Improving Triple Bottom Line (TBL) Performance: Analyzing Impacts of Industry 4.0, Lean Six Sigma and Circular Supply Chain Management

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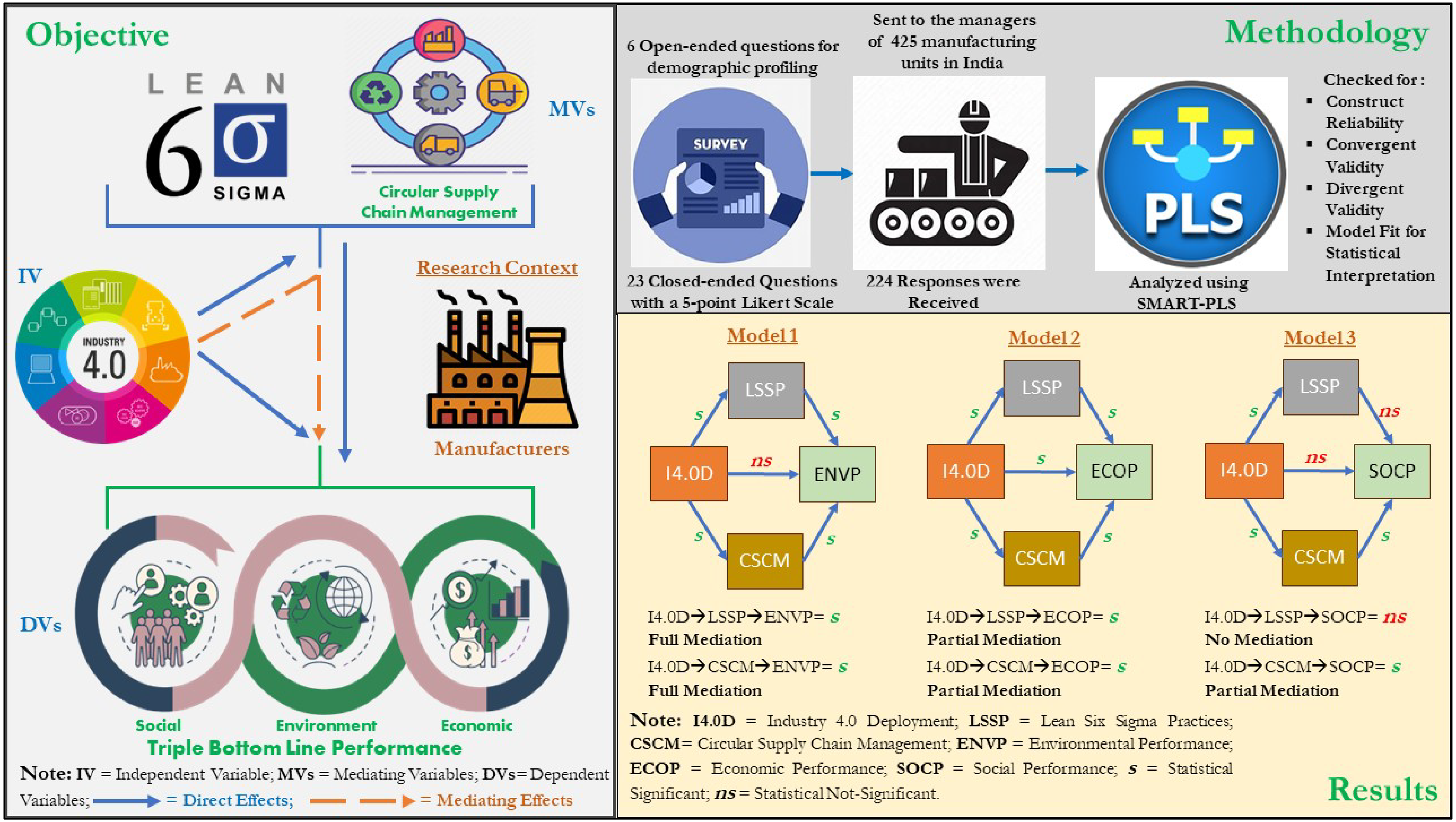
Abstract

The primary objective of the article is to scrutinize the potential benefits of amalgamating industry 4.0 technologies, lean six sigma practices (LSSP), and circular supply chain management (CSCM) to augment overall performance across economic, environmental, and social dimensions, commonly referred to as the triple bottom line. The research uses survey methodology to collect data from senior-level employees in 224 manufacturing organizations and analyze it using structural equation modeling. Based on the analytical findings, it is evident that Industry 4.0 has a direct and significant impact solely on the economic dimension of triple bottom line performance. The relationship between Industry 4.0 and environmental performance is completely influenced by the implementation of LSSP and CSCM. In terms of social performance, the impact of LSSP appears to be not significant, whereas CSCM acts as a full mediator. Finally, with economic performance, LSSP and CSCM partially mediate between the industry 4.0 deployment and triple bottom line performance. There are some limitations, such as the potential lack of generalizability due to the inclusion of a specific demographic and time frame, for which alternative research strategies, such as longitudinal studies or case-study-based designs, may be more appropriate. Study results may assist senior management in developing a strategic framework to improve their organization's triple bottom line performance, advance its sustainability initiatives, and bolster its market competitiveness.

Keywords: *Industry 4.0; Lean Six Sigma; Circular Supply Chain Management; Triple Bottom Line Performance; Environmental Performance; Economic Performance; Social Performance; Manufacturing.*

Graphical Abstract



1. Introduction

The manufacturing sector has experienced substantial transformations in recent decades, owing to the advent of novel technologies, intensified worldwide competition, and an escalating recognition of the ecological consequences of operations (Gutierrez et al., 2022; Qi et al., 2023). Consequently, numerous organizations have endeavored to enhance their business activities by implementing novel strategic methodologies such as Industry 4.0 (Arcidiacono et al., 2023; Reza et al., 2024), lean six sigma (Bokhorst et al., 2022), and circular supply chain management (Faisal, 2023). Although these practices have demonstrated favorable outcomes in terms of operational efficiency and sustainability (Castiglione et al., 2022), their interplay and influence on diverse dimensions of business performance remain ambiguous (Bonamigo et al., 2023; Csiki et al., 2023). For example, although manufacturers are recognized as significant contributors to the economy and society through efficient production of goods and job creation (Demartini et al., 2023), scholars have claimed that their operations may have adverse social and environmental consequences, such as pollution, greenhouse gas emissions, and labor exploitation (Subramaniam et al., 2019; C. Zhang et al., 2022). The emergence of the triple-bottom-line (TBL) concept was a response to the challenges faced by organizations as it provided a framework for evaluating their performance beyond economic indicators by incorporating environmental and social parameters (Jum'a et al., 2022; S. A. R. Khan et al., 2022). At its core, the TBL framework prioritizes economic viability, which includes criteria like as profitability, operational efficiency, and market competitiveness (Dubey et al., 2019). Furthermore, the TBL framework recognizes the importance of considering the social dimension, inviting manufacturers to take proactive measures in addressing social concerns, which includes promoting fair labor practices, creating inclusive workplaces, and participating in community development initiatives (Mukhuty et al., 2022). Lastly, through including the environmental dimension, the TBL framework evaluates how manufacturers may enhance the environmental footprint of manufacturing activities, which ranges from resource extraction and production processes to product disposal and its end-of-life considerations (Mangla et al., 2024).

Academic discourse has predominantly espoused the notion that Industry 4.0 amalgamates digital technologies and automation, thereby enhancing operational efficacy and optimizing resource allocation, while also aligning with the social (Asokan et al., 2022), economic (Dev et al., 2020) and environmental dimensions (Y. Li et al., 2020) of the TBL framework. Likewise, academic experts have also advocated for the enactment of lean six sigma and circularity principles in manufacturing to attain a balanced and sustainable approach to business (Agrawal et al., 2023; Farrukh et al., 2022), which takes into account not only the economic benefits but also social welfare and environmental conservation (Mathiyazhagan et al., 2022). The lean six sigma methodology is a management approach that prioritizes the reduction of waste, enhancement of processes, and satisfaction of customers (Ganjavi & Fazlollahtabar, 2023). Its primary objective is to enable organizations to attain economic benefits by eliminating activities that do not add value and enhancing the quality of products (Muganyi et al., 2019). Minimizing waste plays a crucial role in advancing ecological sustainability, whereas involving the workforce in interactions with diverse stakeholders is a strategy to manage the social dimension of TBL performance (Rathi et al., 2022).

Similarly, the circular value chain endeavors to shift away from a linear approach of "extract-produce-consume-dispose" to a closed-loop arrangement that reduces resource utilization and waste production (M. Li et al., 2023). Organizations can reduce environmental impact and create economic value by promoting the reuse, recycling, and remanufacturing of products and materials (Faisal, 2023; van Bueren et al., 2023). Organizations can mitigate their environmental impact and generate economic value by endorsing product reuse, recycling, and remanufacturing (Yuan et al., 2022). Setting up a circular value chain can promote social accountability by fostering stakeholder collaboration (Pitkänen et al., 2023). Scholars have called for further research to gain new insights into how such ‘distinct organizational approaches can work together’ to enhance TBL performance, as there is limited empirical evidence available from only a few countries in a fragmented form (Asokan et al., 2022; Csiki et al., 2023; Gunasekara et al., 2023; Ivanov, 2023). This has formed the basis for the current investigation, considering the novelty of the proposition of examining the interaction between industry 4.0 deployment (I4.0D), lean six sigma practices (LSSP), circular supply chain management (CSCM), and TBL performance. The research results could assist manufacturers in understanding how adopting these approaches can facilitate the establishment of a more sustainable and ethical business environment that is advantageous for both their economic viability and the welfare of the community and the environment.

