continuous learning, resilience, and adaptability

4.3. Strategic Objectives and KPIs for GLSS Implementation

Successful GLSS implementation requires alignment of strategic objectives, KPIs, and digital enablers to embed operational excellence, sustainability, circularity, human-centric innovation, data-driven decision-making, and resilience across processes. Table 4 presents objectives, KPIs, digital enablers, and strategic impacts, linking organizational goals, measurable performance, technologies, and outcomes.

1) Operational Excellence: Enhances efficiency, productivity, and reliability. KPIs: cycle time reduction, defect rate/PPM, OEE, throughput, value-added ratio. ERP, MES, AI optimization, automation, predictive analytics enable workflow optimization and predictive decisions.

2) Environmental Sustainability: Minimizes environmental impact via energy/water efficiency, carbon footprint reduction, waste minimization, and ISO 14001/EMAS compliance. IoT sensors, digital twins, AI dashboards provide continuous, proactive monitoring.

3) Resource Efficiency & Circularity: Optimizes material use, recycling, and reuse. KPIs: material utilization, recycled/reused proportion, LCA scores. AI/ML optimization, blockchain, IoT monitoring enhance transparency and circularity.

4) Human-Centric Innovation: Promotes engagement, skills development, and collaboration. KPIs: employee participation, green skills training, co-created improvement projects, safety incidents, human–machine collaboration. AR/VR training, collaborative platforms, AI decision support enhance workforce capabilities.

5) Data-Driven Decision Making: Leverages real-time data for operational and strategic decisions. KPIs: data accuracy, predictive maintenance triggers, insights implemented, unplanned downtime reduction. IoT networks, AI/ML analytics, digital twins, cloud dashboards enable evidence-based decision-making.

6) Resilience & Adaptability: Ensures effective response to disruptions while maintaining continuous improvement. KPIs: response time, recovery rate, improvement cycles, energy/emission/waste reductions. AI/ML scenario modeling, digital twins, automated alerts, real-time monitoring enhance operational agility and sustainability.

In conclusion, by aligning strategic objectives, KPIs, and digital enablers, the GLSS framework delivers a comprehensive performance management system that integrates operational efficiency, sustainability, circularity, human-centric innovation, and resilience. This alignment enables smart manufacturing systems in Industry 4.0 and 5.0 contexts to achieve measurable gains in productivity, environmental performance, and socio-economic value, fostering both operational excellence and long-term sustainable growth.

Table 4. Strategic Objectives and KPIs.

#	Strategic Objective	KPIs	Digital Enablers	Strategic Impact
1	Operational Excellence	Cycle time reduction (%), defect rate/PPM, OEE, throughput, value-added ratio	ERP, MES, AI optimization, automation, predictive analytics	Streamlined workflows, higher productivity, reduced waste, agile operations
2	Environmental Sustainability	Energy & water use per unit, carbon footprint, waste reduction (%), recycling rate (%), ISO 14001/EMAS compliance	IoT sensors, digital twins, AI-enabled monitoring, sustainability dashboards	Reduced carbon/resource footprint, regulatory compliance, eco-efficient operations
3	Resource Efficiency & Circularity	Material utilization (%), recycled/reused proportion (%), LCA scores, reduction in non-renewable resource use (%)	AI/ML optimization, digital twins, blockchain traceability, IoT monitoring	Lower raw material dependency, cost savings, circular and sustainable production systems
4	Human-Centric Innovation	Employee participation (%), green skills training, co-created improvement projects, safety incidents, human–machine collaboration	AR/VR training, collaborative platforms, AI-assisted decision support, human-digital interfaces	Engaged workforce, innovation culture, safer operations, enhanced human-digital synergy
5	Data-Driven Decision Making	Data accuracy (%), predictive maintenance triggers (%), insights implemented (%), unplanned downtime reduction (%)	IoT networks, AI/ML analytics, digital twins, cloud dashboards	Faster evidence-based decisions, improved transparency, higher operational reliability
6	Resilience & Adaptability	Response time, recovery rate (%), continuous improvement cycles, year-on-year energy/emissions/waste improvement	AI/ML scenario modeling, digital twins, automated alerts, real-time monitoring	Enhanced operational and environmental resilience, agile adaptation, sustainable performance

