Emerald Journal of Manufacturing Technology Management

Integrating Green Lean Six Sigma and Industry 4.0: A Conceptual Framework

Journal:	*Journal of Manufacturing Technology Management*
Manuscript ID	JMTM-03-2022-0115.R2
Manuscript Type:	Article
Keywords:	Lean manufacturing, Green operations, Industry 4.0, Six Sigma, Sustainable production

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Abstract

Purpose: This research proposes a framework to integrate Green Lean Six Sigma (GLSS) and Industry 4.0 to improve organizational sustainability.

Design/methodology/approach: The integration of GLSS and Industry 4.0 is proposed based on theoretical facets of the individual approaches. A generic, conceptual framework of an integrated GLSS-Industry 4.0 approach is then proposed using the application of different tools and techniques of GLSS and Industry 4.0 at different stages of the realization of a project.

Findings: Both approaches have common facets related to enablers and barriers, and the integrated application of tools and techniques of each approach supplements the common focus of both related to sustainability enhancement. The proposed, conceptual framework provides systematic guidelines from the project selection stage to the sustainment of the solution, with the enumerated application of different techniques and tools at each step of the framework.

Originality: This research is the first of its kind to propose the integration of GLSS and Industry 4.0 under the umbrella of a unified approach, including a conceptual framework of this integrated GLSS-Industry 4.0 approach.

Keywords: Green Lean Six Sigma; Industry 4.0; Enablers; Barriers; Framework; Sustainability.

1. Introduction

Increasing demand for customized products, competition, and emphasis on immediate and responsive service are directing industries toward digital transformation (Shokri and Li 2020)(Shahin et al., 2020). Industry 4.0 is a new paradigm that induces considerable improvement through automation and digitization. Industry 4.0, since its announcement at Hannover Messe in 2011, has been a focus of researchers worldwide. In the past decade, Industry 4.0 has been classified as a strategy for making organizations competitive through improvements in quality, productivity, defects, waste, etc. (Lu 2017). Similar objectives are shared by Green Lean Six Sigma (GLSS), which is being adopted by industries over the last decade to improve sustainability. GLSS is an eco-friendly approach that advocates maintaining high product quality while reducing waste, defects, and environmental footprints (Belhadi et al. 2021).

Industry 4.0 induces a wide spectrum of novel technologies to integrate the supply chain (SC). Similarly, operational excellence methodologies (Lean, Six Sigma, and Lean Six Sigma (LSS)) integrated with Industry 4.0 technologies have been used to improve quality and productivity (Chiarini and Kumar 2021). Further, limited research suggests greater strategic and sustainable benefits for organizations and their SC when an integrated approach is followed over standalone approaches (Tortorella et al. 2019). However, no study on the integration of GLSS with Industry 4.0 has been reported in the academic literature.

Therefore, this research intends to answer the following research question: "How can GLSS be integrated with Industry 4.0 to develop a generic framework for improved sustainability of organizations?" This implies examining the applicability of different tools and principles of GLSS and Industry 4.0 at different stages of the realization of the framework. The study provides both a theoretical model and conceptual framework of GLSS-Industry 4.0 that integrates different tools and metrics. The rest of the article is organized as follows. Section 2 reviews related literature, and explores its gaps. Section 3 presents the research methodology. Section 4 proposes the theoretical model of GLSS and Industry 4.0, Section 5 describes the conceptual framework, whereas Section 6 depicts the discussion and implications. The final section presents the conclusions, limitations, and future research opportunities.

2. Literature review

To identify pertinent gaps from previous studies, a comprehensive literature review was conducted.

2.1 Literature search methodology

The research work uses a systematic literature review (SLR) methodology to comprehend different aspects of GLSS-Industry 4.0 and further to develop framework of integrated GLSS-Industry 4.0 approach. SLR induces methodological stringent review as compared to general review with a focus on evidence-based guidelines for research. SLR uses an explicit and inclusive approach so that accuracy can be assured in the literature review. In first phase of SLR, research purpose and goal are identified. Different stages of the SLR are as follows:

Planning stage

This stage enumerates the need for review and developing a review protocol. To find different facets the provide impetus for integration and development of the conceptual framework the adopted review protocol is as follows:

Table 1: Review protocol

Conducting review

This stage states the collection of studies and their analysis by extracting data. In this study, the authors used databases of Science Direct, Web of Science, Emerald, and SCOPUS to provide comprehensive coverage of the literature. The study encompasses peer-reviewed articles to ensure the quality of publications. The selection period of the study was 2011-2022. The start year has been selected as 2011 as this was year of industry 4.0 evolution and green technologies practices also being integrated with other operational excellence methods A snowball approach has been adopted in this study for search criteria of the keywords to further explore terms related to GLSS, Industry 4.0, and COVID-19. For example, GLSS has been replaced with sustainable Lean Six Sigma, Sustainable Six Sigma. Sustainable Lean manufacturing. Similarly, Industry 4.0 has been replaced with digital technologies. . The other selection criteria used for the study is English language only for the papers. The criteria used resulted in all 127 articles at the initial stage of the study including review articles. The PRISMA method has been used in this study to filter articles related to the topic of interest (figure 1). To eradicate duplicate articles the authors used end note software. This resulted in the exclusion of 50 articles.

The abstract of 77 articles were then further analyzed to match the objectives of the study (integration and framework aspects), which lead to the further exclusion of the 24 articles. Thereafter, full-text availability of the articles was considered, which led to the exclusion of 7 more articles. In the final stage of the review, the content of articles was analyzed according to the relevance of the topic related to GLSS, Industry, and sustainability aspects; this further led to exclusion of 3 articles. The final sample encompasses 43 articles, after careful consideration of the articles. The said articles were further analyzed in the reporting stage to find different facets that promote integration of GLSS with Industry 4.0 to support the development of the initial conceptual framework of the integrated GLSS-Industry 4.0 approach.

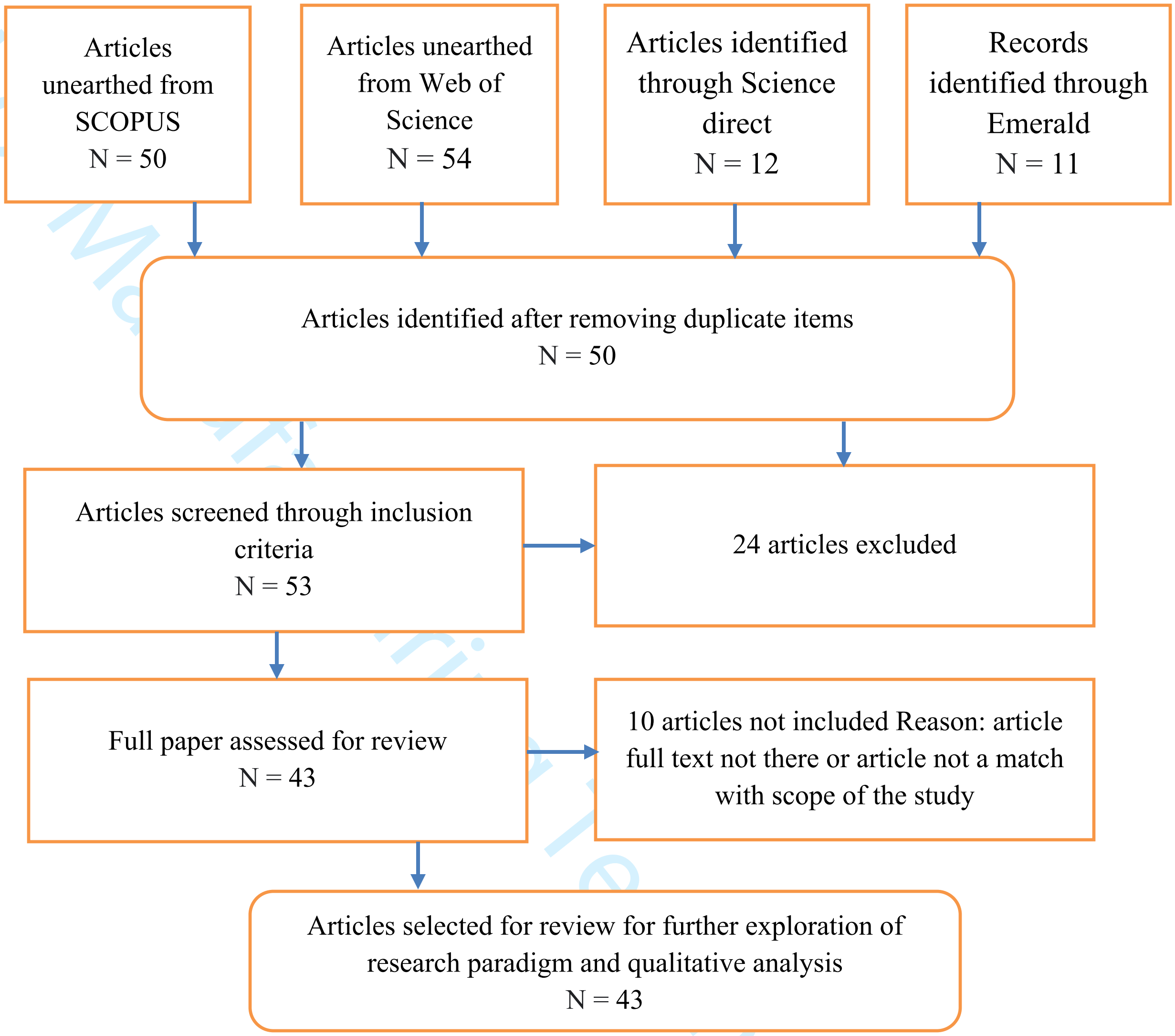

Figure 1: Preferred reporting items for systematic reviews and meta-analysis (PRISMA) flowchart

2.2 Organizational sustainability

Due to increased awareness regarding sustainability, climate change, and human health impacts, industries are in continuous pursuit to incorporate related improvements within their operations (Kaswan et al. 2021). The use of Green technologies (hereafter, Green) allows organizations to reduce the impact of production processes on the environment. The scope of Green operations ranges from product development to the entire product life cycle. It encompasses environmental practices such as Eco design, cleaner production, recycling, reuse, delivery, usage, and dumping of products (Vrchota et al. 2020).

Sustainability and sustainable development (SD) are two vital notions that have gained worldwide attention due to unusual patterns of climate change, and energy consumption. (Purvis et al., 2019). Sustainability is defined as a mechanism to achieve SD (Olawumi and Chan, 2018), where SD is a collective process that involves numerous stakeholders with different salience and powers (Slimane, 2012). SD is meeting the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). Environmental, social, and economic sustainability are three pillars of SD and must be harmonized to achieve overall sustainability. As different stakeholders and metrics are associated with each dimension of sustainability, it is difficult to measure organizational sustainability (Rathi et al., 2022). The precise estimation of sustainability becomes even more difficult due to the complexity of creating realistic measures of the different metrics and subjectivity associated with social metrics. Thus, it is particularly imperative to understand which metrics are to be considered to measure social and environmental sustainability.