In addition, the degree and manner in which regulatory authorities exert pressure on manufacturers to enhance their TBL performance can differ depending on the industry and geographical jurisdiction (Hachem, 2023; M. Li et al., 2023; Y. Li et al., 2020; Tiwari & Khan, 2019). For example, formulating policies and regulations by regulatory authorities is paramount in promoting higher TBL performance (Layaoen et al., 2023; van Bueren et al., 2023). Regulatory authorities may utilize various measures to support corporate responsibility and accountability among manufacturers who have contravened regulations. Such measures may encompass enforcing stricter environmental standards mandating disclosure by companies of their social and environmental impacts or offering tax incentives to prompt sustainable practices (Ahmed & Sarkar, 2019; W. Zhang et al., 2018). Although Industry 4.0 has garnered increasing attention from scholars, there remains a dearth of research on the potential of utilizing LSSP and CSCM to facilitate the capacity of organizations to leverage this technological revolution to enhance TBL performance effectively (Bokhorst et al., 2022; Castiglione et al., 2022; Ivanov, 2023). Previous research has suggested the importance of identifying and analyzing the precise mechanisms and strategies by which Industry 4.0 technologies can effectively implement LSSP and CSCM (I. S. Khan et al., 2023; Touriki et al., 2021; Truant et al., 2024). Strategies for sustainable development are desperately needed as many economies around the world struggle with environmental degradation brought on by things like pollution, deforestation, and resource depletion (Asokan et al., 2022), as well as issues with labor rights, workplace safety, and community development (Tiwari & Khan, 2019). Scholarly investigation is therefore necessary for identifying business-level strategies that can assist manufacturers in achieving strategic growth by improving TBL performance. This point is further emphasized by scholars who contend for the necessity of conducting research that can provide practical guidance for manufacturers grappling with challenges in achieving TBL performance (Paul et al., 2022; Truant et al., 2024). As a result, there exists a research gap in the prior literature that necessitates more investigation to address the research question (RQ) that follows: *How can integrating Industry 4.0 technologies with LSSP and CSCM initiatives enhance TBL performance*?

The paper has multifold contributions to the strategic performance literature. This is the pioneering study that integrates LSSP with CSCM in an empirical setting of an emerging economy. The results of this investigation have significance for specifically evaluating and quantifying the impact of I4.0D, LSSP, and CSCM on TBL performance. This would enhance comprehension of the functional mechanism and allow for more accountable decision-making in the manufacturing sector, as the outcome of this research would highlight potential trade-offs and synergies among these antecedents of TBL performance. Finally, the roadmap discussed in the paper can influence the manufacturers to re-engineer their standard operating procedures and prompt them to innovative ways of collaboration, ensuing positive performance.

The subsequent sections of the article are structured in the following manner. Section 2 presents a literature review that elucidates the critical constructs used in the present investigation, and Section 3 delineates the proposition and hypotheses. Section 4 clarifies the research methodology adopted, and Section 5 presents the results. Sections 6 & 7 present a discussion of results, theoretical implications, and practical implications. Finally, Section 8 concludes the research with limitations and future scope.

2. Theoretical Underpinning

2.1 Industry 4.0 Deployment

"Industry 4.0" refers to the fourth industrial revolution, which integrates advanced technologies such as artificial intelligence, the Internet of Things, and automation into manufacturing processes (Vlachos et al., 2023). In the current epoch of Industry 4.0, manufacturing facilities are transforming intelligent and interconnected systems, where machines and processes can communicate and work together seamlessly in real-time (Dev et al., 2020; Ganjavi & Fazlollahtabar, 2023). Devices and machines with sensors collect required data (Qi et al., 2023), which are subsequently analyzed to extract valuable insights and facilitate informed decision-making (Nouinou et al., 2023). Scholarly evidence demonstrates the efficacy of algorithms powered by artificial intelligence in enabling predictive maintenance, thereby reducing downtime and enhancing productivity in manufacturing facilities (Rai et al., 2021). The deployment of Industry 4.0 is marked by the concept of cyber-physical systems (Queiroz et al., 2022), in which robotics and automation have a prominent role (Ma et al., 2020; Napoleone et al., 2023). This makes manufacturing processes more efficient and adaptable, as robots work with human workers to manage repetitive tasks and enhance productivity (I. S. Khan et al., 2023; Vlachos et al., 2023). Additionally, a certain consortium of scholars contends that the integration of Industry 4.0 technologies allows manufacturers to adopt responsive and customized production strategies, thereby enabling the implementation of just-in-time manufacturing and reducing inventory expenses while simultaneously enhancing the administration of material handling and distribution channels (Bokhorst et al., 2022; Rosin et al., 2020). These technologies even facilitate real-time monitoring of production lines, enabling manufacturers to recognize bottlenecks and streamline workflows within their internal functional departments and across their organizational boundaries (Ivanov, 2023; I. S. Khan et al., 2023).

2.2 Lean Six Sigma Practices

The amalgamation of lean manufacturing and six sigma methodologies constitutes the LSSP. Overproduction, excess inventory, and unnecessary transportation are just a few examples of non-value-added activities that may be eliminated using lean principles, resulting in better resource utilization and shorter lead times (Bokhorst et al., 2022; Touriki et al., 2021). On the other hand, Six Sigma focuses on detecting and analyzing process variations using statistical approaches and data analysis, enabling organizations to identify underlying causes of issues and execute effective remedial measures (Choo, 2022). The integration of these methods fosters interdepartmental cooperation, delegates responsibility to employees to recognize and rectify procedural deficiencies, and advocates for evidence-based decision-making, ultimately cultivating a culture of continuous improvement within manufacturing organizations (Ganjavi & Fazlollahtabar, 2023; Gutierrez et al., 2022). The systematic deployment of LSSP guarantees optimizing manufacturing processes, minimizing waste, and reducing defects, eventually contributing to improved customer satisfaction and sustained business success (Jum'a et al., 2022; Tortorella et al., 2019).

2.3 Circular Supply Chain Management (CSCM)

CSCM pertains to adopting methodologies and procedures to establish a self-sustaining system that optimizes resource utilization and minimizes waste generation across all supply chain stages (Faisal, 2023). In other words, this closed-loop process system entails the incorporation of circular economy principles into the various stages of sourcing, production, distribution, and disposal, with manufacturers prioritizing sustainability through practices such as recycling, remanufacturing, and product lifecycle extension (M. Li et al., 2023; van Bueren et al., 2023). The effective implementation of CSCM necessitates establishing collaborative and coordinated efforts among diverse stakeholders, encompassing suppliers, manufacturers, distributors, and customers (Gunasekara et al., 2023; Pitkänen et al., 2023). For example, manufacturers build strategic relationships with suppliers to ensure the availability of recycled or sustainable materials, which may even include establishing reverse logistics systems to facilitate the collection and processing of end-of-life products for reuse or recycling (Dev et al., 2020). The long-term goal of developing a more sustainable and resilient manufacturing sector relies heavily on CSCM because of its efforts to lessen the use of scarce resources, decrease environmental impact, and promote a more sustainable business model.

2.4 Triple Bottom Line (TBL) Performance

TBL Performance pertains to assessing and quantifying an organization's determination and achievement predicated on three interrelated facets: environmental, economic, and social (S. A. R. Khan et al., 2022). This embodies a comprehensive methodology for evaluating performance, considering the organization's influence on people, the environment, and profits (Layaoen et al., 2023; Tiwari & Khan, 2019). From an environmental perspective, the assessment evaluates an organization's ecological impact and dedication to sustainable methodologies, encompassing aspects such as energy utilization, waste disposal, greenhouse gas discharges, water consumption, and the implementation of environmentally conscious technologies (Castiglione et al., 2022; Y. Li et al., 2020). From an economic perspective, it refers to an organization's financial performance, profitability, and economic growth by considering various factors such as revenue generation, cost management, and return on investment (Dev et al., 2020; Subramaniam et al., 2019). From a social perspective, it pertains to the influence an organization has on society, encompassing its workforce, clientele, suppliers, and surrounding communities (Layaoen et al., 2023; Pitkänen et al., 2023). This encompasses factors such as the well-being of employees, diversity and inclusivity, customer contentment, ethical business conduct, and involvement in community affairs (Asokan et al., 2022).

2.5 Resource Orchestration Theory

Providing foundational backing from an established theory is a crucial aspect of any empirical investigation because it provides a direction for developing propositions, the credibility of analysis, and the comprehension of results (Shaver, 2014). The current research draws upon the resource orchestration theory (ROT), which is based on the resource-based view of the firm and is well-regarded within the domain of strategic management (Chavez et al., 2023; Wong et al., 2018), to explicate the underlying proposition. The ROT is a conceptual framework that explains how organizations attain long-term competitive advantage by nurturing, efficiently managing, and using existing resources (Kumar et al., 2022). ROT recognizes, in particular, that organizations that operate in dynamic environments where resources can become obsolete or lose their competitive value over time must develop the ability to reconfigure, redeploy, and create new combinations of resources in order to maintain a competitive advantage (Asiaei et al., 2021). The ROT in concern, within the framework of Industry 4.0, places significant emphasis on integrating and optimizing diverse resources, including but not limited to technology, human capital, and sustainable practices (Cao et al., 2022). This research also examines the significance of lean six sigma methodologies, which are designed to optimize operational efficacy and minimize inefficiencies (Muganyi et al., 2019; Rathi et al., 2022), in conjunction with CSCM strategies, which prioritize sustainable resource utilization and waste reduction (Faisal, 2023; M. Li et al., 2023). The aforementioned practices are regarded as crucial resources that can be orchestrated and harmonized to attain triple bottom-line efficacy, encompassing the economic, social, and environmental facets (Chavez et al., 2022; Wong et al., 2018). Viewed through the lens of ROT, this research endeavors to delineate the strategic amalgamation and synchronization of resources and operational excellence practices as pivotal determinants in accomplishing superior performance across the triple bottom line framework.

