

Analysis of factors influencing Circular-Lean-Six Sigma 4.0 implementation considering sustainability implications: An exploratory study

Dounia Skalli^a, Abdelkabir Charkaoui^a, Anass Cherrafi^b, Alireza Shokri^c, Jose Arturo Garza-Reyes^d, Jiju Antony^c

- (a) Faculty of sciences and Technique, Hassan First University of Settat, Morocco; (b) EST-Safi, Cadi Ayyad University, Marrakech-Safi, Morocco; (c) Faculty of Business and Law, Northumbria University, Newcastle, UK; (d) Centre for Supply Chain Improvement, University of Derby, Derby, UK

Abstract

In this study, we develop a new paradigm, Circular Lean Six Sigma 4.0 (CLSS4.0) to promote manufacturing sustainability. This paper aims to provide a practical and holistic view of the drivers and barriers that can help companies design an integrated CLSS4.0 model. The paper is based on a qualitative exploratory study using multiple case studies within 12 Moroccan manufacturing firms conducted through semi-structured interviews with top executive managers. The results show that the drivers are related to expected operational and environmental performance, increasing customer requirements, gaining competitive advantage and market growth while barriers are related to insufficient tangible (finance, human and equipment) and intangible (skills and techniques) resources, data privacy, technical issues and management support. The proposed framework identifies the assessment of drivers and barriers and their attributes as a starting point for managers to lead the CLSS4.0 transformation, thereby contributing to its successful implementation. To the best of our knowledge, this study is among the very first studies to discuss the CLSS4.0 drivers and barriers. It could be useful to managers as a diagnostic tool to assess their ability to implement CLSS4.0 before investing in the initiative.

Keywords: Lean Six Sigma, Industry 4.0, Circular Economy, Drivers, Barriers, Qualitative study.

1. Introduction

Sustainability is defined generally as the capacity to endure and maintain a balanced and healthy ecosystem, economy, and society that can meet the needs of the present without compromising the ability of future generations to meet their own needs (Kiel et al. 2017). It involves balancing economic growth and development with social progress and environmental protection. The concept can be applied to many different areas, including environmental sustainability, economic sustainability, social sustainability, and cultural sustainability. Indeed, the subject is increasingly relevant in the changing world, where issues such as climate change, resource depletion and social inequality are becoming ever more pressing (Cherrafi et al. 2016).

In the industrial landscape, sustainability is commonly used as a guiding principle for achieving long-term success and reducing environmental impact (Seuring et Müller 2008). By considering the environmental and social impacts of their operations, industrial organizations can identify ways to reduce waste, conserve resources, and minimize their carbon footprint. This not only benefits the environment and society as a whole, but it can also lead to cost savings and improved efficiency for the organization itself.

Throughout the past three decades, numerous definitions of sustainability have emerged, each with varying wording and focus depending on the context and field (Dixit et Chaudhary 2020; Gatto 1995; Morelli 2011; Missimer, Robèrt, et Broman 2016). In this study, we adopt the definition of sustainability based on the triple bottom line (TBL) approach proposed by (Elkington 1994) as it offers a comprehensive framework that considers the social, environmental, and economic dimensions of sustainability in the manufacturing industry. This allows a holistic evaluation of organizational performance and facilitates meaningful comparisons and discussions within the existing body of sustainability research. According to this approach, the enduring sustainability of organizations relies on maintaining the balance and interdependence of three essential elements, i.e. economy, environment and society. This study does not prioritize the superiority of any individual element but rather recognizes the significance of achieving an equilibrium among all three to sustain organisations. Specifically, our research focuses on the economic facet of sustainability, exploring how economic factors contribute to sustainable practices and outcomes. By examining the economic dimension of sustainability, our study aims to offer insights and recommendations for promoting sustainable economic practices while considering the broader context of the environmental and social aspects.

Given the above arguments and the challenge of climate change, pollution and resource scarcity induced by their activities (Edwin Cheng et al. 2022), manufacturing companies are looking for innovative and competitive paradigms to streamline their operational processes, gain productivity, reduce the damage to the environment and become sustainable. Industrial activities are considered a major source of global environmental pollution and resource waste, which should actively and significantly contribute to promoting sustainability (Sharma et al. 2023). To this end, manufacturers are required to integrate environmental practices as part of their business strategies in order to mitigate resource depletion and environmental damage (Cherrafi et al. 2021) and gain a competitive advantage simultaneously (Trevisan et al. 2023). Yet manufacturing companies remain faced with the cost of doing business sustainably. While adopting sustainable practices may entail short-term costs, the long-term benefits can offset these costs in terms of savings, reputation and market competitiveness.

