Department of Industrial Engineering & Maintenance

Integrating Green and Lean Six Sigma for Sustainable Manufacturing: A Comprehensive Review and Framework

BOKHARI Meriem Lyna

BENFERHAT Yasmine

Master's thesis in Industrial Engineering

BOKHARI Meriem Lyna , BENFERHAT Yasmine ,

Advisor:
RAHMOUNE Mahdi

Co-advisors:
KERROUCHI Slimane

Academic year:
2024-2025

Abstract: This study examines the application of Green and Lean Six Sigma (GLSS) methods in manufacturing as tools that ensure the sustainable development of a company. The literature review highlights the trade-offs and synergetic effects of these methodologies and defines the key factors that favor their success. The study addresses critical questions such as the necessity of GLSS implementation, what obstacles will arise during implementation and what improvements can be expected in terms of business processes and ecology. This study proposes a conceptual model to help practitioners address specific issues and promote effective use of GLSS across a range of manufacturing environments. Furthermore, the study explores the integration of GLSS within the frameworks of Industry 4.0 and 5.0. It highlights the synergies between digital transformation, human-centric innovation, and sustainable operational excellence. This work could form a relevant documentary basis for future research. It also opens up new avenues of reflection for corporate practitioners, providing several practical suggestions for enhancing the use of GLSS and integrating production with environmental requirements.

Key-Words: Sustainable manufacturing, Green Lean Six Sigma, Environmental sustainability, Environmental KPIs, GLSS Framework, Industry 4.0, Industry 5.0

Contents

1. Introduction

In recent years, there has been growing global awareness of environmental issues, driven by concerns over climate change, resource depletion and the increasing strain on ecosystems. As industries continue to intensify, the environmental consequences of traditional manufacturing practices have become more and more apparent. In response, organizations urgently need to rethink their sustainable development strategies[1]. Traditional manufacturing approaches have generally focused on improving performance and reducing costs, often at the expense of environmental impact. However, with the growing awareness of environmental issues, organizations are now confronted with the critical task of minimizing their environmental footprint while maintaining operational efficiency [1, 2]. It was within this context that emerged the Green Lean Six Sigma (GLSS) as a promising business methodology that integrates the principles of Lean Manufacturing, Six Sigma, and Green Manufacturing into a unified framework. By combining Lean Six Sigma's feedback in process development and waste reduction with Green Manufacturing's environmental sustainability goals, GLSS which aims create synergy that enhances both operational performance and environmental sustainability. This integration offers the potential to transform manufacturing processes, enabling organizations to reduce waste, conserve resources and lower their carbon footprint while simultaneously increasing productivity, product quality and overall competitiveness[1, 2]. At the same time, the emergence of Industry 4.0 and Industry 5.0 has introduced new technological capabilities and human-centered approaches that further amplify the potential impact of GLSS initiatives [3]. Industry 4.0, with its emphasis on digitalization, automation, and smart systems, offers powerful tools to optimize manufacturing processes, improve resource efficiency, and enable real-time environmental monitoring [4]. Industry 5.0 goes beyond digital integration by focusing on human-machine collaboration, resilience, and sustainability, aligning perfectly with GLSS's objectives of operational excellence and ecological responsibility [5]. The synergies between GLSS and these industrial paradigms open new avenues for more intelligent, flexible, and sustainable manufacturing systems[6, 7].

Moreover, the incorporation of Environmental Key Performance Indicators (EKPIs) into GLSS frameworks provides a structured and measurable approach to assessing environmental performance. EKPIs enable organizations to monitor their progress towards sustainability goals and ensure that improvements achieved through GLSS initiatives are quantifiable and aligned with broader ecological objectives [8].

This paper provides a comprehensive review of the literature on GLSS, exploring its theoretical foundations, implementation challenges, and practical applications. The research aims to identify the critical factors that influence the successful adoption of GLSS and propose a robust framework to guide organizations toward more sustainable practices [1]. The article is structured as follows: Section 2 provides a detailed overview of the research methodology, focusing on the systematic literature review process used to gather and synthesize relevant studies. Section 3 discusses the foundations of Green Manufacturing, Lean Manufacturing, and Six Sigma, as well as their integration within the GLSS framework. We highlight their synergies and potential challenges. Section 4 and 5 identifies the benefits of integrating GLSS, emphasizing its impact on environmental sustainability, operational efficiency, and cost reduction. Section 6 presents a practical framework for GLSS implementation, detailing the necessary phases and tools for successful adoption. Section 7 and 8 focuses on Environmental KPI, which are crucial for assessing the success of GLSS implementation in achieving sustainability goals, and addresses the challenges encountered in GLSS implementation, providing practical solutions to overcome these obstacles. Section 9 presents a case study that demonstrates the real-world application of the GLSS framework and its positive impact on sustainability. Section 10 examines GLSS in the context of Industry 4.0 and 5.0, exploring how technological advancements contribute to its implementation and effectiveness. Section 11 and 12 presents a discussion of the findings and the broader implications of GLSS for sustainable manufacturing practices. It is followed by the limitations of the study, recognizing potential constraints and suggesting areas for future research. Finally, Section 13 concludes the paper by summarizing the key findings and proposing directions for future research in the field of GLSS .

2. Research methodology

To discover the studies gaps and synthesize understanding on Green Lean Six Sigma (GLSS), a scientific literature review (SLR) was conducted following an obvious and express technique established into a couple of phases. The review aims to guarantee a rigorous method while addressing the crucial factors of GLSS.

A general of 24 articles from scienceDirect by Elsevier, Emerald Insight, IEEE Xplore, MDPI, Taylor and Francis Group, and Open Access sources, had been decided on and analyzed to pick out the studies gaps and trends. These articles protected subjects which includes sustainability factors associated with Lean, Green, and Six Sigma, in addition to techniques for undertaking choice and prioritization, also there integration in 4.0 and 5.0 industry. Relevant key phrases like "Lean", "Green Lean", "Green Lean Six Sigma", "sustainability", "KPIs", "4.0 industry " and " industry 5.0 " guided the choice technique. To keep focus, research emphasizing theoretical factors of Lean and Lean Six Sigma had been excluded.

3. Foundations of Green, Lean, and Six Sigma

The concepts of Green, Lean, and Six Sigma are based on distinct but complementary principles, each contributing to the improvement of industrial performance in a targeted manner. GLSS is an integrated approach that combines three distinct methodologies, each with its own objectives and benefits:

- **Lean Manufacturing** aims to eliminate waste and non-value-added activities from manufacturing processes. Lean concepts seek to simplify processes, shorten lead times, and increase overall efficiency. Notably, Lean does not explicitly address environmental concerns. Lean aims to remove two kinds of waste: process waste (overprocessing, transportation, inventory, and quality faults), and operational waste (unnecessary motions, overproduction, and waiting)[9].
- **Green Manufacturing** emphasizes environmental sustainability by minimizing the negative impact of manufacturing processes on the environment. This approach involves waste reduction, resource efficiency, and pollution prevention. Green practices include reducing hazardous emissions, eliminating unnecessary resource consumption, recycling, and minimizing health risks throughout the manufacturing process[9].
- **Six Sigma** is a data-driven approach focused on reducing process variation and defects. It uses the DMAIC (Define, Measure, Analyze, Improve, Control) methodology to ensure consistent quality and process evidence improvements[9].