3. Hypotheses and Research Framework Development

3.1 Industry 4.0 Deployment and Triple Bottom Line Performance

The deployment of Industry 4.0 is characterized by the utilization of sophisticated technologies that have the potential to enhance the efficiency, productivity, and sustainability of manufacturing operations (Asokan et al., 2022; Faisal, 2023). Industry 4.0 enables deploying intelligent and interconnected systems in which Internet of Things sensors and data analytics can monitor and optimize industrial processes' energy consumption, to minimize carbon emissions and energy costs (Chavez et al., 2023; Y. Li et al., 2020). The predictive maintenance and real-time monitoring capabilities of Industry 4.0 systems can mitigate equipment failures, resulting in increased resource efficiency and addressing both environmental and economic benefits from industrial operations (Dubey et al., 2019). Furthermore, implementing automation and robotics technologies optimizes production processes, increasing output levels and enhancing product quality (Duman & Akdemir, 2021). Real-time data analysis enables improved decision-making, inventory management, supply chain logistics, and production planning, which may result in lower operating costs, higher profitability, and increased market competitiveness (Longo et al., 2021; Margherita & Braccini, 2021). The advent of collaborative robots and artificial intelligence technologies has the potential to automate hazardous and monotonous tasks, thereby reducing the likelihood of workplace accidents and injuries (Caselli et al., 2021; Thulasy et al., 2022). Furthermore, upskilling employees to collaborate with cutting-edge technologies can augment job contentment and foster individual development (Vereycken et al., 2021). By encouraging safer and more pleasant working circumstances, I4.0D increases the workforce's overall well-being and job security, resulting in greater social performance (Mukhuty et al., 2022). Even though the rollout of I4.0D in the manufacturing sector provides several benefits, it may also unfavorable affect TBL's performance. A concern that may arise is the potential displacement of human labor by automation and robotics technologies, resulting in the loss of employment opportunities and potential societal upheaval (Satyro et al., 2022). Moreover, adopting sophisticated technologies necessitates substantial financial investments, presenting financial hurdles for manufacturers (Bag et al., 2022). In addition, the dependence on interrelated systems and technological infrastructure gives rise to cybersecurity vulnerabilities, such as unauthorized access to sensitive information and the misappropriation of intellectual property, thereby jeopardizing economic and societal dimensions (Süzen, 2020). Given the divergent perspectives on the relationship between I4.0D and TBL performance, the present study posits the following hypotheses.

H1. *Industry 4.0 deployment positively impacts triple bottom line performance, i.e., (a) environment, (b) economic, and (c) social dimensions.*

3.2 Industry 4.0 Deployment and Lean Six Sigma Practices

The principles of Industry 4.0 and lean six sigma methodologies exhibit a close correlation (Bonamigo et al., 2023; Vlachos et al., 2023), as their shared objective is to enhance and streamline manufacturing operations. I4.0D pertains to assimilating cutting-edge digital technologies into manufacturing (Satyro et al., 2022). Conversely, lean six sigma is a methodology that centers on reducing waste, enhancing efficiency, and improving quality (Farrukh et al., 2022; Rathi et al., 2022). Industry 4.0 technologies provide the foundation for capturing and analyzing massive volumes of real-time data from production processes (I. S. Khan et al., 2023). This approach is consistent with lean six sigma principles, highlighting the significance of data-driven decision-making and continual improvement (Bokhorst et al., 2022). The real-time data and insights provided by Industry 4.0 technologies enable lean six sigma practitioners to implement proactive measures, such as automated processes and self-optimizing systems, to prevent defects and reduce variation in production, allowing them to identify inefficiencies, bottlenecks, and areas of waste more effectively (Bonamigo et al., 2023; Khanzode et al., 2021). As an example, digital twin modelling (an Industry 4.0 technology) becomes crucial during the design phase as it allows for efficient validation and testing to identify any inefficiencies promptly (L. Zhang et al., 2023). Through the creation of a digital replica of the manufacturing system or process, engineers have the ability to simulate different scenarios and pinpoint potential bottlenecks or areas that could be enhanced (Maheshwari & Devi, 2024). Such prior studies have demonstrated the potential of this technology to simulate various layouts, workflows, and equipment configurations, enabling the identification of the most optimal setup, ultimately for enhancing the efficiency of manufacturing systems. Following the design phase, digital twins technology holds the provision to provide real-time feedback to the physical Lean Six Sigma system throughout the operational phase, enabling continuous improvement and optimization (Maheshwari & Devi, 2024; L. Zhang et al., 2023). As a result, empirical research indicates that the utilization of Industry 4.0 technologies can enhance the adoption of lean six sigma methodologies by increasing the level of interconnectivity and interaction among machines, systems, and relevant stakeholders (Ganjavi & Fazlollahtabar, 2023; Rosin et al., 2020). This enhanced connectivity enables seamless information flow, faster response times, and better coordination, supporting the implementation of lean principles like just-in-time production and synchronized workflows (Khanzode et al., 2021; Vlachos et al., 2023). Hence, deploying Industry 4.0 technologies increases data accessibility, enables predictive analytics, enhances connectivity and collaboration, and empowers self-optimization (Pongboonchai-Empl et al., 2023; Tortorella et al., 2019). These factors support lean six sigma implementation more effectively and efficiently, ultimately improving manufacturers' productivity, quality, and competitiveness (Bokhorst et al., 2022; Vlachos et al., 2023). Several empirical studies imply that I4.0D may have a detrimental effect on lean six sigma techniques, which might be due to an overreliance on technology, which may shift emphasis away from human engagement and the core concepts of lean six sigma (Alieva & von Haartman, 2020; Bag et al., 2023). Drawing upon the aforementioned arguments, a hypothesis has been put forth for empirical examination.

H2. *Industry 4.0 deployment positively impacts lean six sigma practices.*

3.3 Industry 4.0 Deployment and Circular Supply Chain Management

One of the most significant effects of I4.0D on CSCM is improved visibility and traceability (I. S. Khan et al., 2023), as the Internet of Things devices and sensors are embedded in products, materials, and packaging, making it possible to track and monitor their lifecycle from production to disposal (Agrawal et al., 2023; Faisal, 2023). The improved level of visibility provided by Industry 4.0 technologies such as artificial intelligence, blockchain, cloud computing and big data analytics, allows for more effective resource management, waste reduction, and seamless integration of circular practices, including recycling and remanufacturing (Eisenreich et al., 2022; Kurniawan et al., 2023). Sophisticated analytical techniques can detect inadequacies and functional obstructions within the supply chain, thus empowering organizations to make judicious choices to optimize resource distribution, reduce waste, and augment their circular operations' overall efficacy (Kayikci et al., 2022). I4.0D also has the potential to better communication and collaboration among supply chain partners by establishing interconnected systems and real-time data sharing (Taddei et al., 2022). This allows stakeholders to operate more effectively and simplifies the exchange of information, resources, and waste materials, thus encouraging the adoption of circular practices such as product sharing, remanufacturing partnerships, and closed-loop material flows (Laskurain-Iturbe et al., 2021). One illustration of this is the utilization of blockchain-based smart contracts to automate transactions and enforce predefined rules, eliminating the need for intermediaries (Choi et al., 2023; Sternberg et al., 2023). Such a system greatly enhances trust and efficiency in circular supply chain operations (He et al., 2023). Furthermore, blockchain technology possesses the potential to authenticate recycled materials and refurbished products, effectively deterring counterfeit activities and guaranteeing adherence to circular economy regulations (Mangla et al., 2024). Recent studies present evidence that incorporating quick response (QR) code, radio frequency identification (RFID), and even biological features or edible chemical signatures could enhance the authentication and verification of products in the circular supply chain (Leng et al., 2019; Paul et al., 2022). Nevertheless, there exist research studies that suggest that the actualization of Industry 4.0 projects in the larger setting of CSCM encounters significant challenges on various socio-technical aspects, which could potentially lead to a functional collapse (Agrawal et al., 2023; Trevisan et al., 2023). Given the above arguments, the study posits:

H*3.* *Industry 4.0 deployment positively impacts circular supply chain management.*

3.4 Lean Six Sigma Practices (LSSP) and Triple Bottom Line Performance

LSSP integrates lean manufacturing concepts with statistical techniques to minimize waste, maximize efficiency, and reduce defects and variances, empowering organizations to simplify processes, remove irrelevant steps, and optimize resource allocation (Alkunsol et al., 2019; Sreedharan et al., 2018). As a result, an organization can attain higher operational efficiency and productivity levels, thereby positively impacting the economic facet of the TBL performance (Muganyi et al., 2019). Additionally, enacting LSSP can foster environmental accountability by identifying and eliminating ecological inefficiencies, enabling organizations to curtail their utilization of resources, energy, and carbon emissions (Farrukh et al., 2022). These endeavors enhance the environmental aspect of the TBL performance by reducing the organization's ecological footprint and fostering sustainable methodologies (Belhadi et al., 2021; Khanzode et al., 2021). In addition, empirical evidence has demonstrated that deploying LSSP promotes a culture of continuous improvement and higher employee engagement (Pongboonchai-Empl et al., 2023). By engaging employees in problem-solving and process improvement initiatives, organizations can potentially augment job satisfaction, elevate productivity, and fortify relationships with their workforce (Chavez et al., 2022). Organizations that engage in LSSP demonstrate a commitment to social responsibility and bolster their reputation within their communities by actively engaging in community development and addressing social needs (Alkunsol et al., 2019; Erdil et al., 2018). However, scholarly evidence also indicates that the failure of an operational excellence project (such as lean six sigma) can be attributed to inadequate leadership support, insufficient employee engagement, or inadequate resource allocation (Sunder M & Prashar, 2023). The hypotheses presented herein are derived from the aforementioned arguments.

H4. *Lean six sigma practices positively impact triple bottom line performance, i.e., (a) environment, (b) economic, and (c) social dimensions*

3.5 Circular Supply Chain Management and Triple Bottom Line Performance

The interdependence between CSCM and TBL performance is evident, as the former's strategies substantially influence every aspect of the latter. Material and manufacturing costs may be decreased if organizations use circular economy strategies, including recycling, reusing, and remanufacturing (Farooque et al., 2022; Gunasekara et al., 2023). This not only creates new income streams via the formation of secondary markets for recycled or refurbished items, but it also improves profitability, financial performance, and the long-term viability of the business model (Dey et al., 2020; M. Li et al., 2023; Liu et al., 2023). Thus, considering the economic aspect of TBL performance, adopting CSCM can potentially enhance revenue generation, minimize expenses, and optimize resource allocation. Organizations can achieve environmental sustainability over the long run by minimizing their carbon footprint and ecological impact by implementing product life extension, closed-loop systems, and eco-friendly disposal methods (Eisenreich et al., 2022; Mahdiraji et al., 2022). These approaches could help conserve natural resources, reduce the effects of climate change, and preserve ecological systems, all of which contribute to the environmental aspect of TBL performance. Moreover, circular initiatives frequently entail collaborations with suppliers, customers, and neighbouring communities, facilitating collaborations and creating shared value. This, in turn, bolsters the organization's standing, reinforces customer allegiance, and draws the attention of socially responsible investors (Farooque et al., 2022; Vegter et al., 2023). Therefore, it can be argued that CSCM emphasizes corporate accountability and fosters valuable stakeholder relationships, thereby ensuring long-term sustainability from a societal standpoint (Del Giudice et al., 2021; Sudusinghe & Seuring, 2022). Drawing upon the limited extant literature, which posits a positive association between CSCM and TBL performance (Agyabeng-Mensah et al., 2022; Dey et al., 2020; Farooque et al., 2022; Liu et al., 2023), it is recommended that additional research be undertaken to corroborate these results across various geographical regions. Thus, the current investigation puts forth the following hypotheses.