2.3 Background on Green Lean Six Sigma

The history of GLSS can be traced back to Toyota Production System (TPS), better known as Lean in Western culture (Kaswan and Rathi 2020a). Lean reduces waste from systems through streamlined processes and systematic reduction of non-value added (NVA) activities. However, it does not directly address environmental aspects and has minimal focus on reducing variation (Garza-Reyes 2015). Six Sigma focuses on reducing variation and associated defects, providing a robust method to realize a sound product (Ruben et al, 2017). However, it does not directly address issues related to environmental and social sustainability (Sreedharan et al., 2018). Therefore, there is a need to incorporate Green with both Lean and Six Sigma to achieve a holistic improvement approach, i.e. Green Lean Six Sigma (GLSS) (figure 2). Several existing studies have found that LSS is effective in supporting Green methods to achieve enhanced environmental sustainability (Belhadi et al. 2021; Sony and Naik 2020). Table 2 depicts prominent case studies of GLSS, including sectors, tools, and main contributions.

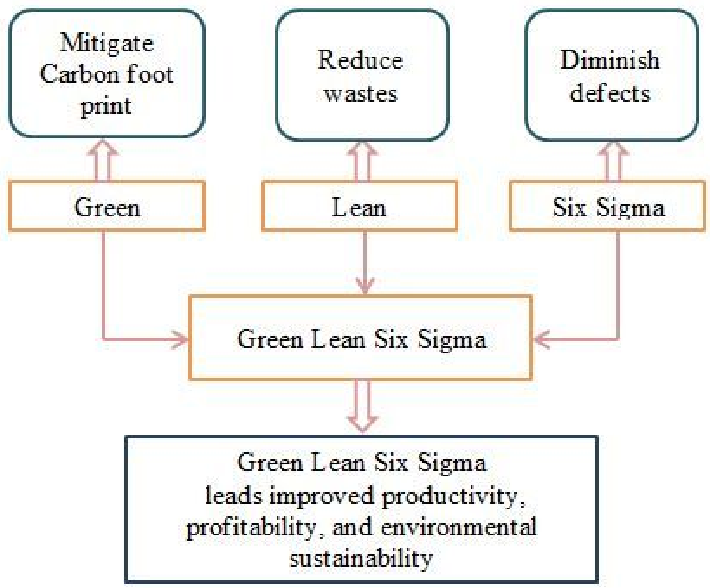

Figure 2: Green Lean Six Sigma (GLSS) (Rathi et al. 2022)

Table 2: Prominent case studies on GLSS

The integration of LSS and Green comes with difficulties. As stated by Powel et al. (2017) and Ershadi et al. (2021), existing efforts focus primarily on the economic aspect and they overlook environmental sustainability, possibly due to a large number of potential environmental metrics. The inclusion of Green metrics involves many stakeholders, including customers, organizations, governments, etc. These wide spectra of constituents have different, and sometimes conflicting, interests, creating difficulty in data gathering and analysis. Thus, there is a need for big data, as it provides an effective method to gather and analyze a holistic set of data, aiding in the effective judgment on Green measures of sustainability. GLSS integration with Industry 4.0 technologies such as big data will make the workplace "smarter," enhance decision capability, and ensure improved environmental sustainability.

2.4 Industry 4.0 technologies and their synergy with sustainability

Industry 4.0 is built on the development of novel technologies including 3D printing, IoT, cyber-physical systems (CPS), and big data (Zheng et al. 2021). Digital technologies of Industry 4.0 (figure 2) are interconnected to provide an authentic set of data to companies to conduct analyses that facilitate quick decision-making and change implementation (Katoozian and Zanjani, 2022).

The overall impact of these technologies provides better operations, real-time adaptation, control over processes, reduction of waste, and improved organizational sustainability (Khanzode et al., 2021).

Industry 4.0 fits into the wide spectrum of industrial sustainability. It supports the optimization of processes and contributes to environmental sustainability (Beltrami et al. 2021). CPS, cloud computing, 3D printing, and artificial intelligence systems within Industry 4.0 enable an automatic solution to industrial problems. Industry 4.0 aims to maximize efficiency and reduce waste, so Green is seen as a significant constituent of Industry 4.0 (Vrchota and Pech 2019). The combination of Industry 4.0 and Green can also be seen in reverse logistics, i.e., product management at the end of the product life cycle (Kiel et al. 2017).

Specifically, big data provides a wide spectrum of data related to process parameters and facilitates analyses resulting in the optimum selection of parameters. Sensors enabled by machines support quick changeovers, reduce error due to human involvement, and facilitate the accurate location of parts, which further leads to waste reduction. Additive manufacturing facilitates faster production and reduces material waste, contributing to environmental sustainability. Industry 4.0 also enables visual design, simulation, product support, and product design, and helps in the reduction of associated resource usage (Birkel et al., 2019). Virtual and augmented reality, autonomous robots, and sensor-enabled technical systems support workers in terms of repetitive and hazardous tasks, facilitating stress reduction and improved work satisfaction. Industry 4.0 technologies such as big data and CPS allow the integration of intelligent systems into the manufacturing and logistics system. This integration makes product tracking and end of the lifecycle practices, such as product reuse and recycling, easier, and facilitates a closed-loop SC (Strandhagen et al. 2017).

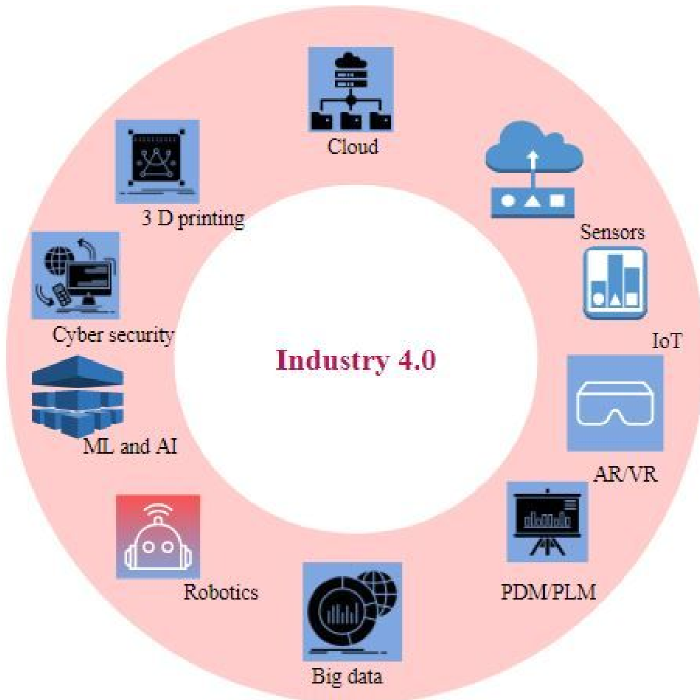

Figure 3: Industry 4.0 model

2.5 Industry 4.0 and operational excellence methods: Integration review

There are limited prior studies on the integration of Industry 4.0 and operational excellence methods, such as Lean and LSS. Although the integration of Lean and Industry 4.0 is in its infancy, initial evidence suggests that it leads to an improvement in waste, costs, and productivity. Dalenogare et al. (2018) integrated Lean with Industry 4.0 and found that Industry 4.0 overcomes the limitations of Lean especially when the product differs in terms of variety. Shahin et al. (2020) also explored the integration of Lean tools and Industry 4.0 technologies to improve the operational dynamics of companies. They argue that Lean has proven its worth to improve operational efficacy, but Lean on its own is not capable of coping with current market trends. Shorter product life cycles and demand for customized products require quicker changeovers, frequent changes in processes, and faster production than existing Lean practices deliver. To support these needs, industries are being directed toward digital technologies such as wireless technologies, big data, cloud computing, etc. In the literature, some studies have focused on the integration of specific Lean practices and Industry 4.0 technologies. For example, the integration of CPS and Jidoka provides a flexible configuration network to test the assembly of connecting rods, which results in considerable cost reduction (Ma et al., 2017). Mayer et al.

(2018) implemented an IoT and Lean-enabled conditional monitoring system in a stamping process for monitoring the stamping force, resulting in the reduction of wear and better scheduling of the process. Chen and Chen (2014) introduced a real-time VSM enabled by RFID that provides measures to automatically monitor material flow. Wang (2016) introduced an intelligent predictive maintenance system (IPdM), where data mining was applied to data gathered through CPS to detect possible faults. Therefore, it can be deduced from the limited available literature that Lean practices can be integrated with Industry 4.0 for improved organizational performance in economic sustainability. Although given the previously noted synergies between Lean and Green and between Industry 4.0 and sustainability, it seems logical that integration of Lean and Industry 4.0 would also lead to the improvement of the environmental sustainability, this is not directly addressed in the existing literature.

Similarly, in the literature, few studies related to the possible integration of LSS with Industry 4.0 exist. Jayaram et al. (2016) explored the integration of LSS with Industry 4.0 in the context of global SC. They claimed that LSS and Industry 4.0 complement each other, but, contrary to the existing research on Lean and Industry 4.0, Jayaram et al. (2016) suggested that Industry 4.0 implementation must precede LSS execution. However, their study provided limited insights related to how LSS tools can be integrated with Industry 4.0 technologies. Other studies suggest an integrated LSS-Industry 4.0 approach leads to improvement in metrics such as cycle time, waste, and quality, but do not identify any impact on environmental metrics (Chiarini and Kumar 2021).

The integration of GLSS with Industry 4.0 supplements organizational capacity to reduce emissions and ensures a robust method to incorporate different technologies and facets of Industry 4.0 at different levels of operations. Therefore, it can be deduced from the investigation of the literature that LSS-Industry 4.0 integration is still in the early stages, and, from the authors' best knowledge, no study related to integrating GLSS with Industry 4.0 exists. Thus, the aforementioned gaps in the literature provide direction and impetus for this research.

2.6 Summary of research gaps

In the literature, limited research related to integrating Lean and LSS with Industry 4.0 exists. The research on the synergy between Industry 4.0 and sustainability is also limited. To the best of the authors' knowledge, no previous research on integrating GLSS with Industry 4.0

technologies has been conducted. In addition, there is no evidence of research related to an execution framework of an integrated GLSS-Industry 4.0 approach to provide systematic incorporation of Industry 4.0 technologies and GLSS tools. Although studies related to GLSS frameworks exist outside the Industry 4.0 context, organizations still face difficulties in deploying the GLSS approach due to the non-availability of a specific toolset to be employed at different steps of a GLSS project Thus, increasing research interest in Industry 4.0, GLSS, and sustainability, and lack of relevant implementation frameworks provided an impetus to conduct this research.

3. Research methodology

The methodology adopted in this study consists of two phases (figure 4). Phase 1 focuses on the theoretical exploration of the integration between GLSS and Industry 4.0, whereas phase 2 focuses on the development of the proposed conceptual framework.

