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Pathway towards green Lean Six Sigma and industry 4.0 adoption: exploring its critical success factors in a developing economy

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Abstract

Purpose – The present work investigates Critical Success Factors (CSFs) for the successful execution of Green Lean Six Sigma (GLSS) in the Indian manufacturing sector in alignment with Industry 4.0 (I4.0).

Design/methodology/approach – A systematic literature review (SLR) was conducted to ensure a comprehensive and structured examination of existing studies. Relevant articles were sourced from well-established electronic databases, including Science Direct, Taylor & Francis, Elsevier, Emerald, Google Scholar and Scopus, to identify the CSFs for the integration of GLSS with I4.0 technologies. Grey relational analysis was subsequently applied to prioritize the identified CSFs. Additionally, the findings of the study were validated using the best-worst method.

Findings – This study aims to identify and model the CSFs of GLSS-I4.0 initiatives that are crucial for the successful implementation of GLSS in manufacturing environments aligned with I4.0 technologies. A comprehensive review of the existing literature was carried out to identify 27 relevant CSFs within the GLSS-I4.0 framework that effectively address the specific needs of the manufacturing sector. The study reveals that CSFs 21 (Focused on leveraging technological innovation and industry best practices), CSFs 13 (Managing organizational change within GLSSI4.0 initiatives), CSFs 18 (Built-in flexibility and responsiveness within the GLSSI4.0 model), CSFs 10 (An organized approach to embedding I4.0 within GLSS), CSFs 1 (Robust project management and supervision), CSFs 19 (A culture of adaptability and continuous improvement aligned with GLSSI4.0 implementation), CSFs 20 (Institutional readiness for GLSS implementation supported by I4.0 technologies) and CSFs 12 (Availability of standard operating procedures for GLSS-I4.0 integration) were recognized as highly significant CSFs in enabling the successful integration of GLSS with I4.0 technologies and were considered as most significant CSFs for integrating GLSS approach with I4.0 technologies.

Research limitations/implications – The study provides a strategic roadmap for the practitioners to facilitate the effective execution of GLSS practices within the I4.0 context. The integration of GLSS with I4.0 technologies offers a significant competitive advantage in the contemporary industrial landscape by enhancing an organization's ability to deliver customized products that meet dynamically evolving customer requirements.

Originality/value – This study represents the first comprehensive investigation of CSFs for integrating GLSS with I4.0 technologies in the context of the Indian manufacturing sector Keywords: Manufacturing sectors; Green Lean Six Sigma; Industry 4.0; Critical Success Factors; Gray Relational Analysis; Best Worst Method.

Keywords Manufacturing sectors, Green Lean Six Sigma, Industry 4.0, Critical success factors, Gray relational analysis, Best worst method

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1. Introduction

Industrial sectors play a crucial role in contributing to India's Gross Domestic Product (GDP) (Jain and Ajmera, 2020). The Indian government has launched key schemes like "Make in India" and "Digital India" to boost the development of manufacturing organizations. To strengthen the manufacturing ecosystems, the Indian government has introduced major initiatives such as Make in India and Digital India, aimed at accelerating industrial growth and technological advancement. Consequently, manufacturing organizations are increasingly exploring effective quality improvement strategies to respond to the evolving and dynamic demands of consumers. In the contemporary economic landscape, there is heightened awareness of the environmental and social challenges faced by businesses (Yacob *et al*., 2019). Issues such as climate change and environmental pollution have prompted stakeholders to place greater emphasis on environmentally sustainable products and services (Kwon, 2020). Organizational sustainability is characterized by the use of clean, energy-efficient processes to produce goods and services, while also improving operational performance, ensuring the health and safety of employees, communities and consumers and offering fair compensation to all workers (Thakur and Mangla, 2019; Kaswan *et al*., 2021). As a result, manufacturing industries are being driven to implement sustainable practices aimed at lowering emissions and fulfilling their environmental responsibilities (Parmar and Desai, 2020). Therefore, sustainable manufacturing is becoming the strategy of choice for modern industries, offering an economically practical approach to reducing pollution and conserving resources across the entire product life cycle (Ibrahim and Kumar, 2025). The GLSS is distinct as a green concept that aims at the enhancement of the ecological performance of an organization, Lean targets the elimination of wastes and non-value-added activities and Six Sigma is employed for the minimization of product defects (Yadav *et al*., 2023a, b). However, if executed together, these approaches can better address the ecological anxieties of industrial sectors by reducing waste, value addition, emissions and resource preservation (Huo *et al*., 2019).

Industry 4.0 is a novel pattern encouraging substantial enhancement by automation and digital transformation (Khanzode *et al*., 2021). Chiarini and Kumar (2022) employed Structural Equation Modelling (SEM) in Indian steel manufacturing organizations to establish the relationship between inventory mechanization practices and productivity. Skalli *et al.* (2023) utilized TISM and their interrelations by MICMAC analysis to expose the barriers to initiative suppleness in an insurance firm. Singh and Rathi (2024) stated that I4.0 technologies and LSS are now accessible to all companies in almost all nations, though their approval and execution will distinguish their concert and a major concern factor for enhancing competitiveness. A study examining the pathway toward the adoption of GLSS concept and I4.0 in a developing economy is necessary to tackle sustainability challenges, develop context-appropriate adoption frameworks, address execution constraints and strengthen industrial competitiveness (Ibrahim and Kumar, 2025). Such research offers empirical insights to support firms and policymakers in achieving environmentally sustainable, digitally driven and operationally efficient industrial development (Yadav *et al*., 2023a, b). Although GLSS and I4.0 are increasingly acknowledged as important drivers of sustainability and operational excellence, organizations especially in developing economies have limited understanding of CSFs necessary for their effective integration (Khanzode *et al*., 2021). Most existing research considers GLSS and I4.0 independently, providing insufficient empirical insights into the organizational, technological and environmental conditions that support their combined implementations (Samanta *et al*., 2024). As a result, organizations often experience disjointed adoption efforts, limited use of digital technologies for sustainability purposes and inconsistent performance outcomes.

However, several authors have identified barriers and critical success factors (CSFs) for the execution of the GLSS approach (Yadav *et al*., 2023a, b) and Industry 4.0 (Samanta *et al*., 2024) independently/distinctly for several kinds of firms, but less research has been carried out on the CSFs of GLSS with Industry 4.0 technologies.

The purpose of the current work is to identify the CSFs that contribute to the execution of the GLSS approach incorporation with I4.0 skills in the setting of manufacturing industries and rank these barriers by using the Gray relational analysis (GRA). GRA is an effective indicator for exploring the correlation between series with less data and could overcome the limitations of the arithmetic technique. GRA has been successfully applied to solve a variety of MCDM problems.