H5. *Circular supply chain management positively impacts triple bottom line performance, i.e., (a) environment, (b) economic, and (c) social dimensions.*

3.6 Mediating Role of Lean Six Sigma Practices and Circular Supply Chain Management

The ROT places significant emphasis on aligning and integrating resources across various levels and functions within an organization and extending beyond the organization (Asiaei et al., 2021; Chavez et al., 2022). LSSP and CSCM represent distinct operational excellence programs (Belhadi et al., 2021; Vegter et al., 2023), with the former focusing on internal organizational operations and the latter stressing external organizational processes (Farooque et al., 2022; M. Li et al., 2023). ROT emphasizes integrating these practices into core operations to encourage multi-stakeholder collaboration and cultivate a culture of continuous improvement, suggesting their mediating role in the association between I4.0D and TBL performance (Chavez et al., 2023; Wong et al., 2018). In other words, by effectively orchestrating these resources, manufacturers can optimize the benefits of I4.0D and achieve sustainable outcomes across the TBL. Studies in the past suggest that these operational excellence strategies play a mediating role between technology adoption and performance outcomes (Agyabeng-Mensah et al., 2022; Belhadi et al., 2020; Swierczek, 2023; Zhao et al., 2023), which needs to be empirically investigated under diverse demographic circumstances to offer new insights.

H6. *Lean six sigma practices mediate the interaction between Industry 4.0 deployment and triple-bottom-line performance, i.e., (a) environment, (b) economic, and (c) social*

H7. *Circular supply chain management mediates the interaction between Industry 4.0 deployment and triple bottom line performance, i.e., (a) environment, (b) economic, and (c) social*

Drawing upon the above hypotheses, the research framework for the current investigation has been formulated, and Figure 1 depicts the same.

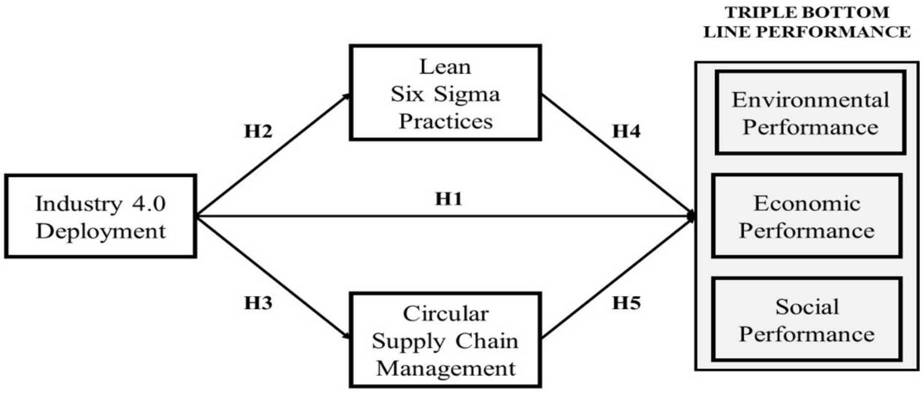


Figure 1 Research Framework of Current Investigation

4. Methodology

4.1 Survey Instrument

The development of a survey instrument holds significant importance in acquiring precise and pertinent data for research or investigation objectives (Chavez et al., 2023; Y. Li et al., 2020). Scholars have emphasized the importance of developing instruments with careful consideration to ensure that they are clear, comprehensive, and reliable (Layaoen et al., 2023). Consistent with this approach, the current investigation utilized established indicators for the constructs under examination, which were derived from previous research (Del Giudice et al., 2021; Dubey et al., 2019; Sreedharan et al., 2018; Subramaniam et al., 2019; Tortorella et al., 2019). Adopting indicators from previous research was a logical choice due to their proven validity and reliability, which establishes a strong basis for novel investigations. Therefore, the research team can be assured of the accuracy and consistency of the measurements. In addition, utilizing identical or comparable modified items as previous studies enables us to directly compare results across studies conducted in various geographical locations. The Appendix contains the survey questionnaire and information on their adoption sources from previous studies. To ensure content validity, the questionnaire was reviewed by a panel of experts consisting of three professors specializing in operations management and four industry practitioners employed in reputable manufacturing firms. The survey instrument utilized a 5-point Likert scale to measure the items for each construct, with response options ranging from 1 (strongly disagree) to 5 (strongly agree), as indicated by the respondents.

4.2 Data Collection

The present study utilizes a quantitative methodology, employing survey data collected from a representative sample of large manufacturing organizations in India. Some review papers have indicated the need for more quantitative survey-based research for empirical generalization (Agrawal et al., 2023; Sudusinghe & Seuring, 2022; Touriki et al., 2021), which prompted this study. This recommendation is also grounded on the predominance of qualitative and case study methodologies in extant scholarship within this domain (Pongboonchai-Empl et al., 2023). The Indian manufacturing sector is a research context due to the country's status as a significant contributor to global pollution (Dahiya & Singh, 2021). Indian regulatory authorities have also strongly emphasized the identification of a macro-mechanism to reduce the adverse consequences of commercial operations in the manufacturing sector (Subramanian & Suresh, 2023). A cross-sectional design is favored for the current investigation due to its adaptability and economic nature (Agyabeng-Mensah et al., 2022). The sample drawn for the current investigation comprises clients from a well-established consulting firm specializing in operational excellence methodologies. This firm offers business solutions to various industries, including manufacturing, retail, and third-party logistics companies, operating globally.

The research team made a formal request to the designated contact person within the consulting firm to carry out a random distribution of the survey questionnaires to directors and senior managers who are employed in Indian manufacturing organizations that have been judged to have implemented Industry 4.0 technologies, LSSP, and CSCM in a concurrently. The research team posits that this sampling is appropriate for conducting research within India's distinctive social, cultural, and economic milieu. Most Indian manufacturing organizations are family-owned businesses, where personal relationships are more important than formal interactions with individuals they do not know. Acquiring data from such firms for research purposes can be challenging unless it is obtained through established consulting agencies. The research team first contacted a key resource person who oversees/leads Industry 4.0 projects in manufacturing organizations, with the assistance of a designated liaison at the consulting firm. The respondents with whom the research team communicated were not exclusively engaged in Industry 4.0 projects but also maintained credible dialogue with the functional managers and upper management of their respective organizations overseeing lean six sigma and circular supply chain operations before completing the survey. Consequently, they will probably respond to the survey. The research team requested all participants to consult with their respective team members or refer to the minutes of their meetings to minimize the possibility of reporting bias.

Out of the 425 questionnaires that were distributed, 224 respondents completed and returned them, making them eligible for data analysis. This results in a response rate of 52.71%, which can be considered adequate. Subsequently, following the prescribed procedure of detecting common method bias (Kock, 2017), the research team conducted a collinearity assessment to ascertain its presence. The variance inflated factor (VIF) values were computed and found to be 1.839, which falls below the established threshold of 3.3 (Dubey et al., 2019; Kock, 2017). This indicates that the predictive model remains unaffected by any prevailing methodological biases. Subsequently, to evaluate the non-response bias (Armstrong & Overton, 1977), a t-test was performed to compare the characteristics of organizations that responded early to the survey with those that responded late. The results indicated no statistically significant difference between the two groups at a significance level of p-value$<$0.05. Table 1 presents a comprehensive overview of the demographic characteristics of those who responded.

Table 1 Demographic Summary of Participating Respondents

Number of Employees	N (%)	Nature of Operating Sector	N (%)
201-500 Employees	56 (25.00%)	Automotive Component	33 (14.73%)
501-750 Employees	43 (19.20%)	Cement	23 (10.27%)
751-1000 Employees	67 (29.91%)	Chemical	74 (33.04%)
>1000 Employees	58 (25.89%)	Pharmaceutical	94 (41.96%)
Age of the Organization	**N (%)**	**Designation of Respondent**	**N (%)**
10-20 Years	69 (30.80%)	Chief "X" Officer	53 (23.66%)
21-30 Years	54 (24.11%)	Director	43 (19.20%)
31-40 Years	33 (14.73%)	Functional Manager ("Y")	71 (31.70%)
>40 Years	68 (30.36%)	Plant Manager	57 (25.45%)

N – Number of Observation; % – Percentage, "X" – Administrative OR Executive OR Finance OR Technology; "Y" – Environmental OR Production OR Quality OR Supply Chain

5. Results

The current investigation utilizes partial least square structural equation modeling (PLS-SEM) for examining the proposed hypotheses. The PLS-SEM technique has certain advantages over the Covariance-Based Structural Equation Modelling (CB-SEM) approach since it is more robust and ideal for exploratory research or situations with a limited sample size because it does not need distributional assumptions (Sarstedt et al., 2016, 2022). PLS-SEM can handle complex models that involve high-dimensional data and non-linear associations, making it a versatile and valuable tool in various research contexts (Hair et al., 2020). Lastly, PLS-SEM provides the opportunity to evaluate measurement and structural models concurrently, thereby facilitating the investigation of both the predictive power and the causal relationships within the models (Sarstedt et al., 2022). Three alternative structural equation models were developed for the current study, with model 1 concentrating on environmental performance, model 2 on economic performance, and model 3 on social performance. Per the prescribed methodology for conducting PLS-SEM (Hair et al., 2020; Sarstedt et al., 2016), it is necessary to analyze the measurement model and determine its fitness before concluding concerning the corresponding structural model.