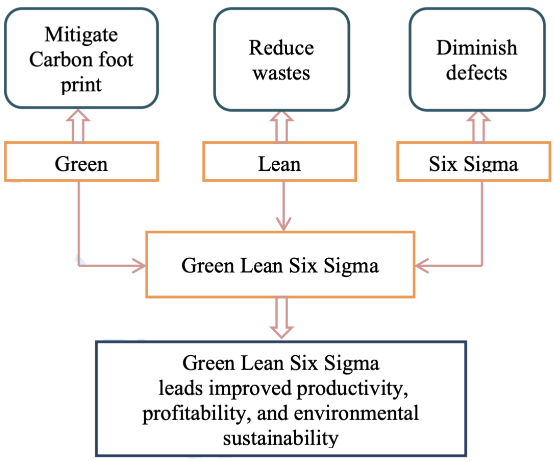

Figure 1: Conceptual Green Lean Six Sigma model (Kaswan and Rathi, 2021a) [9]

4. Benefits of GLSS Integration

The integration of GLSS offers multiple benefits, impacting environmental performance, operational efficiency, and social performance, while promoting a comprehensive approach to sustainability .

- **Improved Environmental Performance:** GLSS method greatly improves environmental efficiency [9, 11]. It reduced emissions and energy use by a vast amount while efficiently managing resources at the same time [1, 12, 13]. This approach tries to reduce environmental impacts as much as possible through environmental practice. It is thus a way of being environmentally aware and respecting it by reducing negative effects on the planet [11, 13–15] .
- **Improved Operational Efficiency :** When efforts such as waste minimization, throughput streamlining, and lead time reduction are involved, GLSS significantly contributes to the organization's overall productivity[13, 16]. Part and parcel of the GLSS implementation is not only bettering the customer's experience and thus the product's quality but also resulting in the lowering of costs which ultimately contributes to the betterment of the processes[13].
- **Reduction of Hazardous Materials:** Implementing GLSS can reduce the use of hazardous chemicals[17] and promote the substitution of toxic materials with less dangerous alternatives[18].
- **Integration with Industry 4.0 :** The combination of GLSS with Industry 4.0 can enhance sustainability performance by using new technologies. For example, the utilization of Cyber-Physical Systems (CPS) is recognized as a part of Industry 4.0 that may assist GLSS [17].
- **Continuous Improvement :** GLSS emphasizes constant progress and environmental consciousness[1]. Analyzing environmental elements and value stream implications aids in identifying chances for improvement in industrial operations [18].
- **Framework for Implementation:** GLSS offers a framework for discovering and choosing suitable projects, establishing project objectives, and creating execution frameworks [9, 13].

5. Proposed Framework for GLSS Implementation

GLSS implementation frameworks are typically structured in several steps, which may vary slightly across sources, but broadly include the following:

5.1. Phase 1: Project Selection

Project selection is a critical step in implementing GLSS initiatives, and it significantly impacts the overall success of sustainability efforts1 [9]. The primary aim of project selection should be to identify areas within an organization where significant improvements in sustainability can be achieved [9]. In fact, a significant percentage of

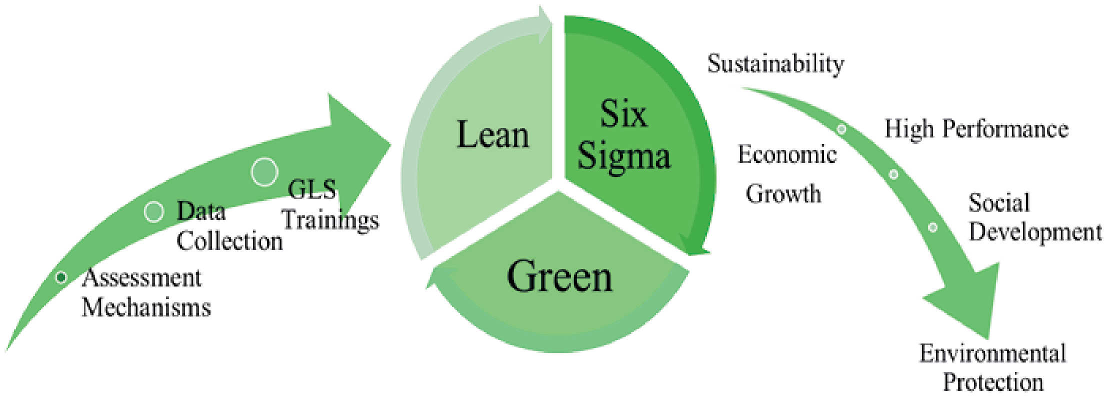

Figure 2: Integration and implementation of GLSS model [10]

Six Sigma projects, up to 40 % fail because of improper project selection [19].

- **Key selection criteria:** Key selection criteria for a GLS project include environmental impact, social aspects, productivity, material efficiency, and waste reduction. Environmental impact is a key metric aimed at cutting emissions, waste and energy consumption [18]. LCA is a key tool for assessing the environmental impact, identifying areas of improvement [9, 13, 16]. Goals include a reduction in greenhouse gas (GHG) emissions, water consumption, acidification and waste generation [1, 14, 18]. Further, a GLS project is chosen on the basis of sustainability oriented criteria [9]. Social aspects include improving employee working conditions, safety and training. It also encompasses things like a job such as career opportunity, health and safety in the work environment. A Social LCA also offers the social impact to be assessed [1, 9]. Productivity means enhancing process efficiency, reducing downtime, and optimizing resource use. Reduction of defects, optimization of space utilization and resource management [1, 9, 13]. And to eliminate waste and improve flow, lean practices are used [13, 16]. Material efficiency refers to an efficient use of equipment and material [1]. It takes into account material efficiency, reusability and recyclability within the product life cycle [1, 9]. It usually incorporates core principles of the circular economy, turning waste into resource value and putting it in the maximum usage of the resources [18]. Waste reduction involves strategies such as reducing the storage and holding costs. Techniques that would improve material efficiency for example lean manufacturing and design for disassembly [1], minimizing excess inventory and corresponding costs by reducing overproduction [9], guided by the fundamental principles of the 3Rs: Reduce, Reuse, and Recycle [18].

  Project Selection Process :

  1. **Data Collection:** To identify potential projects a thorough analysis of the organization is needed to be done. Among these are real time data collection and exchange. The most critical data often originates from the shop floor [9, 11].
  2. **Criteria Weighting:** The weight assigned to each criteria of selection differs according to industry needs and the relative importance of each criterion. Weights may be determined using the entropy method [9].
  3. **Project Evaluation:** Weighted criteria is then used for evaluation of each potential project. For project ranking, this project uses Grey Relational Analysis (GRA) [9].
  4. **SWOT Analysis:** Adding a SWOT (Strengths, Weakness, Opportunities, Threats) will help understand where the company is now and the potential issues [19].
  5. **Validation:** Validation of the project selection and adaptation of the framework to the shop floor is central to the framework and relies on expert input and participation of company personnel. The framework is refined using the feedback from industry personnel [9, 11].