Furthermore, the outcomes of the current study have been authenticated by the best worst method (BWM). BWM is a multi-criteria decision-making technique that employs two vectors of pairwise comparison to obtain the criteria weights. Firstly, the best (most attractive, most important) and the worst (least attractive, least critical) criteria are recognized by the decision-maker, after which the best criterion and worst criterion are compared to the other criteria by using a number on a (1–9) scale (Rezaei, 2014). The present study offers significant theoretical implications for researchers and newcomers in the field of integrated GLSS with I4.0 technologies, particularly in the context of improving the productivity of manufacturing sectors. The findings of this study offer valuable practical insights for the Indian manufacturing sectors. The techniques employed in this study serve as a strategic roadmap for practitioners, guiding the execution of more effective GLSS practices within the context of I4.0.

The present study has been conducted to address the subsequent research questions:

RQ1. To what extent do industrial experts agree on the relative importance of each CSFs for the successful implementation of GLSS approach integrated with I4.0 technologies?

RQ2. To evaluate and rank the validated CSFs for successful integration of these approaches by applying GRA technique

RQ3. To evaluate and assign relative importance weights to the CSFs for effective GLSS-I4.0 execution through BWM

The current work is organized into eight sections. Section 1 provides an introduction to the research. Section 2 outlines the literature search methodology by the PRISMA approach, background on Green Lean Six Sigma (GLSS) Approach, Industry 4:0, Integration of GLSS with Industry 4.0, research gaps and identification of CSFs for Green Lean Six Sigma Integrated Industry 4.0 (GLSSI). Consequently, the next section presents the research method adopted to carry out the present work. Section 4 depicts discussions on findings. Section 5 describes the theoretical and practical implications of the present work. Section 6 presents conclusions, and the last section provides limitations and a future research agenda of the current work.

2. Literature review

This part of the present work comprises a systematic literature review through the PRISMA approach, background on the GLSS Approach and Industry 4:0, and Integration of GLSS and Industry 4.0. This section also contains recognized research gaps suitable for the current work.

2.1 Systematic literature review through the PRISMA approach

The articles have been taken from well-recognized journals and tagged with keywords like GLSS, Industry 4:0, CSFs, sustainability, integration of GLSS and I:4.0 for execution in manufacturing sectors. The Prisma Approach (as shown in Figure 1) has been adopted to carry out the systematic literature review in this research work. Firstly, the authors searched articles from Springer, Elsevier, Emerald, Science Direct, Scopus, Web of Science, etc. databases. Only English-language, peer-reviewed international journal articles published from 2000 to 2024 were considered. Initially, a total of papers (N = 600) were recognized. However, after the preliminary review, manuscripts (N = 250) were excluded as they did not contain pertinent information related to the designated focus on CSFs.

In the inspection phase, some articles (N = 350) have been screened. Out of these articles, some articles (N = 80) were excluded based on the title and abstract. After that, reports of the

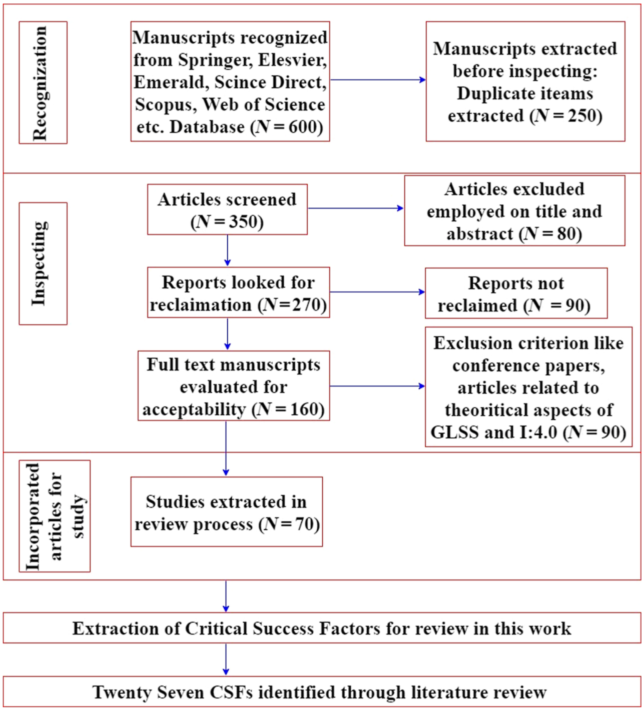

Figure 1. PRISMA approach

articles (N = 270) were looked up for reclamation, and papers (N = 90) reports were not reclaimed. Then, later, full-text manuscripts (N = 160) were evaluated for acceptability. Papers (N = 90) came under the exclusion criterion employed on conference papers, and articles related to theoretical aspects of GLSS and Industry 4.0. At last, articles (N = 70) were extracted for the review process in the present work (Referring Appendix: A). Finally, the screened research papers identified 27 CSFs and consulted with the industrial personnel.

2.2 Background on the green Lean Six Sigma approach and industry 4:0

The origins of GLSS can be linked to the Toyota Production System (TPS), widely recognized as Lean in Western nations (Gholami *et al*., 2021). Green technology, Lean and Six Sigma are complementary approaches, each capable of offsetting the limitations of the others (Cherrafi *et al*., 2017). While Lean is appreciated for its effectiveness in quantifying waste, it falls short in measuring environmental impacts and identifying potential environmental hotspots (Vinodh *et al*., 2016). Six Sigma emphasizes minimizing variation and defects, offering a reliable approach to achieving high-quality products at reasonable costs (Gaikwad *et al*., 2020). However, this concept does not specifically report on the challenges associated with eco-friendly and societal sustainability aspects (Gahlot and Yadav, 2022). Thus, there is a requirement to integrate the green concept with equally Lean and SS to attain an all-inclusive enhancement tactic, known as GLSS, to get eco-friendly products in an organization (Kaswan *et al*., 2023; Singh *et al*., 2023). Figure 2 illustrates a combined model of GLSS.