5. Conclusion and Future Work

This study demonstrates the transformative potential of Green Lean Six Sigma (GLSS) for sustainable smart manufacturing in the Industry 4.0 and 5.0 era. By combining Lean efficiency, Six Sigma's data-driven problem-solving, and environmental management principles, GLSS simultaneously enhances operational performance, product quality, and sustainability outcomes. A systematic literature review examined the integration of Lean, Six Sigma, and green practices with advanced digital enablers—including IoT, CPS, AI, robotics, cloud computing, blockchain, additive manufacturing, and big data analytics—highlighting key drivers, benefits, challenges, and research gaps in sustainability integration, digital readiness, and human–technology collaboration.

Building on these insights, the study proposes a strategic GLSS framework that extends the DMAIC methodology by embedding sustainability, circular economy principles, and human-centric innovation across all phases. Structured around five pillars—Technological Enablement, Human-Centric Management, Sustainable Materials and Processes, Policy and Governance Alignment, and Operational Integration and Performance Measurement—the framework leverages AI, IoT, digital twins, and predictive analytics to provide a holistic, adaptive, and data-driven roadmap for resilient, eco-efficient, and socially responsible manufacturing systems.

The framework enables organizations to optimize operational efficiency, product quality, and process reliability while embedding environmental stewardship, circularity, and workforce empowerment. By integrating operational excellence with sustainability and human-centric innovation, GLSS offers a robust methodology for achieving long-term resilience, competitiveness, and socio-economic value, demonstrating how digital transformation and sustainability initiatives can be aligned to achieve operational, environmental, and social objectives concurrently.

Theoretical Implications: This study contributes a unified conceptual model integrating Lean, Six Sigma, sustainability, and Industry 4.0/5.0 technologies. It advances understanding of how operational excellence, digitalization, and environmental stewardship can be combined to support sustainable smart manufacturing, providing a foundation for future empirical research.

Practical Implications: The framework offers a structured methodology for embedding sustainability and digital technologies into manufacturing operations, enabling real-time monitoring, predictive analytics, circular production practices, and continuous process optimization, thereby enhancing efficiency, environmental performance, and organizational adaptability.

Managerial Implications: Managers can align strategic objectives, KPIs, and workforce capabilities to foster continuous improvement, circularity, and human-centric innovation. Integrating digital tools, sustainability metrics, and workforce engagement supports evidence-based decision-making, improving operational performance, regulatory compliance, and social responsibility.

Study Limitations: As a conceptual, literature-based study, empirical validation is required across industries, organizational scales, and regulatory contexts. Additionally, while focused on current Industry 4.0/5.0 technologies, the integration of emerging technologies—such as AGI, quantum computing, and emotional AI—remains unexplored.

Future Research Directions: The implementation of GLSS and Green Industrial Systems (GIS) faces five interrelated dimensions of challenges, each revealing critical research gaps:

1) Technological Challenges: Barriers include interoperability issues among AI, IoT, blockchain, and CPS, cybersecurity risks, energy constraints, and fragmented data. Future research should develop interoperable infrastructures, AI-assisted Life Cycle Assessment (LCA) tools, digital twins, and standardized sustainability metrics to enable real-time monitoring, predictive analytics, and optimized performance.

2) Human and Organizational Challenges: Workforce skill gaps, insufficient training, resistance to change, and low organizational readiness hinder adoption. Future studies should explore participatory management, cultural transformation, change management frameworks, and strategies to enhance digital literacy and human–technology collaboration.