- **Tools and Techniques Used:** Several tools and techniques have been used to implement the GLSS approach, among them [9]: SIPOC Diagram (Suppliers, Inputs, Process, Outputs, Customers), used to understand existing processes. Project Charter, which documents roles, timelines, and project scope. Prioritization techniques and the Voice of the Customer (VOC), which are key tools for project selection; Value Stream Mapping (VSM) and Environmental Value Stream Mapping (EVSM), used to analyze value flows and environmental impacts; 5 Whys Analysis, a technique used to identify root causes of problems; Pareto Chart, which helps prioritize problems based on their impact; and the Cause-and-Effect Diagram, which aids in visualizing potential causes of a problem.
- **Additional Insights:** data collection through questionnaires, which then rank criteria with respondents rating their response using a Likert scale. The weights of criteria are also determined

using responses of manufacturing personnel. A framework for evaluation of projects in terms of the projects' criteria and their sensitivity is proposed. For further analysis, the responses are normalized. In grey relational analysis, a deviation sequence is calculated. Robustness is provided by the calculated grey relational grade using a method of sensitivity analysis [9].

5.2. Phase 2: Current State Assessment

The current state assessment in a GLSS project is a critical step for understanding the starting point and measuring progress [20]. It involves a thorough evaluation of environmental, social, and operational performance, relying on direct data for the most reliable insights [18].
GLSS success starts after initial assessment. It provides a baseline for being able to track how performance improves over time for organizations. The assessment identifies inefficiencies and waste in existing processes that offer important guidance for improvement efforts [9, 14]. Furthermore, it serves to select suitable GLSS project areas, identifying critical areas with the most potential of substantial gains in sustainability as well as efficiencies [9, 13].

- **Data Collection :**
  Direct data collection is prioritized due to its high reliability. It includes measurements of material, water and energy consumption as well as waste and emission levels[9, 18]. Working conditions and safety are rigorously assessed and, more so, social impacts such as the working conditions [9, 14].
  Direct measurements, production data, and real time monitoring systems are the data sources [9, 11, 18] .In addition, feedback from industrial personnel, interviews with staff and performance KPI are analyzed [11]. Sensors, IoT technologies, and cyber–physical systems (CPS) enable significant improvements in the monitoring and data collection process through real time [14].
- **Analysis Tools and Techniques:**
  Environmental Value Stream Mapping (EVSM), this tool is used to visualize value streams and identify waste [9, 16]. EVSM helps evaluate cycle time and material consumption at each process step, thereby pinpointing areas for improvement [16]. Life Cycle Assessment (LCA) evaluates the environmental impact and social sustainability of processes, covering all stages from raw material extraction to waste disposal [9, 16]. A statistical tools may be used too like Pareto charts, regression analyses, and hypothesis testing help in identifying the most significant issues [9].
- **Metrics and Indicators :** The effectiveness of GLSS initiatives must be tracked and evaluated, and a comprehensive set of metrics is essential for doing this. KPI encompass:
  Environmental Metrics: Such indicators are the green energy coefficient, acidification potential and other indicators referring to green and social performance. In addition, metrics of water pollution reduction and of greenhouse gas emissions are relevant for measuring environmental impact [20].
  Operational Metrics: Operational efficiency and quality are guided by the type of measures like deviations, downtime, defects per million opportunities (DPMO) and process capabilities [9].
  Sustainability Metrics: Assessment includes scores based on reusability potential and recyclability potential, resource efficiency and other indicators of a circular economy [9].

5.3. Phase 3: Root Cause Analysis

Root cause analysis is a crucial step in GLSS that enlightens the fundamental reasons of the waste and inefficiencies instead of putting band aid covers. The only way you can be sure that solutions address the root causes of problems is by adopting this approach, which results in better, more sustainable improvements [17].

- **Objectives of Root Cause Analysis:** Its primary aim is to determine the critical causes for the deficiency of an organization leading to deprived operations in a sustainable way so that immediate action is exerted for rectifying the same. Root cause analysis can not only help improve operations but also identify opportunities that will improve sustainability by reducing energy consumption, waste production and environmental impact [17].
- **Data Collection and analysis:** A key element of root cause analysis is collecting data, numeric Data or categorical data to ensure a better analysis. Sources of data can be observables on-site, sensors on the machinery, and feedback from employees. It allows us to compare data to standards, and determine if we need to focus on that area. After date collection we need to analyse this data, data analysis is essential for pinpointing problem areas, detecting patterns or trends, and quantifying the extent of inefficiencies. This data-driven approach relies on facts rather than assumptions and can include the use of Pareto charts, regression analysis, and principal component analysis[17].
- **Tools for Root Cause Analysis:** Essential tools are used to identify the underlying causes of problems, including Cause-and-effect diagrams (also known as Ishikawa or fishbone diagrams) is used to visualize the potential causes of a problem by categorizing them. This method structures thinking by organizing causes (e.g., the 5Ms: Manpower, Material, Method, Environment, and Management), which helps in identi-

S.No.	Sub criteria	References	Main criteria	Label
1	Material efficiency	Indicators, O. E. C. D. (2011).	Material related	CR1
2	Reusability potential	Amrina and Yusof (2011); Ma et al. (2020)		
3	Recyclability potential	Ma et al. (2020)		
4	Defects reduction	Indicators, O. E. C. D. (2011).	Productivity	CR2
5	Space utilization	Self-developed		
6	Optimum utilization of resources	Indicators, O. E. C. D. (2011).		
7	GHGs release intensity	Amrina and Yusof (2011); Huijbregts et al. (2017)	Environmental aspects	CR3
8	Water use intensity	Ma et al. (2020)		
9	Terrestrial acidification	Ma et al. (2020)		
10	Employment opportunity	Siebert et al. (2018)	Social aspects	CR4
11	Health and safety	Amrina and Yusof (2011);Siebert et al. (2018)		
12	Work ambiance	Siebert et al. (2018)		
13	Inventory optimization	Indicators, O. E. C. D. (2011).	Waste related	CR5
14	Overproduction	Self-developed		
15	Skill and training aspects	Indicators, O. E. C. D. (2011).	Facility related	CR6
16	Machine utilization	Self-developed		
17	Reliability of machines	Self-developed		

Figure 3: Criteria for the selection of the GLS project [9]

fying the most likely root causes. The 5 Whys method involves repeatedly asking "why" (typically five times) to go beyond superficial causes and find the root cause of a problem. This encourages a thorough investigation into the reasons behind inefficiencies. Failure Mode and Effects Analysis (FMEA) is used to identify potential failures in a process, evaluate their risks, and establish preventive measures. FMEA is particularly helpful in anticipating problems and minimizing their impacts[9].
Once potential causes are identified, the next step is to reduce and prioritize them by focusing on the most critical ones using tools like the Pareto chart to rank causes by importance. This prioritization guides the Solution Identification and Implementation phase, where targeted actions are developed and applied to address the most impactful root causes

5.4. Phase 4: Solution Identification and Implementation

Solution identification and implementation are critical steps in a GLSS project, following root cause analysis. These steps aim to convert the identified causes into tangible actions to improve efficiency, sustainability, and quality.

- **Solution Identification:** A thorough root cause analysis is then used to come up with the solutions to the problems identified[9]. As a result, the selection of the right corrective action follows upon this understanding. Improvement strategies are often categorized into four main quadrants:[9, 11]
  1. **Avoid:** Fixing the symptoms without addressing the root cause of the issue, i.e. changing process parameters.
  2. **Substitute:** Reusing products in ways that preserve the value of the materials they contain, including recycling. Redesigning products for disassembly, which may also include special processing methodologies such as capitalization or remanufacturing, when products cannot be completely avoided.
  3. **Circulate:** Becoming iterative systems which use the creation of waste as a system of recycling or reusing it into valuable resources.
  4. **Eliminate:** This contribution redefines the concept of waste according to ISO by targeting its root cause, namely the process or work behavior that makes certain activities necessary.
- **Solution Implementation:** The process of implementing a solution involves such a methodical way of working that involves a lot of testing and modifications in lines with feedback. This iterative approach guarantees that the solutions are sustainable and effective. Solutions can include a range of topics, including [9]:
  1. **Modifications to production processes :**These process changes include changing the way manufacturing phases are arranged, changing machine settings and consistently employing equipment.
  2. **Optimization of material management:**Material management optimization is

the act of enhancing supply chain logistics, handling and storage in an attempt to reduce waste and maximise material flow.