5.1 Measurement Models

Following established procedures for conducting PLS-SEM (Sarstedt et al., 2022), it is essential to assess the dependability and soundness of constructs through exploratory factor analysis, Cronbach Alpha (α), composite reliability (CR), average variance extracted (AVE), Fornell-Larcker criterion, and Heterotrait-Monotrait ratio (HTMT), prior to engaging in path analysis as part of the structural model. Table 2 displays that most of the factor loadings for items corresponding to each construct in the structural models exceeded the threshold value of 0.7 (Gutierrez et al., 2022; Hair et al., 2020). Any factor loadings that fell below the threshold were excluded from the path analysis. Table 2 also indicates that the values of Cronbach Alpha (α), composite reliability (CR), and average variance extracted (AVE) exceeded the predefined threshold of 0.7, 0.7, and 0.5, respectively. These results confirm the presence of convergent validity among the three measurement models. To assess discriminant validity, the Fornell-Larcker criteria was used, with results in Table 3 revealing that the square root of AVEs surpassed the correlation values, suggesting a successful model fit across all three structural equation models. Furthermore, based on the HTMT ratio results presented in Table 3, it was observed that all values within each model were below the threshold of 0.85 (Hair et al., 2020; Sarstedt et al., 2022), thereby indicating satisfactory levels of discriminant validity. Lastly, Table 2 presents the R^2 and Q^2 Values are crucial for assessing the efficacy and goodness-of-fit of the three PLS-SEM models (Hair et al., 2020). The R^2 metric in PLS-SEM quantifies the extent to which the model accounts for the variance in the data, whereas Q^2 metric assesses its predictive validity. The two metrics demonstrated satisfactory outcomes (Hair et al., 2020), suggesting that R^2 values exhibited moderate predictive accuracy, ranging from 0.270 to 0.573 in model 1, 0.272 to 0.500 in model 2, and 0.316 to 0.385 in model 3, while Q^2 values exhibited significant predictive relevance, with values greater than 0.000.

Table 2 Results of Measurement Model: Convergent Validity, Indicator Loadings, and Internal Consistency Reliability

Construct	Factor Loadings					α	CR	AVE	R^2	Q^2
	IS1	IS2	IS3	IS4	IS5					
MODEL 1: I4.0D →LSSP/CSCM→ENVP										
I4.0D	0.797	0.598*	0.807	0.755		0.704	0.700	0.619		
LSSP	0.660*	0.721	0.783	0.772	0.754	0.730	0.729	0.650	0.270	0.248
CSCM	0.779	0.624*	0.818	0.885	0.819	0.845	0.852	0.683	0.324	0.308
ENVP	0.823	0.795	0.797			0.734	0.757	0.648	0.573	0.241
MODEL 2: I4.0D →LSSP/CSCM→ECOP										
I4.0D	0.793	0.603*	0.813	0.754		0.704	0.700	0.619		
LSSP	0.665*	0.736	0.768	0.777	0.748	0.753	0.754	0.573	0.272	0.250
CSCM	0.783	0.610*	0.818	0.881	0.820	0.845	0.850	0.896	0.324	0.308
ECOP	0.744	0.854	0.812			0.728	0.737	0.648	0.500	0.269
MODEL 3: I4.0D →LSSP/CSCM→SOCP										
I4.0D	0.770	0.603*	0.821	0.773		0.701	0.702	0.621		
LSSP	0.795	0.665*	0.749	0.819	0.673*	0.705	0.722	0.622	0.385	0.372
CSCM	0.769	0.638*	0.818	0.894	0.819	0.845	0.861	0.683	0.316	0.300
SOCP	0.876	0.912	0.765			0.810	0.817	0.728	0.368	0.168

Note(s): I4.0D – Industry 4.0 Deployment; LSSP – Lean Six-Sigma Practices; CSCM – Circular Supply Chain Management; ENVP – Environmental Performance; ECOP – Economic Performance; SOCP – Social Performance; IS. – Items; α – Cronbach Alpha; CR – Composite Reliability; AVE – Average Variance Extracted; R-square value calculating using PLS algorithm. *Items Dropped

Table 3 Results of Measurement Model: Discriminant Validity

MODEL 1: I4.0D →LSSP/CSCM→ENVP				
	I4.0D	**LSSP**	**CSCM**	**ENVP**
I4.0D	**0.787**	*(0.718)*	*(0.724)*	*(0.708)*
LSSP	0.520	**0.758**	*(0.653)*	*(0.718)*
CSCM	0.569	0.523	**0.826**	*(0.735)*
ENVP	0.512	0.582	0.614	**0.805**
MODEL 2: I4.0D →LSSP/CSCM→ECOP				
	I4.0D	**LSSP**	**CSCM**	**ECOP**
I4.0D	**0.787**	*(0.718)*	*(0.724)*	*(0.739)*
LSSP	0.521	**0.757**	*(0.653)*	*(0.737)*
CSCM	0.569	0.528	**0.826**	*(0.748)*
ECOP	0.534	0.584	0.629	**0.805**
MODEL 3: I4.0D →LSSP/CSCM→SOCP				
	I4.0D	**LSSP**	**CSCM**	**SOCP**
I4.0D	**0.788**	*(0.736)*	*(0.725)*	*(0.559)*
LSSP	0.620	**0.788**	*(0.636)*	*(0.506)*
CSCM	0.562	0.496	**0.826**	*(0.702)*
SOCP	0.421	0.394	0.593	**0.853**

Note(s): I4.0D – Industry 4.0 Deployment; LSSP – Lean Six-Sigma Practices; CSCM – Circular Supply Chain Management; ENVP – Environmental Performance; ECOP – Economic Performance; SOCP – Social Performance; The bold and underlined values (diagonal values) are $\sqrt{AVE}$ of the respective construct; The values shown below the diagonal values are the Fornell-Larcker Criterion results; and the values (in parentheses and italics) shown above the diagonal values are the Heterotrait-Monotrait Ratio (HTMT) results.

5.2 Structural Models

Given that survey data is complex and contains multiple underlying constructs, structural models allow researchers to rigorously test propositions by examining the strength and significance of the relationships between variables in the survey data (Faisal, 2023; Gutierrez et al., 2022). Hence, after assessing the adequacy of measurement models, structural models were developed to investigate the proposed associations among the constructs, employing a bootstrapping technique with 5000 iterations. Figures 2-4 depict the outcomes of structural models, while Tables 4-5 list a concise summary of the same.

Structural Model 1

The results of the first structural model, which regards environmental performance as the dependent variable, are presented in Figure 2. In order to complement the illustrative depiction (Figure 2), the results are collated and summarized in tabular form in Table 4-5. The current evidence does not support the direct impact of the deployment of Industry 4.0 on environmental performance (i.e., *H1a:* $\beta = 0.069, p = 0.336$). This finding contradicts numerous previous research studies (Belhadi et al., 2020; Y. Li et al., 2020; Liu et al., 2023). The aforementioned observation can be elucidated by the remaining hypotheses in the model that have been determined to hold statistical significance (Table 4). The statistical analysis reveals that I4.0D has a significant impact on LSSP and CSCM, thus providing support for hypotheses 2 and 3 (i.e., *H2:* $\beta = 0.520, p = 0.000$; *H3:* $\beta = 0.569, p = 0.000$). This finding is consistent with previous research (Faisal, 2023; Mahdiraji et al., 2022; Rosin et al., 2020; Tortorella et al., 2019; Vlachos et al., 2023), indicating that the technological capabilities provided by Industry 4.0 technologies enhance the process-level capabilities that are based on the principles of lean six sigma and circularity. Results shown in Table

4 provide evidence in favor of hypotheses H4a and H5a, indicating that the implementation of operational excellence practices, such as LSSP and CSCM, has a positive effect on environmental performance (i.e., *H4a:* $\beta = 0.265$, $p = 0.000$; *H5a:* $\beta = 0.536$, $p = 0.000$). The findings align with prior studies conducted in this domain (Farooque et al., 2022; Ganjavi & Fazlollahtabar, 2023). This study reveals that, compared to LSSP, CSCM has a significant impact on improving environmental performance. Such assertion is additionally substantiated by the outcomes of the mediation analysis delineated in Table 5. Based on a review of the results in terms of direct and indirect effects, it can be concluded that the total effect of I4.0D on environmental performance (*total effect = 0.512 and total indirect effect = 0.443*) is channeled through both LSSP (i.e., *H6a: indirect effect = 0.305*) and CSCM (i.e., *H7b: indirect effect = 0.138*), demonstrating complete mediation, which is a unique scholarly contribution of this study.

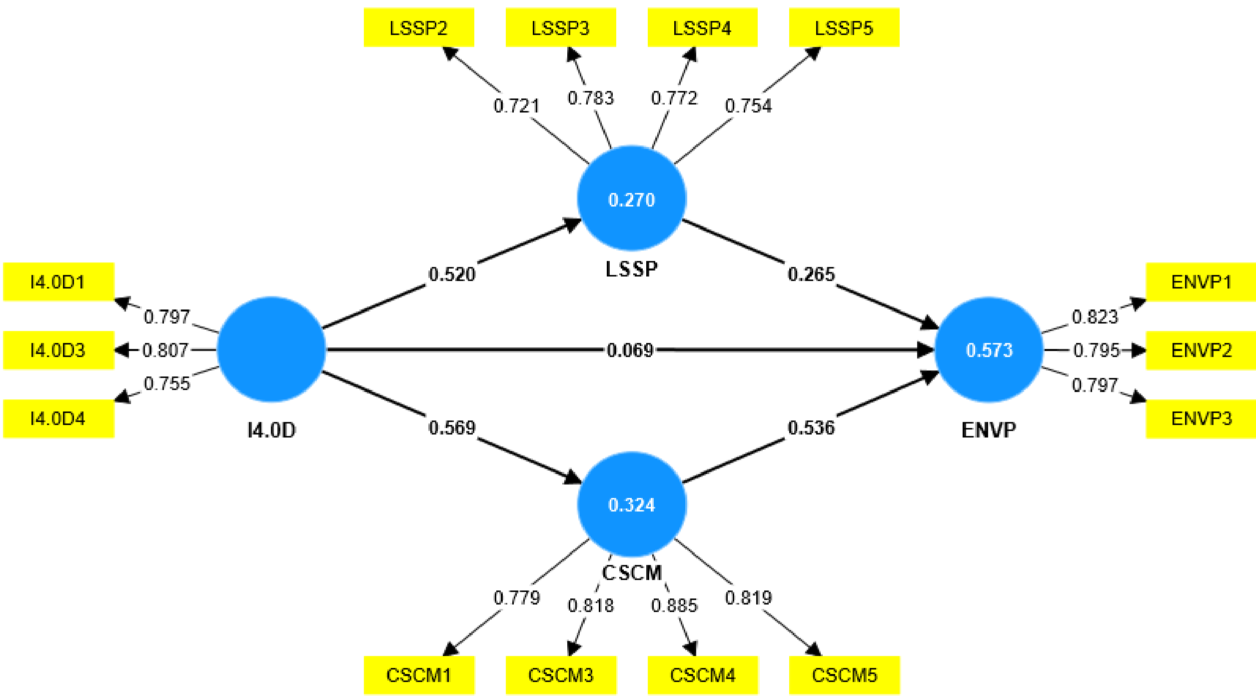


Figure 2 Results of Structural Model 1

Note(s): *I4.0D – Industry 4.0 Deployment; LSSP – Lean Six-Sigma Practices; CSCM – Circular Supply Chain Management; ENVP – Environmental Performance.*