Phase 1: To comprehend the synergy and develop the integration between GLSS and Industry 4.0, the authors reviewed different facets that promoted the integration of the two operational excellence methods. For this, different enablers of integrated GLSS-Industry 4.0 were identified from the literature. The enablers stimulate the integration of GLSS and Industry 4.0 and improve organizational readiness to execute the new initiative. Furthermore, different barriers to the integrated approach were identified. Barriers hinder the execution of the approach, and thus provide different insights related to the approach, ultimately also helping ensure its success. Moreover, to support the integration of the two approaches, existing frameworks for integrating different operational excellence methods and Industry 4.0 were also reviewed. That is, the existing frameworks for integrating Lean and Industry 4.0, Green and Industry 4.0, and sustainability with Industry 4.0 can contribute to fostering the integration of GLSS and Industry 4.0. Moreover, the common end goal of GLSS and Industry 4.0 is to make organizations more competitive through improved resource utilization, production rates, environmental impact, and organizational culture; this common goal further strengthens the integration between the two approaches. The output of this phase is the theoretical integration model discussed in Section 4 of this paper.

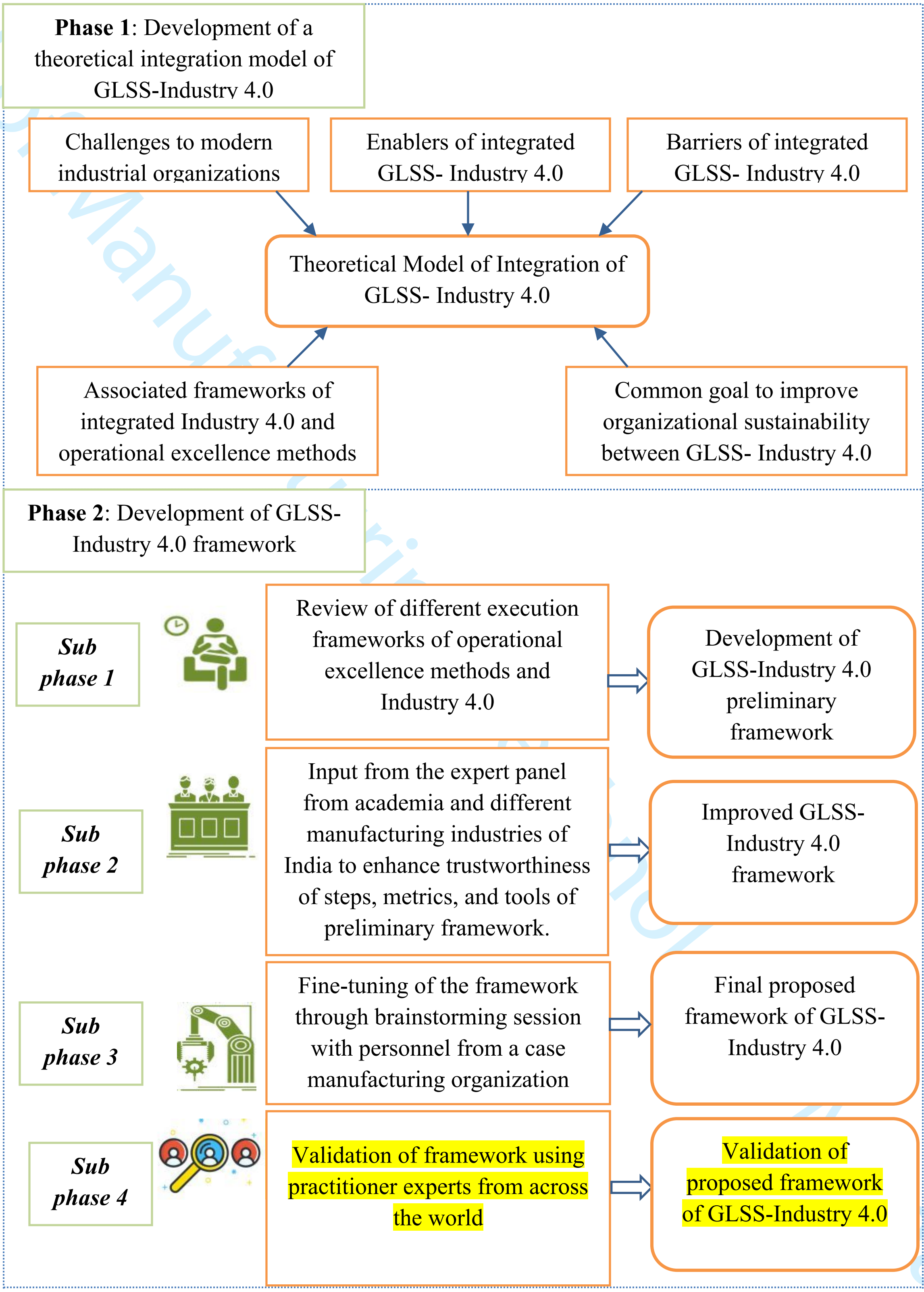

Figure 4. Research methodology

Phase 2: In this phase, a conceptual framework of integrated GLSS-Industry 4.0 has been proposed with different tools at each stage of the execution. The research design here consists of three sub-phases.

In the ***first sub-phase***, to develop the preliminary framework, existing literature was reviewed that explored integration between Lean and Industry 4.0, Green and Industry 4.0, LSS and Industry 4.0, and sustainability and Industry 4.0. Then, different frameworks related to LSS with environmental facets, GLSS with sustainability measures, Industry 4.0, and operational excellence methods were also explored to develop the preliminary framework of an integrated GLSS and Industry 4.0 approach. The reviewed frameworks are summarized in table 2. The overall structure of the preliminary framework, as well as the recommendations for the incorporation of different GLSS tools and metrics, were modelled on the GLSS frameworks of Kaswan and Rathi (2020a) and Rathi et al. (2022), who organized their frameworks around the five DMAIC steps. Meanwhile, the suggestions for the incorporation of different Industry 4.0 technologies were based on the reviewed literature related to Industry 4.0. As described below, this preliminary framework was then modified based on input from an expert panel and case study personnel.

In the ***second sub-phase***, to increase the reliability of the preliminary framework, an expert panel was approached. A total of 77 experts in different prominent manufacturing industries in India were contacted through their industries and via LinkedIn and asked to complete a survey providing their feedback on the preliminary framework. A total of 38 experts agreed to validate the preliminary framework; however, only 27 returned the feedback to the authors on time. The experts were chosen based on the following criteria:

(1) Work as an academician or in a manufacturing industry.

(2) Experience with LSS/GLSS/Sustainability/ Industry 4.0 projects.

(3) At least 15 years of experience in academics or industry.

Experts provided different suggestions to improve the framework to make it more robust, as presented in table 3.

In the ***third sub-phase***, to fine-tune the framework, inputs were taken from the personnel of a case manufacturing company through brainstorming sessions. The manufacturing industry is located in the national capital region of India and is a prime OEM of fuel injector pumps and other allied components. The organization is ISO: 9001.2008 and QS14001 certified and aims to have high customer satisfaction through the delivery of high-specification components. The selected industry expressed numerous operational concerns, including reduced utilization of available machines, a higher than desired defect rate, and a low level of automation; meanwhile, the industry also strives for emission reduction and a means of assessing social sustainability. Inputs were taken from 32 personnel from the case industry (1 general manager, 5 senior managers, 6 deputy managers, and 20 senior engineers) through five brainstorming sessions. As per feedback received from the case industry (table 4), significant changes have been made to the initially-developed preliminary framework to finalize it.

Table 3: Frameworks reviewed to formulate a preliminary framework of GLSS-Industry 4.0

Table 4: Input from experts and case industry personnel to develop the GLSS-Industry 4.0 framework

In the ***final sub-phase***, to validate the developed framework, the viewpoint of practitioners with expertise in operation excellence approaches, Green technology, and Industry 4.0 technologies across the world was sought. This validation method is in line with previous studies that have also validated conceptual frameworks of Lean with Industry 4.0 using opinions from experts (Tortorella et al. 2021). Since this research focusses on framework development of an integrated GLSS-Industry 4.0 approach, we aimed at practitioners that were utilizing Green technology methods, operational excellence methods, and I4.0 technologies. The respondents also must play a leadership role in their companies, so that they could have a broader view of their companies and respective processes.

For the validation, the authors developed a questionnaire instrument embedded with different questions related to the potential of the framework to improve sustainability, the appropriateness of the tools provided with each stage, and the potential for future adoption of the developed framework. The questionnaire was sent to 40 expert practitioners across the globe who had significant experience in conducting operational excellence approaches and Industry 4.0 practices. 25 complete questionnaires were received; the demographics of the responding practitioners are given in table 5. The questionnaire is appended in the supplementary files.

Table 5: Demographic detail for the practitioners of OPEX, Green technology and Industry 4.0

Overall, the feedback of the experts supported the validity of the proposed framework, and also suggested a few final modifications to the framework. Specifically, the practitioners suggested incorporation of additional tools (fishbone diagram, SWOT, BDA, 7S, etc.) at different steps of execution. The practitioners also provided valuable feedbacks on the synergy of tools and techniques of GLSS and I4.0, and provided other useful insights to make the developed framework to be more practicably adaptable. The practitioners found that the developed framework, with the suggested changes, was capable to improve the different quality, social and environmental metrics of the industry.

4. Proposed theoretical integration model of Green Lean Six Sigma with Industry 4.0

Although GLSS and Industry 4.0 are two different methods, they are synergetic as they jointly focus on the reduction of wastes and defects and optimum resource utilization. Therefore, common principles and tools of these unique approaches can be integrated under the GLSS-Industry 4.0 approach. The proposed theoretical integration model of GLSS with Industry 4.0 (figure 5) provides a novel model of sustainability enhancement for organizations. In the proposed model, enablers work as inputs as they facilitate organizations to successfully execute the novel method (Kaswan and Rathi 2020b). Barriers also serve as key inputs to the integration model as they facilitate organizational readiness for implementation by unearthing hidden aspects and potential stumbling blocks. Tools of GLSS and technologies of Industry 4.0, when applied to the unique processes and context, serve common purposes to reduce wastes, defects, and emissions. Thus, the tools and techniques of both approaches can be integrated at different stages of the realization of a product or service. The output of the model is in terms of all the key dimensions of sustainability as the main theme of both approaches is to make organizations more sustainable. Thus, both approaches provide a synergy that fosters their integration under the umbrella of GLSS-Industry 4.0.

