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Green Lean Six Sigma Practices: A Scale Development and Measurement Model from an Engineers Perspective

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Title: “Green Lean Six Sigma Practices: A Scale Development and Measurement Model from an Engineers Perspective”

To: Journal of Manufacturing Technology Management Editorial Office

Re: Response to Editor – a minor revision

Dear Editor,

We are uploading (1) the response below to the editor’s comment and (2) a revised manuscript with highlights in green indicating improvements in “Quick Value Overview”.

Your time and consideration are highly appreciated.

Best regards,

Corresponding author

July 23, 2024

Response to Editor Comments

Recommendation: **Minor Revision**

Comments:
I have read the reviewers' comments, and have read through your manuscript carefully. As a result, I am now in a position to conditionally accept your paper for publication; however, you must first make a minor revision. This relates to your quick value overview. This quick value overview is not in accordance to the intended purpose. In the last decision letter I provided you with examples of good quick value overviews that are concrete and concise. It is not obvious that you have looked at these examples. For instance, statements like "the study provides a novel theoretical framework" are not concrete. Please revise your quick value overview so that it does what it is supposed to do. Also, the examples provided no bulleted lists so it is unclear why you would formulate your quick value overview like that. Please take the time to develop an effective Quick Value Overview. Attach your detailed and anonymous response to the reviewers to the revised manuscript. I recommend doing this in the front so that it will be the first thing that the reviewers will see for the revision.

Response: the comment has been applied – please see 'Quick value overview'; we have accordingly improved it. Thank you for your consideration and comment.

Green Lean Six Sigma Practices: A Scale Development and Measurement Model from an Engineers Perspective

Abstract

Purpose

Since the advent of Industry 4.0, there has been a growing research interest in developing the Green Lean Six Sigma concept in the direction of achieving sustainable development, primarily aligned with Goal 12 of the agenda. Given that the concept is still in its early stages of exploration and requires further development through empirical validation, opportunities exist for innovative research. Yet, difficulties arise in adopting this green initiative due to an inadequate understanding of its strategic practices. Thus, this study aims to establish strategic practices facilitating its adoption in the Industry 4.0 era and develop a validated multi-item scale to measure the practices.

Design/methodology/approach

A three-phase methodological approach is designed to perform the techniques of exploratory and confirmatory analyses in the manufacturing context. To be a sound study, engineers have been involved since they play a pivotal role in the realm of manufacturing; however, the existing research on engineers' viewpoints on this subject is limited, emphasizing the need for further investigation.

Findings

Upon validation of the ultimate fallouts, the analyses demonstrated a confirmatory model with eighteen scales determining five practices: strategic integrity, human resource management, technologies and tools, eco-production, and eco-networks. The findings further revealed robust correlations among these core practices within the model.

Originality

The contribution of this study entails depicting and discussing a measurement model for future research since there is currently no empirically validated model available to measure this multidimensional green initiative.

Keywords: Green Lean Six Sigma, Industry 4.0, Manufacturing sustainability, Responsible consumption and production, Scale development, Empirical analyses

Quick value overview

Interesting because – This study addresses the critical alignment with 2030 Sustainable Development Goal 12 by delving into the integration of Green Lean Six Sigma (GLSS) within Industry 4.0. By uniquely incorporating an engineering perspective, it establishes strategic practices that facilitate its adoption in manufacturing, where achieving sustainable production poses significant challenges. This research stands out as it presents the first study to develop and validate a scale and measurement model for this green initiative.

Theoretical value – While existing literature reveals an increasing interest in adopting GLSS for developing sustainable manufacturing, this study stands apart by investigating GLSS concerning its strategic practices and performance levels. This research not only develops a validated scale but also proposes a measurement model that correlates GLSS performance levels with five strategic practices deemed crucial for its effective deployment.

Practical value – For practicing managers, it is critical to understand the extent of GLSS implementation within their organizations. By leveraging the developed scales and practices encapsulated in the measurement model, practitioners are empowered to assess the maturity level of GLSS adoption, gain insights into the current state, develop effective implementation plans, and benchmark against best practices across industries.

1. Introduction

The 2030 Sustainable Development Goal 12, mapped to the topic, stresses that global consumption and production—a driving force of the worldwide economy—are not exploiting the natural resources responsibly, i.e., they rely on the utilization of the natural resources in a manner perpetuating detrimental effects on "our common future (WCED, 1987)". This arises from the fact that various industrial activities exert a negative impact on the environment and society, depleting momentous resources while producing hazardous waste and emissions (Gholami et al., 2023). As an illustration, the United States Environmental Protection Agency (US EPA) observed that the majority (88%) of the 29.3 billion pounds of production-related waste managed in the U.S. for 2021 originated from manufacturing sectors (US EPA, 2023). Thus, the growing concerns surrounding the goal have generated more pressure on such industries, compelling them to adopt more effective green paradigms; the paradigms necessitate a heightened organizational concentration on environmental impact, taking into account its interplay with economic and social growth as well as its intrinsic value, such as Green Lean Six Sigma (Marcus and Fremeth, 2009; Gholami et al., 2021).

Ever since the emergence of the fourth industrial wave (Industry 4.0), there has been a growing research interest in integrating green practices into the lean Six Sigma (LSS) model (Letchumanan et al., 2022). This hybrid model, renowned for its efficacy in waste reduction and quality improvement through the minimization of process variability (Jamil et al., 2020; Chiarini and Kumar, 2021; Yadav and Al Owad, 2022), is hence evolving into a potent green paradigm known as Green LSS (GLSS). By merging the principles of LSS with a dedicated emphasis on environmental sustainability, GLSS seeks to achieve operational excellence while minimizing the environmental impact (Garza-Reyes, 2015; Cherrafi et al., 2017). Thus, this innovative initiative intends to incorporate the best of both worlds, harnessing the efficiency and effectiveness of LSS while proactively tackling environmental issues; by doing so, it can contribute to promoting sustainable and responsible consumption and production practices in the industrial realm. Although the definition of GLSS is numerous and differs among researchers, it is important to apply a more accurate definition to integrate the concept. The definition suggested by Gholami et al. (2021) and Letchumanan et al. (2022)—GLSS is "*a business strategy contributing to the circular economy*" via embracing the Rs, i.e., reduce, reuse, recycle, etc., through (digital) green

Gemba walks—is found to be more comprehensive in this study. According to Akter et al. (2022), the circular economy is considered a crucial knowledge domain in the sustainable development (SD) ethos, particularly in line with Goal 12 of the agenda. Thus, embracing the principles of a circular economy and developing relevant strategies can significantly help achieve SD Goal 12's targets.

To contribute to the aforesaid research interest, this study concentrates on establishing strategic practices facilitating the adoption of GLSS in Industry 4.0. In this era, there are some considerable studies investigating the development of lean manufacturing (e.g., Tardio et al., 2023), green production (e.g., de Sousa Jabbour et al., 2018), lean Six Sigma (e.g., Chiarini and Kumar, 2021), and green lean Six Sigma (e.g., Garza-Reyes, 2015; Belhadi et al., 2020; Gholami et al., 2021; Letchumanan et al., 2022). Nevertheless, the movement appears somewhat limited in the era of Industry 4.0 and requires momentum to create a substantial perspective, especially concerning the GLSS subject (Letchumanan et al., 2022). It is believed that scarcity of resources and ever-changing customer demand have driven researchers and practitioners to develop such green strategies (Hariyani and Mishra, 2023). However, motivating firms to adopt GLSS as a holistic approach is not easy due to a lack of awareness about GLSS and the strategic practices enabling its adoption (Letchumanan et al., 2022; Hussain et al., 2023). As stressed by Farrukh et al. (2023), the current literature on GLSS practices is insufficient despite the undeniable worth of the GLSS strategy; thus, empirical investigations are necessary in this domain to establish the strategic practices that can enable manufacturers in effectively implementing GLSS. Despite this empirical importance, cutting-edge research on this subject is still limited and inconclusive. According to Kaswan et al. (2023), limited research has investigated and integrated GLSS in the context of Industry 4.0. Yet, there has been no systematic attempt to develop a valid gauge of it and/or to assess its influence throughout products (value design), processes (value creation), and systems (value recovery), as they are widely recognized as essential pillars of manufacturing. This paper thus addresses this gap in the academic literature by drawing the research question: *What are the strategic practices that facilitate the adoption of GLSS in the Industry 4.0 era, and how can a validated multi-item scale be developed to measure these practices effectively?*

Within this context, this research aims to establish strategic practices facilitating GLSS adoption in the Industry 4.0 era and develop a validated multi-item scale to measure its practices. For this purpose, the study utilized a methodology that adhered to the approach outlined by Bagozzi et al. (1991), which has been recently employed by Turker (2009), Gholami et al. (2016), and Borges et al. (2021) to generate a measurement scale and establish strategic practices in their respective domains. Upon validation of the findings, the contribution of this research also entails proposing a measurement model to narrow the aforementioned gap, thereby opening up a new window for research. From a practical perspective, this paper contributes by providing a comprehensive understanding of the extent to which GLSS is implemented in organizations, as this is crucial to effectively manage GLSS initiatives. This comprehension can aid managers in identifying gaps, directing their efforts, and consequently enhancing GLSS outcomes. It can also enable them to conduct internal or external benchmarking across various business units or operations, as well as with competitors. Moreover, gaining a deeper understanding of GLSS and its relevance to sustainable and responsible consumption and production would be advantageous for external stakeholders, including policymakers or third-sector establishments. Such visions can hence facilitate the development of new regulations, training programs, or laws aimed at promoting GLSS adoption in the Industry 4.0 era. With its groundbreaking insights and visionary outlook, this study ignites the spark of a paradigm shift to embark upon a green initiative toward a new era of operational excellence.