3. **Introduction of new technologies :** Automation or 3D printing to use new technology to improve productivity and reduce environmental effect.
4. **Employee development and training:** Ensuring staffs have adequate ability or know how to successfully adopt and sustain the innovative solutions.
5. **Supplier collaboration:** Fostering strong relationships with suppliers to optimize and improve overall supply chain sustainability.

- **Tools and techniques :**
  Current variety of tools and techniques are employed for evaluating the effectiveness of proposed solutions. Others used are the Pugh matrix, Design of Experiments (DOE), and Critical to Quality (CTQ) analysis to assess the strength and weakness of the various options[9]. An integrated approach which uses both GLSS tools and Industry 4.0 technologies, deliver the most innovative and sustainable solutions. Sustainability related indicators are reevaluated following implementation to confirm the achievement of desired outcomes. Value Stream Maps are also changed in order to reflect the changes brought about by implemented solutions [10].

5.5. Phase 5: Sustain and Control

The Sustain and Control phase of a GLSS project is critical for ensuring that improvements are maintained over time. This phase includes corrective actions and measures to guarantee continuous improvement. The key aspect of the Sustain and Control phase is maintaining improvements , the goal is to make sure the new process or solution keeps working like it's supposed to be. A quick correction to the deviation from a desired process or performance can be achieved with an Out of Control Action Plan (OCAP). This will allow any topics of problems to be resolved smoothly, with that stability of improvements. Standard Operating Procedures (SOPs): Standardization is such an important part of SOPs to standardize a process done better, in a consistent way and using the best practice possible. In the long term this helps to keep-up performance. Continuous monitoring allows further opportunity for improvement to be identified and variations that might not have been identified previously to be detected. It means that project performance is continually tracked. At the end of which after applying the best solutions the whole project is reevaluated according to some indicators of sustainability. This provides confirmation that the performance obtained during the early stage of the project is indeed better. The solutions are thrown away until the results are better, and what works is spread to other parts of the organization. An OCAP will then be created to identify other solutions that may be more efficient. To apply the solutions, staff must be trained and must be aware of their role in the work of continuous improvement. To control important input and output variables of operational and environmental practices, tools like Poka Yoke, visual management and Total Productive Maintenance are being used. Real time visual monitoring of process performance is possible using cyber technology. The outputs of the Sustain and Control phase are fed back into the heterostatic input control loop of the GLSS process. If the results do not give satisfactory results, the continuity improved cycle starts from the project selection process and new project is initiated [9] .

6. Environmental KPI

6.1. Definition and Importance of Environmental KPIs

Environmental KPI are measures that reflect an organization's environmental performance against its broader objectives and targets. They enable companies to measure, manage, and communicate their environmental impacts in a meaningful. The integration of sustainable concerns has gained importance in societal and economic discussions over the past few decades[21]. Faced with increasing pressure to improve the quality, efficiency, and sustainability of services, the adoption of environmental KPIs is becoming essential. These indicators are not only important for regulatory compliance and penalty prevention, but they also contribute to better overall performance, bringing financial gains, improving talent retention, and strengthening market position and reputation [21]. In essence, environmental KPIs transform environmental concerns into actionable data, allowing organizations to track their progress toward more sustainable operations.

6.2. The Role of Environmental KPIs in GLSS Integration

The significance of Environmental KPI in GLSS is that it provides a connecting point between operation efficiency and ecological sustainability. They contribute to :

- Identify where company processes affect the environment (emissions, resource use, waste) [21].
- Track progress toward sustainability goals, such as lowering carbon emissions or increasing recy-

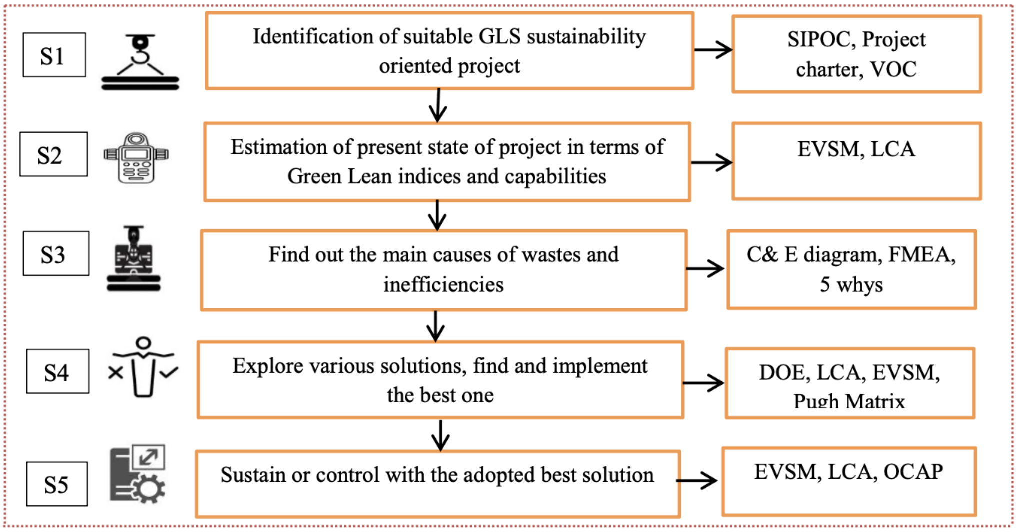

Figure 4: Green Lean Six Sigma implementation framework [15]

cling [22] .

- Support informed decision-making and continuous improvement by providing measurable data [8, 21].
- Communicate sustainability efforts transparently to stakeholders [21].
- Ensure compliance with environmental regulations and standards, avoiding legal risks [22].

6.3. A structured approach to selecting environmental KPIs in manufacturing

A structured approach is proposed to identify the appropriate environmental KPIs for the manufacturing sector. This framework is organized into three main steps :

1. Building an environmental KPI data base: Step one involves collecting preliminary KPIs and selection criteria from various sources, such as publications to ensure they align with manufacturing processes[8] .
2. KPI Categorization: The second step involves organizing the many potential KPIs into two-dimensional matrix, manufacturing element (horizontally) and environmental element (vertically), to identify potentially unmonitored aspects and track indirect impacts [8].
3. Ranking KPIs according to a specific objective: Third step allows for prioritizing KPIs based on their relevance to specific environmental objectives through stakeholder input and evaluation criteria. KPIs with the highest scores are deemed the most effective for achieving sustainability goals [8].