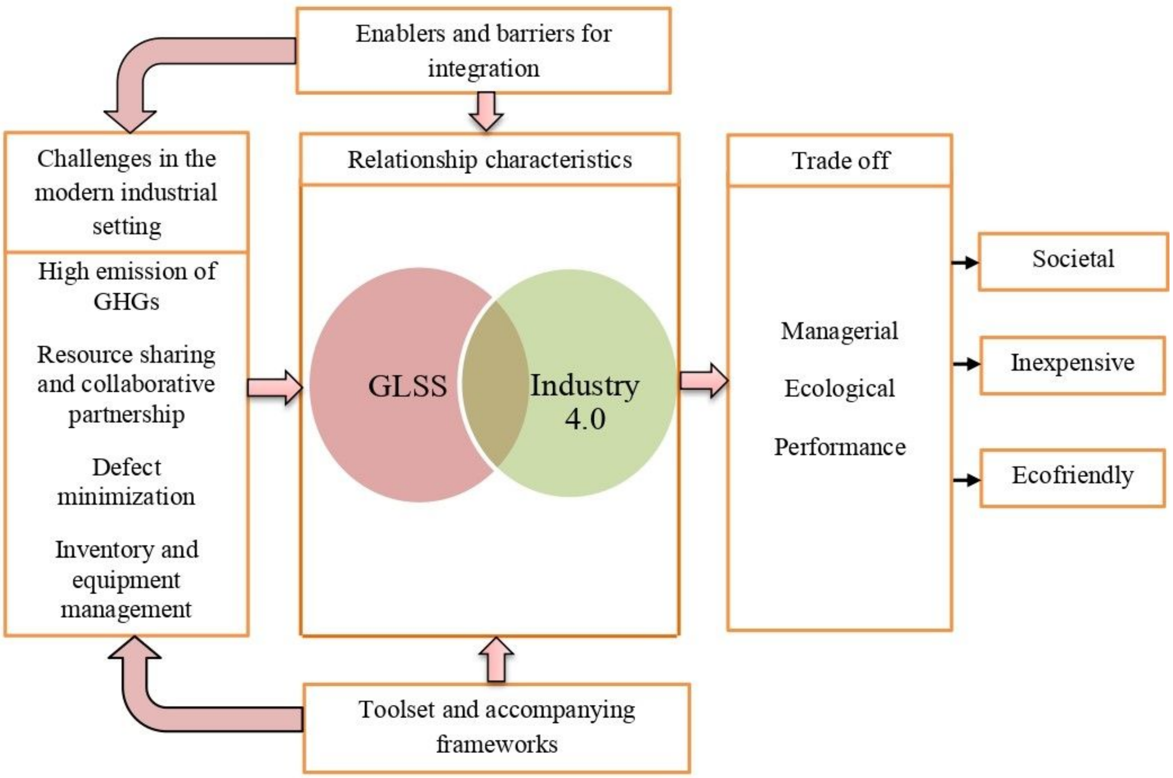

Figure 5. Proposed theoretical integration model of GLSS-Industry 4.0

Table 6 enumerates different enablers related to the implementation of an integrated GLSS and Industry 4.0 approach found in the literature on Lean, LSS, GLSS, and Industry 4.0, respectively. Managerial commitment, integration of technologies, and financial credit are key enablers to ensure the successful execution of this integrated approach (Karnik et al. 2021). Management aspiration to enhance sustainability may be a significant driving force behind the introduction of Integrated GLSS Industry 4.0 technologies. By applying digital, environmental, and social assessment/improvement tools, industrial managers can strengthen both their decision-making and performance appraisal.

Table 7 depicts different barriers to implementing this approach drawn from the literature. Lack of organizational readiness to adopt new technologies due to lack of technical know-how, difficulty in integrating different technologies, lack of management commitment, and poor organizational culture are key barriers to implementing this novel approach (Kaswan et al. 2021).

Table 6. Enablers of integrated GLSS-Industry 4.0 approach

Table 7. Barriers to integrated GLSS-Industry 4.0 approach

5. Proposed integrated Green Lean Six Sigma-Industry 4.0 framework

As GLSS-Industry 4.0 integration is in its infancy, to foster this sustainable approach, it is essential to have a generic framework that describes the systematic application of integrated GLSS-Industry 4.0. This research proposes a conceptual, systematic framework of the integrated GLSS-Industry 4.0 approach (figure 6) that can be implemented by any industry, as described in the following sub-sections.

Step 1: Identify a suitable project

In the first step, a suitable project is identified by the organization. For this, the voice of stakeholders (voice of customers and business), level of waste, environmental footprints, defects, etc. is taken into consideration. In this regard, it is recommended that the project be conducted in a particular segment/section of the organization selected to kick off this sustainable approach. Previous research suggests that 40% of GLSS projects fail due to inappropriate project identification (Kaswan et al. 2021). Therefore, to identify a suitable project, a careful study of the organization is needed, including real-time data collection and exchange. First, different criteria were finalized against which a project will be evaluated (such as different materials, productivity, environmental, social, waste, and facility metrics). Thereafter, weights of criteria are established based on the requirement of the industry. Once the weights are established, each project is evaluated against the criteria and the final score is calculated. The project which exhibits the highest score is selected for the execution of the framework. It was recommended, based on the feedback from the practitioners, to embed a SWOT analysis for funneling the project as it enabled know-how of the current position and scenario of the industry undertaken and what were the possible threats and opportunities for the firm at present. Based on the systematic understanding of the possible assets, pitfalls, and possible opportunities and threats (from competitors, regulation, and other regulatory or governmental bodies), the project undertaken was further considered for the next step of the execution of the framework. An inclusive application of different Industry 4.0 tools and techniques such as big data and sensors are required to gather and analyze data in this step. Once the project is selected, a project charter is created, which outlines the role of the project team, deadlines, and scope.

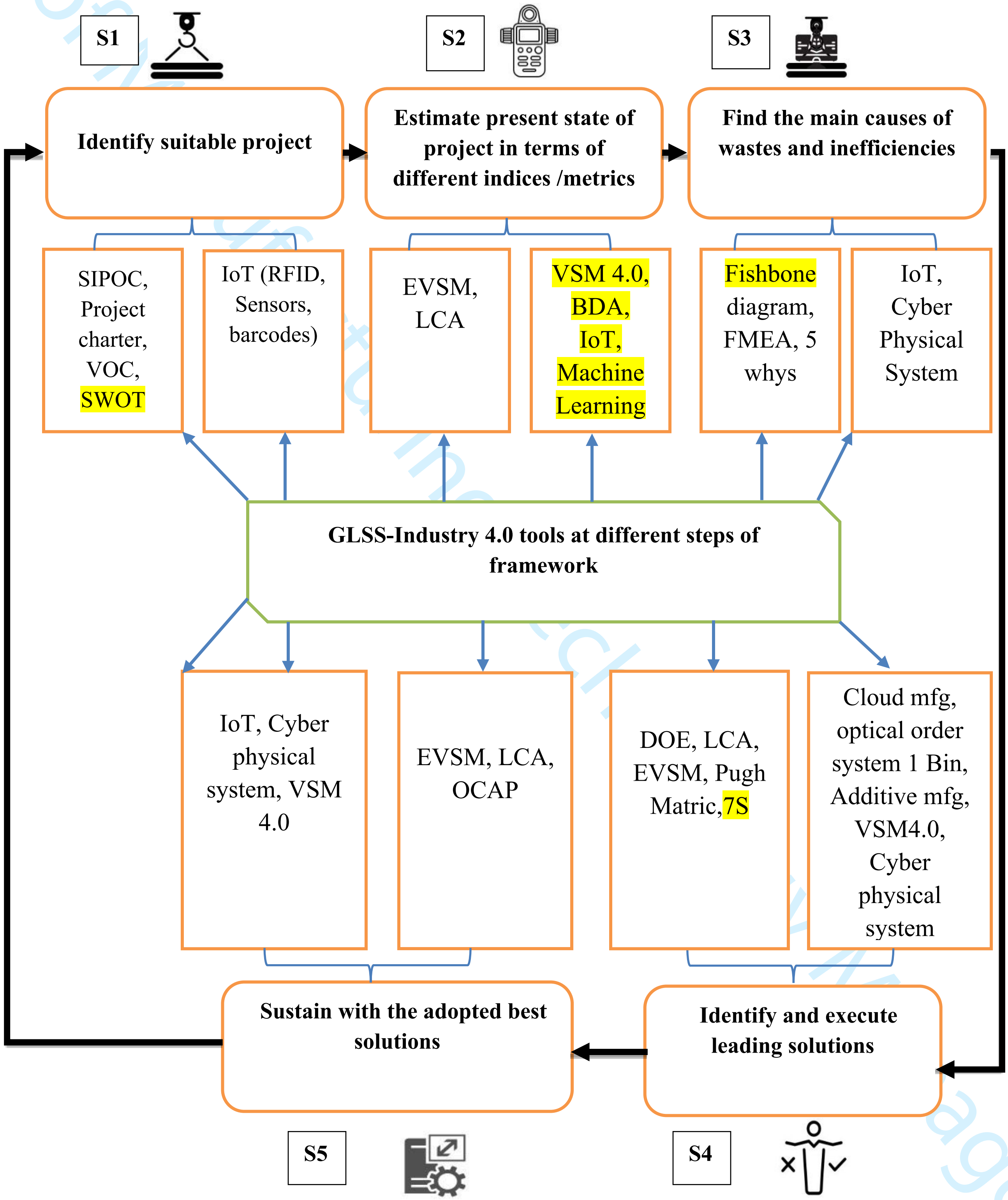

Figure 6: Proposed integrated GLSS-Industry 4.0 framework

Step 2: Estimate the present state of the project in terms of different indices and metrics

In this step, the current state of the considered project is estimated with different sustainability metrics. This step aligns with the popular belief that measurement is a prerequisite for identifying reasons for low performance. Metrics related to deviation, downtime, defects per million opportunities (DPMO), and capabilities are estimated using GLSS tools. Complex data patterns related to multifactorial expressions, such as the power required for starting a spindle, need smart tools to gauge such metrics. Moreover, some industries experience fluctuation in the power, which further increases the complexity of establishing an energy utilization model. For achieving energy-efficient production, machine energy consumption must be adjudged in real-time. Inclusive applications of sensors, big data, and CPS supplement real-time data collection, monitoring, and assessment of the different elements associated with the process under consideration. For example, due to the incorporation of different sensors in the Industry 4.0 model, a wide range of data was collected. Machine learning's deep neural network (DNN) can then be applied to find the energy consumption trends based on data gathered using continuous monitoring through sensors.

The energy consumption trend works as an effective metric that can be optimized to reduce industrial energy consumption. Further, other Green metrics, such as green energy coefficients, consumption of greenhouse gases (GHG), eutrophication, acidification, etc. are calculated using LCA. SLCA is required to monitor performance in different metrics related to social sustainability (labor rights, social economy, community engagement, and value chain responsible practices) to find the overall social sustainability of the industry. The application of big data enables the collection and analysis of large data sets of different sub-parameters related to the four major parameters of social sustainability to estimate final social sustainability. A model to estimate the final social sustainability is presented in figure 6. Furthermore, value stream mapping 4.0 (VSM 4.0) supplements the estimation of traditional metrics related to cycle time, lead time, material, water waste, etc.