Pongboonchai-Empl *et al*. (2024) stated that the Fourth Industrial Revolution represents the most recent stage in the evolution of industry since its inception in the 18th century, which began with the first manufacturing revolution, marked by the introduction of steam engines as

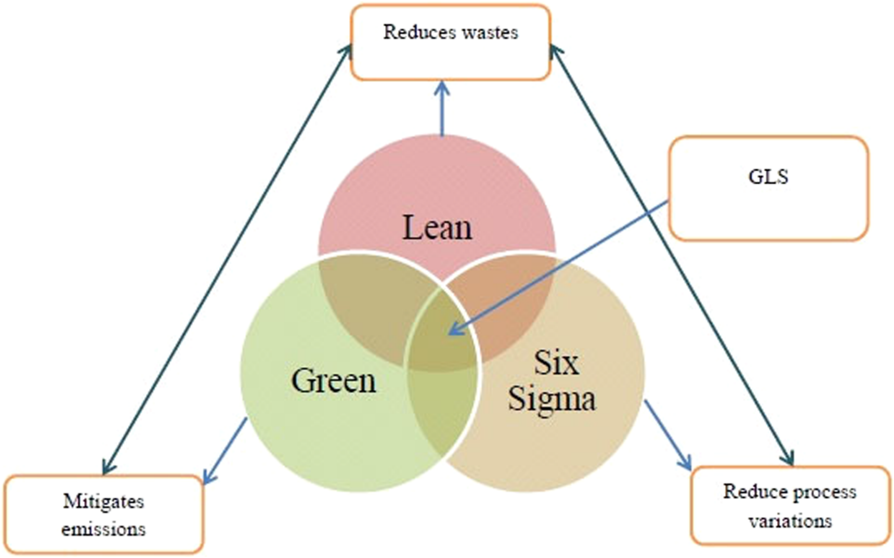

Figure 2. Integrated model of GLSS. **Source**: Yadav *et al.* (2021)

a pivotal innovation. Through the application of cyber-physical systems (CPS), the Internet and intelligent systems with improved human–machine communication, I:4.0 facilitates the whole communication across the value chain (Chiarini and Kumar, 2022) and enables real-time monitoring of production systems (Tortorella *et al.*, 2019; Fatorachian and Kazemi, 2021). Industry 4.0 constitutes distinct technologies as shown in Figure 3.

2.3 Integration of GLSS with industry 4.0

Limited prior studies have been conducted on integrating I4.0 with functional superiority approaches like GLSS, which is relatively scarce. Siegel *et al.* (2019) investigated the impact of I4.0 and lean manufacturing on achieving functional excellence by surveying 108 European industries. Shahin *et al.* (2020) invested in the use of Lean tools alongside I4.0 technologies to enhance the functional performance of the firms. Singh *et al.* (2021a, b) suggested that a combined Lean Six Sigma (LSS) and I4.0 strategy enhances metrics such as cycle time, waste reduction and quality but does not significantly affect the environmental metrics. Kaswan *et al.* (2023) presented a theoretical framework for integrating GLSS and I4.0 by the application of distinct tools and methods of these approaches at the distinct phases of the understanding of the project.

2.4 Research gaps

The existing literature contains limited research on the integration of Lean and LSS with I4.0, and studies exploring the synergy between I4.0 and sustainability are similarly scarce. To the best of the author's knowledge, less work has been carried out for integrating GLSS and I4.0 technologies. Kaswan *et al.* (2023) presented a theoretical framework for integrating GLSS and I4.0 by the application of distinct tools and methods of these approaches at the distinct phases of the understanding of the project. Furthermore, there is no evidence to prioritize and rank CSFs for integrating GLSS and I4.0 technologies through the GRA technique and further authenticated by the BWM method in the context of manufacturing industries. Therefore, to fill this gap, the present study dispenses factual evidence to improve the understanding of CSFs

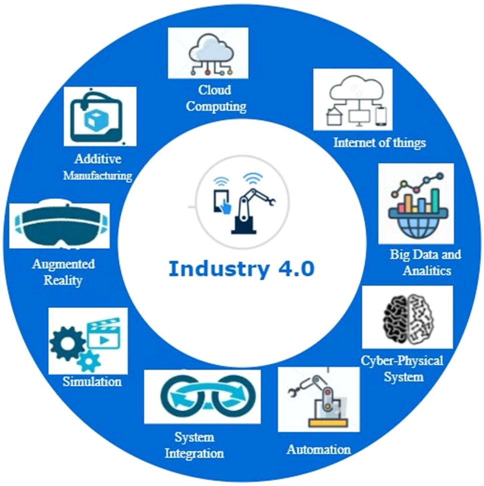

Figure 3. Technologies that establish Industry 4.0

for integrating these concepts. Therefore, the noted literature gaps have provided a way for the current study.

2.5 Identification of critical success factors for integrated GLSS industry 4.0

CSFs are considered key enablers for achieving organizational goals and ensuring effective quality management and performance. In response to this challenge, we have identified 27 CSFs (see Table 1) that may enable the incorporation of GLSS with I4.0 technologies.

3. Research methodology

This research adopted a three-phase methodological approach. In the first phase, the study focused on the identifying CSFs that enable the integration of GLSS with I4.0 technologies within the industrial organizations. For this purpose, a structured questionnaire was designed and administered to industrial practitioners and academic experts to obtain their perspectives. The second phase involved prioritizing the identified CSFs using the GRA technique. Figure 4 illustrates the overall research methodology employed in this study.

3.1 Phase 1: formation of the questionnaire for the survey, collection of data and evaluation of the reliability of data

In the initial phase of the study, an extensive review of the existing literature was conducted to identify the CSFs relevant to manufacturing industries in the Indian context. Based on this analysis, 27 CSFs were identified. Subsequently, a structured questionnaire was developed and distributed to industry experts, researchers, academicians and mid-to-senior level professionals from the various manufacturing sectors across India. The survey employed a five-point Likert scale, where a rating of 5 represented the most critical CSF to be prioritized, and a rating of 1 represented the least CSF. Initially, approximately 240 manufacturing professionals from Indian industries were contacted through email, telephone and personal visits to explain the concept of GLSS and I4.0 integration within organizations. Referring Appendix B, the questionnaire has been circulated approximately to the 240 manufacturing professionals (including: industry personals, concerned researchers, academicians) via email, telephonically and in-person visits to get their insights on subject matter. Out of 240

Table 1. List of critical success factors for integrating GLSS with Industry 4.0

No.	Critical success factors (CSFs)	Explanation of CSF	References
CSFs1	Robust project management and supervision	Robust project management capabilities enable organizations to effectively implement new infrastructure and initiatives, thereby supporting successful GLSS-I4.0 execution	Swarnakar *et al.* (2019)
CSFs2	Effective cooperation and alignment of interests among shareholders	Successful implementation of any change model, including I4.0, depends on strong collaboration across processes, employees and organizational units	Singh and Rathi (2020)
CSFs3	Effective communication at all organizational levels	Effective communication facilitates a quick understanding of concepts and guidelines, supporting the operative implementation of GLSSI initiatives	Samanta *et al.* (2024)
CSFs4	Adoption of sustainable packaging solutions	It states the execution of eco-friendly materials and practices in the design, production and use of packaging	Yadav *et al.* (2023a, b)
CSFs5	Adoption of environmentally sustainable transportation methods	Adopting environmentally sustainable transportation practices is critical to reducing environmental impacts, conserving resources and supporting sustainable urban development	Shokri and Li (2020)
CSFs6	The extent of executive leadership support for the alignment of GLSS and I4.0 initiatives	Through the involvement of senior management, workplace staff, operatives and other stakeholders are given appropriate consideration and support	Samanta *et al.* (2024)
CSFs7	Tracking performance following the integration of I4.0 and GLSS	A specialized recital intensive care system is essential to measure structural performance and enhance the administration of manufacturing operations	Singh *et al.* (2021a, b)
CSFs8	Promote greater coordination and integration across the supply chain to facilitate GLSS-I4.0 implementation	Incorporating the GLSSI approach into the supply chain demands dedication to sustainability, minimizing waste and fostering ongoing improvement	Sony and Naik (2020)
CSFs9	Educational initiatives for advanced technologies and GLSS	Organizations must allocate financial resources and dedicate time to training and educating their employees	Caiado *et al.* (2018)
CSFs10	An organized approach to embedding I4.0 within GLSS	To ensure overall effectiveness, process enhancement initiatives and infrastructure projects must be implemented using a systematic and coordinated approach	Gholami *et al.* (2021)