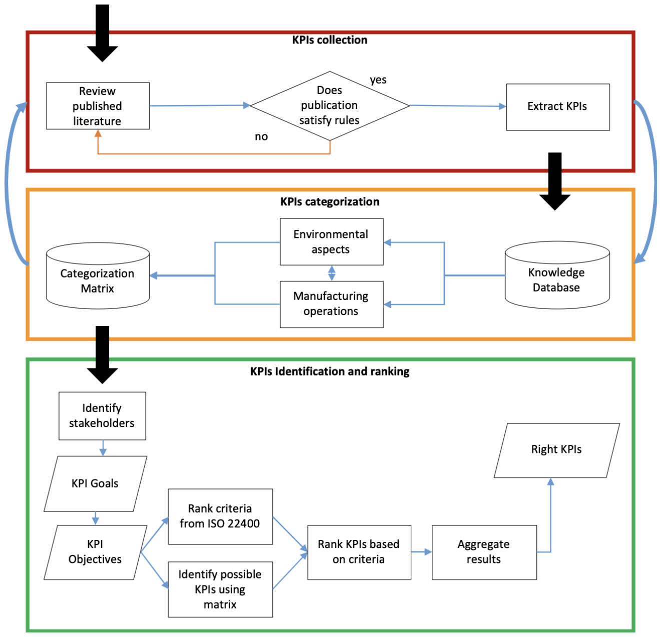

Figure 5: High-level schematic of the KPIs framework [8]

6.4. Key environmental KPIs

To operationalize these sustainability principles within a GLSS framework, a set of specific environmental KPIs can be monitored. These indicators provide a concrete basis for evaluating and continuously improving environmental performance in manufacturing operations [22]. The following examples illustrate key areas of focus[22]:

1. Electric-powered or low-emission fleet units: This KPI tracks the percentage of the fleet which is either fleet-electric or admeets low-emission criteria.

2. Reduction in carbon emissions: This KPI seeks to track down the reduction in the company's (GHG) emissions.
3. Waste Reduction: this KPI evaluates efforts to reduce waste generation.
4. Number of ISO 14001 certified branches: this KPI measures how much of the company's operations are certified to ISO 14001, which is an internationally accepted environmental management system.
5. Water consumption per unit of revenue (€): this KPI assesses the use of water efficiency by correlating the amount of water used to revenue generated.
6. Third-party rating: This KPI prompts companies to get an independent review of their environmental benchmark by external framework e.g. CDP, EcoVadis Erdamber Achilles.
7. Legal proceedings – environment: This KPI monitors the count of the lawsuits related to the environmental episodes[22].
8. Environmental incidents / near misses: This KPI measures the number of real environmental accidents (spills) and potential ones incidental to environmental aspects [22].

Environment
1. Electric powered/low emission units in fleet
2. Reduction in carbon emissions
3. Reduction in waste
4. Number of branches ISO 14000 certified
5. Water consumption per € unit turnover
6. Third party rating
7. Legal proceedings – environment
8. Environmental incident / near miss

Figure 6: ERA Sustainability KPIs 2.0 for Environmental [22]

7. Challenges and Solutions for GLSS Implementation

7.1. Challenges to GLSS Implementation

GLSS implementation faces various challenges, including organizational, technical, behavioral, and managerial obstacles that can hinder its successful adoption [9, 13]. These challenges can vary depending on the organizational context and geographical location [13, 17]. Here are some specific challenges to GLSS implementation:

- Lack of awareness of sustainability and fear of failure. In some cases, resistance to change can come from a lack of understanding on how important it can be to be sustainable and the benefits of it. In addition, because organizations may fear that GLSS implementation will be unsuccessful, they may not adopt this approach [19].
- Resource constraints and lack of expertise. GLSS implementation is a major undertaking, which necessitates a time, money, and quality of personnel investment [15]. Resource lack makes it difficult to adopt GLSS, in particular, for SMEs. Then there is a lack of trained and experienced staff on GLSS methods, as well as associated tools, which is a major obstacle [1, 15].
- Lack of management commitment and unfavorable organizational culture. Any change initiative requires commitment and support of management. If an organization's culture is not open to change, collaboration, and innovation and if it does not practice it, it is difficult for GLSS to be implemented [1, 15].
- Difficulty in integrating different technologies and poor selection of GLSS tools. GLSS as an integration with other technologies, like what is known as Industry 4.0 is complex and requires the specific expertise and resources. Failure of the project can occur when the wrong GLSS tools are selected at different implementation phases [1, 15].
- Lack of implementation methodology. A lack of generic implementation framework for GLSS that could be applicable in different processes, organizational cultures, and industry is observed [1, 15].
- Gaps in measuring environmental impact. It is unclear if LSS approach can quantify environmental indicators and hotspots or will enhance environmental sustainability [1, 15].
- Lack of synergies between objectives and continuous improvement. Often it is difficult to align GLSS goals because the organizational goals and the continuous improvement efforts seem to be out of few lines [1, 15].
- Economic constraints and lack of standardization procedures. Organizations can be slowed down with the costs of implementing new technologies and training. The absence of standard procedures may limit the crossing of the entire supply chain by GLSS-Industry 4.0 technologies [1, 15].
- Cybersecurity challenges. Furthermore, the security and availability of data exchanged by various partners through the supply chain is a much under-addressed difficult problem [1, 15].

7.2. Overcoming GLSS Implementation Challenges

The successful implementation of GLSS requires overcoming several challenges, such as organizational resistance and technical obstacles, which must be addressed strategically to ensure optimal adoption. Here are some solutions[15]:

- Training and Awareness / Training and Education. Organizations that use the LSS approach should focus on solid training programs. It includes educating the public about doing something about the environment, and how to daily do it. It's also important to teach them how small, consistent efforts can help the environment in their daily routines.

- Management Support / Cultural Shift. Leadership plays a key role in getting GLSS off the ground. Management has to take the first step, build trust within the organization, and foster a culture where continuous learning and improvement are the norm. The organization must create an organizational culture that welcomes green practices and further emboldens continuous improvement. That shift calls for a positive attitude towards sustainability initiatives.
- Project Selection. It is critical to choose the right GLSS projects to have a high sustainability impact. SIPOC diagram, project charters and prioritization tools can help identify what initiatives to focus on.
- Implementation Frameworks. The GLSS implementation process is made simple with the development of clear and step-by-step frameworks. These frameworks should be adaptable enough to incorporate each other depending on the goals and achieve green goals.
- Strategic Partnerships / Addressing Knowledge Barriers. Technical expertise and enhancing training possibilities can be shared with environmental organizations, academic institutions, as well as research bodies. It's important to close knowledge gaps by refining employee skills, choosing the right tools for the job, and making sure everyone has access to the resources they need.
- Financial Support. The financial side of GLSS can be challenging, but governments and banks can help by offering loans, grants, and supportive policies to ease the burden.
- Continuous Improvement. Sustainability shouldn't be a one-time effort. It needs to be woven into the organization's philosophy of continuous improvement so it becomes a long-term habit.
- Performance Metrics. To stay on track, companies should develop clear ways to measure their progress. Tracking sustainability performance ensures that efforts align with industry goals and make a real difference.

8. Case Study Example

A case study in the iron ore industry illustrates the application of GLSS to reduce graphite and dust pollution, demonstrating how the integration of LSS principles can lead to both environmental and operational improvements. This case follows DMAIC approach, and the first step begins with **problem definition** where the company (Company X), being an iron ore exporter, set a reduction criterion of 20 % in graphite and dust emissions at the desulfurization plant. Although the emissions were within statutory norms, the graphite and dust were causing environmental concerns [11].

In the **measurement phase** , the company measured the levels of graphite and dust in micrograms per cubic meter (ug/m^3) at four key locations: the slag dryer, coke screen, baghouse, and iron ore screening. The average levels recorded at 2.68, 2.29, 1.71 and 1.92 ug/m^3 were initial[11].