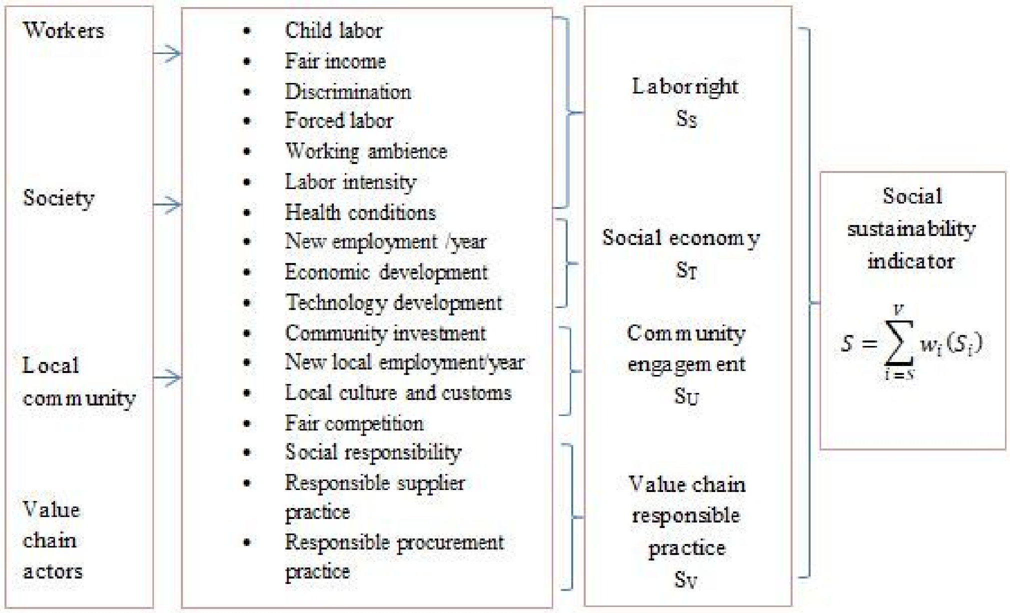

Figure 7. Social sustainability assessment model for industry

Step 3: Find the main causes of waste and inefficiencies

In this step, the reasons for the current level of waste, emissions, and social sustainability are determined. For this, the entire project is mapped in terms of value-added (VA) and NVA activities. Then, based on the specific NVA activities identified, brainstorming sessions are planned where organizational members unearth possible reasons for the same. Tools, failure mode and effect analysis (FMEA), 5 why, cause-and-effect (C & E) diagram, etc. are used at this stage to determine possible reasons for inefficiencies. Big data and other statistical tools can be applied to identify clusters of possible causes for low organizational sustainability. For this, a large set of data are collected from different sources, such as observations from persons working on the shop floor, from different sensors equipped with machine tools, and from every facet of the organization related to production. Data gathered is matched with set standards and if a deviation is present, this is reported to management, and possible reasons for the same are identified using brainstorming sessions.

After this, the search focuses on constricting the causes to a relatively small number that are potentially most significant. Tools such as Pareto chart, principal component analysis, regression, etc., are used at this juncture. The outcome of this step is the identification of critical reasons for reduced organizational efficacy that need immediate action to ensure a sustainable business.

Step 4: Identify and execute leading solutions

In this step, solutions are proposed and tested, and the best ones are implemented. The solutions provided at this stage will often include GLSS tools and/or Industry 4.0 technologies, such as: Replacing an existing

- Computer numerical control (CNC) machine with a 3 dimensions (3D) printing machine to save energy and material
- Use of kaizen activities to improve the environmental performance of the industry
- Redesigning a work cell with a collaborative robot (COBOT) and augmented reality (AR)
- Managing the flow of material through an integrated application of 5S, sensors, and Radio-Frequency Identification (RFID)
- Improving logistics through a smart human interface (3D glass and tablet) with the intervention of augmented reality

One possible solution for maintenance and energy-efficient production systems is the use of CPS-powered smart machine tools to manufacture the products. CPS brings together a physical and virtual world where smart objects communicate and interact with one another (Zheng et al., 2018). Smart machine tools are a combination of different CPS. Critical components of the machine tools are enabled with RFID tags to identify unique physical objects. Various sensors, cameras, and different data acquisition devices are attached to machine tools to gather data on critical components and the machining process. Data gathered are then transferred, integrated, and managed by communication services. Different communication technologies such as Ethernet, 4G, etc., can be used to transmit data depending on data acquisition devices. Further, after gathering all data, a digital twin for each critical component is modelled to comprehensively represent its physical attributes and real-time status simultaneously. Standardized data communication protocols and information modelling methods such as MTConnect are used to translate data gathered from different devices that can be used for most software applications. Data gathered is used by smart visibility services. The status of critical components of the machine tools is adjudged by remotely located mobile devices such as smartphones and tablets by using data sets obtained from field-level devices. Statistical reports on machine tool status can be directly estimated using ERP packages, thus fostering seamless communication between shop floor manufacturing and high-level decision-making. Comprehensive data is gathered by saving each critical component in the cloud and locally by recording real-time data provided by communication devices. DNN enable energy-efficient manufacturing through the use of high-quality data sets. Input and output determination is the first procedure in DNN. The input includes machine tools, cutting tools, materials of parts to be machined, other parameters, machining strategies, transporters, and auxiliaries. The output is the energy consumption of each stage during the machining processes. Different cutting tools possess different parameter ranges (e.g., cutting velocity and feed rate). The machine tool, cutting tool, and material jointly determine the cutting energy consumption, which thus becomes a variable energy demand. The relationship between the combination of parameters and cutting energy consumption can therefore be established via DNN to provide an optimum set of parameters for maximum energy utilization. Moreover, prognostic and health management algorithms can be applied to data gathered from components to estimate the health status of each critical component so that proactive maintenance can be applied to avoid machine failure or avoid machine downtime. Figure 8 depicts a CPS-enabled system for predictive maintenance and energy-efficient production.

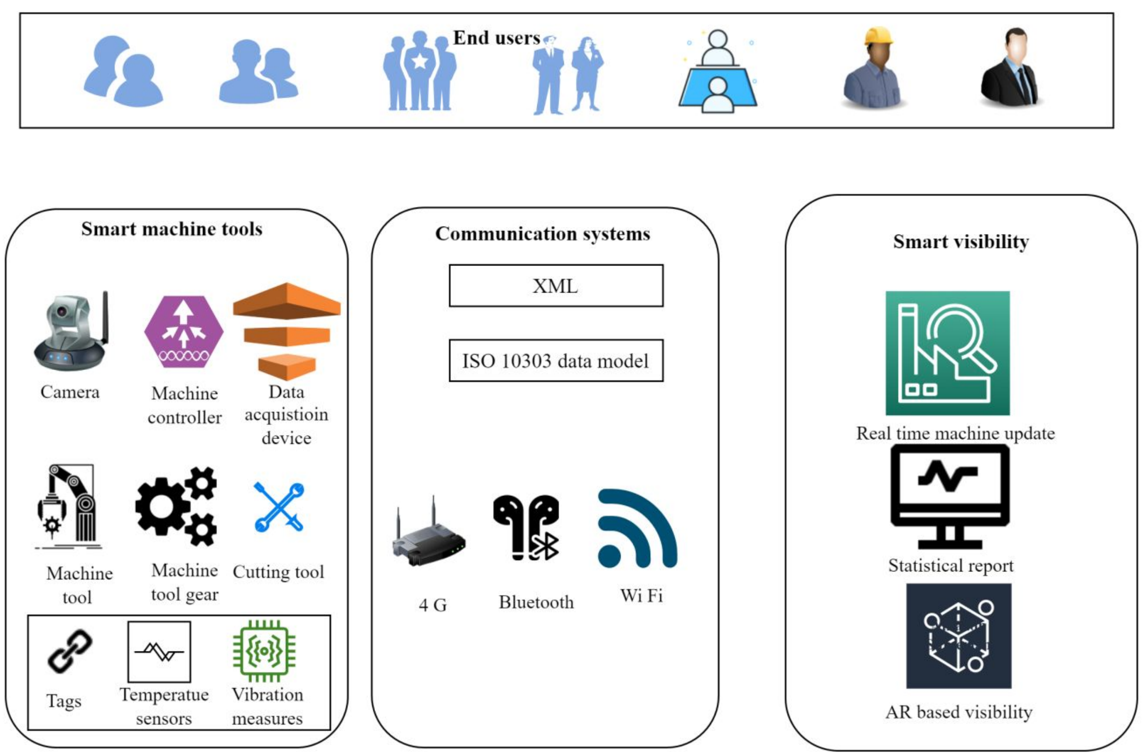

Figure 8: CPS-powered machine tool system for predictive maintenance and energy-efficient production

To improve environmental and social sustainability, various kaizen activities can be carried out. For improving ecological aspects, a comprehensive LCA may be applied to measure environmental sustainability. Thereafter, measures such as water recirculation systems and the use of non-stick lining for water tanks can be used to reduce water usage. In addition, a large amount of data is provided through big data and subsequent optimization of machining parameters, leading to better machining and reduced usage of materials. These kaizen measures can lead to improvement in environmental sustainability, once LCA is re-conducted. Further, the organization can also plan socially-focused kaizen activities such as education of the local population in terms of usage and disposal of different products and components. Such activities are expected to increase sales of products, responsible usage and disposal of the products and components, and feedback to the company for further product enhancements. A high degree of creativity is desired from participating employees to identify the best solutions among the available ones. The team should also recognized that the integrated application of GLSS tools and Industry 4.0 technologies often leads to the most promising solutions for improved organizational sustainability. Tools such as the Pugh matrix, Design of Experiments (DOE), and Critical to Quality (CTQ) have been used here to identify the strengths and weaknesses of the proposed solutions. Once the best solutions are identified, the entire VSM is revised to support the best-identified solutions. Metrics related to sustainability are re-evaluated to check whether adopted solutions realize their potential. The promising solutions have been documented, concerned persons have been trained in the different facets of the solutions, and solutions were launched in the concerned organization.

Step 5: Sustain with the adopted best solutions

This step of the proposed integrated GLSS-Industry 4.0 framework focuses on completing the selected project and transferring the improved work process to the organization with procedures for maintaining the required benefits. In this step, supporting methods are developed, and documentation is completed to sustain full-scale implementation. To ensure sustained gains through the adopted methods, AR/sensor-assisted Poka-yoke and Jidoka are used to ensure safety and reduce errors in the work process. To monitor the process, tools such as cyber technologies could be used to allow visual control in real-time process performance. In this step, the performance of the project should be monitored continuously over the long term; if variations from the adopted process or performance are found, then a required OCAP must be initiated. Finally, after the application of the best solutions, the entire project should be re-evaluated in terms of the different sustainability metrics. If the performance with the adopted solution is better than the measuring step (step 2), then solutions would be sustained and launched in other parts of the organization.

6. Discussion

Although it is impossible to have zero negative environmental impact, there are always ways to reduce it. LSS has been widely used by organizations to improve organizational performance but comparatively, few attempts have been made to explore the efficacy of GLSS. Moreover, to remain competitive in this volatile, uncertain, complex, and ambiguous (VUCA) world, organizations have to adopt technologies that promote quick steps, information exchange, safety, and environmental consciousness. Integrated GLSS-Industry 4.0 is a unique approach to support these aims. Yet, the integration of eco-friendly approaches with Industry 4.0 is still in the early phases. One significant challenge for organizations that want to incorporate GLSS and Industry 4.0 technologies is the lack of a unified road map. Previous research has found that the incorporation of LSS with Industry 4.0 faces challenges related to the identification of different metrics and tools at numerous junctures of the LSS project (Chiarini and Kumar 2021). This research provides a detailed investigation into enablers, barriers, tools, and metrics that facilitates managers and other practitioners to have a comprehensive understanding of this integrated approach. Furthermore, this study also proposes a framework for implementing this integrated approach that will prompt organizations to mitigate current levels of emissions, waste, and defects.