To address the aforementioned challenges and achieve sustainable manufacturing, various approaches have been extensively studied and empirically tested, demonstrating their effectiveness in integrating sustainability into manufacturing processes such as lean management, six sigma (SS), green approach, zero defects manufacturing (ZDM), Eco-design and eco-innovation. Six Sigma is a data-driven methodology that reduces defects and improves quality (Andersson, Eriksson, and Torstensson 2006), whereas ZDM focuses on preventing defects during the manufacturing process. Green practices refer to environmentally friendly initiatives and actions while eco-design integrates environmental considerations throughout the entire product design and development process (Giuffrida and Mangiaracina 2020).

Previous studies have explored the intersections between LSS and sustainability in the context of green practices. As a result, the concept of Green Lean Six Sigma has gained significant notoriety and firmly established its contribution to achieving long-term sustainability goals. Green LSS emphasizes process optimization and waste reduction while considering sustainability aspects (Garza-Reyes 2015). Six Sigma and Zero Defects are quality management (QM) methodologies primarily focused on quality improvement (QI). They offer organizations structured frameworks and techniques to drive continuous improvement and attain higher levels of quality and customer satisfaction. However, QM and QI are distinct concepts, as highlighted by Juran and Gryna in their book on Quality Planning and Analysis published in 1993. While QM encompasses a broader range of strategies and methodologies, QI specifically targets improving quality over time. Six

Sigma emphasizes process efficiency and defect reduction through statistical analysis while ZDM aims for zero defects by integrating quality management principles with digital tools for real-time monitoring and optimization. ZDM aims to achieve defect-free production, indirectly promoting sustainability through waste reduction while, on the other hand, Eco-design/Eco-innovation focuses on environmentally conscious product and process design to minimize environmental impact (Psarommatis et al. 2019; Dahmani et al. 2021; Fragapane et al. 2023). Each approach addresses sustainability in manufacturing from a different perspective but ultimately aims to drive positive economic prosperity for manufacturing firms. It results in increased revenue through customer satisfaction, cost savings through defect reduction, and improved efficiency and productivity.

However, given the evolving nature of manufacturing systems and the continuous pressure to integrate sustainable practices into manufacturing operations, new perspectives can be explored by combining innovative approaches such as circular economy (CE) principles and industry 4.0 (I4.0) technologies with LSS to promote sustainable performance (Ghaithan et al. 2023). Various researchers have proposed various integrated approaches to address the challenges of transforming the industrial sector into a more sustainable industry (Bucea-Manea-țoniș et al. 2021; Kaswan et al. 2023; Cherrafi et al. 2022). This article presents an integrated framework that combines CE, LSS and I4.0 to meet the requirements of sustainable manufacturing.

We build on the CE, LSS, and I4.0 concepts to introduce a new perspective in sustainability called Circular Lean Six Sigma 4.0 (CLSS4.0), defined in this paper as the embodiment of I4.0 technologies and CE practices with the LSS continuous improvement strategy. This combination will lead to more sustainable results. CLSS4.0 can therefore be promoted as a new perspective to accelerate sustainability. In our perspective, sustainability is considered an intrinsic value covering three concepts, namely LSS, CE and I4.0. The circular economy is conceived as a sustainable and innovative solution to the pressing environmental challenges we face today. By adopting a circular economy approach, companies can minimize waste and maximize resource efficiency, resulting in reduced carbon emissions, better resource management and a healthier environment. It focuses on the reuse of materials and resources rather than the traditional linear economy of buy, use and waste. It aims to reduce the production and consumption of new materials and energy while maximizing the use of resources by reusing and recycling them. This reduces waste and keeps resources in use for longer, creating more efficient and

sustainable systems. The CE is receiving increasing attention both academically and in practice and is being positioned as a sustainable model offering solutions to resource depletion and waste management problems (Cherrafi et al. 2022; Edwin Cheng et al. 2022). The benefits of circular economy can be seen from an economic, social and environmental perspective. Economically, a circular economy can help to create more efficient and sustainable economic systems that create less waste, while increasing employment and productivity. It can also help reduce material and energy costs, making companies more competitive, and can increase consumer spending power. Socially, circular economy can help reduce inequalities by creating jobs in the recycling industry, increasing access to resources for low-income communities, and helping to alleviate poverty. It can also reduce the global burden of pollution through reduced resource and energy consumption. Environmentally, circular economy can help reduce the use of resources and energy, reduce pollution, and mitigate climate change by reducing waste and emissions. It also helps preserve valuable resources by encouraging reuse and recycling. By reducing waste and developing efficient energy usage, it can also reduce environmental damage and promote sustainable development. In literature, many researchers have demonstrated that CE has a positive impact on the cost-effectiveness and long-term viability of manufacturing businesses (Hina 2022), where the recycling of materials and assets creates both additional wealth and new revenues (Bag et al. 2022; Edwin Cheng et al. 2022).