The team **analyzed** metal transfers between ladles and dust emissions from sources identified as locations with graphite generation for a significant source[11].

In the **improvement phase** , the process design was improved, the de dusting system modified, and bag house debris was soaked before loading to improve the bag house performance. Action was prioritized for implementation based on slag pot dumping trials[11].

During the **control phase** , standardized operating procedures (SOPs) were created to oversee metal transfers and solution transfers in order to continue to improve by way of control documentation[11].

After completing one year, we could see that the targets of reducing graphite and dust emission were realized in all four areas, and levels declined to 2.18, 2.03, 1.48 and 1.64 ug/m^3, from the target levels of 2.15, 1.83, 1.37 and 1.53 ug/m^3 respectively. In this case the tools used were group discussion, brainstorming, Five Whys analysis, SMART goals, project charter, statistical analysis, Environmental Value Stream Mapping (EVSM), multi voting systems, takt time, waste identification and control charts [11].

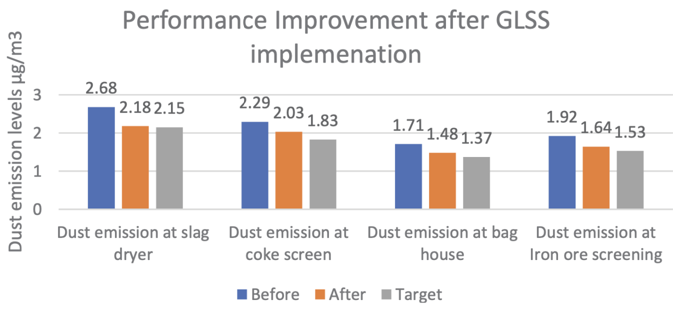

Figure 7: Performance improvement in graphite and dust levels [11]

- **Feedback from employees is presented below:**
- Concerning value specification that incorporates environmental aspects, one employee stated: "Customer needs are paramount to the organization. They must be met. But the organization should also analyze in detail what the environmental impact would be in order to meet customer needs. I want to give an example from my company, where our customer wants a large ship-

ment of iron ore to export, but if we don't mine sustainably, we will leave nothing for our children". This reflection underscores the need to align customer needs with environmental impact and adopt green initiatives to mitigate it[11].

- In relation to the VSM with environmental considerations, one employee noted: "VSM is a very important tool for representing the process of satisfying customer value. However, we need to be creative when using conventional VSM to include elements that will benefit the environment." [11].
- On the subject of the importance of creating flows while considering environmental impact, one employee was asked: "As lean professionals, we used to design flows based on the seven wastes prescribed in the lean methodology. But in modern organizations, due to the implementation of green initiatives, streamlining flows while taking into account the reduction of gases harmful to the atmosphere is very important."[11].
- Regarding the demand-driven system integrating environmental dimensions, one employee commented: "Customers are very attentive to products that will preserve our environment. There is a high demand for such products. Organizations can use this customer need to design systems that will benefit them all." [11].
- Creating perfection while considering environmental performance, one employee clarified: "Creating a state of perfection while considering environmental performance is a challenge for the organization. It is one idealistic thing to start an initiative and another to achieve perfection." [11].
- The importance of organizational culture for the success of GLSS, one employee commented: "A company that has a vision, a mission, and a predisposition toward green initiatives will be better positioned to implement such Green LSS initiatives. Because every employee will be motivated and imbued with the corporate culture to save energy or reduce greenhouse gases. "Therefore, for the successful implementation of the Green LSS framework, organizations must establish policies, visions, and missions focused on sustainability and green management [11].

In this case study, we see how when LSS tools are combined via the GLSS framework, companies can improve efficiency and reduce operational and environmental waste. By integrating these methodologies with green initiatives the pollution is addressed and the industry is enabled to practice sustainable practices. Applying the DMAIC approach, the company achieves optimized environmental performance and operational effectiveness and demonstrates how GLSS could generate sustainable outcome [11].

9. GLSS in the Era of Industry 4.0 and 5.0 :

The integration of GLSS with the paradigms of Industry 4.0 and Industry 5.0 offers new opportunities and challenges for achieving sustainable, resilient and human-centered manufacturing systems. This section explores the synergies between GLSS and the digital technologies of Industry 4.0 and then discusses the evolution toward Industry 5.0, highlighting the need for a more holistic and ethical approach.

9.1. Synergies between GLSS and Industry 4.0

The integration of GLSS approach with Industry 4.0 offers an exciting opportunity to leverage quality, productivity and environmental and social sustainability benefits in manufacturing firms, for modern industries, sustainability has to be incorporated into manufacturing practice and GLSS, has emerged as an effective strategy. By combining the principles of LSS and sustainability, GLSS aims to enhance operational efficiency while minimizing environmental impact, adopting the 3R concepts: reduce, reuse, recycle. As advanced technologies like IoT, CPS, AI, and big data analytics are used in Industry 4.0 [23], GLSS can be implemented to reduce emissions and wastes and sustain practices[24]. The following table provides a detailed exploration of the synergies between specific Industry 4.0 technologies (e.g., IoT, AI) and GLSS tools, highlighting how these technologies enhance its effectiveness of GLSS practices [4, 7, 24]:

GLSS Tools	Associated Industry 4.0 Technologies	Synergy Description
Value Stream Mapping (VSM)	IoT and Big Data	Automated digitization of value streams, real-time process data collection, dynamic waste analysis.
DMAIC (Six Sigma)	Big Data Analytics and Artificial Intelligence (AI)	Predictive analysis for faster root cause identification, data-driven decision-making.
5S (Lean)	IoT and Smart Sensors	Automatic monitoring of workplace order and cleanliness, with anomaly-triggered alerts.
Poka-Yoke (Error proofing)	AI and Smart Sensors	Intelligent detection and automatic prevention of human or machine errors.
Statistical Process Control (SPC)	Big Data and Cloud Computing	Continuous real-time monitoring of quality indicators and secure cloud data storage.
Green Kaizen (Continuous Green Improvement)	Digital Twins and Simulation	Virtual simulation of green improvement ideas before deployment, energy efficiency optimization.
Eco-Design (Sustainable Design)	3D Printing and IoT	Rapid eco-friendly prototyping with significant reduction in material waste.
Green Manufacturing (GM)	Big Data Analytics, IoT and Cloud	Continuous monitoring of environmental performance extends throughout every stage of the product lifecycle through the use of smart systems.