Structural Model 2

Figure 3 depicts the outcomes of the second structural model, in which economic performance serves as the dependent variable. Intriguingly, all direct hypotheses within this structural model are accepted (Table 4). Commencing with the discussion, it can be noted that I4.0D exerts a direct impact on the economic performance (i.e., hypothesis H1b: $\beta = 0.162$, $p = 0.014$), an observation that is also applicable to LSSP (i.e., *H2:* $\beta = 0.521$, $p = 0.000$) and CSCM (i.e., *H3:* $\beta = 0.569$, $p = 0.000$). Consistent with previous research (Kayikci et al., 2022; Y. Li et al., 2020), I4.0D appears to have a positive effect on economic performance (H1b), which may encourage businesses to strategically implement the industry 4.0 technologies in order to increase revenues. The results suggest that both LSSP (i.e., *H4b:* $\beta = 0.300$, $p = 0.000$) and CSCM (i.e., hypothesis H5b: $\beta = 0.379$, $p = 0.000$) exert a significant impact on economic performance which is consistent with prior studies highlighting their strategic significance (Chavez et al., 2022; Jum'a et al., 2022; Liu et al., 2023). The findings of the direct hypotheses (Table 4) and indirect hypotheses (Table 5) show that LSSP (i.e., *H6b: indirect effect = 0.156*) and CSCM (i.e., hypothesis H7b: indirect effect = 0.216) have a partial mediating role in the relationship between I4.0D and economic performance (total effect = 0.534 and total indirect effect = 0.372), which may be regarded as a distinctive contribution of the present work.

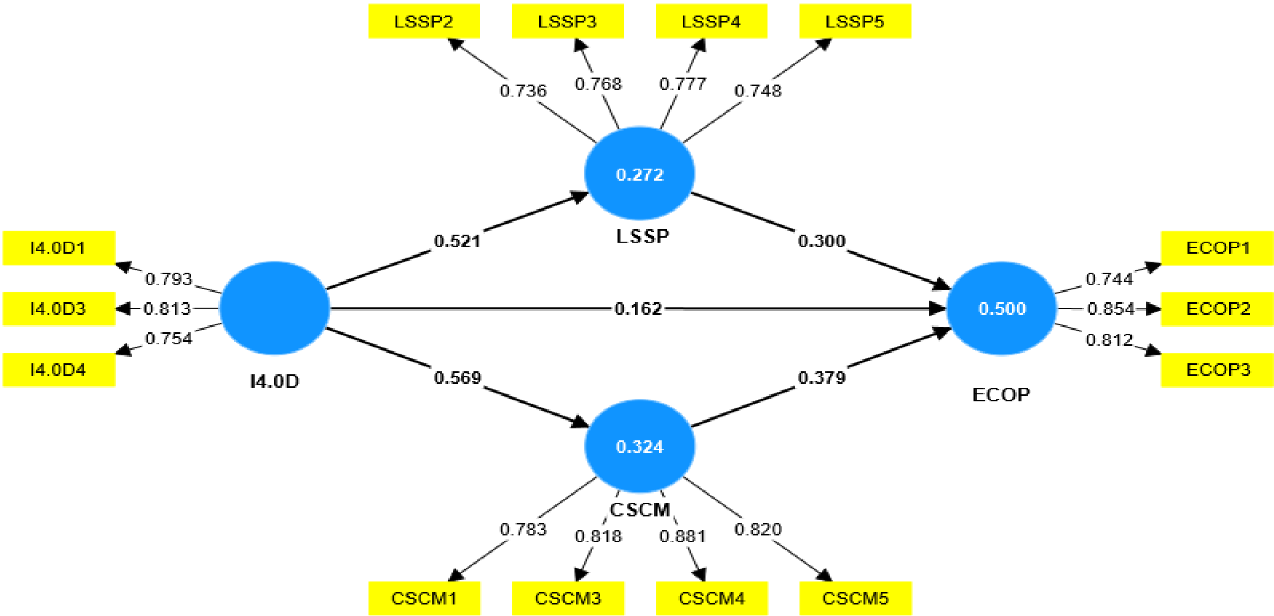


Figure 3 Results of Structural Model 2

Note(s): *I4.0D – Industry 4.0 Deployment; LSSP – Lean Six-Sigma Practices; CSCM – Circular Supply Chain Management; ECOP – Economic Performance.*

Structural Model 3

Figure 4 displays the outcomes of the third structural model wherein social performance is regarded as the dependent variable. The results of the third structural model exhibit differences from the preceding two structural models to the first hypothesis when compared to the first structural model (Table 4), the fourth hypothesis when compared to the second structural model (Table 4), and the sixth hypothesis when compared to both previous structural models (Table 5). The present study does not provide evidence for the direct effect of Industry 4.0 on social performance (i.e., *H1c: β = 0.080, p = 0.310*), which is incongruent with the results of previous research (García-Muiña et al., 2021; Torrent-Sellens et al., 2023). The third structural model, like the preceding two structural models, demonstrates that the effect of I4.0D on LSSP (i.e., *H2: β = 0.620, p = 0.000*) and CSCM (i.e., *H3: β = 0.562, p = 0.000*) is significant, lending credence to the second and third hypotheses. The fourth hypothesis, which posits that LSSP directly affects social performance, was not substantiated (i.e., H4c: β = 0.096, p = 0.264). This result contradicts prior research findings (Afum et al., 2023; Chavez et al., 2022) and might be attributed to the fact that LSSP focuses primarily on operational efficiency and may have overlooked broader social and ethical considerations. The fifth hypothesis, which proposes a direct relationship between CSCM and social performance, has been confirmed (i.*e., H5c: β = 0.500, p = 0.000*), consistent with previous research findings (García-Muiña et al., 2021; Vegter et al., 2023). Finally, based on the results of both direct and indirect effects, it is possible to infer that the total effect of I4.0D on social performance (total effect = 0.421 and total indirect effect = 0.341) is transmitted via the indirect mechanism of CSCM (i.e., hypothesis H7c: indirect effect = 0.280), indicating its role as a partial mediator in the process, whereas the mediating role of LSSP has not been established (i.e., *H6c: indirect effect = 0.060*). The results derived from hypotheses 6-7 are distinctive additions to the literature that researchers might explore further in the future to provide new perspectives.

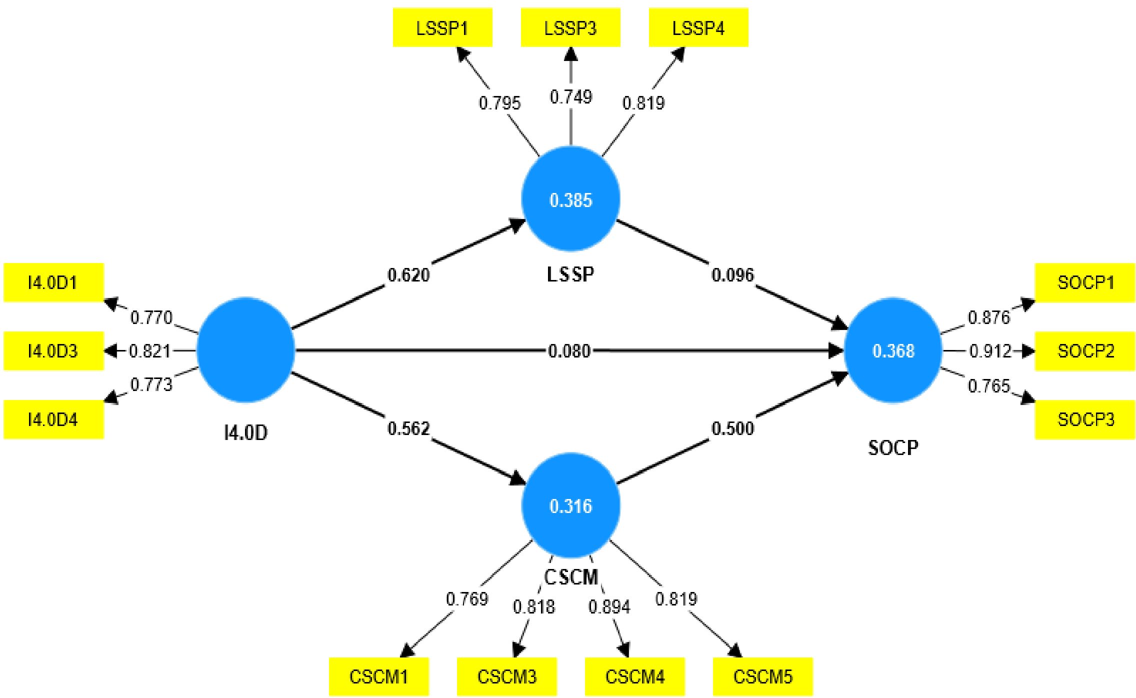


Figure 4 Results of Structural Model 3

Note(s): *I4.0D – Industry 4.0 Deployment; LSSP – Lean Six-Sigma Practices; CSCM – Circular Supply Chain Management; SOCP – Social Performance.*