3) Material and Process Constraints: Barriers include high implementation costs, limited scalability of sustainable materials, complex supply chains, and circular process adoption challenges. Future research should investigate scalable sustainable materials, circular supply chain integration using

IoT and blockchain, and predictive, resource-efficient production models to improve flexibility, reduce waste, and enhance sustainability performance.

4) Policy, Regulatory, and Market Barriers: Fragmented regulations, overlapping standards, inconsistent sustainability metrics, and limited cross-sector collaboration impede adoption. Future research should focus on harmonizing sustainability metrics, assessing regulatory and incentive impacts, and strengthening collaboration among industry, academia, and government to support scalable implementation.

5) Operational Challenges: Integrating Lean, Six Sigma, sustainability, and digital technologies into unified operational frameworks is complex. Future research should design integrated GLSS operational frameworks combining these approaches with Industry 5.0 principles, supported by digital dashboards, predictive maintenance, and decision-support systems to ensure resilient and adaptive industrial systems.

In conclusion, successful adoption of GLSS and GIS requires a coordinated, multidimensional approach addressing technological, human, material, policy, and operational challenges. Aligning future research with these interdisciplinary gaps will advance GLSS as a robust, evidence-based framework for sustainable, high-performance, and human-centered manufacturing in the Industry 4.0 and 5.0 eras.

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Abbreviations:

Abbreviation	Full Term	Definition
AI	Artificial Intelligence	Systems performing tasks requiring human intelligence, including analytics.
AIM	Asset Integrity Management	Ensures safe, efficient, and reliable asset performance.
AIoT	Artificial Intelligence of Things	AI is integrated into IoT devices for automation and predictive maintenance.
AR	Augmented Reality	Overlays digital info onto the physical environment for visualization or training.
BIM	Building Information Modeling	Digital representation of infrastructure for design and operation.
CEPs	Circular Economic Practices	Resource-efficient, reuse, and closed-loop production strategies.
CPS	Cyber-Physical Systems	Combines computational algorithms with physical processes for real-time control.
DMAIC	Define, Measure, Analyze, Improve, Control	Lean Six Sigma methodology for structured process improvement.
DT	Digital Twin	Virtual model of physical assets for simulation and monitoring.
ERP	Enterprise Resource Planning	Software managing core business processes and resources.
ESG	Environmental, Social, and Governance	Criteria for sustainability and ethical impact in decisions.
GIIoT	Green Industrial IoT	IoT applications enhancing industrial sustainability.
GIS	Green Industrial Systems	Systems optimized for efficiency, low environmental impact, and socio-economic value.
GLSS	Green Lean Six Sigma	Framework combining Lean Six Sigma, sustainability, digital, and human-centric innovation.
IoT	Internet of Things	Network of devices enabling real-time data collection and communication.
KPI	Key Performance Indicator	Quantifiable metric to evaluate operational, environmental, or social performance.
LSS	Lean Six Sigma	Combines Lean (waste reduction) and Six Sigma (defect reduction) for quality improvement.
MES	Manufacturing Execution System	Platforms for real-time monitoring and control of manufacturing operations.
ML	Machine Learning	AI subset where systems learn from data to improve performance.
OEE	Overall Equipment Effectiveness	Metric evaluating equipment productivity considering availability, performance, and quality.
R&D	Research and Development	Activities for innovation, design, and process improvement.
RAMS	Reliability, Availability, Maintainability, Safety	Measures evaluating system performance, reliability, and safety.
RCM	Reliability-Centered Maintenance	Maintenance strategy ensuring reliability while minimizing risk.
SLR	Systematic Literature Review	Structured review summarizing and synthesizing evidence.
SMEs	Small and Medium-sized Enterprises	Organizations of limited scale, often driving innovation.
TPM	Total Productive Maintenance	Maintenance approach emphasizing proactive and preventive strategies.
VR	Virtual Reality	Immersive digital environments for simulation, training, and visualization.

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