(*continued*)

Table 1. Continued

No.	Critical success factors (CSFs)	Explanation of CSF	References
CSFs11	Eco-management system	A well-implemented eco-management system allows organizations to incorporate environmental factors into their everyday operations, embedding sustainability into their core business strategy	Pandey *et al.* (2018)
CSFs12	Skills, capabilities and competencies associated with design thinking	As a specialized and evolving problem-solving approach, it is fundamentally driven by the recognition and satisfaction of previously unaddressed customer needs	Singh *et al.* (2021a, b), Samanta *et al.* (2024)
CSFs13	Availability of standard operating procedures for GLSS-I4.0 integration	As this concept is comparatively new, organizations often lack well-defined SOPs to guide employees and maintain systematic operational processes	Sony and Naik (2020), Gaikwad *et al.* (2020)
CSFs14	Managing organizational change within GLSS-I4.0 initiatives	This is essential for the effective implementation of GLSS-I4.0 initiatives within organizations, as it facilitates employee adoption and adaptation to new technologies and work practices	Raval *et al.* (2021), Rathi *et al.* (2023)
CSFs15	Ready access to precise, reliable and current information	The prompt and precise retrieval of data helps organizations gain benefits and a competitive edge	Gaikwad *et al.* (2020)
CSFs16	Engaged and proficient workforce	Building an engaged and skilled workforce requires offering the necessary tools, resources and environment for employees to succeed	Pongboonchai-Empl *et al.* (2024)
CSFs17	Sufficient access to capital for investing in new technologies and implementation of GLSS-I4.0 practices	Emerging organizations require financial resources for principal savings to develop the capacity and abilities necessary for a combined strategy	Stankalla *et al.* (2018)
CSFs18	Process oversight and governance for GLSSI	The GLSSI methodology minimizes process variation, eliminates non-value-added activities and enables real-time monitoring and control	Yadav *et al.* (2023a, b)
CSFs19	Specialized information management system	In addition to systematic data collection and analysis, a key managerial priority is the implementation of a dedicated information management system	Gholami *et al.* (2021)
CSFs20	Aligning business strategies and information systems for GLSS-I4.0 integration	Since I4.0-enabled systems generate a large volume of data, effectively utilizing this data demands a consistent management approach	Kaswan *et al.* (2021)

(*continued*)

Table 1. Continued

No.	Critical success factors (CSFs)	Explanation of CSF	References
CSFs21	Embracing a philosophy of continuous improvement	Adopting a continuous enhancement mindset involves creating a culture that prioritizes innovation, teamwork and learning	Shamsi and Alam (2018)
CSFs22	Built-in flexibility and responsiveness within the GLSS-I4.0 model	Organizational agility in rapidly learning and integrating new processes, systems and technologies is essential for the effective implementation of GLSS-I4.0 initiatives	Yadav and Desai (2017)
CSFs23	A culture of adaptability and continuous improvement aligned with GLSSI4.0 implementation	The presence of a positive organizational culture greatly facilitates the successful execution of organizational change initiatives	Kaswan *et al.* (2023)
CSFs24	Institutional readiness for GLSS implementation supported by I4.0 technologies	The structural readiness comprises physical and adaptive infrastructure, leadership attitudes, employee commitment and stakeholder alignment	Sony and Naik (2020), Gholami *et al.* (2021)
CSFs25	Focused on leveraging technological innovation and industry best practices	As with any organizational practice, success largely depends on the organization's capacity to adapt to evolving environmental conditions	Dalenogare *et al.* (2018)
CSFs26	An informed understanding of data security and privacy challenges	During organizational change, employees require a strong sense of security. The implementation of I4.0 principles enables continuous data generation to support ongoing, data driven operational decision-making	Kaswan and Rathi (2020)
CSFs27	Reliable data collection and retrieval	It emphasizes the processes used to collect and retrieve system-stored data, rather than focusing solely on the availability of accurate and timely information	Ershadi *et al.* (2021)

professionals only 130 filled the questionnaire, and 115 of them were found valid and chosen for further analysis. The professionals selected all had over 18 years of experience in their field. The details and profiles of the experts are depicted in Table 2.

Before employing techniques like GRA and BWM, a reliability test was carried out with SPSS version 25.0. After inputting the response into SPSS version 25.0, Cronbach's alpha (α) and item-total correlations (CITC) were calculated. The values of Cronbach's alpha (α) and CITC were evaluated against the threshold levels to assess the consistency and reliability of the survey responses (as presented in Table 2). As per Porter *et al.* (2008), items with an α value greater than 0.7 are considered consistent and reliable. Additionally, a CITC value exceeding 0.3 indicates that an item is associated with a composite score of all items within the same set. In this reliability test, 4 CSFs (as presented in Table 3) had CITC values below 0.3 (Indicated in bold), meaning these items like CSFs11 (Eco-management system), CSFs 16 (Engaged and proficient workforce), CSFs18 (Process oversight and governance for GLSSI) and CSFs21 (Embracing a philosophy of continuous improvement) did not exhibit a similar construct with the other 23 items. As a result, four CSFs were excluded from the previously identified CSFs