Table 4 Assessment of Structural Models

Path	β	t	p	CI		VIF	Decision
				2.5%	97.5%		
MODEL 1: I4.0D →LSSP/CSCM→ENVP							
H1a: I4.0D → ENVP	0.069	0.962	0.336	-0.066	0.215	1.644	Not Supported
H2: I4.0D →LSSP	0.520	8.605	0.000	0.404	0.641	1.000	Supported
H3: I4.0D →CSCM	0.569	12.075	0.000	0.479	0.665	1.000	Supported
H4a: LSSP → ENVP	0.265	3.807	0.000	0.132	0.403	1.531	Supported
H5a: CSCM → ENVP	0.536	8.092	0.000	0.408	0.669	1.653	Supported
MODEL 2: I4.0D →LSSP/CSCM→ECOP							
H1b: I4.0D → ECOP	0.162	2.453	0.014	0.034	0.292	1.644	Supported
H2: I4.0D →LSSP	0.521	8.725	0.000	0.409	0.642	1.000	Supported
H3: I4.0D →CSCM	0.569	12.138	0.000	0.480	0.664	1.000	Supported
H4b: LSSP → ECOP	0.300	4.202	0.000	0.162	0.439	1.541	Supported
H5b: CSCM → ECOP	0.379	4.689	0.000	0.225	0.539	1.659	Supported
MODEL 3: I4.0D →LSSP/CSCM→SOCP							
H1c: I4.0D → SOCP	0.080	1.015	0.310	-0.071	0.234	1.890	Not Supported
H2: I4.0D →LSSP	0.620	15.014	0.000	0.520	0.687	1.000	Supported
H3: I4.0D →CSCM	0.562	11.589	0.000	0.457	0.647	1.000	Supported
H4c: LSSP → SOCP	0.096	1.152	0.249	-0.066	0.264	1.541	Not Supported
H5c: CSCM → SOCP	0.500	6.298	0.000	0.328	0.638	1.544	Supported

Note(s): I4.0D – Industry 4.0 Deployment; LSSP – Lean Six-Sigma Practices; CSCM – Circular Supply Chain Management; ENVP – Environmental Performance; ECOP – Economic Performance; SOCP – Social Performance; β – Path coefficient; t – t value; p – probability value; CI – Confidence Interval; and VIF - Variance Inflation Factor.

Table 5 Total Effects and Unique Indirect Effects of Industry 4.0 Deployment on Triple Bottom Line Performance through Lean Six Sigma Practices and Circular Supply Chain Management as Mediators

	COEF	t	p	CI 5%	CI 95%	Decision
MODEL 1: I4.0D →LSSP/CSCM→ENVP						
Total Effects	0.512	8.370	0.000	0.394	0.633	
Total Indirect Effects	0.443	9.561	0.000	0.362	0.544	
Unique Indirect Effects through						
1. Lean Six Sigma Practices (H6a: I4.0D→LSSP→ENVP)	0.138	3.411	0.001	0.068	0.225	Supported (Full Mediation)
2. Circular Supply Chain Management (H7a: I4.0D→CSCM→ENVP)	0.305	6.582	0.000	0.226	0.405	Supported (Full Mediation)
MODEL 2: I4.0D →LSSP/CSCM→ECOP						
Total Effects	0.534	10.226	0.000	0.433	0.640	
Total Indirect Effects	0.372	7.923	0.000	0.292	0.472	
Unique Indirect Effects through						
3. Lean Six Sigma Practices (H6b: I4.0D→LSSP→ECOP)	0.156	3.716	0.000	0.081	0.247	Supported (Partial Mediation)
4. Circular Supply Chain Management (H7b: I4.0D→CSCM→ECOP)	0.216	4.119	0.000	0.121	0.328	Supported (Partial Mediation)
MODEL 3: I4.0D →LSSP/CSCM→SOCP						
Total Effects	0.421	8.600	0.000	0.326	0.517	
Total Indirect Effects	0.341	5.751	0.000	0.234	0.468	
Unique Indirect Effects through						
5. Lean Six Sigma Practices (H6c: I4.0D→LSSP→SOCP)	0.060	1.129	0.259	-0.038	0.172	Not Supported
6. Circular Supply Chain Management (H7c: I4.0D→CSCM→SOCP)	0.281	5.515	0.000	0.191	0.390	Supported (Partial Mediation)

Note(s): I4.0D – Industry 4.0 Deployment; LSSP – Lean Six-Sigma Practices; CSCM – Circular Supply Chain Management; ENVP – Environmental Performance; ECOP – Economic Performance; SOCP – Social Performance.

6. Discussion

The research constitutes a novel endeavor to explicate a mechanism to optimize environmental, economic, and social performance. The study proposes that I4.0D, LSSP, and CSCM are necessary antecedents of such functional mechanisms, which have been analyzed in a unified framework drawing upon the theoretical underpinning of ROT. The results of this study advocate novel perspectives while partly corroborating the fragmented evidence found in previous research on various propositions. The first hypothesis posits an examination of the direct impact of I4.0D on TBL performance, where the findings suggest that I4.0D has had a discernible influence on economic performance but not on environmental and social performance. This implies that deploying Industry 4.0 technologies improves operational effectiveness, reduced expenses, and higher productivity, thereby contributing to economic growth, as many previous studies have highlighted (Chavez et al., 2023; Dubey et al., 2019). While studies have suggested that I4.0D has the potential to influence environmental sustainability through resource optimization and waste reduction indirectly (Agyabeng-Mensah et al., 2022; Mukhuty et al., 2022), its direct impact on environmental and social performance appears to be less pronounced in the current investigation. One potential explanation for this is that the immediate effects of I4.0D on environmental and social performance may not be readily observable. Companies may need a considerable length of time to reorganize their operations, establish new procedures, and fully incorporate aspects of sustainability. Thus, it is probable that the current investigation does not completely capture the long-term impact of Industry 4.0 technologies on environmental and social performance, which future research may seek to determine. Despite the findings which put the ROT into question (Afum et al., 2023), this study emphasizes the need for additional research and exploration of strategies that effectively integrate Industry 4.0 technologies with environmental and social objectives in order to maximize the positive impact on sustainability. The second and third hypotheses, which suggest that I4.0D influences LSSP and CSCM, have been consistently corroborated across all three structural models encompassing three distinct dimensions of TBL performance - results that are consistent with previous research (Bokhorst et al., 2022; Bonamigo et al., 2023; Kayikci et al., 2022; Taddei et al., 2022). This demonstrates that integrating I4.0D with LSSP improved process visibility, decision-making, and waste reduction (Vlachos et al., 2023), while integrating I4.0D with CSCM improves traceability, transparency, and closed-loop practices (Agrawal et al., 2023; Faisal, 2023).

Although practitioners contend that programs like LSSP and CSCM are mainly intended to improve performance outcomes, the results of the study are generally in line with previous studies (Eisenreich et al., 2022; Khanzode et al., 2021; Liu et al., 2023; Muganyi et al., 2019), with one exception where LSSP is observed not to influence social performance (Afum et al., 2023). The CSCM has been identified as having strategic significance due to its considerable influence on TBL performance's environmental, economic, and social dimensions. The results of hypothesis 5 emphasize that by adopting CSCM, organizations can achieve a comprehensive and sustainable approach to their operations, resulting in a more balanced and responsible business model (Agyabeng-Mensah et al., 2022). Recognizing the importance of CSCM in achieving TBL goals can help organizations align their strategies, processes, and stakeholder engagements to drive positive impacts across multiple dimensions of sustainability. The findings on hypothesis 4 suggest that LSSP significantly influences environmental and economic performance while having no discernible impact on social performance. Scholarly debate may have been sparked by the apparent contradiction between such results and prior studies (Afum et al., 2023; Chavez et al., 2022), which suggest that while LSSP may increase product quality, process improvement, employee contentment, and customer satisfaction (Alkunsol et al., 2019; Belhadi et al., 2020). It is important to note that social performance is a multifaceted and complex aspect that can be impacted by various factors beyond the purview of LSSP. Moreover, it is plausible that any benefits to society are mediated by economic and environmental performance, which future researchers can investigate to provide fact-based explanations.

The resultant findings have also influenced the mediation hypotheses (i.e., hypotheses 6 and 7) related to LSSP and CSCM concerning the association between I4.0D and TBL performance. Full mediation was observed in the case of environmental performance, while partial mediation was observed in the case of economic performance, while only CSCM was accountable for partial mediation in the case of social performance. Furthermore, upon analyzing the indirect impact of both LSSP and CSCM on the impact of I4.0D on TBL performance, it was noted that CSCM exhibited a more significant contribution to TBL performance than LSSP. Although no obvious explanation exists for such a result, it is essential to note that the relative contributions of LSSP and CSCM on the linkage between I4.0D and TBL performance may vary depending on the specific context and industry. Using a qualitative and longitudinal research approach, more study is needed to investigate the mechanism through which CSCM and LSSP interact with I4.0D and their distinct contributions to TBL performance. Understanding these dynamics could explain such observations and assist organizations in prioritizing and integrating the most effective approaches to achieving their long-term strategic goals.

7. Implications

7.1 Theoretical Contributions

One of the theoretical implications derived from the present investigation is the contribution to the ROT (Chavez et al., 2022; Wong et al., 2018). It can be inferred that organizations can optimize their resource allocation and utilization, leading to improved TBL performance by effectively orchestrating the I4.0D, LSSP, and CSCM. To begin, the findings of the current investigation have challenged the theoretical contribution of prior scholarship by negating the impact of I4.0D on environmental and social performance (Belhadi et al., 2020; Liu et al., 2023). An analogous phenomenon has been noted about LSSP, wherein its absence concerning the impact on social performance has challenged the theoretical basis of previous scholarly work (Torrent-Sellens et al., 2023). In light of these observations, it advances, in particular, by introducing a new dimension to the ROT, which contends that the effect of I4.0D on every facet of TBL performance is channeled via the integration and successful orchestration of CSCM, which has a considerably significant impact compared to LSSP.

Furthermore, the present study yields a theoretical implication that underscores the importance of effectively integrating, orchestrating, and aligning organizations' diverse resources to attain superior performance (Asiaei et al., 2021; Chavez et al., 2023). This study represents an initial exploration within operations and supply chain management, highlighting the interplay between LSSP and CSCM as part of a unified framework. The results provide credence to ROT by proving their integrated nature in pursuit of TBL performance.