As such, this paper is structured as follows: Section 2 provides a review of the literature to offer an understanding of the subject matter; Section 3 explains the research methodology; Section 4 delves into the analyses and results; Section 5 elaborates on the discussion of the findings and the proposed measurement model; and finally, Section 6 presents the conclusion.

2. Literature review

Green Lean Six Sigma (GLSS) has emerged as a cohesive embodiment of potent continuous improvement strategies and is evolving as a burgeoning research trend since the inception of the fourth industrial wave, commonly referred to as Industry 4.0, which gained widespread recognition in 2011 (Gholami et al., 2021; Letchumanan et al., 2022).

The genesis of lean begins with Eiji Toyoda and Taiichi Ohno for their contributions to developing the Toyota Production System in the 1950s through process improvement and standard work practices (Womack et al., 2007). Since then, the concept has significantly evolved due to its philosophy, in particular, after publicizing the seminal work "The Machine that Changed the World", which outlines that being lean is more beneficial since it uses less of everything in comparison with mass production. It mainly aims to develop high-quality goods or services at the lowest possible price and in the shortest amount of time via waste elimination (Lee et al., 2021; Abu et al., 2022; Henao and Sarache, 2023). Under lean, waste is conceptualized as "anything other than the bare minimal equipment, materials, components, space, and time required to add value to the product" (Russell and Taylor, 2000).

Other than lean, which is renowned for its focus on Muda (i.e., waste elimination), the Mura-based (i.e., inconsistency elimination) Six Sigma approach is another effective strategy (Jamil et al., 2020), initially introduced in the 1980s as a quality improvement methodology; its roots can be traced back to Motorola, an electronics company based in the United States (Braunscheidel et al., 2011). The implementation of a Six Sigma program aims to reduce the influence of subjective decision-making by consistently utilizing data collection, analysis, and presentation techniques (Maleyeff and Kaminssky, 2002). It particularly benefits companies aiming to enhance their bottom line and reduce defects by treating defects as process- or product-based opportunities (Matthew et al., 2005; Letchumanan et al., 2022).

In the late 1990s and early 2000s, LSS emerged as an integrated emblem of the two aforementioned methodologies for continuous improvement (Cherrafi et al., 2016). Research has demonstrated the effectiveness of this integration in enhancing business profits and competitiveness (Salah et al., 2010; Jamil et al., 2020; Yadav and Al Owad, 2022), process improvement, production cost reduction, and maximizing shareholder value through quality enhancement (Gijo et al., 2018; Laureani and Antony, 2019). It achieves this by applying the tools and techniques of both strategies. According to Snee (2010), LSS is the complete package of tools and techniques for the generation of continuous improvements. In practice, LSS utilizes the established Six Sigma DMAIC (Define-Measure-Analyze-Improve-Control) framework, integrating lean tools at various stages to create synergistic effects between Six Sigma and lean methodologies for process enhancement. The success of LSS as one of the best-known hybrid continuous improvement methodologies has led many organizations across the globe to adopt it to address their operations and become more competitive (Gijo et al., 2018; Belhadi et al., 2020).

In line with the sustainable development (SD) philosophy, which was popularized by the Brundtland report as “our common future (WCED, 1987)”, there has been an increasing interest in research to integrate green practices into the LSS model, known as Green LSS (GLSS), aiming to effectively improve the economic and environmental performance of organizations. The literature presents numerous arguments in which environmental sustainability performance can significantly be improved through such an effective integration, for instance, by optimizing the utilization of natural resources and energy, minimizing the production of wastewater, and reducing the usage of electricity, compressed air, and greenhouse gas emissions (Cherrafi et al., 2017; Powell et al., 2017; Erdil et al., 2018). In an industrial application, Gholami et al. (2021) demonstrated the effectiveness of GLSS in lessening the consumption of chemicals and energy by 28% and 21%, respectively. GLSS, by adopting its strategic practices, fosters a cultural transformation that accelerates the acceptance and commitment of administrations to environmental sustainability projects (Cherrafi et al., 2017; Kalemkerian et al., 2022; Hussain et al., 2023). This indicates that its implementation in the industry requires the establishment of strategic practices that aim to maximize operational and environmental values across all levels of products, processes, and systems. As mentioned by Belhadi et al. (2020), Gholami et al. (2021), and Letchumanan et al. (2022), it incorporates green product design, green technology, and green production, and such practices must be applied through the entire lifecycle of products. Therefore, the practices should cover strategic initiatives facilitating the adoption of GLSS in the manufacturing industry (Farrukh et al., 2023). Delving into the relevant GLSS studies, as reviewed below, strategic practices enabling its adoption for developing environmental sustainability have been unveiled to some extent, but are yet to be confirmed.

Kumar et al. (2015) studied sustainable GLSS in India using interviews, surveys, and statistical analysis. They identified 44 practices and highlighted the top five: team member training and recognition, top management commitment, effective scheduling, continuous improvement, and quality human resources. Gandhi et al. (2018) ranked green lean practices in Indian manufacturing using the fuzzy TOPSIS-SAW method. They identified the top five practices as top management commitment, technology up-gradation, current legislation, future legislation, and green brand image. Pandey et al. (2018) ranked 18 GLSS practices in the Indian manufacturing industry using the AHP method. They categorized the practices into five main categories: top management, quality, internal factors, supplier and customer, and green practices. Kaswan and Rathi (2019) prioritized 12 main practices of GLSS in the Indian context using the ISM-MICMAC method. The practices were categorized into eight levels. The top-level practices included organizational readiness, top management commitment, understanding of green technology and statistical tools, and linking GLSS to business objectives. Parmar and Desai (2020) evaluated sustainable GLSS practices in Indian manufacturing organizations. They identified 26 key practices and used the fuzzy DEMATEL method for analysis. The study highlighted "top management commitment and involvement" as the most crucial enabler, followed by "organizational readiness". Technological practices were not considered in the study. Farrukh et al. (2020) presented a review paper on 35 critical factors for the successful implementation of GLSS. The study addressed GLSS practices through tools like DMAIC, VSM, LCA, 5S, etc., rather than as independent factors.

In more recent studies, Singh et al. (2021) analyzed and finalized 22 out of 30 identified GLSS practices in Indian MSMEs using the best-worst method. Practices were categorized into five groups: environmental, strategic, cultural, resources, and linkage-based. The study utilized the Best Worst Method (BWM) for analysis. Ershadi et al. (2021) investigated the significance of "technology readiness level" as a key enabler for implementing GLSS projects in Iran. They emphasized its role in GLSS project implementation and identified 28 practices for further analysis. Letchumanan et al. (2022), by drawing on a thorough literature review, analyze and finalize 27 out of 30 identified GLSS enablers establishing five key practices. This study pioneers the development of an exploratory measurement model for operationalizing GLSS in Industry 4.0. Rathi et al. (2022) contend that GLSS represents a sustainable development strategy. Through the utilization of an ISM-MICMAC methodology, they discovered that the practices of management commitment and financial availability hold paramount importance in achieving successful GLSS implementation within the Indian healthcare facility. Hussain et al. (2023) assessed 28 out of 32 practices for GLSA adoption in Pakistan's construction industry. Using the ISM-MICMAC method, the study identified the top five influential practices as energy efficiency, government incentives, waste minimization, resource conservation and recycling, and water efficiency. Hariyani and Mishra (2023) have recognized and examined the 14 practices associated with the implementation of integrated sustainable-GLSS-agile in Indian manufacturing industries. Their analysis revealed that competition, customer demand, technological changes, supply chain pressure, cost benefits, incentives, top management commitment, and future legislation emerge as the most significant practices. In another study, Farrukh et al. (2023), by drawing on the natural resource and institutional theory views, investigated GLSS adoption in flexible packaging manufacturing organizations in New Zealand and Pakistan holding distinct cultural backgrounds, identifying 16 practices categorized as internal (operational, organizational, and environmental) and external (related to the state, society, and market) practices.

Upon review of the literature, it is evident that the subject being studied is relatively young and in need of cutting-edge research to develop valid and reliable scales to measure and analyze the strategic practices and their impact on the GLSS performance and conduct confirmatory studies to establish a commonly accepted measurement model (Letchumanan et al., 2022; Farrukh et al., 2023). Despite its empirical significance, contemporary research on this subject remains unconfirmed and inadequate. Hitherto, there has been no systematic effort to create a reliable measure of it and/or to evaluate its impact across products (value design), processes (value creation), and systems (value recovery), all of which are widely acknowledged as fundamental pillars of manufacturing. Therefore, this paper endeavors to fill this void in the academic literature by accomplishing the research purpose. The following section outlines a methodological approach that has been used to enrich this area of investigation.