The evolution of industrial manufacturing systems has revealed real advances and innovation resulting from the era of digitization called I4.0 referring to the fourth industrial revolution, making smarter, more connected production systems possible (Cherrafi et al. 2022). I4.0 advancements have allowed manufacturers to reduce costs, increase scalability, improve efficiency, increase compliance with regulations, and the accuracy of their products. Additionally, these technologies have enabled factories to be monitored in real-time and provide insights into the production process (Lasi et al. 2014). Furthermore, I4.0T involves support for operational and environmental excellence. Industry 4.0 has far-reaching implications on the social sustainability side. It has the potential to greatly increase efficiency and productivity, reduce the cost of production, improve safety, decrease energy consumption, reduce the cost of services, create new market opportunities and increase the competitiveness of enterprises in their respective markets. Lean Six Sigma (LSS) methodology is well established to help manufacturers meet the challenges of sustainability (Cherrafi et al. 2017). LSS involves a

set of methods and tools for process improvement(Dounia Skalli, Charkaoui, et Anass 2022). It combines lean, which focuses on eliminating waste in a process to become more efficient and Sigma, which looks at improving the quality of a process to reduce defects and increase customer satisfaction(Alexander, Antony, et Cudney 2021). The goal of LSS is to identify and eliminate any errors or inefficiencies in a process to save time and money while providing the highest possible customer satisfaction. LSS is based on the principle of continuous improvement and focuses on eliminating process defects(Antony et al. 2022). The use of LSS encourages and supports the development of sustainable processes and products, helping organizations to become more sustainable over time. It provides a framework for organizations to effectively measure and track their environmental impact, allowing to continuously improve the sustainability performance. The interaction between LSS and sustainability performance has been widely debated over the last few years, and evidence from previous studies has revealed a strong synergistic effect (Belhadi et al. 2020a). The literature has highlighted a great synergy between I4.0 and CE practices and their valuable impact on sustainability(Ghaithan et al. 2023). I4.0 technologies and LSS are presented in the literature as powerful tools for improving sustainability performance in manufacturing firms(Dounia Skalli et al. 2023). The integration of LSS and I4.0 known as LSS4.0 has the potential to be an important part of the answers to sustainability. Furthermore, LSS and CE practices can leverage various I4.0 technologies to provide economic, operational and environmental benefits to companies. The adoption of the triple approach of I4.0, CE and LSS would have a tremendously positive effect on the three sustainability dimensions. However, it is not yet clear which driving factors and barriers are most critical to the success of CLSS4.0 adoption, and how knowledge of these factors can influence the decision-making process concerning CLSS4.0 deployment.

Despite the recent growing interest and various studies exploring the drivers and barriers of the three concepts (LSS, CE and I4.0) alone or in dual combination, as well as the different research streams proposed, existing research to support their combination remains very limited while knowledge on drivers and barriers is missed(Belhadi et al. 2020a; Kurdve et Bellgran 2021). Most prior studies have relied on theoretical research and statistical methods in their research design. Previous literature has studied the implementation of I4.0, LSS and CE in a fragmented way, without proposing a comprehensive integrated framework to address how they interact and influence sustainability.

To our knowledge, there is no research in the literature investigating the drivers and barriers of CLSS4.0 implementation towards the sustainability performance of manufacturing companies. This study, therefore, aims to fill these gaps in the literature by exploring the drivers and barriers in the Moroccan manufacturing companies' context. Despite their critical importance, the drivers and barriers factors to CLSS4.0 adoption have not received significant scholarly attention and thus no empirical evidence has been reported in the academic literature.

Based on the above argument and the very limited body of knowledge in this area, an extensive comprehension of these elements is needed. The driving and hindering factors have a major influential role in the decision-making process for adopting CLSS4.0. Accordingly, we argue for the need to explore these elements, as a better understanding of these elements will boost a company's commitment to this initiative. Hence, empirical research is required to advance knowledge in this field. In this line, an exploratory study is necessary to mitigate this gap in the literature and develop insights. Compared to earlier studies, this paper examines both drivers and barriers to develop a comprehensive interpretation of the CLSS4.0 scale based on in-depth case studies and interviews within Moroccan multinational manufacturing companies. The contribution of our study stems from the conceptualization of a new decision tool for sustainability.