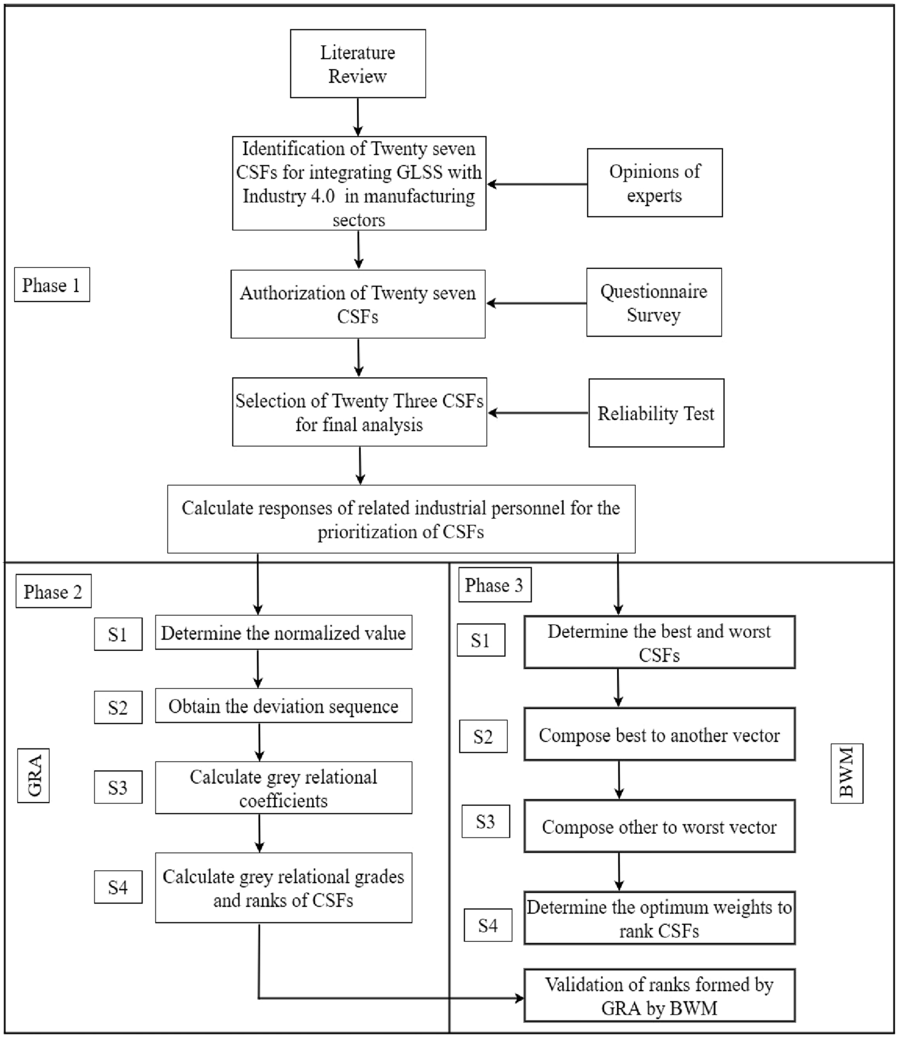

Figure 4. Research methodology. **Source**: Authors' own creation

listed in Table 1. Ultimately, a total of 23 CSFs (with revised codes CSFs 1 to CSFs 23) were selected for further study and analysis, as shown in Table 4.

3.2 Phase 2: prioritization of CSFs for integrating GLSS with industry 4.0 in the context of the manufacturing sector by the GRA technique

The GRA technique was also introduced after examining the issue and consulting with the decision-maker team. After identifying CSFs and developing the questionnaire, the next step is prioritizing these CSFs using GRA analysis. The steps involved in GRA are as follows:

Step 1: Determine the normalized value

Table 2. Details and profiles of the experts

S. No.	Work profile	Number of people	Average experience (Years)	Expertise	Industry/ Academia	Qualification
1	Plant Manager	22	20	GLSS	Industry	MBA
2	Design Head GLSS	20	16	GLSS	Industry	MBA
3	Research and Development (R&D) Head (Innovation)	24	20	I4.0	Industry	MBA M. TECH
4	Consultant Master belt	21	21	GLSS Trainer	Industry	M.TECH
5	Production Manager	18	17	GLSS + I4.0	Industry	B. TECH, MBA
6	Professor, Associate Professor and Assistant Professor	10	14	Quality + I4.0	Academia	PHD

Source(s): Authors' own creation

Table 3. Consistency and reliability of survey response by Cronbach's alpha (α) and item-total correlations (CITC)

Sr. No.	CSFs	No. of items	CITC value	Value of α if items deleted
1	CSFs1	115	0.662	0.842
2	CSFs2	115	0.774	0.882
3	CSFs3	115	0.512	0.852
4	CSFs4	115	0.412	0.843
5	CSFs5	115	0.492	0.801
6	CSFs6	115	0.552	0.821
7	CSFs7	115	0.601	0.811
8	CSFs8	115	0.471	0.871
9	CSFs9	115	0.391	0.812
10	CSFs10	115	0.712	0.824
11	*CSFs11*	*115*	*0.241*	*0.844*
12	CSFs12	115	0.422	0.831
13	CSFs13	115	0.561	0.871
14	CSFs14	115	0.441	0.851
15	CSFs15	115	0.371	0.841
16	*CSFs16*	*115*	*0.211*	*0.803*
17	CSFs17	115	0.394	0.844
18	*CSFs18*	*115*	*0.192*	*0.829*
19	CSFs19	115	0.491	0.814
20	CSFs20	115	0.712	0.887
21	*CSFs21*	*115*	*0.181*	*0.818*
22	CSFs22	115	0.394	0.879
23	CSFs23	115	0.471	0.822
24	CSFs24	115	0.641	0.825
25	CSFs25	115	0.499	0.809
26	CSFs26	115	0.571	0.854
27	CSFs27	115	0.496	0.848

Source(s): Authors' own creation

Table 4. Final screened CSFs after employing reliability test

Code	CSFs
CSFs1	Robust project management and supervision
CSFs2	Effective cooperation and alignment of interests among shareholders
CSFs3	Effective communication at all organizational levels
CSFs4	Adoption of sustainable packaging solutions
CSFs5	Adoption of environmentally sustainable transportation methods
CSFs6	The extent of executive leadership support for the alignment of GLSS and I4.0 initiatives
CSFs7	Tracking performance following the integration of I4.0 and GLSS
CSFs8	Promote greater coordination and integration across the supply chain to facilitate GLSS-I4.0 implementation
CSFs9	Educational initiatives for advanced technologies and GLSS
CSFs10	An organized approach to embedding I4.0 within GLSS
CSFs11	Skills, capabilities and competencies associated with design thinking
CSFs12	Availability of standard operating procedures for GLSS-I4.0 integration
CSFs13	Managing organizational change within GLSS-I4.0 initiatives
CSFs14	Ready access to precise, reliable and current information
CSFs15	Sufficient access to capital for investing in new technologies and implementation of GLSS-I4.0 practices
CSFs16	Specialized information management system
CSFs17	Aligning business strategies and information systems for GLSS-I4.0 integration
CSFs18	Embracing a philosophy of continuous improvement
CSFs19	A culture of adaptability and continuous improvement aligned with GLSSI4.0 implementation
CSFs20	Institutional readiness for GLSS implementation supported by I4.0 technologies
CSFs21	Focused on leveraging technological innovation and industry best practices
CSFs22	An informed understanding of data security and privacy challenges
CSFs23	Reliable data collection and retrieval

Source(s): Authors' own creation

The initial step consists of standardizing the data gathered with the assistance of experts within the organization. The responses provided by experts o' on CSFs 'i' are aggregated and represented as 'C_{io}'.

$$C_{io} = \frac{C_{io} - min\, C_{io}}{max\, C_{io} - min\, C_{io}} \tag{1}$$

We have collected opinions based on the feedback from industry personnel, including the plant and production manager (P&PM), research and development head (R&DH), consultant master belt (CMB) and academicians (A), including professors, associate professors and assistant professors. Table 5 depicts responses from industrial and academician employees.