3. Research Methodology

This research was conducted by following a three-phase methodology (Fig. 1) aligned to the approach delineated by Bagozzi et al. (1991), which has also been applied in recent research by Turker (2009), Gholami et al. (2016), and Borges et al. (2021) to develop a new scale in their respective fields. In phase I, the review process involved the utilization of academic databases, Scopus and Web of Science, renowned for their extensive coverage of global research. Additionally, Google Scholar was used to ensure that no relevant documents were overlooked, considering the limited research available on this specific topic. This enabled us to design an initial set of relevant scales. In order to appraise the initial set of scales and establish a factorial structure, exploratory factor analysis (EFA) was used in phase II. A comprehensive assessment necessitates the effective participation of stakeholders who possess the capacity to influence or be affected by decisions. Adhering to the criteria outlined by Turker (2009) and Hair et al. (2010), 102 professional/chartered engineers were engaged, as they occupy pivotal roles as stakeholders, both internally and externally, in addressing developmental issues within the manufacturing context.

In phase III, confirmatory factor analysis (CFA) was undertaken in three sequential steps (see Fig. 1) to determine the authenticity of the model derived from EFA and to scrutinize all the hypotheses concerning the relationships between observed and unobserved variables using the new empirical dataset. CFA is chosen as the appropriate method for evaluating the factorial structure as it is hypothesis-driven, as endorsed by previous studies (e.g., Bagozzi et al., 1991; Turker, 2009; Gholami et al., 2016; Borges et al., 2021). Hence, in this study, the EFA-based model and the corresponding hypotheses were assessed using the CFA technique. In accordance with the criteria set by Hair et al. (2010), a total sample of 229 engineers was included in the study. Engineers play a pivotal role in the realm of manufacturing and thus their insights into GLSS practices hold significant relevance for decision-makers when assessing the adoption and/or effectiveness of such initiatives. Furthermore, it is worth noting that there is a scarcity of research on engineers' perspectives regarding GLSS, underscoring the need for further investigation into this subject. Thus, in this study, the survey instruments were designed and disseminated to engineers affiliated the Malaysian board of engineering in the field of manufacturing and industrial engineering. However, this board includes members who are engaged globally, working across multinational corporations. This aspect is crucial as it implies a broader international influence and diversity beyond the geographical limits of Malaysia itself. The engineer designation is recognized by various professional associations operating in specific regions, including the US, the UK, France, Canada, etc. These associations are responsible for certifying individuals who have demonstrated a high level of competence in their respective fields, ensuring that engineers adhere to professional standards and ethics, and maintaining the quality and integrity of the engineering profession. The methodological process (Fig. 1), was implemented and elaborated in the following section.

Insert Fig. 1 in here

4. Analysis and results

This section is structured based on the three methodological phases introduced in the preceding section of the current research.

4.1. Scale design phase

In this phase, a comprehensive search was conducted for studies related to GLSS using the Scopus database, which is regarded as an eye on global research. The query string used was ((“Green”) AND (“Lean”) AND (“Six Sigma” OR “6Sigma”)) within TITLE-ABS, which yielded identifying relevant articles. Subsequently, a manual selection process was undertaken by reviewing abstracts and full texts to identify an initial set of scales. This process resulted in selecting 10 papers that explicitly discussed relevant statements in terms of drivers, enablers, and/or critical success factors: Kumar et al. (2015), Gandhi et al. (2018), Pandey et al. (2018), Kaswan and Rathi (2019), Parmar and Desai (2020), Farrukh et al. (2020), Singh et al. (2021), Ershadi et al. (2021), Letchumanan et al. (2022), and Mishra (2022), as discussed in Section 2. Next, the item-based checklist was modified using the following criteria suggested by Johnson and Morgan (2016): (1) ensuring the relevance of each item to the scale's objective, (2) maintaining clarity, consistency, and objectivity in the assertions, (3) using easily understandable language, (4) verifying and removing words with ambiguous meanings, (5) reviewing items that were excessively long, (6) checking for the use of overly technical terms or uncommon words in the practitioner setting, and (7) verifying and eliminating slang, colloquialisms, jargon, and abbreviations.

For content validity, the item set was presented to four experts from both academic and industry backgrounds to verify its alignment with the intended objectives. Despite extending invitations to ten academics and ten professional engineers for their involvement in the study, only four experts consented to participate, potentially due to a gap in specific expertise. The validation process was divided into two consecutive interview stages. In the initial stage, two academic experts with expertise in GLSS and direct ties to the project were consulted. Their task was to assess the pertinence and scaling intention of each item based on the above-mentioned criteria. This stage concluded with the identification of 30 facilitating items. The subsequent stage involved collaboration with two professional engineers, who brought extensive experience in environmental management and LSS projects. The purpose was to gauge the comprehensibility and evaluative capacity of the items concerning the scale's measurement objective. Unless both engineers concurred on an item's lack of relevance, no item was to be reconsidered or removed. In this instance, no suggestions were made for the removal, addition, or modification of items, leading to the conclusion that all 30 items were pertinent and understandable. Accordingly, a total of 30 relevant items were considered during this phase, as shown in Table 1.

Insert Table 1 in here

4.2. Exploratory phase

To assess the initial set of items and establish a factorial structure, exploratory factor analysis (EFA) was used. Being a comprehensive assessment requires the active involvement of stakeholders who possess the ability to impact or be impacted by the decisions. In this phase of the research, out of 261 emailed questionnaires, 102 were completed and usable, yielding an acceptable response rate of 39.08% (Turker, 2009; Hair et al., 2010; Abu et al., 2022). Thus, 102 professional/chartered engineers participated in the study, given their crucial roles as key stakeholders, both internally and externally, in addressing developmental issues within the manufacturing sector. Table 2 outlines the demographics of the participants in this exploratory phase. Survey-based research offers a range of scientifically supported methods, settings, and data sources for data collection; nevertheless, questionnaires stand out as the predominant method for gathering data in this type of research (Turker, 2009; Hair et al., 2010). Thus, the survey questionnaire was constructed adhering to the criteria recommended by Johnson and Morgan (2016), as discussed in the previous section. A five-point Likert scale was accordingly applied to collect the data; where the values 1 to 5 indicate ‘strongly disagree’ to ‘strongly agree’, respectively. There were two main parts in the questionnaire. The first part comprised questions about the respondents' backgrounds (see Table 2). The subsequent parts were accordingly designed to determine the importance of the statements in the understudied context.

Insert Table 2 in here

Bartlett's test of sphericity (BTS) and the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, which have often been utilized to test the factorability of data and confirm the adequacy of sampling, are highly recommended for applying EFA, particularly when the participant-to-item ratio is less than 5:1 (Rezaei et al., 2017; Abu et al., 2022). For an EFA to be regarded as appropriate, the minimum proposed KMO index (which goes from 0 to 1) is 0.6, and BTS must be significant at the 0.05 level of significance (Hair et al., 2010). In the current study, BTS was significant at $p < 0.001$ and the KMO index was 0.9, indicating that the application of EFA is appropriate for the data.

To determine the reliability of the scale and to create an articulated factorial structure, principal component factor analysis alongside varimax-rotation was applied. This technique, which is one of the most widely used EFA methods to effectively distinguish the factors, considers the overall variance and discovers factors with minor levels of unique variance (Turker, 2009; Hair et al., 2010). The objective was to achieve a factor structure where each variable loads highly on one factor and has minimal loading on others, facilitating a clearer distinction between the factors. As indicated in the literature, a factor is considered significant if it has a loading of 0.50 or higher. Considering the unrotated factor matrix displayed a complex pattern of factor loadings, with substantial cross-loadings, the rotation method was hence employed to enhance interpretability. Three items were consequently found to be omitted—I4, I6, and I25—due to having low factor loadings (Table 3).

Table 3 demonstrates the factorial structure of the GLSS practices using SPSS; 27 out of the set 30 items with loadings exceeding 0.50 were consequently kept, resulting in a five-factor structure with acceptable eigenvalues exceeding 1.0 and explaining 62.18% of the total variance. After evaluating the verified items and their characteristics in each factor, the factors were labeled based on the literature as practices relating to 1. Strategic Integrity (SI: 8 items), 2. Human Resource Management (HRM: 5 items), 3. Technologies and Tools (TT: 4 items), 4. Eco-Production (EP: 5 items), and 5. Eco-Networks (EN: 5 items), respectively. The rationale behind grouping items under these five strategic practices is previously discussed in Section 5.1. To verify that the mentioned practices are consistent internally, a reliability test using Cronbach's alpha was carried out, yielding 0.91, 0.84, 0.77, 0.8, and 0.78, respectively (Table 3). These results indicate that the

EFA-based structural model of GLSS practices is internally consistent and reliable for use in our confirmatory research.

Insert Table 3 in here

4.3. Confirmatory phase

A quantitative analytic method known as confirmatory factor analysis (CFA) was used in this phase to determine the authenticity of the EFA-based model and to test all the hypotheses regarding the relationship between the observed and unobserved variables via the new empirical dataset. It is asserted that CFA is the proper method for analyzing the factorial structure as it is hypothesis-driven (Bagozzi et al., 1991; Turker, 2009). It can examine a conceptually grounded theory by assessing the harmony between the factors' theoretical designation and the actual data. In short, it allows for the acceptance or rejection of a hypothesis (Hair et al., 2010; Gholami et al., 2016; Borges et al., 2021). Hence, the EFA-based model and the resulting hypotheses were assessed using the CFA method. This method was executed in three steps, as detailed below.