The adoption of CLSS4.0 will help processes, resources and energy optimization while reducing cost and quality defects, thereby generating added value, profitability and competitive advantage.

Given the purpose of the study to explore the drivers, barriers and best practices for the successful adoption of CLSS4.0 initiatives, three research questions arise:

RQ1. What are the main drivers and barriers of CLSS4.0?

RQ2. What are the best practices and actions to be taken to overcome the various barriers and challenges?

RQ3. In what ways can manufacturing companies implement the integrated CLSS4.0 approach?

Accordingly, this research aims to achieve the following objectives:

1. identify the drivers and barriers to CLSS4.0 adoption as well as the best practices for mitigating barriers and challenges
2. propose a comprehensive structured CLSS4.0 framework to promote sustainability.

To achieve the objectives of the study, multiple case studies based on semi-structured interviews were employed as a solution methodology. By applying this approach, we can gain a comprehensive understanding of the drivers and barriers factors affecting CLSS4.0 adoption and sustainability. Additionally, the semi-structured interviews can provide rich qualitative data on the experiences and perspectives of industry experts, which can be used to identify best practices and develop a comprehensive CLSS4.0 framework.

Overall, this research makes several contributions. Firstly, we are responding to the growing interest among scientists in further exploring the new facets of sustainability enabled by I4.0 technologies and CE practices. There is a great need for studies aimed at improving our knowledge of how to combine the three approaches of LSS, CE and I4.0 to promote sustainability. Our study is an important initial effort towards enhancing our understanding of the factors affecting CLSS4.0 adoption sustainability in manufacturing, particularly in emerging economies. The fact that authors take an example from an emerging economy, such as Morocco, is a unique contribution to the literature. This is because research on sustainability in emerging economies is scarce, and our study has the potential to provide valuable insights into how these approaches can be implemented in such contexts to promote sustainability. Second, the CLSS4.0 integrated paradigm is complex. Therefore, clarifying the drivers and barriers with existing adopters can help improve the adoption success rate for future initiatives.

This paper is organized into five sections. The literature background is presented in Section 2. The research methods are discussed in Section 3. Section 4 examines the semi-structured interviews' insights and presents a holistic framework for promoting digitalization and circularity as organizational capabilities. In section 5 we discuss the findings and highlight the theoretical and practical implications derived from our study. Finally, Section 6 presents the conclusion as well as limitations and directions for future research.

2. Conceptual background

2.1 Literature review

To identify relevant insights into potential drivers and barriers as well as research gaps concerning an integrated CLSS4.0 approach from past studies, a systematic literature review (SLR) was performed following the well-established PRISMA protocol (Xiao et Watson 2019; Ghobakhloo et al. 2022) as presented in (Fig. 1). PRISMA is recognized as a rigorous and widely accepted methodology for conducting SLR. It is widely

considered to be a valuable method for defining a specific concept and fostering theory development (Seuring et Müller 2008). The use of SLR guarantees rigour, precision and reproducibility of results. It involves a four-step process that includes identifying relevant studies, screening and selecting studies based on inclusion and exclusion criteria, extracting data from the selected studies, and finally synthesizing and reporting on the results. By following this methodology, the review is likely to be more thorough and transparent, reducing potential biases and increasing the reliability of the findings. After defining the research objectives and main research questions, we identified relevant studies in several high-quality search engines and databases, mainly Elsevier, Scopus, Emerald, Springer, Taylor and Francis, Wiley Online Library, and Google Scholar for the period between 2011 and June 2023. The initial search period 2011 was chosen by the authors because it is the year of the advent of I4.0. The search strings included the selected keywords listed in Table 1, using Boolean operators (AND and OR). The keywords selection was based on previous studies (D. Skalli, Charkaoui, et Cherrafi 2022)

Table 1: Summary of the review protocol

Unit of analysis	Journal articles
Review period	2011 to June 2023
Search Engines/Databases	Elsevier, Scopus, Emerald, Springer, Taylor and Francis, Wiley Online Library, and Google Scholar.
Keywords	Lean, Six Sigma, Lean Six Sigma, continuous improvement Industry 4.0: smart manufacturing, digital transformation, digital technologies, digital capability, Circular Economy, drivers, driving factors, barriers, obstacles, motivations, challenges.
Inclusion/Exclusion Search criteria (SC):	(SC1) Peer-reviewed articles including review articles, theoretical and empirical studies (SC2) English language (SC3) Full-text availability for reading (SC4) Content relevance conference papers, book and book chapters, and white papers.
Total evaluated papers	38 journal papers