Step 2: Obtain the deviation sequence

In this stage of GRA, the deviation sequence (Δ) is derived using equation (2), Table 6 represents the calculated deviation sequence.

$$\Delta = \max C' - C' \tag{2}$$

Step 3: Compute Gray relational coefficients

In the next step, Equation (3) is used in the third stage to get the Gray relational coefficients (K_{io}). In this case, max (Δ) signifies the largest value of the deviation sequence while min(Δ) indicates its minimum value. K value is assumed to be 0.5. The Gray relationship coefficients are shown in Table 7.

Table 5. Responses from industrial and academician employees

CSFs	P&PM	R&DH	CMB	A
CSFs 1	44	29	28	42
CSFs 2	35	28	30	28
CSFs 3	40	35	28	30
CSFs 4	35	30	38	27
CSFs 5	40	35	27	40
CSFs 6	29	34	34	42
CSFs 7	42	40	39	40
CSFs 8	28	29	42	41
CSFs 9	44	35	32	31
CSFs 10	29	31	31	27
CSFs 11	40	35	25	30
CSFs 12	27	31	31	36
CSFs 13	25	29	32	37
CSFs 14	38	35	40	41
CSFs 15	22	28	36	32
CSFs 16	33	38	31	46
CSFs 17	27	28	38	40
CSFs 18	30	29	26	31
CSFs 19	28	30	26	26
CSFs 20	32	35	26	28
CSFs 21	23	29	22	31
CSFs 22	35	30	28	42
CSFs 23	28	30	25	25

Source(s): Authors' own creation

Table 6. Deviation sequence calculated

CSFs	P&PM	R&DH	CMB	A
CSFs 1	0.818182	0.615385	0	0.142857
CSFs 2	0.590909	0.230769	0.8	0.095238
CSFs 3	0.818182	0.615385	0.3	0.238095
CSFs 4	0.590909	0.230769	0.8	0.095238
CSFs 5	0.818182	0.615385	0.25	0.714286
CSFs 6	0.318182	0.538462	0.6	0.809524
CSFs 7	0.909091	1	0.85	0.714286
CSFs 8	0.272727	0.153846	1	0.761905
CSFs 9	1	0.615385	0.5	0.285714
CSFs 10	0.318182	0.307692	0.45	0.095238
CSFs 11	0.818182	0.615385	0.15	0.238095
CSFs 12	0.227273	0.307692	0.45	0.52381
CSFs 13	0.136364	0.153846	0.5	0.571429
CSFs 14	0.727273	0.615385	0.9	0.761905
CSFs 15	0	0.076923	0.7	0.333333
CSFs 16	0.5	0.846154	0.45	1
CSFs 17	0.227273	0.076923	0.8	0.714286
CSFs 18	0.363636	0.153846	0.2	0.285714
CSFs 19	0.272727	0.230769	0.2	0.047619
CSFs 20	0.227273	0.538462	0.75	0.142857
CSFs 21	0.045455	0.153846	0	0.285714
CSFs 22	0.590909	0.230769	0.3	0.809524
CSFs 23	0.272727	0.230769	0.15	0

Source(s): Authors' own creation

Table 7. Gray relational coefficients

CSFs	P&PM	R&DH	CMB	A
CSFs 1	0.379333	0.488294	1	0.777777
CSFs 2	0.458333	0.68421	0.37037	0.842832
CSFs 3	0.687499	0.619047	0.526315	0.488371
CSFs 4	0.642857	0.764706	0.333333	0.396226
CSFs 5	0.379333	0.448275	0.76923	0.677419
CSFs 6	0.785792	0.764706	0.50505	0.46667
CSFs 7	0.458333	0.68421	0.62505	0.381818
CSFs 8	0.333333	0.448294	0.50505	0.636363
CSFs 9	0.379333	0.448294	0.62505	0.677419
CSFs 10	1	0.866666	0.416666	0.6
CSFs 11	0.687499	0.866666	0.384615	0.411793
CSFs 12	0.578947	0.764706	0.714285	0.636363
CSFs 13	0.917442	0.764706	1	0.636363
CSFs 14	0.333333	0.764706	0.62505	0.381818
CSFs 15	0.379333	0.448294	0.666666	0.411793
CSFs 16	0.611111	0.619247	0.526315	0.842832
CSFs 17	0.61111	0.481482	0.454545	0.381818
CSFs 18	0.647059	0.68421	0.76923	1
CSFs 19	0.642857	0.68421	0.714285	0.913043
CSFs 20	0.458333	0.866666	0.555555	0.777777
CSFs 21	0.785792	1	0.333333	1
CSFs 22	0.687499	0.481482	0.4	0.777777
CSFs 23	0.521053	0.448294	0.714285	0.777777

Source(s): Authors' own creation

$$\mathrm{K_{io}} = \frac{min(\Delta) + kmax(\Delta)}{\Delta io + kmax(\Delta)} \tag{3}$$

Step 4: Determine the Gray relational grades and rank the CSFs

In the fourth step of the GRA process, the grey relational grade ($\mathrm{Y_{io}}$) is computed using equation (4):

$$\mathrm{Y_{io}} = 1 \Big/ \mathrm{n} \sum_{1}^{n} \mathrm{Kio} \tag{4}$$

Here, "n" represents the number of respondent groups within the industry under study. In this case, $n = 8$. The grey relational grade is established, and based on this data, CSFs are ranked. Table 8 depicts the grey relational grades and the corresponding ranks of CSFs for integrating GLSS with I4.0.

3.3 Phase 3: prioritization of CSFs for integrating GLSS with industry 4.0 in the context of the manufacturing sector by the BWM method

BWM is a multi-criteria decision-making method that uses two vectors of pairwise comparisons to determine the criteria weights. Initially, the decision-maker identifies the best (most significant or most desirable) and worst (least important or least desirable) criteria.