Figure 8: Synergies between GLSS and Industry 4.0 [by students]

9.2. Enhancing GLSS with Industry 5.0: Advancing Beyond Industry 4.0

Industry 5.0 enhances GLSS by going beyond the digitalization and automation of Industry 4.0 by introducing a human-centered approach, emphasizing collaboration between humans and advanced technologies, and more strongly integrating sustainability and well-being objectives into digital transformations [3, 5, 6]. Here's how Industry 5.0 enhances GLSS in addition to Industry 4.0:

- Human Machine Synergy for Sustainability boosted: While Industry 4.0 mainly relies on automation to raise the efficiency Industry 5.0 emphasizes on synergy between humans and machines [3]. In the context of GLSS, this implies that workers' human knowledge, imagination and analytical thinking are deliberately combined with the power of advanced technologies to spot and implement even more innovative and customized sustainability solutions. Industry 5.0 addresses the need to return human workers to factories to partner with machines to boost efficiency of process that has a sustainability related component to it [6].
- Emphasis on Sustainability and Well-being: Unlike Industry 4.0, which could potentially overlook the human cost of process optimization and did not have as strong a focus on environmental protection, Industry 5.0 integrates sustainability and well-being into its digital transformations. For GLSS, this translates into an increased emphasis on sustainable manufacturing, combining advanced technologies with sustainable practices to reduce environmental impacts. Industry 5.0 now integrates sustainability objectives into its digital transformation. The industries of the future hold a key position in addressing societal challenges, including the preservation of natural resources and combating climate change [3].
- Sustainable Personalization Focused on Humans: Industry 5.0 enables mass customization with high precision and low cost, integrating sustainable and resilient thinking. This personalization can be guided by the specific needs of customers identified through human interaction, while optimizing resource utilization and minimizing waste, which aligns with GLSS objectives. Digital Twins in Industry 5.0 allow companies to simulate and predict the socio-environmental footprint of their products across their entire life cycle, from design to final consumption, helping to align industrial practices with more sustainable standards [3]. Smart Additive Manufacturing (SAM) helps to reduce the consumption of materials and resources, in addition to its ability to save energy resources, leading to pollution-free environmental production [6].
- Industry 5.0 promotes sustainable innovation through a partnership of technological capacities with human creativity and ethical values. Mobilizing joint efforts between humans and machines allows designers and engineers to produce sustainable and ethical products and processes. The sustainability-oriented innovation principle of Industry 5.0 builds fundamental operational elements which enable resilient and efficient and

environmentally responsible operational models aligned with GLSS objectives [6].

- Industry 5.0 focuses on human applications of data analysis developed through Industry 4.0 methods to support sustainable decisions. The utilization of human experience and knowledge when reviewing data from Industry 5.0 technologies results in more significant sustainable outcomes within GLSS approaches. AI together with big data technology supports DMAIC's Define phase by transitioning from subjective manual methods toward embedded data-based approaches that gather information from various sources while recognizing patterns with major environmental and operational effects [6].

In summary, Industry 5.0 enriches GLSS by adding an essential human dimension, reinforcing the commitment to environmental and social sustainability, and fostering closer collaboration between humans and advanced technologies to achieve truly sustainable operational excellence. Industry 5.0 does not replace Industry 4.0, but evolves it towards a more holistic paradigm where technology serves humans and the planet. The integration of Industry 5.0 technologies into the cycle of GLSS can significantly enhance both sustainability and efficiency of production processes [3].

Figure 9: Conceptual Green Lean Six Sigma model (Kaswan and Rathi, 2021a) [9]

10. Discussion

GLSS integrates operational efficiency and sustainability, providing a phased, tool-supported approach [11, 13]. Case studies have validated its applicability in reducing pollution and enhancing sustainability [11]. GLSS achieves efficiency and sustainability by incorporating waste, variation, environmental emissions, and process improvements, making use of the strengths of LSS and sustainable technologies [9, 12, 13]. Unlike LSS, which prioritizes operational quality, GLSS considers the whole breadth of sustainability as well as social factors, according to [11, 13]. A project-based, phased, and structured framework is followed in GLSS, with key project selection being supported by instruments such as LCA, SLCA, DOE, and the Pugh Matrix [9, 13]. The use of Industry 4.0 technologies, notably IoT, Big Data, AI, and smart sensors, assists in green initiatives by making it possible to monitor processes, optimize them, and use predictive analytics, thereby increasing the effectiveness of GLSS approaches and pushing for sustainability [17, 24]. Manufacturers require KPI aligned with the Triple Bottom Line (TBL) framework to effectively monitor and improve sustainability across social, economic, and environmental dimensions, linking targets to stakeholder expectations [3, 8]. Several case studies validate GLSS's applicability in reducing pollution, GHG emissions, and improving energy efficiency, cycle time, and lead time, emphasizing the need for employee involvement, financial resources, and adequate training [11, 15, 20]. Industry 5.0 further advances this approach by focusing on human-centric cooperation and leveraging AI and big data analytics combined with the GLSS DMAIC cycle to better define sustainability objectives and track environmental performance [24].

11. Limitations

The Research on integrating sustainable practices, particularly concerning GLSS and related methodologies, faces several limitations. There is a reliance on existing literature, often based on a limited selection of articles, which constrains scope and originality of findings. Studies proposing frameworks for integrating lean, agile, resilient, and green approaches often depend on a small number of prior works, limiting the exploration of new perspectives or methodologies. The focus on the manufacturing sector restricts generalization, as sectors like healthcare, services, or education remain less researched. Research often targets specific industries such as construction, mining, or food processing. A lack of standardized sustainability metrics persists. Financial and environmental performance can be assessed differently, and social indicators are subjective, making it difficult to accurately measure sustainability. Some frameworks also neglect one or more dimensions of sustainability (economic, environmental, and social). There is a lack also of practical validation and empirical research. Many frameworks lack real-world testing. While case studies exist, they are often exploratory, with limited scope and generalizability, creating a gap between theory and practice. Also a limited comparative studies across countries, cultures, or company sizes further restrict understanding of contextual factors affecting the effectiveness and generalization of sustainability practices. The development of environmental KPIs faces both theoretical and practical limitations. Research constrains the breadth and depth of KPIs, and data collection lacks industry-specific granularity. There is no universally standardized set of KPIs for environmental sustainability across the manufacturing sector [8]. Regarding Industry 4.0, despite vast data opportunities, the actual relevance of its technologies to environmental performance is unclear. Leveraging big data requires specific BDA capabilities and EP focus, with limited empirical validation of their relationship [3, 7]. The integration of Industry 5.0 with GLSS is largely conceptual. Its success assumes access to advanced technologies, digital infrastructure, and organizational commitment to sustainability and operational excellence. Given its nascent stage, sector-specific empirical research is needed to validate its sustainability impact [3]. These limitations do not negate the value of sustainable approaches but emphasize the need for further research. Future research should focus on empirically validating models, integrating Green Lean with Circular Economy and Industry 5.0 technologies, developing practical tools, analyzing drivers and barriers, redefining KPIs, and expanding applications to underexplored sectors and regions.

12. Conclusions

This review highlighted the transformative potential of GLSS for sustainable manufacturing by integrating LSS and environmental practices to optimize industrial performance while minimizing environmental impact. The integration of these approaches not only improves efficiency but also reduces emissions, contributing to the circular economy [9].
The proposed framework for GLSS implementation demonstrates that structured integration is crucial for success. Relying on key factors such as leadership commitment, employee involvement, and the adoption of appropriate technologies[1, 11, 12]. Measuring its impact requires the use of sustainability KPI that cover environmental (emissions, energy consumption, waste), economic (costs, resource efficiency) and social (employee well-being, community engagement) dimensions [8]. However, significant challenges remain in GLSS implementation, particularly cultural barriers and technological constraints, which must be addressed to maximize its benefits [1, 11, 12].
Case studies and research on GLSS applications in both developed and developing countries have provided valuable insights into its impact and outcomes. Nevertheless, further research is needed to quantify sustainability impacts, explore applications across additional industries, and refine performance measurement tools[9]. Additionally, The integration of Industry 4.0 technologies, such as the IoT and CPS, offers significant potential to optimize GLSS practices by providing real-time data and facilitating the automation of sustainable processes[7, 24]. The integration of Industry 5.0 technologies with GLSS enhances sustainability and efficiency through real-time optimization and smart systems. Despite some challenges, this synergy drives sustainable manufacturing forward. Future research should refine measurement tools and broaden applications across industries [3].
In conclusion, GLSS offers a promising approach to enhancing overall business performance while simultaneously contributing to environmental sustainability and operational efficiency. It serves as a strategic lever for organizations aiming to become leaders in sustainable manufacturing on a global scale.