4.3.1. Measurement model specification

This step addressed the following questions (Hair et al., 2010): 1) "What is the factorial model needing to be examined?" and 2) "What is the measurement scale to assess the model?". These questions were answered based on the findings obtained by EFA, which provided a systematic specification of an empirically validated factorial model. Table 3 revealed that the EFA-based factorial structure has a theoretical and reliable basis, thereby indicating its appropriateness for confirmatory assessment. Thus, the EFA-based model comprising 27 items was accordingly applied to this end.

4.3.2. Confirmatory survey design

Three questions were put forth in designing the confirmatory survey (Hair et al., 2010): 1) "What is the appropriate measurement sample size?", 2) "How are samples taken?", and 3) "What sampling technique is used?". Hair et al. (2010) recommended a sample size of more than 150 if a model holds seven or fewer constructs with modest communalities. In survey research, data collection is primarily conducted using questionnaires. Non-probabilistic convenience sampling is often used for collecting data that is opinion-based, e.g., the consumers' perception of a particular product or service design.

In the current study, 270 questionnaires were distributed (10:1) to engineers using non-probabilistic convenience sampling. Engineers are among the key stakeholders in manufacturing; hence, their perception of GLSS practices is important for the decision-makers in evaluating the initiative's performance. Also, research on the perspective of engineers regarding GLSS is limited, which highlights the importance of further exploration of this topic. Table 2 outlines the demographics of the participants in this confirmatory phase. The questions were administered using a five-point Likert scale similar to EFA, whereby 1 denotes strongly disagree and 5 strongly agree. The answers were gathered within a period of 53 days from the start date. Out of that overall total, 229 emailed questionnaires were usable for further analysis, representing a response rate of 84.81%.

4.3.3. Validity and reliability tests

Upon model specification and data collection, the measurement scales and model were assessed for reliability and validity. It involved the application of CFA to test the hypothetical model's goodness-of-fit. The IBM®SPSS®AMOS™26 software was used for this purpose due to its integrity—AMOS supports the SPSS format. This feature allows for the utilization of reliable goodness-of-fit measures, standardized residual analysis, and modification indices (M.I.) assessment for factorial models. In fulfilling the set criteria, numerous fit indices were utilized to determine the model's fitness. The items' standardized loadings and standardized residuals, which indicate the status of the constructs convergent validity, along with the construct reliability (CR) value, were finally examined (Hair et al., 2010; Gholami et al., 2016; Abu et al., 2022).

The results displayed in Table 4 reveal that the default CFA model (Fig. 2), as assessed by AMOS, does not meet the required fit criteria. The probability of encountering a discrepancy as substantial as 682.410 was found to be highly significant at $p < 0.001$. This outcome indicates a compelling need for adjustments in the model's specification to improve its fit with the observed data. After a thorough examination of the content and characteristics of the items, regression weights with exceptionally high values were removed from the default CFA. Subsequently, nine items, specifically SI4, SI5, SI6, HRM2, HRM5, TT4, EP4, EN3, and EN5, were excluded from the analysis. The CFA was then re-run with the remaining 18 items to evaluate the model's validity, as illustrated in Fig. 3.

Insert Fig. 2 in here

Insert Table 4 in here

The outcomes presented in Table 4 indicate that all the values exceeded the predefined criteria for an acceptable goodness-of-fit, thus establishing the appropriateness of the modified model's goodness-of-fit. In the modified model, all path coefficients were found to be significant ($p < 0.001$), underscoring the substantial contributions of the items to their respective factors. Furthermore, the items' standardized loadings within the five constructs exceeded 0.5, as depicted in Fig. 3, affirming the high convergent validity of the constructs. Additionally, the standardized residuals were within acceptable bounds, demonstrating a standard normal distribution with absolute values lower than two, as detailed in Table 5. To evaluate construct reliability, the composite reliability (CR) test was applied, with SI, HRM, TT, EP, and EN exhibiting CR values of 0.82, 0.73, 0.82, 0.69, and 0.73, respectively. These comprehensive assessments collectively confirm the structural reliability and validity of the GLSS measurement model, which encompasses five practices and 18 developed scales, as documented in Table 5.

Insert Fig. 3 in here

Insert Table 5 in here

5. Discussion

The findings of this study were categorized into three phases according to the applied methods (Section 3), which helped achieve the research purpose. As elaborated in the previous section, the assessments confirmed the structural reliability and validity of the GLSS measurement model, which includes five practices and 18 developed scales, as finalized and elaborated in Table 6.

Insert Table 6 in here

5.1. Proposed measurement model and theoretical implications

Considering the analyses and findings of this study, a hypothetical measurement model is proposed in Fig. 4, which establishes a connection between GLSS performance levels and the five strategic practices. Consequently, the subsequent hypotheses are formulated below.

Insert Fig. 4 in here

H1. *SI significantly influences GLSS performance*. SI refers to the consistent alignment between a company's strategic plans, commitments, and actual implementation. It emphasizes the importance of ensuring that the actions and practices of an organization are in line with its stated goals and strategies (Mavis et al., 2019). Thus, when an organization has strategic integrity, it is more likely to prioritize GLSS initiatives and allocate resources to support them. This can lead to increased employee engagement and participation in GLSS initiatives, as well as improved customer satisfaction and loyalty due to the organization's commitment to environmental sustainability. Also, SI can help to identify areas where GLSS initiatives can be integrated into all levels of the organizational products, processes, and systems throughout the product life-cycle (cf. Kumar et al., 2015; Gandhi et al., 2018; Pandey et al., 2018; Kaswan and Rathi, 2019; Farrukh et al., 2020; Singh et al., 2021; Ershadi et al., 2021; Letchumanan et al., 2022; Mishra, 2022).

H2. *HRM significantly influences GLSS performance*. HRM is a critical aspect of organizational success (Gholami et al., 2016), and thus its impact on GLSS performance cannot be overlooked (cf. Kumar et al., 2015; Gandhi et al., 2018; Pandey et al., 2018; Kaswan and Rathi, 2019; Parmar and Desai, 2020; Farrukh et al., 2020; Singh et al., 2021; Ershadi et al., 2021; Letchumanan et al., 2022; Mishra, 2022). It involves the effective management of an organizational workforce; hence, by creating a culture of environmental sustainability and continuous improvement through effective recruitment, selection, training, development, retention, and compensation practices, organizations can achieve their GLSS goals and improve their overall sustainability performance.

H3. *EP significantly influences GLSS performance*. EP refers to the integration of environmental considerations into the design and production of goods and services. It involves the use of environmentally sustainable materials, processes, and technologies to minimize the environmental impact of production while maintaining or improving product quality and performance (Dinh et al., 2022). The integration of eco-production into GLSS can help businesses achieve a more sustainable and efficient production process while also improving product quality and performance, reducing costs, and enhancing their reputation for environmental responsibility (cf. Kumar et al., 2015; Pandey et al., 2018; Parmar and Desai, 2020; Farrukh et al., 2020; Singh et al., 2021; Letchumanan et al., 2022).

H4. *TT significantly influences GLSS performance*. The effective adoption of GLSS is in part due to the incorporation of TT. To further enhance this notion, it is imperative to consider Industry 4.0 technologies (e.g., BDA; see Belhadi et al., 2020), as their integration with GLSS tools (e.g., E-VSM; see Gholami et al., 2021) can lead to greater operational efficiency. Although Silva et al. (2021) have provided an outline of Industry 4.0 competencies for GLSS deployment, the effective amalgamation of these two evolving notions is still in its early stages (Letchumanan et al., 2022). Hence, there is a pressing need for innovative research on the subject; however, conducting such research would provide academic professionals, practitioners, and other stakeholders with new perspectives and guidelines to capitalize on the benefits of this convergence (Lee et al., 2021).

H5. *EN significantly influences GLSS performance*. EN can be interpreted as a type of open eco-innovation (Fabrizi et al., 2022) involving individuals and organizations working together, sharing knowledge and ideas, and collectively contributing to the development of sustainable practices and technologies. Incorporating EN into GLSS can impact suppliers, customers, and the management system in several ways (cf. Kumar et al., 2015; Pandey et al., 2018; Parmar and Desai, 2020; Farrukh et al., 2020; Ershadi et al., 2021; Singh et al., 2021; Letchumanan et al., 2022). From a supplier perspective, it can help organizations identify suppliers that are more environmentally responsible and sustainable. From a customer perspective, incorporating EN into GLSS can improve customer satisfaction by providing them with products and services that are more environmentally friendly. By taking into account the interconnectivity of various ecological networks, organizations can identify potential risks and vulnerabilities in their management systems and take proactive measures to mitigate them.

H6. *The strategic practices are interconnected, i.e., there exists a robust relationship among them.* As evidenced in the CFA model (Fig. 3) and depicted in Fig. 4, which showcases the potential connections among the five strategic practices, this hypothesis is formulated to investigate the interrelationship among these practices.