Step 1: Identification of CSFs for integrating GLSS with Industry 4.0 within a manufacturing environment

Table 8. Gray relational grades and ranking of CSFs for integrating GLSS with I4.0

CSFs	GRG	Rank
CSFs 1	0.585966	5
CSFs 2	0.480049	13
CSFs 3	0.447583	16
CSFs 4	0.439501	17
CSFs 5	0.456284	15
CSFs 6	0.495511	10
CSFs 7	0.428852	19
CSFs 8	0.397666	21
CSFs 9	0.426214	20
CSFs 10	0.633117	4
CSFs 11	0.48587	11
CSFs 12	0.511197	8
CSFs 13	0.71649	2
CSFs 14	0.43512	18
CSFs 15	0.396938	22
CSFs 16	0.505239	9
CSFs 17	0.395618	23
CSFs 18	0.647534	3
CSFs 19	0.581959	6
CSFs 20	0.530952	7
CSFs 21	0.735529	1
CSFs 22	0.466144	14
CSFs 23	0.481365	12

Source(s): Authors' own creation

In this step, CSFs were recognized by a literature review and by consulting with industrial personnel. Table 9 depicts the characteristics and demographic background of respondents.

Step 2: Determine the best and worst barrier

From the finalized LSS barriers identified the best (most attractive, most important) and the worst (least attractive, least critical) barriers or decision criteria dependent on the expert's opinions.

Table 9. Features and demographic context of defendants

S. No.	Work profile	Number of people	Average experience (Years)	Expertise	Industry/ Academia	Qualification
1	Plant Manager	23	21	GLSS	Industry	MBA
2	Design Head GLSS	21	15	GLSS	Industry	MBA
3	Research and Development (R&D) Head (Innovation)	25	19	I4.0	Industry	MBA M. TECH
4	Consultant Master belt	20	20	GLSS Trainer	Industry	M.TECH
5	Production Manager	17	18	GLSS + I4.0	Industry	B. TECH, MBA
6	Professor, Associate Professor and Assistant Professor	11	13	Quality + I4.0	Academia	PHD

Source(s): Authors' own creation

Step 3: Industrial personnel are detecting predilection of the best decision criterion (C) over another decision criterion, with the help of 9 point measure (statistics among 1 and 9; in which for number 1: C is likewise significant to k, and for number 9: C is enormously more significant than k). The outcome is the best-to-others (CO) vector as follows:

$$D_C = (a_{C1}, a_{C2}, a_{C3}, \ldots\ldots.., a_{Cn}) \tag{5}$$

However, C_k designates the preference of best criterion (C) over any criterion k, and it is clear that $a_{CC} = 1$.

Step 4: Industrial personnel are also detecting predilection of all the decision criteria over worst criterion (Z), with the help of a 9 point measure (statistics between 1 and 9; in which for number 1: k is likewise significant to Z and for number 9: k is enormously more significant than z), that outcomes in others to worst (OZ) vector as follows.

$$D_z = (a_{z1}, a_{z2}, a_{z3}, \ldots\ldots.., a_{zn})^T \tag{6}$$

Where a_{kz} designates the preference of any criterion k over the worst criterion Z, and it is clear that $a_{zz} = 1$. Table 10 depicts the best to others and others to the worst preference.

Step 5: Determine the optimum weights (z_1^*, z_2^*, z_3^*,. . .. . z_n^*) for all CSFs for integrating GLSS with Industry 4.0 within the manufacturing environment

Table 10. Preference table for CSFs for integrating GLSS with Industry 4.0

CSFs	Preference for the best over others	The preference of others for the worst
CSFs 1	4	6
CSFs 2	5	7
CSFs 3	6	4
CSFs 4	6	2
CSFs 5	6	3
CSFs 6	7	2
CSFs 7	9	1
CSFs 8	1	6
CSFs 9	8	4
CSFs 10	3	5
CSFs 11	7	5
CSFs 12	6	7
CSFs 13	2	8
CSFs 14	8	2
CSFs 15	4	7
CSFs 16	7	4
CSFs 17	5	4
CSFs 18	7	3
CSFs 19	5	2
CSFs 20	5	3
CSFs 21	1	9
CSFs 22	5	7
CSFs 23	8	3

Source(s): Authors' own creation

To attain weights of CSFs, we take into consideration the Linear Programming (LPP) Model of BWM.

The optimum weights ought to be obtained such that the maximum absolute differences for all k could be minimized for

$$\left\{ \left| ZD\text{-}\ a_{BjZk} \right|, \left| zj - akzZz \right| \right\}$$

or homogenously:

$$\text{Min}\ \text{maxk}\ \{ |ZD - aDkzk|, |zk - akzZz| \}$$

Subjected to

$$\Sigma zk = 1$$

$$k$$

$$zk \geq 0, \text{ for all } k \tag{7}$$

Then,

$$\text{Min}\ \xi L$$

Subjected to

$$\left| zD - aDkzk \right| \leq \xi L, \text{ for all } k$$

$$\left| zk - akzzz \right| \leq \xi L, \text{ for all } k$$

$$\Sigma\ zk = 1$$

$$k$$

$$zk \geq 0, \text{ for all } k \tag{8}$$

Problem (8) is a linear optimization problem with an exclusive solution, values for optimum weights (z_1^*, z_2^*, z_3^*,... z_n^*), and the optimum objective function value ξ_L are determined by solving it. Table 11 depicts the ranks of LSS barriers by using the BWM technique.

4. Discussion of findings

The analysis and prioritization of CSFs for the effective execution of quality enhancement methods, from the perspective of the current shifts in manufacturing, are the key concerns for establishing a firm's competitive position in the market (Ershadi *et al.*, 2021). Previous studies have independently explored the CSFs of GLSS and I4.0 (Samanta *et al.*, 2024). Researchers have recognized CSFs based on literature reviews and expert opinions, but have not addressed the reliability testing necessary to finalize these factors before employing decision-making techniques (Yadav *et al.*, 2023a, b). In this study, 27 CSFs were recognized from the prevailing literature and finalized for the Indian manufacturing context through expert consultations, followed by a reliability test to ensure consistency. These test results demonstrated strong

Table 11. BWM weighted to rank LSS barriers sectors

Sr. No.	CSFs	BWM weight	BWM rank	GRG	GRA rank
1	CSFs 1	0.119232	5	0.585966	5
2	CSFs 2	0.0294215	13	0.480049	13
3	CSFs 3	0.0212565	16	0.447583	16
4	CSFs 4	0.0202214	17	0.439501	17
5	CSFs 5	0.0245898	15	0.456284	15
6	CSFs 6	0.043280	10	0.495511	10
7	CSFs 7	0.0175236	19	0.428852	19
8	CSFs 8	0.0122547	21	0.397666	21
9	CSFs 9	0.0158235	20	0.426214	20
10	CSFs 10	0.125220	4	0.633117	4
11	CSFs 11	0.031228	11	0.48587	11
12	CSFs 12	0.078465	8	0.511197	8
13	CSFs 13	0.196231	2	0.71649	2
14	CSFs 14	0.0198254	18	0.43512	18
15	CSFs 15	0.0101252	22	0.396938	22
16	CSFs 16	0.051329	9	0.505239	9
17	CSFs 17	0.0094524	23	0.395618	23
18	CSFs 18	0.154224	3	0.647534	3
19	CSFs 19	0.104265	6	0.581959	6
20	CSFs 20	0.083245	7	0.530952	7
21	CSFs 21	0.247272	1	0.735529	1
22	CSFs 22	0.0252154	14	0.466144	14
23	CSFs 23	0.0302147	12	0.481365	12

Source(s): Authors' own creation

consistency, with a Cronbach's alpha (α) value above 0.8. Then, the GRA technique is employed to rank and understand the emphasized interrelationship between these CSFs. The results of the present work have been validated through the BWM technique.