As a result, a total of 76 articles was initially identified, which was then reduced to 58 studies after removing duplicates. The list of articles was then examined and filtered using the following inclusion and exclusion criteria, presented in Table 1. We considered only (1) peer-reviewed journal papers including both empirical and conceptual studies (2) written in English, (3) available in full-text reading and (4) consistent with the study

purpose. Only articles addressing the drivers and barriers to LSS, CE, and I4.0 paradigms within the manufacturing industry landscape were considered, whereas conferences, books and book chapters, and white papers were considered as exclusion criteria. Performing the four screening rounds in line with the inclusion and exclusion criteria presented in Table 1 led to the exclusion of 20 articles as demonstrated in Appendix 2. Finally, in the last stage of analyzing and reporting, a total of 38 articles were considered relevant and valuable to the analysis, and then a full-text content analysis was conducted for each of these articles during the report development phase to find the multiple factors that support the CLSS4.0 integrated approach, as well as the barriers that hinder it. Details of the relevant papers assessed in this study, including, authors, journal, and methodologies used are presented in Appendix 1. (Further completed details of articles assessed in this study can be provided by the authors on request). Considering the aforementioned inclusion and exclusion criteria, we were faced with some challenges in conducting the SLR, including insufficient literature available about CE and I4.0 in the manufacturing sector of emerging economies. However, we tried to overcome this challenge through careful keyword selection, accurate screening and cross-checking among the team.

Figure 1 appears here

2.2 Drivers of CLSS4.0

For successful CLSS4.0 implementation, it is critical to know what motivates companies to adopt CLSS4.0. The main competitive advantage of a company resides now in its power to meet the requirements of customers and stakeholders and to generate value as well as to acquire new capabilities related to sustainable organizational performance (Chaouni Benabdellah, Zekhnini, et Cherrafi 2021). Thus, high competitiveness level has pushed companies to seek innovative and cost-effective strategies (Lasi et al. 2014; Bauer et al. 2018). By adopting CE practices and new digital technologies of Industry 4.0, companies can increase their productivity and profitability and promote sustainability. Empirical evidence has demonstrated the strong effect of LSS, CE and I4.0 concepts, alone or in combination, on improving business performance (Belhadi et al. 2020b; Buer, Strandhagen, et Chan 2018; Edwin Cheng et al. 2022; Kamble, Gunasekaran, et Dhoni 2020). In today's challenging and dynamic market environment, gaining a competitive advantage and improving performance is the main

priority and strategic focus of manufacturing companies(Ivanov et al. 2021). LSS has shown for decades its potential to eliminate waste and reduce process variability leading companies to operational excellence. However, with the advent of Industry 4.0 technologies such as sensors, Cyber-physical systems (CPS), Internet of Things (IoT), Big Data Analytics (BDA) and simulation among others, there is a major expectation of customized products and increased manufacturing capabilities (e.g., resiliency, agility, sustainability, flexibility)(Ivanov et al. 2021). I4.0 refers to a new way of managing the organization based on emerging technologies with the ability to collect and analyze big data in real-time throughout the value chain to monitor and control product quality, detect deviations and failures, and adjust production systems leading to operational efficiency (Kristoffersen et al. 2020). Similar goals are shared by circular economy, which has emerged as an alternative strategy to address resource efficiency and saving costs. Among the most revealing results of the literature review analysis is the profound compatibility in drivers between the three concepts. Theoretical and practical evidence suggests that the three concepts are complementary, and thus share common driving factors, namely customer satisfaction, increased revenues, and reduced losses, defects, and waste(Gandhi, Thanki, et Thakkar 2018). (Y. Ali et al. 2021; Cherrafi et al. 2016; Nascimento et al. 2019). The combination of LSS and I4.0 called LSS4.0 is classified as a strategy for making organizations competitive through improvements in defects, quality, productivity and waste (Buer, Strandhagen, et Chan 2018). CE shares the same objectives as LSS4.0 and is progressing rapidly as a promising manufacturing strategy to generate value, and improve productivity and competitiveness by optimizing the use of energy, natural resources and waste(Rosa et al. 2020). CE replaces the concept of "end-of-life" with a circulatory logic using various strategies such as remanufacturing, reuse, recycling, reduction, return, and restoration, among others (Edwin Cheng et al. 2022; Hina 2022; Leipold et al. 2021; Geissdoerfer et al. 2017). The integration of the proposed CE 9Rs framework throughout all stages of the value and supply chain is a practically complicated process, hence there is a need to find a trade-off between the business plan, operational performance and environmental concerns(Acerbi et Taisch 2020). Accordingly, implementing advanced digital technologies of I4.0 can mitigate the complexity by automating tasks, providing real-time monitoring, allowing predictive maintenance, and improving data collection and analysis capabilities for good decision-making, thereby improving environmental and operational performance (Zekhnini et al. 2021).