The logical integration of GLSS and I4.0 is being established through the development of a framework. I4.0 is an enabler when implementing Six Sigma as it helps to capture a big set of data. By leveraging I4.0 technology, LSS (or Lean and Six Sigma separately) makes use of data-driven methods. Similarly, process improvements can better leverage innovative technologies, such as data collection and analysis. The framework proposed represents the basic tenets of LSS, Green manufacturing and I4.0, and it will be a guiding beacon for companies to demonstrate environmental consciousness in the era of disruptive technologies. Tools provided at numerous steps of the execution framework add to the identification, analysis, and improvement of different metrics related to sustainability. The steps involved in the execution framework present a systematic application of the well-established DMAIC method with a closed-loop system to assure sustainability dynamics. During the validation of the framework, practitioners suggested including a closed-loop framework to ensure sustainability, thus this feedback directly from sustain phase to project selection has been inserted in the framework. A project that is not able to provide the required set of results during the sustain phase must be sent back to the project selection stage to identify another project that taps higher potential for sustainability improvement. It is further recommended based on the feedback from the practitioners to embed SWOT analysis for the funnelling of the project, as it enables the identification of the possible threats and opportunities for the firm at present. Based on the systematic understanding of the possible assets, pitfalls, opportunities and threats (from competitors, regulation, and other governmental bodies), a project undertaken is further considered for the next step of the execution of the framework. The framework steps are established beginning with the selection of a project that exhibits a high level of sustainability improvement if executed sequentially in the subsequent steps. Different metrics related to all aspects of sustainability are assured using different tools such as LCA, SLCA, IoT, big data, and machine learning. LCA is one of the most viable tools to assess environmental metrics when there is a large set of data present. Moreover, the systematic application of big data provides a large set of data that is further analyzed by SLCA to find different metrics related to social sustainability. To analyze reasons for low sustainability different non-value-added activities are identified and brainstorming sessions are planned where organizational members unearth possible reasons for the same. Tools such as failure mode and effect analysis (FMEA), 5 why, fishbone diagram, etc. are used at this stage to determine possible reasons. Big data and other statistical tools are applied to identify clusters of possible causes for low organizational sustainability. For this, a large set of data are collected from different sources, such as observations from persons working on the shop floor, from different sensors equipped with machine tools, and from every facet of the organization related to production. After this, the search focuses on constricting the causes to a relatively small number that are potentially most significant. Tools such as Pareto chart, principal component analysis, regression, etc., are used at this juncture. The outcome of this step is the identification of critical reasons for reduced organizational efficacy that need immediate action.

Practitioners suggested including simulation tools to assess risk analysis; for this, simulation tools like EVSM are inserted in the analysis phase, to understand what the process will look like after required measures are undertaken so that wastes of time and other resources can be avoided. EVSM based on enabled features provides how the process will look after the incorporation of required changes; this leads to foreseeing or simulating the process, which will lead to considerable savings in time before actual execution. If the results through EVSM do not look promising during the trial, then additional changes are incorporated and EVSM is executed again. Big data provides a wide spectrum of data related to processing parameters and facilitates analyses resulting in the optimum selection of parameters. CPS-powered smart machine tools support energy-efficient production, while sensors enabled by machines support quick changeovers, reduce error due to human involvement, and facilitate the accurate location of parts, which further leads to waste reduction. Additive manufacturing facilitates faster production and reduces material waste, contributing to environmental sustainability. To improve environmental and social sustainability, various kaizen activities should be utilized. Measures such as water recirculation systems and the use of non-stick lining for water tanks can be used to reduce water usage. In addition, a large amount of data is provided through big data and subsequent optimization of machining parameters, leading to better machining and reduced usage of materials. These kaizen measures lead to improvement in environmental sustainability, once LCA is re-conducted. Further, the industry can also plan socially-focused kaizen activities such as education of the local population in terms of usage and disposal of different products and components. Such activities are expected to increase sales of the products, responsible usage and disposal of the products and components, and feedback to the company for further product enhancements. To ensure sustained gains through the adopted methods, AR/sensor-assisted Poka-yoke and Jidoka are used to ensure safety and reduce errors in the work process. To monitor the process, tools such as cyber technologies are used to allow visual control in real-time process performance. In this sustain phase of the framework, the performance of the project is monitored continuously for a longer duration; if variations from the adopted process or performance are found, then a required OCAP is initiated. Finally, after the application of the best solutions, the entire project is re-evaluated in terms of the different sustainability metrics. If the performance with the adopted solution is better than the measuring step (step 2), then solutions are sustained and launched in other projects within the organization.

Feedback from the validation phase indicates the provided toolset in the framework is appropriate for practical application within a service or manufacturing organization. Further changes can be proposed in the framework depending on the obstacles encountered during its implementation. Further, the feedback suggests the framework is promising to improve all aspects of sustainability (social, environmental, or economic). While all dimensions should be considered, their relative importance will vary based on the company's needs and the industry it operates.

To support the application of the framework, a certain skill set needs to be defined for the employees working at management and non-management levels. GLSS and Industry 4.0 are new paradigms for many industries; thus, an organization that plans to implement either of these practices or the integration of both needs to closely plan and monitor the relevant pieces of training. Further, this will also be a big challenge for human resources as GLSS-I4.0 is in its infancy. Investment will always be necessary for at least one of three dimensions: hiring (acquiring knowledge), training (developing the necessary knowledge), and technology/infrastructure. Further, training and development will help to deploy the framework with minimum resistance and optimal utilization of resources. The extent of investment will depend upon the nature of the industry and its business model. For example, many SMEs will have to invest significantly in the technologies, people, and training for implementation. For other industries where LSS concepts are already implemented and in use, they will not require robust training in LSS. However, there will certainly be a need for staff with new qualifications, especially, employees who are proficient in IoT, big data, and cloud systems. Lean managers will require additional training in digitization and Industry 4.0. Organizations need to make some further investments in digitizing processes and implementing I4.0. In these cases, the incorporation of GLSS will only be a change in management principles, the adoption of new working methods, and research into the continuous improvement of the organization.

The proposed framework will serve as a checklist to ensure that all dimensions and building blocks are considered. It can help companies identify high-impact initiatives and develop robust roadmaps with clearly defined phases, targets, and timelines for implementing those initiatives. It can also be used for measuring and refining initiatives over a multi-year period once a company has developed its transformation roadmap. To ensure the success of the integrated framework, companies need to have a Lean management infrastructure. Otherwise, this structure can be a source of digital waste, especially if the technology infrastructure has an insufficient employee portfolio. The proposed framework overall follows the format of DMAIC, which is a familiar practice among practitioners and supports organizations to implement an integrated GLSS-Industry 4.0 approach through the suggested framework. Although the integration of digital technologies would require adequate skillset, which would be different as compared to the traditional ways of working, the basic theme behind the working would be a simple and familiar one. The proposed framework can be used in industrial settings due to its simple format and specifically in SC where many of the processes are already integrated with Industry 4.0. Quality inspections are monitored online, which provides real-time data. Automated production lines are specifically designed to give minimum waste and variations in the product. Thus, LSS and Industry 4.0 aspects are already in place in many SC applications. The integrated model of GLSS-I4.0 would be milestone in terms of increasing sustainability and eliminating waste. The developed framework can connect industrial processes, and standardize with good logic the way to focus continued improvement utilizing different sets of GLSS-Industry tools and techniques.

Embedding GLSS-Industry 4.0 initiatives in organizational objectives makes everyone liable for the success of this sustainable approach. Therefore, different tools and techniques of this approach must be integrated with organizational objectives so that the success of the approach can be sustained. Table 8 presents different tools and techniques of integrated GLSS-Industry 4.0 at different steps of project execution. As can be seen, many have applicability at multiple steps. Further, synergies between the two toolsets prompt the integration of the GLSS and Industry 4.0 approaches under a unified approach. For instance, the application of specific Industry 4.0 technologies often supports Green initiatives, and, conversely, GLSS tools often support the implementation of Industry 4.0. Thus, the combined application of tools and techniques within an integrated approach leads to better project selection, assessment of different metrics, and identification of the best solution to enrich organizational sustainability.

Table 8: Tools and Techniques of Integrated GLSS-Industry 4.0 at different steps of the project

The application of integrated GLSS-Industry 4.0 through the theoretical model and the proposed framework contributes to the body of literature focused on achieving more resilient and sustainable organizations. Siegel et al. (2022) presented a framework of Green Lean based on the theoretical construct but lacked measures to assess social and environmental sustainability; the present study demonstrates how the organization can assess these metrics using GLSS tools such as LCA and SLCA. In addition, the current study advances earlier research related to the integration of Lean (e.g., Shahin et al., 2020) and LSS (e.g., Chiarini and Kumar, 2020) with Industry 4.0 by providing methods to identify, assess, and improve different metrics related to environmental and social sustainability. Moreover, the study also advances existing GLSS studies, such as Rathi et al. (2022), by enumerating how different technologies of Industry 4.0 can be embedded within a GLSS project. Further, the application of different technologies of Industry 4.0 to make the system more environmentally sustainable also adds to the existing GLSS framework proposed by Cherrafi et al. (2016). For example, this study depicts how the CPS-based model from the machine tool literature can be used to provide predictive machine maintenance and energy-efficient production cells.

6.1 Implications

There is an immense need to accelerate the global response to mitigate emissions through the use of eco-friendly operational measures. The proposed integrated GLSS-Industry 4.0 approach supports organizations to improve environmental as well as operational efficacy. This study provides impetus to practitioners to adopt the integrated GLSS-Industry 4.0 approach through insights from the theoretical model and execution framework. The implementation framework provides step-by-step guidelines for practitioners to execute this approach, including different tools and techniques to apply at different steps. This research motivates practitioners to reexamine operations and resources, and incorporate sustainability methods. Researchers can also use the insights regarding different tools, techniques, enablers, and barriers of this integrated approach. Strengthening the theoretical knowledge base of this integrated approach will further foster researchers' capability to identify and assess different metrics related to sustainability.

The study also has potential policy implications for governmental and environmental agencies by suggesting applications of different tools and techniques of an integrated approach to foster sustainability pursuits. It provides recommended methods to assess and improve social and environmental sustainability. Further, the study supports manufacturers and ecologists to implement a GLSS-Industry 4.0 approach to reinforce organizational image on a global platform through systematic improvement in sustainability metrics. Society can ultimately benefit from this study in terms of improved emissions, workplace safety, and utilization of precious natural resources through the application of the integrated approach.