Riding on the GLSS performance, it is implied that the development and deployment of GLSS practices should be traced throughout the total product lifecycle (Gandhi et al., 2018; Pandey et al., 2018; Kaswan and Rathi, 2019; Farrukh et al., 2020; Singh et al., 2021; Ershadi et al., 2021; Letchumanan et al., 2022; Mishra, 2022; Hussain et al., 2023; Hariyani and Mishra, 2023; Farrukh et al., 2023), i.e., from preproduction, production, use through post-use stages, with active involvement in delving the initiative into products (value design), processes (value creation), and systems (value recovery), as they are widely recognized as essential pillars of manufacturing (Gholami et al., 2022). In summary, existing literature reveals an increasing interest in adopting GLSS for developing environmentally sustainable production; however, none of these studies investigates the subject in relation to the aforementioned performance levels. Considering major criteria influencing these levels (cf. Jawahir et al., 2006; Jayal et al., 2010; Gholami et al., 2022;2023), the subsequent hypotheses are accordingly formulated.

H7. *At the product level*–GLSS may contribute to improving initial investment, direct/indirect costs, losses, material use, energy use, waste and emissions, product end-of-life management efficiency, product quality and durability, functional performance, safety and health impact, and regulations and certifications effectiveness. **H8.** *At the process level*–GLSS may contribute to improving industrial cost, environmental friendliness, energy consumption, personnel health, and waste. **H9.** *At the system level*–GLSS may contribute to improving net profit, capital charge, manufacturing cost, operational performance, material use and efficiency, energy use and efficiency, water use and efficiency, waste and emissions, product end-of-life, health and safety, and stakeholder engagement.

5.2. Managerial Implications

This research transcends mere theoretical exploration by offering a pragmatic measurement model to bridge the existing gap in the field, thereby catalyzing further scholarly inquiry. It not only advances academic knowledge by proposing a measurement model, but also impacts practical applications by elucidating the extent of GLSS implementation in organizations. This comprehensive understanding is vital for managing GLSS initiatives effectively, allowing managers to pinpoint deficiencies and optimize efforts, thereby improving GLSS outcomes. Additionally, the study's insights facilitate benchmarking both within and across organizations, as well as against competitors. Importantly, it offers a deeper comprehension of GLSS's role in promoting sustainable and responsible consumption and production, i.e., Goal 12 of the SD agenda, valuable to external stakeholders like policymakers and non-profit organizations. This understanding can guide the formulation of new regulations, training programs, and laws to encourage GLSS adoption in the context of Industry 4.0. Thus, the study heralds a paradigm shift, encouraging the embrace of green initiatives and setting a course towards enhanced operational excellence in a new era.

6. Conclusions and future research directions

Goal 12 of the 2030 SD agenda highlights the irresponsible use of natural resources in global consumption and production, which is a driving force of the worldwide economy, leading to detrimental effects on the environment and society. Manufacturing industries considerably contribute to this concern by depleting resources and producing hazardous waste and emissions. The importance of GLSS in achieving this goal has already been demonstrated. Given GLSS's nascent development with a distinct identity in the Industry 4.0 era and the absence of a validated empirical model for its application and measurement, this study was aimed at establishing strategic practices that facilitate its adoption in the manufacturing context and developing a validated multi-item scale to measure the practices. To achieve this, a three-phase methodological approach was developed to apply exploratory and confirmatory analytical techniques in the manufacturing context.

After validating the final results, the analysis showed a model that confirms five practices: ‘strategic integrity’ consisting of five scales, ‘human resource management’ consisting of three scales, ‘technologies and tools’ consisting of three scales, ‘eco-production’ consisting of four scales, and ‘eco-networks’ consisting of three scales. The findings also indicated the presence of strong correlations between the fundamental practices outlined in the model, suggesting an area for further exploration in future research. The contribution of this study also entails delving into a comprehensive measurement model, thereby paving the way for future research endeavors. This is particularly significant considering the current dearth of an empirically validated model that can effectively capture the multifaceted nature of GLSS. By presenting and discussing this well-defined measurement model, this study fills a gap in the existing literature and offers a foundation for further exploration and analysis in the field. By leveraging the scales, practices, and consequently a comprehensive model, practitioners can be empowered to assess the maturity level of GLSS adoption, gain insights into the current state, devise effective implementation plans, and benchmark against best practices across industries.

This study serves as a confirmatory investigation aimed at developing a measurement model for GLSS. The research findings, although preliminary and not definitive, provide valuable insights and suggest areas for further investigation. While efforts have been made to comprehensively review the current literature on GLSS practices, it is important to acknowledge that there may be additional strategic practices that need to be considered. This may involve exploring mediators or incorporating new items while excluding existing ones in certain cases. By conducting a systematic analysis, this research has laid the foundation for a more in-depth exploration, as discussed and depicted in Fig. 4 and Table 6, thereby offering valuable insights that can be further explored. The lack of geographic information on the respondents may also be regarded as a limitation of the current study; thus, future investigations are encouraged to incorporate the geographic domiciles of respondents. Integrating such information may offer an understanding of localized trends, thereby rendering the implications more insightful.

References

Abu, F., Saman, M. Z. M., Garza-Reyes, J. A., Gholami, H., & Zakuan, N. (2022). Challenges in the implementation of lean manufacturing in the wood and furniture industry. *Journal of Manufacturing Technology Management*, *33*(1), 103-123.

Akter, M. M. K., Haq, U. N., Islam, M. M., & Uddin, M. A. (2022). Textile-apparel manufacturing and material waste management in the circular economy: A conceptual model to achieve sustainable development goal (SDG) 12 for Bangladesh. *Cleaner Environmental Systems*, *4*, 100070.

Bagozzi, R.P., Yi, Y., Phillips, L.W., (1991). Assessing construct validity in organizational research. *Administrative Science Quarterly,* 36 (3), 421-458.

Belhadi, A., Kamble, S. S., Zkik, K., Cherrafi, A., & Touriki, F. E. (2020). 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.

Bhat, V. S., Bhat, S., & Gijo, E. V. (2021). Simulation-based lean six sigma for Industry 4.0: an action research in the process industry. *International Journal of Quality & Reliability Management*, *38*(5), 1215-1245.

Borges, T. D. M. D., Ganga, G. M. D., Godinho Filho, M., Delai, I., & Santa-Eulalia, L. A. (2021). Development and validation of a cleaner production measurement scale. *Journal of Cleaner Production*, *299*, 126907.

Braunscheidel, M. J., Hamister, J. W., Suresh, N. C., & Star, H. (2011). An institutional theory perspective on Six Sigma adoption. *International Journal of Operations & Production Management*, 31(4), 423–451.

Cherrafi, A., El Fezazi, S., Govindan, K., Garza-Reyes, J.A., Mokhlis, A., & Benhida, K., (2017). A framework for the integration of Green and Lean Six Sigma for superior sustainability performance. *Int. J. Prod. Res*, 55(15), 4481-4515.

Cherrafi, A., Elfezazi, S., Chiarini, A., Mokhlis, A., & Benhida, K. (2016). The integration of lean manufacturing, Six Sigma and sustainability: A literature review and future research directions for developing a specific model. *Journal of Cleaner Production*, *139*, 828-846.

Chiarini, A., & Kumar, M. (2021). Lean Six Sigma and Industry 4.0 integration for Operational Excellence: evidence from Italian manufacturing companies. *Production Planning & Control*, *32*(13), 1084-1101.

de Sousa Jabbour, A. B. L., Jabbour, C. J. C., Foropon, C., & Godinho Filho, M. (2018). When titans meet–Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. *Technological Forecasting and Social Change*, *132*, 18-25.

Dinh, M. T. T., Su, D. N., Tran, K. T., Luu, T. T., Duong, T. H., & Johnson, L. W. (2022). Eco-designed retail packaging: The empirical conceptualization and measurement. *Journal of Cleaner Production*, 379, 134717.

Erdil, N.O., Aktas, C.B., & Arani, O.M. (2018). Embedding sustainability in lean six sigma efforts. *Journal of Cleaner Production*, 198, 520–529.

Ershadi, M.J., Taghizadeh, O.Q. & Molana, S.M.H., (2021). Selection and performance estimation of Green Lean Six Sigma Projects: a hybrid approach of technology readiness level, data envelopment analysis, and ANFIS. *Environmental Science and Pollution Research*, 1-18.

Fabrizi, A., Guarini, G., & Meliciani, V. (2022). Environmental networks and employment creation: Evidence from Italy. *Journal of Cleaner Production*, *359*, 132056.

Farrukh, A., Mathrani, S. & Taskin, N., (2020). Investigating the Theoretical Constructs of a Green Lean Six Sigma Approach towards Environmental Sustainability: A Systematic Literature Review and Future Directions. *Sustainability*, 12(19), 8247.

Farrukh, A., Mathrani, S., & Sajjad, A. (2023). An exploratory study of green-lean-six sigma motivators for environmental sustainability: Managerial insights from a developed and developing economy. *Business Strategy and the Environment*.

Gandhi, N.S., Thanki, S.J., & Thakkar, J.J., (2018). Ranking of drivers for integrated lean-green manufacturing for Indian manufacturing SMEs. *J. Clean. Prod.,* 171, 675-689.

Garza-Reyes, J.A. (2015). Green lean and the need for Six Sigma. *International Journal of Lean Six Sigma, 6*(3), 226–248.

Gholami, H., Abdul-Nour, G., Sharif, S., & Streimikiene, D. (Eds.). (2023). *Sustainable Manufacturing in Industry 4.0: Pathways and Practices*. Singapore: Springer Nature Singapore.