7.2 Practical Implications

The research presents significant pragmatic ramifications for administrators overseeing manufacturing operations in enhancing their TBL performance. The findings of the current investigation emphasize the importance of adopting industry 4.0 technologies to enhance the performance of LSSP and CSCM, which have been shown to improve the TBL performance. Hence, it is advisable for process administrators within manufacturing entities to implement a strategic framework aimed at attaining TBL performance, which holds considerable strategic significance. A detailed course of action is delineated in the following plan.

- **Assess Current State:** It is recommended that managers perform a comprehensive evaluation of their organization's current procedures, methodologies, and technological systems related to operational excellence and continuous improvement strategies (Erdil et al., 2018; Ivanov, 2023). Managers must concentrate on determining the strengths, limitations, and opportunities for improvement.
- **Set Clear Objectives:** It is imperative for managers to propose a strategic, operational plan that incorporates pertinent elements of Industry 4.0, LSSP, and CSCM, along with distinct goals and targets aimed at enhancing TBL performance (Bag et al., 2023; Rosin et al., 2020), in properly positioning with their prior assessment. Managers must also ensure that such objectives align with their organization's sustainability strategy and mission.

- **Develop a Roadmap:** It is recommended that managers collaborate with senior management to develop a comprehensive action plan that delineates the necessary measures, timeline, and resources required to execute the intended changes (Sunder M & Prashar, 2023). In addition, managers should contemplate forming a cross-functional team to supervise the implementation process and guarantee efficient coordination.
- **Invest in Technology and Infrastructure:** At this stage, managers should evaluate the optimal methodologies employed by their competitors through process quality function deployment (Choo, 2022). This will enable them to allocate the requisite resources toward deploying Industry 4.0 technologies, including but not limited to automation systems, data analytics tools, and IoT devices (Ivanov, 2023). Managers should conduct process capability studies to determine whether existing infrastructure should be upgraded or modified to support the integration of these technologies and enable seamless data flow (Vlachos et al., 2023).
- **Train and Engage Employees**: Managers should prioritize comprehensive training programs to provide employees with the skills and knowledge required for LSSP and CSCM (Subramaniam et al., 2019). At this juncture, it is imperative for managers to explore social innovation that can facilitate employee engagement and motivate proactive involvement in improvement endeavors (Farooque et al., 2022; Jum'a et al., 2022).
- **Foster Collaboration and Partnerships:** After streamlining internal stakeholders, managers must establish collaborations with suppliers, customers, and industry partners to foster knowledge sharing, innovation, and sustainable practices throughout the supply chain (Sudusinghe & Seuring, 2022). Managers can also look into opportunities for collaborative projects and initiatives to drive collective improvements (Kayikci et al., 2022).
- **Implement Lean Six Sigma Methodologies:** Managers should now incorporate the envisioned Lean Six Sigma strategies into their organization's operations, stressing waste reduction, quality improvement, and continuous improvement wherever the operational

process necessitates (Alkunsol et al., 2019; Muganyi et al., 2019). Managers must now set clear performance metrics and utilize data-driven techniques to identify areas for improvement.

- **Adopt Circular Supply Chain Management:** Managers should also simplify and incorporate circularity ideas into internal operations and supply chain processes, such as waste reduction, recycling, and reuse initiatives (Farooque et al., 2022). It is imperative to devise a strategic plan involving suppliers and customers in forming a closed-loop system that optimizes resource utilization while minimizing environmental impact.
- **Monitor and Measure Performance:** Managers should establish key performance indicators (KPIs) to assess the effect of I4.0D, LSSP, and CSCM on TBL performance (Asokan et al., 2022; Vlachos et al., 2023). Managers must establish a systematic audit plan to collect and analyze data regularly to identify progress, milestones, and areas that need more attention.
- **Continuous Improvement and Adaptation:** Managers must prioritize establishing a reward and recognition system to foster a culture of continuous improvement by encouraging employees to explore possibilities for process advancement and innovation (Sreedharan et al., 2018). Managers should break down functional silos and review and adapt strategies regularly based on feedback, market trends, and emerging technologies to stay ahead of the curve.
- **Communicate and Celebrate Success:** Managers must effectively communicate the positive outcomes and accomplishments that have resulted from the integration of I4.0D, LSSP, and CSCM (Belhadi et al., 2020). Managers may disseminate accounts of successful outcomes within and beyond the organization to stimulate and invigorate employees and stakeholders (Bag et al., 2023; Kumar et al., 2022).
- **Evaluate and Update:** At this juncture, managers should carry out regular assessments to gauge the efficacy of the executed initiatives and make requisite adaptations to stay

competitive. It is imperative for managers to remain up-to-date with the latest developments in Industry 4.0, lean six sigma, and circular practices to ensure perpetual improvement and sustainability.

8. Conclusion

The current study investigated the potential of deploying Industry 4.0 technologies to improve organizations' TBL performance by examining the role of LSSP and CSCM. In response to the proposed RQ, the current research has illuminated the noteworthy prospects and benefits that may ensue from the amalgamation of stated operational excellence approaches. To begin with, the results of this investigation show that I4.0D enables organizations to create leaner and more sustainable processes, which holds tremendous potential for achieving TBL performance. However, it is essential to recognize that successful implementation requires careful planning, robust infrastructure, and organizational commitment. Overcoming challenges such as data security, skill gaps, and resistance to change is critical for harnessing the full benefits of these approaches. Ultimately, organizations that embrace Industry 4.0 technologies and implement a comprehensive strategy for sustainability and productivity can establish themselves as industry pioneers, creating value for their stakeholders and contributing to a more sustainable future.

The study's limitations must also be considered when interpreting the results. A limitation of the study is its cross-sectional design, which precludes the establishment of causal relationships. Since the data is collected simultaneously, it becomes arduous to ascertain the temporal sequence of events and causality. Furthermore, cross-sectional studies depend on self-reported data, which could potentially be influenced by recall and social desirability biases. The survey format may impose limitations on the comprehensiveness of the information gathered, possibly disregarding significant contextual factors. Consequently, it is recommended that forthcoming researchers in this domain employ a research methodology that incorporates both longitudinal and case study designs. This approach will facilitate a more comprehensive understanding of the present investigation's results or provide fresh perspectives. Furthermore, the present investigation is constrained by its confined focus on the Industry 4.0 paradigm. We therefore advocate for including aspects of Industry 5.0 in future studies. Industry 5.0 signifies a notable advancement beyond Industry 4.0, highlighting a transition towards a paradigm that prioritizes societal value, human-centeredness, resilience, and sustainability (Narula et al., 2024). Given the philosophical foundation of Industry 5.0, which strives to create a more inclusive, adaptable, and environmentally sustainable industrial ecosystem, it would be relevant to investigate how these emerging social-technical practices affect TBL performance via LSSP and CSCM.

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Appendix

Part A: Demographic Details of Respondent
Name of the Respondent:
Organization & Location:
Designation of the Respondent:
Number of Years in Business Operations:
Number of Employees:
Nature of Operating Sector:

Part B: Questionnaire

(Respondents have to respond to each question on a 5-point Likert Scale with 1 – Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, and 5 – Strongly Agree)

Industry 4.0 Deployment *(Adopted from Tortorella et al., 2019)*

- Our organization has strategically invested in cloud computing technologies to enhance various aspects of its operations, including product development, supply chain management, and productivity management.
- Our organization has made a substantial investment in integrative technological platforms that utilize advanced technologies such as additive manufacturing, 3D printing, virtual reality, and augmented reality.
- Our organization has made a strategic investment in remote monitoring systems that incorporate process control sensors and leverage the internet of things.
- Our organization has made substantial investments digital automation systems that utilize advanced technologies such as artificial intelligence, big data analytics, predictive analytics, and machine learning.

Lean Six Sigma Practices *(Adopted from Sreedharan et al., 2018)*

- Our organization proactively conducts root cause analysis to determine the fundamental causes behind manufacturing process issues or product defects, in situations involving inefficiency or failure to meet expectations.
- Our organization places considerable emphasis on utilizing visual management tools such as Kanban boards, process maps, and visual work instructions to improve communication and increase process visibility within the factory shopfloor.
- Our organization places considerable emphasis on establishing a functional structure aimed at reducing operational wastes (such as Muda, Mura, and Muri), with the ultimate goal of ensuring the consistency and reliability of manufacturing processes.
- Our organization documents and standardizes best practices in manufacturing processes to promote uniformity and encourage knowledge exchange.
- Our organization regularly performs process capability studies to verify that manufacturing processes comply with customer requirements and specifications.

Circular Supply Chain Management (*Adopted from Del Giudice et al., 2021***)**

- Our organization places significant emphasis on facilitating the deployment of sustainable initiatives, encompassing a range of practices such as material reuse, remanufacturing, and recycling.
- Our organization possesses the necessary digital resources to effectively monitor the reuse and recycle activities across its supply chain operations.
- The product design and manufacturing activities of our organization support the practice of material reuse, remanufacturing, and recycling.

- The procurement and governance procedures of our organization endorse the practice of material reutilization, remanufacturing, and recycling.
- Our organization is committed to the principles of material reuse, remanufacturing, and recycling, and these tenets are reflected in the way we manage our human resources.

Environmental Performance *(Adopted from Dubey et al., 2019)*

Relative to our most relevant competitors over the last three years,

- our organization has significantly lowered its carbon emissions.
- our organization has made a substantial shift towards adopting cleaner energy alternatives.
- our organization has made considerable progress in reducing environmental waste (solid, water, and hazardous).

Economic Performance *(Adopted from Subramaniam et al., 2019)*

Relative to our most relevant competitors over the last three years,

- our organization has experienced substantial growth in its market share.
- our organization has observed a significant rise in return on investments.
- our organization has witnessed a noteworthy increase in both sales' revenue and net profit margin.

Social Performance (*Adopted from Subramaniam et al., 2019)*

Relative to our most relevant competitors over the last three years,

- our organization has improved in overall stakeholder welfare and betterment.
- our organization has improved in community health and safety.
- our organization has improved protection of claims among public.