7. Conclusion, limitations, and future research agenda

The paper proposes that an integrated GLSS-Industry 4.0 approach leads to the mitigation of emissions, by making processes automated, streamlined, and more responsive, which eventually results in the specification of sustainable products. Integration of GLSS and Industry 4.0 has been proposed based on theoretical elements: enablers, barriers, tools, and techniques. Enablers work as boosters of the implementation approach, whereas barriers work as hindrances; a systematic understanding of both facilitates mitigation actions and the development of theoretical "know-how" behind the execution of the proposed integrated GLSS-Industry 4.0 approach. Further, an initial, generic conceptual framework of integrated GLSS-Industry 4.0 has been proposed, providing a method to execute the integrated approach starting from project selection to sustaining the improvements made. The proposed framework has been embedded with key tools and techniques throughout. Despite several contributions, the study has its limitations. A primary one is the conceptual nature of the proposed framework. While literature review, feedback from academic and industry subject matter experts and case industry personnel, and a validation study were used to develop and validate the framework, there is a need to fully test the proposed framework by implementing it in one or more case study organizations. Other future research work can be directed toward determining which enablers and barriers play the most significant role in the success of this integrated approach in different contexts; this can help organizations better focus their scarce resources when implementing this integrated approach.

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Table 1: Review protocol

Unit of analysis	Journal articles of GLSS-Industry 4.0
Analysis type	Qualitative
Study time frame	2019-2022
Field of search	Keywords, title, abstract
Databases	Science Direct, Web of Science, Emerald, SCOPUS
Articles included in the study	43

Table 2: Prominent case studies on GLSS

Reference	Sector	Tools used	Main contribution
Cherrafi et al. (2017)	Food	(Suppliers, inputs, process, outputs, and customers) SIPOC, Project charter, 5S, Total Productive Maintenance (TPM), Green VSM, 3 R	Reduction in energy and water consumption
Ruben et al. (2017)	Automotive	EVSM, LCA, SIPOC, DMAIC, Kaizen, 7S, Pareto chart, DOE	Reduction of environmental impacts to 33 Pt from 42 Pt
Erdil et al. (2018)	Healthcare	Project charter, Process map, SIPOC, Critical-to-quality tree, Five whys	Reduction of hazardous chemicals in treated wastewater
Zhu, Johnson, and Sarkis (2018)	Healthcare	VSM, 5S, Root cause analysis, SIPOC, Fishbone diagram, Process mapping	Elimination of paper waste and reduction of carbon emissions in the medication delivery system.
Wang et al. (2019)	Electrical	K-sigma level, Quality index, capability analysis, 4R principles	Prolonged maintenance intervals, Evaluation of suppliers based on Green performance
Shokri and Li (2020)	Manufacturing	Quality-oriented CTQ, Design of experiments, Green oriented CTQ, Environmental impact analysis	Reduced energy consumption, Reduced environmental impact
Sony and Naik (2020)	Mining	DMAIC, Five whys, Project charter, Green wastes, Environmental goals & metrics	Reduction of dust pollution
Ershadi et al. (2021)	Chemical	Process diagram, Pareto chart, SPC, EVSM, LCA	Reduced consumption of chemicals and energy in the operations

Table 3: Frameworks reviewed to formulate a preliminary framework of GLSS-Industry 4.0

Source	Contribution	Limitations	Economic benefits	Environmental and social benefits	Practical case implementation
Ruben et al., (2017)	Proposed an LSS framework with environmental facets and implemented it within a manufacturing firm.	Included environmental and economic dimensions of sustainability but did not address the issue related to social sustainability.	Y	N	Y
Caiado et al. (2018)	Proposed a framework of GLSS based on the critical success factors for the service industry.	Limited to the service sector and did not provide methods to improve social and environmental sustainability.	Y	N	N
Zheng et al., (2018)	Proposed a framework for Industry 4.0 adoption using the application of different technologies.	Did not address how to estimate environmental and social sustainability	Y	N	N
Siegel et al., (2019)	Formulated an integrated Green Lean framework for SMEs based on the insights from the literature.	Does not encompass Six Sigma components and did not provide measures on how to improve different metrics related to environmental and social sustainability.	Y	N	N
Chiarini and Kumar, (2020)	Investigated possible integration of LSS tools and Industry 4.0 technologies based on grounded theory.	Limited to the integration of LSS with Industry 4.0 and did not address how a formal framework can be developed and executed.	N	Y	N
Kaswan and Rathi, 2020	Formulated an introductory GLSS framework based on literature review.	Did not address how to estimate and improve social sustainability, and was not tested through a case implementation.	Y	N	N
Shahin et al., (2020)	Provides a detailed review and reports on the connection between Lean tools and Industry 4.0 technologies.	Limited to examining integration between Lean and Industry 4.0 (no empirical test of the resulting findings was conducted) and does not	Y	Y	N

		consider social and environmental sustainability.			
Titmarsh et al., (2020)	Proposed a model of Six Sigma from the perspective of Industry 4.0 to achieve sustainable manufacturing requirements.	Did not address how to ascertain environmental sustainability metrics, and which specific tools of Six Sigma to apply to achieve social sustainability	Y	N	N
Belhadi et al., (2021)	Presented a framework of integrated big data and GLSS to improve the environmental performance of a chemical company.	Restricted to improving economic performance; no measures were taken to improve environmental and social sustainability.	Y	N	Y
Ershadi et al, (2021)	Proposed a method for selecting GLSS projects using data envelopment analysis and the concept of readiness level.	Only focuses on the project selection stage of GLSS is implementation.	Y	N	N
Rathi et al., (2022)	Proposed model to improve the environmental and economic sustainability using DMAIC-based framework	Study only encompass GLSS tools and can include industries 4.0 technologies to improve environmental and economic sustainability	Y	Y	Y

Table 4: Input from experts and case industry personnel to develop the GLSS-Industry 4.0 framework

Framework step	Experts input	Case industry personnel input	Modifications made in the framework
Identify suitable project	The initial framework apprised to select a sustainable-oriented project for integrated GLSS execution. However, it lacked the parameters on which project selection should be made. Experts suggested selecting the project based on the following criteria: environmental, social, productivity, material, and waste impact.	Case industry personnel input suggests evaluating each project against each criterion to select the most prominent project that leads to improved organizational sustainability. The changes here suggested by the case industry personnel were to weight the different criteria according to importance.	The preliminary framework only incorporated criteria related to the economic aspect of sustainability. Based on expert input, criteria related to social and environmental sustainability were included to select the most prominent sustainability-oriented projects, and, based on case industry personnel, methods to find the weights of different criteria were also incorporated.
Estimate the present state of the project in terms of different indices and capabilities	Experts suggested including more metrics to estimate the environmental and social sustainability. Experts also suggested utilizing VSM 4.0 and lifecycle assessment (LCA) to estimate different metrics related to environmental sustainability. Moreover, experts suggested incorporating social LCA (SLCA) measures to estimate the social sustainability level of the organization. Experts suggested using the application of sensors, big data, and CPS to find the correct data related to different metrics of sustainability of the organization	To evaluate the existing state of the system, case industry personnel suggested finding the level of material, water, and electricity used in a day to estimate lean and environmental measures of sustainability.	The preliminary framework was more focused on estimating the present system state in terms of Lean metrics. Expert input and case industry personnel input were incorporated to include more dimensions related to social and environmental sustainability.

Find the main causes of waste and inefficiencies	No suggested changes.	The industry personnel suggested that to identify the most likely reasons for low performance, all the responsible causes must be grouped into a few prominent categories, and these categories then evaluated to find the category that is the most responsible for lower organizational sustainability.	The preliminary framework did not include a categorization of the reasons for low performance. Based on input from case industry personnel, different reasons for poor organizational performance are now categorized and the search is narrowed down to identify the prominent categories of causes.
Explore possible solutions, find and implement the best solution to improve sustainability dynamics	Experts suggested incorporating the Pugh matrix so that the strengths and weaknesses of the proposed best solutions can be better evaluated. Experts also suggested embedding the sensors and IoT Industry 4.0 technologies with the 7S, Poka-yoke, and TPM following GLSS tools. Incorporation of Industry 4.0 technologies such as COBOT, AGVs, and VR was also suggested to achieve standardization in operations, minimization of errors, and automation of operations and other logistics-related activities	No suggested changes.	Based on expert suggestions, more tools were incorporated at this step to find the best solution to improve the sustainability dynamics of the industry. In particular, the incorporation of more synergetic tools of GLSS and Industry 4.0 was incorporated to enhance sustainability benefits.
Sustain with the adopted best solutions	Experts suggested using the adopted solution for the long run and estimating metrics related to ecological aspects using LCA, so the sustainability of the adopted solution can be ensured	Case industry personnel suggested using out of control action plan (OCAP) to take any corrective measures if the deviation is observed with the adopted method or solution	Based on the suggestions of experts and case industry personnel, organization performance is re-monitored, an OCAP plan is initiated, and actions are unified within the modified framework.

Table 5: Demographic detail for the practitioners of OPEX, Green technology and Industry 4.0

Expert	Designation	Years of experience in OPEX, Green technology, and /or Industry 4.0 practices	Country/Region
Expert 1	Change and continuous improvement manager	16	Ireland
Expert 2	Consultant	26	Germany
Expert 3	Deputy general manager	25	Italy
Expert 4	Senior engineer	18	United Kingdom
Expert 5	Manager	21	Germany
Expert 6	Sustainable development lab head	31	India
Expert 7	Professor	25	Portugal
Expert 8	Professor	24	New Zealand
Expert 9	Quality improvement manager	17	Switzerland
Expert 10	Senior manager	19	Portugal
Expert 11	Quality assurance engineer	15	USA
Expert 12	Senior lead engineer	28	Japan
Expert 13	Professor	24	United Kingdom
Expert 14	Manager	27	China
Expert 15	Senior manager	30	USA
Expert 16	Maintenance and quality assurance manager	22	Portugal
Expert 17	Chief technology officer	23	Switzerland
Expert 18	Chief executive engineer	19	Oman
Expert 19	Production manager	22	Japan
Expert 20	Quality control inspector	16	USA
Expert 21	Senior product engineer	18	Pakistan
Expert 22	Chief quality control executive	24	Pakistan
Expert 23	Assistant plant manager	25	India
Expert 24	Quality assurance manager	26	Germany
Expert 25	Operation manager	25	South Africa

Table 6: Enablers of integrated GLSS-Industry 4.0 approach

Enablers	Description	References
Managerial commitment	The incorporation of an integrated GLSS-Industry 4.0 approach will provide support for management activities. Management commitment to induce new and technical measures is key to the success of this integrated approach.	(Horváth and Szabó 2019);(Krishnan et al. 2021)
Continuous learning culture	This integrated technology will reveal new avenues for innovation in the business model and empowerment for enhanced innovative capabilities. This will bring the onus to the organizational members to learn new technological aspects and know-how.	(Krishnan et al. 2021)
Alignment of the integrated approach with organizational objectives	Alignment of integrated GLSS-Industry 4.0 with organizational objectives will make all levels of employees responsible for the success of this unified approach.	(Karnik et al. 2021)
Availability of financial credit	Both GLSS and Industry 4.0 are capital intensive due to the incorporation of new technologies and intensive training requirements. Availability of funds within organizations is critical to this integrated method.	(Krishnan et al. 2021)
Organizational readiness	It is imperative to have the organization in a quick decisive and risk tolerant position as inclusion of an integrated GLSS-Industry 4.0 approach will bring new challenges and technological transfer.	(Jain and Ajmera 2020)
Relationship management with SC	As GLSS-Industry 4.0 highly relies on an extensive set of data from all the partners of the SC, the organization must have strategic relations with all partners of the SC to ensure the realization of this unified approach.	(Krishnan et al. 2021)
Data analysis and metrics identification	To ensure sustainability in the selected project, different metrics that cover all dimensions of sustainability must be identified and analyzed.	(Jain and Ajmera 2020); (Karnik et al. 2021)
Innovation in product and service	To be a leader in the world market, an organization needs to induce innovative measures for efficacy, knowledge, know-how, goods, and services.	(Horváth and Szabó 2019)
Standard uniformity	To reinforce the implementation of an integrated GLSS-Industry 4.0 approach, it is imperative to have unified standards for the exchange of information.	(Jain and Ajmera 2020)