Gholami, H., Jamil, N., Mat Saman, M. Z., Streimikiene, D., Sharif, S., & Zakuan, N. (2021). The application of green lean six sigma. *Business Strategy and the Environment*, *30*(4), 1913-1931.

Gijo, E. V., Palod, R., & Antony, J. (2018). Lean Six Sigma approach in an Indian auto ancillary conglomerate: a case study. *Production Planning & Control*, *29*(9), 761-772.

Hair, J.F., Black, W.C., Babin, B.J., Anderson, R.E. (2010). Multivariate Data Analysis: A Global Perspective, seventh ed. Pearson-Hall International, Upper Saddle River, New Jersey.

Hariyani, D. and Mishra, S. (2023). An analysis of drivers for the adoption of integrated sustainable-green-lean-six sigma-agile manufacturing system (ISGLSAMS) in Indian manufacturing industries. *Benchmarking: An International Journal*, 30 (4), 1073-1109.

Henao, R., & Sarache, W. (2023). Effects of lean manufacturing on sustainable performance: results from two conceptual approaches. *Journal of Manufacturing Technology Management*, *34*(8), 1448-1481.

Hussain, K., He, Z., Ahmad, N., Iqbal, M., & Saeed, M. Z. (2023). Establishing a Green, Lean and Six Sigma implementation model for sustainable construction industry: An analysis of driving forces through ISM-MICMAC approach. *Environmental Science and Pollution Research*, *30*(11), 30462-30492.

Jamil, N., Gholami, H., Mat Saman, M. Z., Streimikiene, D., Sharif, S., & Zakuan, N. (2020). DMAIC-based approach to sustainable value stream mapping: towards a sustainable manufacturing system. *Economic research-Ekonomska istraživanja*, *33*(1), 331-360.

Jawahir, I.S., Dillon, O.W., Rouch, K.E., Joshi, K.J., Venkatachalam, A., Jaafar, I.H. (2006). Total Life-Cycle Considerations in Product Design for Sustainability: A Framework for Comprehensive Evaluation, 11–15 September. In: Proceedings of the 10th International Research/expert Conference. Barcelona, Spain.

Jayal, A.D., Badurdeen, F., Dillon Jr., O.W., Jawahir, I.S. (2010). Sustainable manufacturing: modeling and optimization challenges at the product, process and system levels. *CIRP J. Manuf. Sci. Technol*. 2 (3), 144–152.

Johnson, R., Morgan, G., (2016). Scales: a Guide to Development, Analysis, and Reporting, 1.ed. The Guilford Press, New York, p. 289p.

Kalemkerian, F., Santos, J., Tanco, M., Garza-Reyes, J. A., & Viles, E. (2022). Analysing the alignment between the Green Lean and Circular strategies: towards a Circular Lean approach. *Journal of Manufacturing Technology Management*, *33*(6), 1059-1079.

Kaswan, M. S., Rathi, R., Cross, J., Garza-Reyes, J. A., Antony, J., & Yadav, V. (2023). Integrating Green Lean Six Sigma and industry 4.0: a conceptual framework. *Journal of Manufacturing Technology Management*, *34*(1), 87-121.

Kaswan, M.S., & Rathi, R., (2019). Analysis and modeling the enablers of green lean six sigma implementation using interpretive structural modeling. *J. Clean. Prod*., 231, 1182-1191.

Kumar, S., Kumar, N. & Haleem, A., (2015). Conceptualisation of sustainable green lean six sigma: an empirical analysis. *International Journal of Business Excellence*, 8(2), 210-250.

Laureani, A., Antony, J., 2019. Leadership and lean six sigma: a systematic literature review. *Total Qual. Manag. Bus. Excell*. 30 (1-2), 53-81.

Lee, J. K. Y., Gholami, H., Medini, K., & Salameh, A. A. (2023). Hierarchical analysis of barriers in additive manufacturing implementation with environmental considerations under uncertainty. *Journal of Cleaner Production*, 137221.

Lee, J. K. Y., Gholami, H., Saman, M. Z. M., Ngadiman, N. H. A. B., Zakuan, N., Mahmood, S., & Omain, S. Z. (2021). Sustainability-oriented Application of Value Stream Mapping: A review and classification. *IEEE Access*, *9*, 68414-68434.

Letchumanan, L. T., Gholami, H., Yusof, N. M., Ngadiman, N. H. A. B., Salameh, A. A., Štreimikienė, D., & Cavallaro, F. (2022). Analyzing the Factors Enabling Green Lean Six Sigma Implementation in the Industry 4.0 Era. *Sustainability*, *14*(6), 3450.

Maleyeff, J. & Kaminssky, F.C. (2002). Six Sigma and introductory statistics education. *Education & Training*. 44, 82-9.

Marcus, A., Fremeth, R. (2009). Green management matters regardless. *Acad. Manag. Perspect*. 23, 17-26.

Matthew, H., Barth, B. & Sears, B. (2005). Leveraging Six Sigma discipline to drive improvement. *International Journal of Six Sigma and Competitive Advantages*. 1(2), 121-33.

Mavis, C. P., Richter, A., Landau, C., Schmidt, S. L., Simons, T., & Steinbock, K. (2019). What happens when companies (don't) do what they said they would? Stock market reactions to strategic integrity. *European Management Review*, *16*(3), 815-831.

Mishra, M. N. (2022). Identify critical success factors to implement integrated green and Lean Six Sigma. *International Journal of Lean Six Sigma*, *13*(4), 765-777.

Pandey, H., Garg, D., & Luthra, S. (2018). Identification and ranking of enablers of green lean Six Sigma implementation using AHP. *International Journal of Productivity and Quality Management, 23*(2), 187-217.

Parmar, P. S., & Desai, T. N. (2020). Evaluating Sustainable Lean Six Sigma enablers using fuzzy DEMATEL: A case of an Indian manufacturing organization. *Journal of Cleaner Production*, *265*, 121802.

Powell, D., Lundeby, S., Chabada, L., & Dreyer, H. (2017). Lean Six Sigma and environmental sustainability: the case of a Norwegian dairy producer. *International Journal of Lean Six Sigma, 8*(1), 53–64.

Rathi, R., Kaswan, M. S., Antony, J., Cross, J., Garza-Reyes, J. A., & Furterer, S. L. (2022). Success factors for the adoption of green lean six sigma in healthcare facility: An ISM-MICMAC study. *International Journal of Lean Six Sigma*, (ahead-of-print).

Rezaei, G., Gholami, H., Shaharou, A. B. M., Zameri Mat Saman, M., Sadeghi, L., & Zakuan, N. (2017). Shared knowledge mediated correlation between cultural excellence and organisational performance. *Total Quality Management & Business Excellence*, *28*(3-4), 427-458.

Russell, R.S., & Taylor, B.W. (2000). Operations Management. PrenticeeHall, Englewood Cliffs.

Salah, S., Rahim, A. & Carretero, J.A. (2010). The integration of Six Sigma and lean management. *International Journal of Lean Six Sigma, 1*(3), 249-274.

Silva, I. B., Cabeça, M. G., Barbosa, G. F., & Shiki, S. B. (2021). Lean Six Sigma for the automotive industry through the tools and aspects within metrics: a literature review. *The International Journal of Advanced Manufacturing Technology*, 1-27.

Singh, M., Rathi, R., & Garza-Reyes, J. A. (2021). Analysis and prioritization of Lean Six Sigma enablers with environmental facets using best worst method: A case of Indian MSMEs. *Journal of Cleaner Production*, *279*, 123592.

Snee, R. D. (2010). Lean Six Sigma–getting better all the time. *International Journal of Lean Six Sigma*, *1*(1), 9-29.

Tardio, P. R., Schaefer, J. L., Nara, E. O. B., Gonçalves, M. C., Dias, I. C. P., Benitez, G. B., & de Castro, A. (2023). The link between lean manufacturing and Industry 4.0 for product development process: a systemic approach. *Journal of Manufacturing Technology Management*, (ahead-of-print).

Turker, D. (2009). Measuring corporate social responsibility: A scale development study. *Journal of Business Ethics*, *85*(4), 411-427.

US EPA (2023). Manufacturing Sectors, United States Environmental Protection Agency. Available online: https://www.epa.gov/trinationalanalysis/manufacturing-sectors (accessed on 01 July 2023).

WCED (1987). Our Common Future, third ed. Oxford University Press, Oxford, UK.

Womack, J.P., Jones, D.T., & Roos, D. (2007). The machine that changed the world: The story of lean production–Toyota's secret weapon in the global car wars that is now revolutionizing world industry. Simon and Schuster, New York.

Yadav, N., & Al Owad, A. (2022). Comparing viewpoints of top management, consultants and employees about Lean Six Sigma. *Journal of Manufacturing Technology Management*, *33*(6), 1150-1170.

Tables

Table 1. The initial set of GLSS items.