Therefore, the study reveals CSFs 21 (Emphasis on technological innovation and practices), CSFs 13 (Change management for GLSSI), CSFs 18 (Flexibility and responsiveness for the GLSSI approach), CSFs 10 (A structured approach to integrating GLSS with I4.0), CSFs 1 (Efficient project coordination and oversight), CSFs 19 (Organizational culture supportive of change during GLSSI adoption), CSFs 20 (Organizational preparedness for adopting GLSS with I4.0 technologies) and CSFs 12 (Access to standard operating procedures (SOPs) for integrating GLSS with Industry 4.0) were considered as most significant CSFs for integrating GLSS approach with I4.0 technologies. CSFs 3 (Effective communication at all organizational levels), CSFs 4 (Adoption of sustainable packaging solutions), CSFs 14 (Access to precise and up-to-date information), CSFs 7 (Tracking performance following the integration of I4.0 and GLSS), CSFs 9 (Educational initiatives for advanced technologies and GLSS), CSFs 8 (Improve the supply chain integration for adopting the GLSSI approach), CSFs 15 (Access to funding for investing in new technologies and GLSS) and CSFs 17 (Strategic alignment of business and information systems for merging GLSS with I4.0) were considered as least significant CSFs for integrating GLSS with I4.0 technologies. Therefore, there is a significant need to integrate the existing GLSS system with a modern smart manufacturing system to effectively capitalize on the competitive and rapidly changing market driven by dynamic demands.

5. Implications

5.1 Theoretical implications

The current work offers valuable theoretical insights for prospective researchers and beginners in the field of GLSS and I4.0, focusing on enhancing the productivity of Indian manufacturing sectors. The present study provides important theoretical contributions for the researchers and emerging scholars in the domain of GLSS integrated with I4.0 technologies, particularly with respect to enhancing productivity in manufacturing sectors. By applying GRA technique, the study prioritizes the identified CSFs, thereby encouraging future researchers to investigate alternative analytical approaches, implementation barriers and associated variables related to the integration. Additionally, BWM technique is employed to evaluate and rank the key CSFs within the manufacturing context. Moreover, this study enriches the existing body of knowledge by highlighting relatively underexplored dimensions of GLSS-I4.0 integration and offers a theoretical foundation for the systematic development of integrated frameworks in future research.

5.2 Practical implications

The findings of this study offer meaningful practical implications for the Indian manufacturing sector. The methodologies applied serve as a strategic roadmap for practitioners, supporting the effective implementation of GLSS practices within the I4.0 environment. Such integration can enhance competitive advantage in the contemporary industrial landscape by strengthening organization's ability to deliver customized products that address evolving customer requirements. Furthermore, this study provides a structured basis for the strategic selection of GLSS practices in conjunction with I4.0 capabilities, thereby maximizing the benefits of their integration. By offering a comprehensive evaluation of CSFs and their interrelationships through GRA and the BWM, the study establishes a robust foundation for practitioners to more effectively integrate emerging I4.0 technologies into GLSS implementation.

6. Conclusions

The present research work explores CSFs for the integration of the GLSS approach with Industry 4.0 technologies in the context of Indian manufacturing organizations. A total of 27 CSF barriers are recognized through the literature review and further authenticated by experts in the industry. Furthermore, a reliability test was conducted, and after inputting the response into SPSS version 25.0, α and CITC values were calculated. In this reliability test, 4 CSFs had CITC values below 0.3, meaning these items, like CSFs11 (Eco-management system), CSFs 16 (Engaged and proficient workforce), CSFs18 (Process oversight and governance for GLSSI) and CSFs21 (Embracing a philosophy of continuous improvement) did not exhibit a similar construct with the other 23 items. As a result, four CSFs were excluded from the previously identified CSFs listed. Ultimately, a total of 23 CSFs were selected for further study and analysis in the present work. Furthermore, the GRA technique has been deployed to prioritize these CSFs for the integration of the GLSS approach with Industry 4.0 technologies. The results have been validated through the BWM technique. The study reveals that CSFs 21 (Focused on leveraging technological innovation and industry best practices) with GRG value of 0.735529, CSFs 13 (Managing organizational change within GLSSI4.0 initiatives) with GRG value of 0.71649, CSFs 18 (Built-in flexibility and responsiveness within the GLSSI4.0 model) with GRG value of 0.647534, CSFs 10 (An organized approach to embedding I4.0 within GLSS) with GRG value of 0.633117, CSFs 1 (Robust project management and supervision) with GRG value of 0.585966, CSFs 19 (A culture of adaptability and continuous improvement aligned with GLSSI4.0 implementation) with GRG value of 0.581959, CSFs 20 (Institutional readiness for GLSS implementation supported by I4.0 technologies) with GRG value of 0.530952 and CSFs 12 (Availability of standard operating procedures for GLSS-I4.0

integration) with GRG value of 0.511197 were considered as most significant CSFs for integrating GLSS approach with I4.0 technologies.

7. Limitations and future research agenda

Despite key contributions, the study is not deprived of limitations. Firstly, this study is entirely restricted to Indian manufacturing organizations. While exploring the CSFs, the interrelationships among them were not taken into consideration. Another drawback of this work is that data were only gathered from fewer respondents. Considering the small sample size, it is not probable to simplify the outcomes for all industrial sectors of other economies. These limitations provide the direction for future research.

(1) Future research should involve large-scale surveys to compare the results obtained through different MCDM techniques, to establish the generalizability of the findings.

(2) CSFs can be applied to other industry sectors such as healthcare, project management, electronics, services and engineering.

(3) For assessing CSFs, graph theory could be applied in future studies.

(4) The researchers can also develop integral measures and a systematic integrated GLSS Industry 4.0 framework.

Supplementary material

The supplementary material for this article can be found online.

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