References

[1] Amna Farrukh, Sanjay Mathrani, and Aymen Sajjad. A natural resource and institutional theory-based view of green-lean-six sigma drivers for environmental management. *Business Strategy and the Environment*, 31(3):1074–1090, 2022.

[2] Mrigendra Nath Mishra. Identify critical success factors to implement integrated green and lean six sigma. *International Journal of Lean Six Sigma*, 13(4):765–777, 2022.

[3] Imane Boumsisse, Mariam Benhadou, and Abdellah Haddout. Optimizing green lean six sigma using industry 5.0 technologies. *Cleaner Waste Systems*, 10:100234, 2025. Open Access under CC BY license.

[4] Mahender Singh Kaswan, Rajeev Rathi, Jiju Antony, Jennifer Cross, Jose Arturo Garza-Reyes, Mahipal Singh, Inder Preet Singh, and Michael Sony. Integrated green lean six sigma-industry 4.0 approach to combat covid-19: from literature review to framework development. *International Journal of Lean Six Sigma*, 15(1):50–79, 2023.

[5] Saeid Nahavandi. Industry 5.0: A human-centric solution. *Sustainability*, 11(16):4371, 2019.

[6] Imane Boumsisse, Mariam Benhadou, and Abdellah Haddout. Exploring the potential synergies between industry 5.0 and green lean six sigma for sustainable performance: A new dimension of operational excellence. *ESIC*, 8.2(S2):1243–1259, 2024.

[7] Amine Belhadi, Sachin S Kamble, Karim Zkik, Anass Cherrafi, and Fatima Ezahra Touriki. The integrated effect of big data analytics, lean six sigma and green manufacturing on the environmental performance of manufacturing companies: The case of north africa. *Journal of Cleaner Production*, 252:119903, 2020.

[8] Ziyad Sherif, Shoaib Sarfraz, Mark Jolly, and Konstantinos Salonitis. Identification of the right environmental kpis for manufacturing operations: Towards a continuous sustainability framework. *Materials*, 15(21):7690, 2022.

[9] Mahender Singh Kaswan, Rajeev Rathi, Jose Arturo Garza-Reyes, and Jiju Antony. Green lean six sigma sustainability–oriented project selection and implementation framework for manufacturing industry. *International Journal of Lean Six Sigma*, 14(1):33–71, 2023.

[10] Khalid Nagadi. Implementation of green, lean and six sigma operations for sustainable manufacturing. a review. *International Journal of Production Management and Engineering*, 10(2):159–171, 2022.

[11] Michael Sony and Subhash Naik. Green lean six sigma implementation framework: a case of reducing graphite and dust pollution. *International Journal of Sustainable Engineering*, 13(3):184–193, 2020.

[12] Wadhah Abualfaraa, Konstantinos Salonitis, Ahmed Al-Ashaab, and Maher Ala'raj. Lean-green manufacturing practices and their link with sustainability: A critical review. *Sustainability*, 12(3):981, 2020.

[13] Rajeev Rathi, Mahender Singh Kaswan, Jose Arturo Garza-Reyes, Jiju Antony, and Jennifer Cross. Green lean six sigma for improving manufacturing sustainability: Framework development and validation. *Journal of Cleaner Production*, 345:131130, 2022.

[14] Fatima Ezahra Touriki, Imane Benkhati, Sachin S Kamble, Amine Belhadi, et al. An integrated smart, green, resilient, and lean manufacturing framework: A literature review and future research directions. *Journal of Cleaner Production*, 319:128691, 2021.

[15] Mahender Singh Kaswan, Rajeev Rathi, Jose Arturo Garza Reyes, and Jiju Antony. Exploration and investigation of green lean six sigma adoption barriers for manufacturing sustainability. *IEEE Transactions on Engineering Management*, 2021.

[16] Florencia Kalemkerian, Javier Santos, Martin Tanco, Jose Arturo Garza-Reyes, and Elisabeth Viles. Analysing the alignment between the green lean and circular strategies: towards a circular lean approach. *Journal of Manufacturing Technology Management*, 33(6):1059–1079, 2022.

[17] Mahender Singh Kaswan, Rajeev Rathi, Jennifer Cross, Jose Arturo Garza-Reyes, Jiju Antony, and Vishwas Yadav. Integrating green lean six sigma and industry 4.0: a conceptual framework. *Journal of Manufacturing Technology Management*, 34(1):87–121, 2022.

[18] Ming K Lim, Ming Lai, Chao Wang, and Yee Lee. Circular economy to ensure production operational sustainability: A green-lean approach. *Sustainable Production and Consumption*, 30:130–144, 2022.

[19] Anass Cherrafi, Jose Arturo Garza-Reyes, Amine Belhadi, Sachin S Kamble, and Jamal Elbaz. A readiness self-assessment model for implementing green lean initiatives. *Journal of Cleaner Production*, 309:127401, 2021.

[20] Manori Pathmalatha Kovilage. Influence of lean–green practices on organizational sustainable performance. *Journal of Asian Business and Economic Studies*, 28(2):121–142, 2021.

[21] Rodrigo Caiado, Daniel Nascimento, Osvaldo Quelhas, Guilherme Tortorella, and Luis Rangel. Towards sustainability through green, lean and six sigma integration at service industry: Review and framework. *Technological and Economic Development of Economy*, 24(4):1659–1678, 2018.

[22] European Rental Association. Sustainability kpis 2.0: Guidance framework, 2021. Available at: `https://www.erarental.org/publications/sustainability-kpis-2-0-guidance-framework/` [Accessed 26 April 2025].

[23] Yong Lu. Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration*, 6:1–10, 2017.

[24] L Thiruvarasu Letchumanan, Hamed Gholami, Noordin Mohd Yusof, Nor Hasrul Akhmal Bin Ngadiman, Anas A Salameh,

Dalia Štreimikienė, and Fausto Cavallaro. Analyzing the factors enabling green lean six sigma implementation in the industry 4.0 era. *Sustainability*, 14(6):3450, 2022.

A. List of abbreviation

- **GLSS:** Green Lean Six Sigma
- **DMAIC:** Define, Measure, Analyze, Improve, Control (Six Sigma methodology)
- **LCA:** Life Cycle Assessment
- **GRA:** Grey Relational Analysis
- **FMEA:** Failure Mode and Effects Analysis
- **SOP:** Standard Operating Procedures
- **OCAP:** Operating Control and Action Procedures
- **Key Performance Indicators:** KPI
- **DOE:** Design of Experiments
- **Pugh Matrix:** Decision-making tool for evaluating alternatives
- **3R:** Reduce, Reuse, Recycle
- **SLR:** Systematic Literature Review
- **GLA:** Green Lean Approach
- **CSR:** Corporate Social Responsibility
- **VSM:** Value Stream Mapping
- **EVSM:** Environmental Value Stream Mapping
- **CTQ:** Critical to Quality
- **CPS:** Cyber-Physical Systems
- **IoT:** Internet of Things
- **AI:** Artificial Intelligence
- **LSS:** Lean Six Sigma
- **CE:** Circular Economy