No	Items	Coding
1.	Top management commitment and support to integrate Green and Lean Six Sigma across all the product development cycle stages	I1
2.	Linking GLSS to organizational vision/mission statements	I2
3.	Organizational readiness for GLSS implementation	I3
4.	Knowledge management	I4
5.	Funds' availability	I5
6.	Firm's reputation	I6
7.	Expedite resources and skills in the implementation process	I7
8.	Culture and supportive ambiance	I8
9.	Employee training and developmental programs	I9
10.	Attracting and selecting employee	I10
11.	Reward and recognition of employee	I11
12.	Employee involvement and empowerment	I12
13.	Teamwork	I13
14.	Effective communication of GLSS schemes among departments	I14
15.	Supplier relationship management	I15
16.	Customer relationship management	I16
17.	Environmental Management System	I17
18.	Material selection and modification	I18
19.	Environmentally-friendly product design practices	I19
20.	Use of environmentally-friendly packaging	I20
21.	Use of environmentally-friendly transportation	I21
22.	Continues improvement practices in environmentally-sustainable manufacturing processes	I22
23.	Effective scheduling	I23
24.	Project selection and management	I24
25.	Market demands for environmentally-friendly products	I25
26.	Government rules and regulations	I26
27.	Technological readiness for GLSS implementation	I27
28.	GLSS tools and techniques for effective data collection and measurement	I28
29.	Technology up-gradation (e.g., use of cleaner technologies)	I29
30.	Equipment up-gradation	I30

Table 2. The respondents' demographic profile.

Demographics	**Study 1 (n = 102)**		**Study 2 (n = 229)**	
	Frequency	(%)	Frequency	(%)
Gender				
Male	71	69.6	121	52.8
Female	31	30.4	108	47.2
Age				
Below 25	-	-	61	26.6
26-35	30	29.4	94	41.1
36-45	62	60.8	65	28.4
Above 46	10	09.8	09	03.9
Current level of study				
Bachelor	62	60.8	132	57.6
Master	23	22.5	70	30.6
PhD	17	16.7	-	-
Other	-	-	27	11.8
Current position				
Academic position	17	16.7	-	-
Industrial position	85	83.3	229	100
Years of experience in current position				
Less than 1 year	-	-	10	04.4
1 to 3 years	-	-	65	28.4
3 to 5 years	-	-	85	37.1
More than 5 years	102	100	69	30.1
Skill/knowledge in				
Lean	-	-	28	12.2
Six Sigma	-	-	31	13.5
Lean Six Sigma	87	85.3	163	71.2
Green Lean Six Sigma	15	14.7	07	03.1
Professional registration				
Eng.Tech.	-	-	71	31.0
Grad.Eng.	-	-	103	45.0
P.Eng.	63	61.8	33	14.4
C.Eng.	39	38.2	22	09.6
Years of registration experience				
Less than 1 year	-	-	11	04.8
1 to 3 years	-	-	30	13.1
3 to 5 years	14	13.7	31	13.5
More than 5 years	88	86.3	157	68.6

Table 3. EFA-based structural model of GLSS practices after rotation.

Items (coding)	**Practices**					**Communalities**
	SI	**HRM**	**TT**	**EP**	**EN**	
I3 (**SI1**)	**0.70**	0.23	0.24	0.16	0.08	0.63
I2 (**SI2**)	**0.67**	0.36	0.08	0.35	0.17	0.74
I1 (**SI3**)	**0.66**	-0.13	0.14	0.36	0.27	0.67
I8 (**SI4**)	**0.64**	0.48	0.04	0.19	0.17	0.71
I24 (**SI5**)	**0.64**	0.29	0.24	0.23	0.15	0.62
I23 (**SI6**)	**0.60**	0.16	0.39	0.08	0.29	0.62
I5 (**SI7**)	**0.54**	0.34	0.17	0.17	0.49	0.71
I7 (**SI8**)	**0.52**	0.10	0.43	0.04	0.42	0.64
I6	0.45	0.30	0.43	-0.05	0.40	Excluded
I25	0.44	0.11	0.41	0.28	0.29	Excluded
I9 (**HRM1**)	0.14	**0.73**	0.23	0.19	0.24	0.70
I12 (**HRM2**)	0.13	**0.66**	0.25	0.22	0.15	0.58
I13 (**HRM3**)	0.23	**0.65**	0.29	0.29	0.09	0.66
I11 (**HRM4**)	0.47	**0.58**	-0.01	0.17	0.20	0.63
I10 (**HRM5**)	0.43	**0.53**	0.18	0.22	0.21	0.59
I4	0.16	0.43	0.20	0.30	0.43	Excluded
I27 (**TT1**)	0.04	0.10	**0.80**	0.10	0.11	0.67
I28 (**TT2**)	0.24	0.23	**0.63**	0.23	0.22	0.61
I30 (**TT3**)	0.37	0.27	**0.56**	0.12	0.05	0.53
I29 (**TT4**)	0.44	0.36	**0.53**	0.14	-0.11	0.64
I22 (**EP1**)	0.10	0.15	0.06	**0.79**	0.26	0.72
I18 (**EP2**)	0.26	0.32	0.13	**0.64**	-0.06	0.60
I20 (**EP3**)	0.27	0.28	0.30	**0.53**	0.14	0.54
I21 (**EP4**)	0.15	0.27	0.29	**0.53**	0.27	0.53
I19 (**EP5**)	0.43	0.22	0.11	**0.51**	0.12	0.51
I15 (**EN1**)	0.18	0.09	0.09	0.48	**0.60**	0.64
I16 (**EN2**)	0.30	0.43	0.21	0.02	**0.58**	0.66
I26 (**EN3**)	0.15	0.48	-0.02	0.20	**0.57**	0.62
I17 (**EN4**)	0.13	0.05	0.45	0.22	**0.52**	0.54
I14 (**EN5**)	0.43	0.23	0.09	0.15	**0.50**	0.52
						Total
Eigenvalues	5.18	4.08	3.24	3.09	3.06	18.65
(variance%)	(17.27)	(13.59)	(10.80)	(10.31)	(10.21)	(62.18)
Cronbach's alpha	0.91	0.84	0.77	0.80	0.78	0.96

Table 4. CFA models' fit summary.

Indices	**Values**		**Criteria**
	Default CFA	**Modified CFA**	
Ratio of chi-square to its degree of freedom (CMIN/DF)	682.410 / 314 = 2.173	142.862 / 125 = 1.143	< 3
Normed-fit index (NFI)	0.736	0.918	> 0.90
Incremental-fit index (IFI)	0.838	0.989	> 0.90
Comparative-fit index (CFI)	0.835	0.989	> 0.90
Goodness-of-fit index (GFI)	0.803	0.937	> 0.90
Adjusted goodness-of-fit index (AGFI)	0.763	0.914	> 0.90
Root mean squared error of approximation (RMSEA) (90% Confidence Interval)	0.072 (0.064–0. 079)	0.025 (0.00–0.04)	< 0.07
Root mean square residual (RMR)	0.068	0.036	< 0.05
PCLOSE	0.000	0.994	> 0.05

Table 5. The modified CFA model's standardized loading matrix.

Practice	Scale	Standardized Residuals*																		Estimate**
		Scales																		
		EN1	EN2	EN4	EP1	EP2	EP3	EP5	TT1	TT2	TT3	HRM1	HRM3	HRM4	SI1	SI2	SI3	SI7	SI8	
EN																				(0.73)
	EN1	0.00																		0.647
	EN2	1.00	0.00																	0.686
	EN4	-0.44	-0.34	0.00																0.722
EP																				(0.69)
	EP1	-0.48	-0.35	-0.46	0.00															0.551
	EP2	0.43	-0.40	0.89	0.19	0.00														0.623
	EP3	-0.16	-1.18	0.18	-0.27	0.62	0.00													0.567
	EP5	0.42	0.48	-0.02	-0.27	0.41	-0.80	0.00												0.646
TT																				(0.82)
	TT1	-0.49	-0.13	-0.03	0.33	-0.06	0.46	0.73	0.00											0.777
	TT2	-1.23	-0.07	0.08	-0.06	-0.87	-0.22	0.51	0.10	0.00										0.796
	TT3	0.67	0.45	0.69	-0.43	-0.96	0.10	0.35	-0.21	0.08	0.00									0.764
HRM																				(0.73)
	HRM1	-0.12	-0.63	0.18	1.20	-0.38	1.25	-0.04	-0.40	0.08	0.35	0.00								0.601
	HRM3	0.07	-0.80	0.12	-0.36	0.00	1.00	-0.52	-0.30	0.10	0.13	0.06	0.00							0.74
	HRM4	0.44	-0.69	1.15	-0.51	-0.29	0.96	-0.96	0.12	-0.54	0.58	-0.34	0.15	0.00						0.707
SI																				(0.82)
	SI1	-0.56	0.94	0.13	0.56	-0.24	-0.71	-0.68	-0.22	-0.09	0.47	0.54	-0.78	-0.68	0.00					0.724
	SI2	0.12	0.69	-0.45	0.65	-0.42	-0.25	1.12	0.28	0.32	-0.39	0.45	-0.24	1.08	-0.33	0.00				0.621
	SI3	-0.77	-0.40	-0.31	1.91	-1.32	-0.29	-0.51	-0.36	-0.22	0.30	0.06	0.18	0.60	-0.06	0.87	0.00			0.624
	SI7	-0.34	-0.22	-0.08	-0.26	0.12	-0.42	0.04	0.12	0.42	0.71	0.48	-0.27	-0.86	-0.49	0.03	0.56	0.00		0.722
	SI8	-0.23	-0.08	0.83	1.04	0.17	-0.24	0.25	-0.10	-0.62	-0.51	1.30	-0.42	0.40	0.64	-0.73	-0.22	-0.04	0.00	0.735

* All standardized residuals are less than two in absolute value.