Table 7: Barriers to integrated GLSS-Industry 4.0 approach

Barriers	Description	References
Lacuna in training	Inadequate training in different facets of improvement is a major factor inhibiting comprehensive change within a business and the adoption of a new approach.	(Kumar, Bhamu, and Sangwan 2021); (Surange et al. 2022)
Investment constraints	Execution of Industry 4.0 and GLSS demands huge investment in the procurement of technology and other aspects.	(Yilmaz et al. 2022)
Organizational culture	A strong culture is one of the most important aspects to continue sustaining initiatives in the competitive environment. Poor organizational culture causes detached employees, mismatched company values, harmful work-life balance, and poor customer relations.	(Horváth and Szabó 2019);(Surange et al. 2022)
Technological readiness	Reducing NVA activities and improving performance metrics requires incorporation of new technologies.	(Khanzode et al. 2021)
Lack of adequate framework	Implementing a novel approach benefits from existing frameworks or standard methods. Otherwise, proper benchmarking cannot be established.	(Surange et al. 2022)
Standardization issue	Integration of GLSS-Industry 4.0 technologies across the SC can be hindered by nonexistence of standards. Lack of standards includes both the need for technology standards and process standardization.	(Horváth and Szabó 2019)
Apprehension related to cyber security	Both of the approaches use a large set of data to analyze different prospects that is shared among different partners of the SC. Thus, data security and accessibility are also major barriers to ensuring success.	(Surange et al. 2022)
Job disruptions	The inclusion of new technology always brings challenges to the existing process and system. It also demands learning new approaches for improvement, and employees often may experience disruption in their current work.	(Kumar et al. 2021)
Technological integration	It is imperative to integrate different technologies of Industry 4.0 and GLSS tools at different steps of the execution of the project.	(Kamble et al. 2018)
Lack of managerial commitment	Execution of any novel approach requires a high level of commitment, as well as faith in employee ability, from the top management of the organization	(Horváth and Szabó 2019)

Table 8: Tools and Techniques of Integrated GLSS-Industry 4.0 at different steps of the project

	Step 1	Step 2	Step 3	Step 4	Step 5
Integrated GLSS-Industry 4.0 tools/techniques	Identify suitable project	Estimate the present state of the project in terms of various Green Lean indices and capabilities	Find the main causes of waste and inefficiencies	Explore various possible solutions, find and implement the best solution	Sustain with the adopted best solution
GLSS tools					
Project charter	√				
VOC	√				
VOB	√				
EVSM		√			
LCA		√		√	
5 whys			√		
Pareto chart			√		
Cause and Effect diagram			√		
Brainstorming			√	√	
Environmental impact analysis				√	
Green Scoreboard				√	
7S				√	
OCAP					√
Kaizen					√
Industry 4.0 technologies					
Big Data	√	√	√		
IoT	√	√	√	√	
Cyber security	√	√			√

CPS		√			
Cloud computing		√	√		
RFID		√	√	√	
Sensors		√	√	√	√
VSM 4.0		√			√
3 D Printing			√	√	
6R				√	
COBOT				√	
AR				√	√

Questionnaire to Validate Integrated Green Lean Six Sigma and Industry 4.0 Conceptual Framework

SECTION-A: (Study Background)

This research intends to answer the following research question: "**How can GLSS be integrated with Industry 4.0 to develop a generic framework for improved sustainability of organizations?**"

To develop the preliminary framework, existing literature was reviewed that explored integration between Lean and Industry 4.0, Green and Industry 4.0, LSS and Industry 4.0, and sustainability and Industry 4.0. Then, different frameworks related to LSS with environmental facets, GLSS with sustainability measures, Industry 4.0, and operational excellence methods were also explored to develop the preliminary framework of an integrated GLSS and Industry 4.0 approach. As described below, this preliminary framework was then modified based on input from an expert panel and case study personnel. To increase the reliability of the preliminary framework, an expert panel was approached. A total of 77 experts from different prominent manufacturing industries in India were contacted. A total of 38 experts agreed to validate the preliminary framework; however, only 27 returned the feedback to the authors on time. To fine-tune the framework, inputs were taken from the personnel of a case manufacturing company through brainstorming sessions. As per feedback received from the case industry, significant changes have been made to the initially-developed preliminary framework to finalize it. Finally, the conceptual framework has been developed and it consist of five steps (refer figure 1).

Step 1: Identify a suitable project

Step 2: Estimate the present state of the project in terms of different indices and metrics

Step 3: Find the main causes of waste and inefficiencies

Step 4: Identify and execute leading solutions

Step 5: Sustain with the adopted best solutions

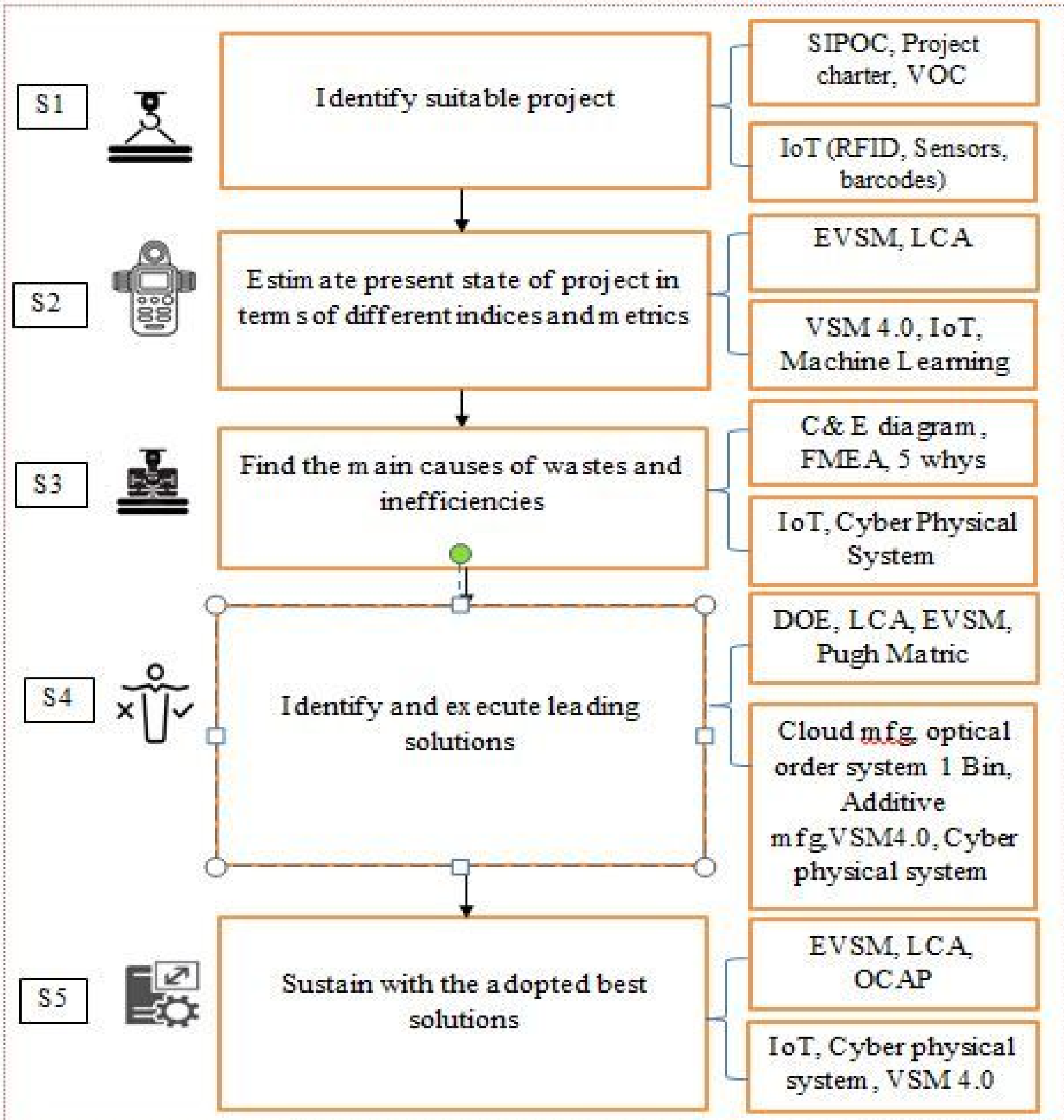

Figure 1: Proposed integrated GLSS-Industry 4.0 framework

SECTION –B (Questionnaire)

This is to solicit your participation in this study to validate the developed framework of integrated GLSS-Industry 4.0 for improved organizational efficacy, as a part of research under the aegis of Lovely Professional University, Khalifa University, Texas Technical University, and

University of Derby. It is assured that the information will be kept confidential and shall be used for academic purpose only. Please provide your useful insight for the research questions so that developed framework can be authenticated from the professional involved in practices of sustainable and advance technologies.

- Organization/ Industry Name:
- Location:
- Name of the Authority:
- Designation:
- Experience:
- Nature of Industry:

Q1. Do you experience that logical integration of Green Lean Six Sigma and Industry 4.0 is being established through developed framework? Why or why not? Any suggestions for improvement?

Q2. Do you experience that the toolset provided with framework is able to identify, estimate, and improve different metrics related to aspects of the sustainability? Why or why not? Any suggestions for improvement?

Q3. Does this framework successfully encapsulate sustainability dimensions with requisite identification and improvement measures? Why or why not? Any suggestions for improvement?

Q4. Do the provided tools of Green Lean Six Sigma and Industry 4.0 at the different stages of the execution framework exhibit synergy? Why or why not? Any suggestions for improvement?

Q5. Is the developed framework being appropriate to select a suitable sustainability oriented project? Why or why not? Any suggestions for improvement?

Q6. Do you believe the developed framework incorporation will require extra training and education on the different perspectives of integrated GLSS-Industry 4.0 approach in order for the implementing organization to tap the full potential of the proposed framework? Why or why not? Any suggestions for improvement?

Q7. Do you believe that an implementing organization will need to hire additional personnel, and/or invest in new technologies to ensure full scale implementation of the proposed framework? Why or why not? Any suggestions for improvement?

Q8. Overall, how useful do you believe the proposed framework will be to organizations seeking to implement an integrated GLSS-Industry 4.0 approach? Please briefly describe the rationale behind your answer.

Q9. Overall, if your organization was interested in implanting an integrated GLSS-Industry 4.0 approach would you recommend using the proposed framework. Why or why not?