** All coefficients are significant ($p < 0.001$). The brackets indicate CR; all values are more than 0.6.

Table 6. Validated multiitem scale to measure GLSS practices.

Practice	**Scale**		**Rating**
Eco-Networks			
	EN1	Supplier management process in place, with active involvement in driving the initiative forward.	
	EN2	Customer relationship management process in place, with active involvement in driving the initiative forward.	
	EN4	Environmental management system in place, with active involvement in driving the initiative forward.	
Eco-Production			
	EP1	Continuous improvement is in place for green manufacturing processes, with active involvement in driving the initiative forward.	
	EP2	Consideration is given to material selection or modification for environmental sustainability, with active efforts to minimize environmental impact throughout the process.	
	EP3	Consideration is given to the use of environmentally friendly packaging, with active efforts to continuously improve the environmental impact of packaging.	
	EP5	Consideration is given to environmentally-friendly product design practices, with active efforts to minimize environmental impact throughout the product life-cycle.	
Technologies and Tools			
	TT1	Technological readiness is in place to support the initiative.	
	TT2	Tools and techniques are in place for effective data collection and measurement, with continuous improvement efforts to enhance the data assortment and measurement process to further the initiative.	
	TT3	Equipment upgrade plans are in place, with continuous improvement efforts to enhance the equipment and machinery to further the initiative.	
Human Resource Management			
	HRM1	Employee training and developmental programs are in place, with continuous improvement efforts to enhance the knowledge, skills, and abilities of employees to further the initiative.	
	HRM3	Teamwork and collaboration are in place, with active engagement from key stakeholders to further the initiative.	
	HRM4	Reward and recognition programs are in place for employees involved in the initiative, with active efforts to recognize and celebrate their contributions.	
Strategic Integrity			
	SI1	Organizational readiness is in place, with active support and commitment from all levels of the organization for furthering the initiative.	
	SI2	There is a link between GLSS and organizational vision and mission statements, with active efforts to align the initiative with the overall strategic goals of the organization.	
	SI3	Top management commitment and support for integrating GLSS throughout the product life-cycle, with active involvement in driving the initiative forward.	
	SI7	The funds' availability is in place to support the initiative.	
	SI8	Resources and skills are in place to expedite the implementation process of the initiative.	

Figures

Fig. 1. The methodological flow.

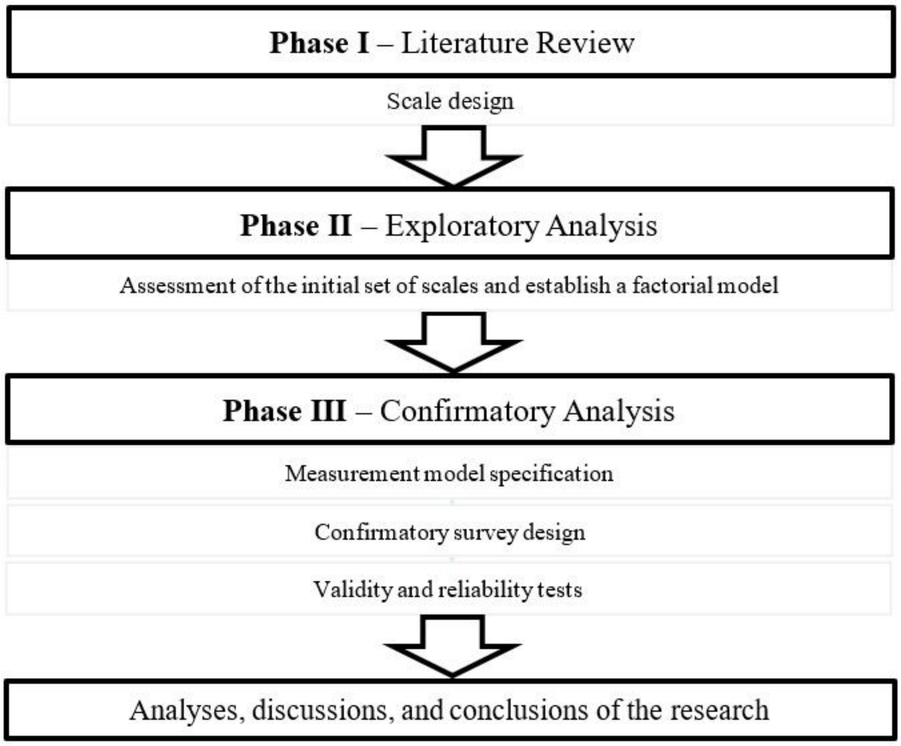

Fig. 2. The initial CFA model’s unstandardized estimates.

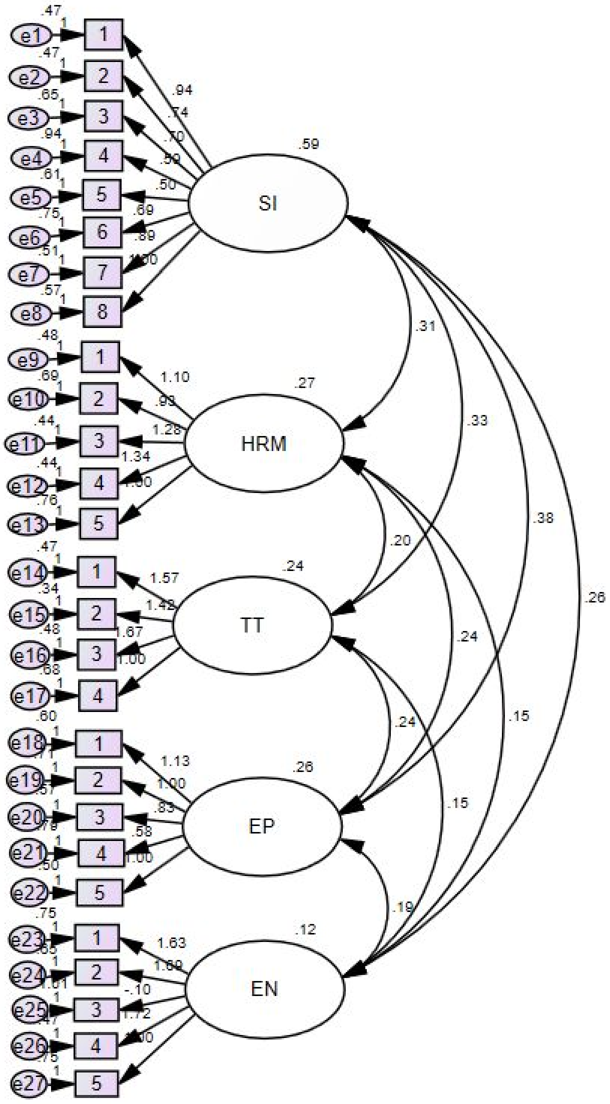

Fig. 3. The modified CFA model's standardized estimates; all coefficients are significant at $p < 0.001$.

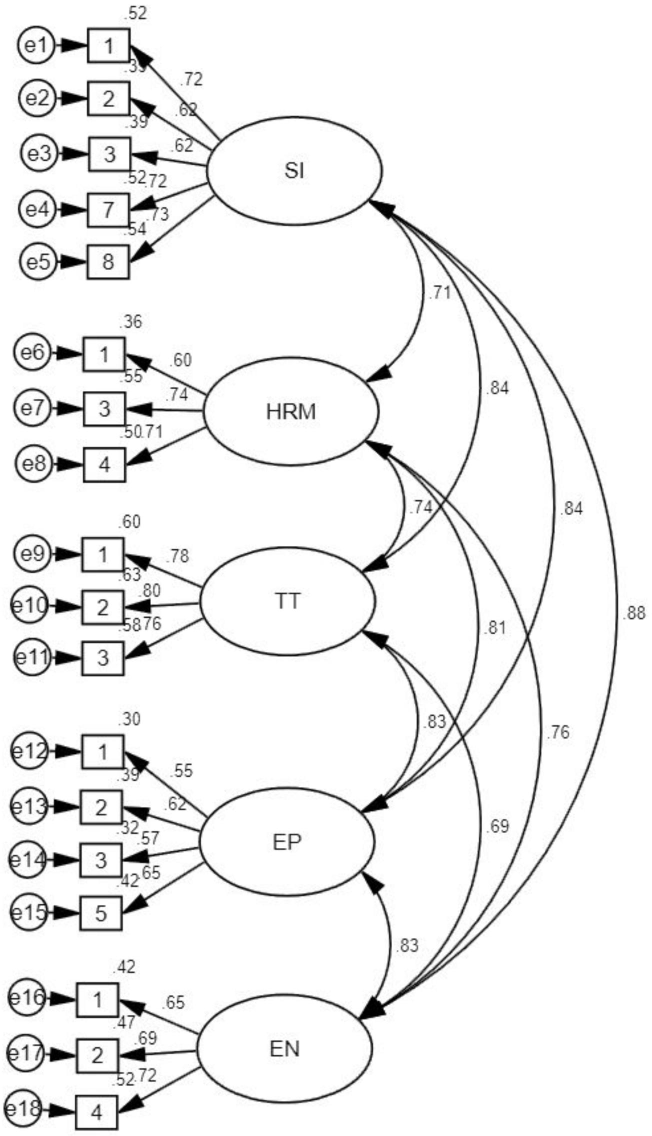

Fig. 4. Proposed measurement model for future research.