2.3 Barriers to CLSS4.0

Along with a comprehensive overview of the driving forces of CLSS4.0, it is therefore essential to consider the barriers and factors that can impede companies from adopting this approach. Being aware of the barriers to CLSS4.0 is crucial for organizations before implementation. Although LSS has been widely applied over the past decades, there remain several challenges impeding its successful adoption. Digital technologies offered by I4.0 can help overcome traditional barriers in operations management. The main barriers to I4.0 adoption as reported by scholars are a high-cost investment, complexity, lack of workforce skills and expertise and resistance to change (Ghobakhloo et al. 2022; Raj et al. 2020; Tura et al. 2019). All studies suggested that the lack of competencies, high-cost investment and technological issues are the main challenges that can mitigate the successful implementation of CLSS4.0. The introduction of new I4.0 digital technologies and CE practices adoption will change processes, generate increased complexity and employee resistance and will require new skills and competencies (Trevisan et al. 2023). Also, the lack of knowledge about the integration roadmap can prevent organizations from embarking on this project. The lack of a well-defined, tested and validated CLSS4.0 implementation model can be a serious barrier. In addition, the lack of estimated financial benefits and the short history of the initiative may limit implementation. Several authors (Kiel et al. 2017; Raj et al. 2020; Ghobakhloo et al. 2022) have identified the lack of financial resources as a major and significant barrier to implementation. Several barriers were specific to Industry 4.0. For example, one of the major barriers associated with Industry 4.0 and supported by several authors are cyber security concerns, data security and privacy risks, infrastructure concerns and standardization (Cimini et al. 2017; Trevisan et al. 2023). Despite these efforts, academics and practitioners still lack empirical knowledge of the common barriers to the implementation of a CLSS4.0 initiative.

The key drivers and barriers of CLSS4.0 implementation are reported in Table 2. Figure 2 depicts the theoretical outline of the CLSS4.0 drivers and barriers.

Figure 2 appears here

Table 2: CLSS4.0 drivers and barriers identified from the literature.

Drivers Factors	References	Barriers factors	References
Growing levels of competition	(Cherrafi et al. 2016; Michael Sony et al. 2021; Touriki et al. 2021)	Limited financial resources	(Alfutaih et Demirkol 2020; Kumar, Singh, et Dwivedi 2020)
Innovative capacity development		Standardization concerns	(A. Khan et Turowski 2016; Raj et al. 2020; Nagy et al. 2018)
Financial factors	(de Jesus et Mendonça 2018; de Sousa Jabbour et al. 2018; Szalavetz 2017)	Infrastructure concerns	
Regulatory compliance	(Tura et al. 2019),	New tools and technologies implementation risks	(Kamble, Gunasekaran, et Dhone 2020; Sevinç, Gür, et Eren 2018)
Governmental incentives and pressure	(Tura et al. 2019; Mhatre et al. 2021; Govindan et Hasanagic 2018; de Jesus et Mendonça 2018)	Unclear financial benefits	(Gupta, Modgil, et Gunasekaran 2020)
Increase dynamic manufacturing capabilities (Agility, flexibility, resilience, Viability)	(Chaouni Benabdellah, Zekhnini, et Cherrafi 2021; Cherrafi et al. 2022; de Jesus et Mendonça 2018)	Lack of strategic business plan	(Jeschke et al. 2017; Singh et Bhanot 2020) (Akdil, Ustundag, et Cevikcan 2018)

Increased process efficiency and performance	(Belhadi et al. 2020a; Burggräf et al. 2020; Kamble, Gunasekaran, et Dhone 2020; Sanders, Elangeswaran, et Wulfsberg 2016; Tortorella et al. 2019; Wagner, Herrmann, et Thiede 2017)	Organizational, managerial and operational changes complexity	(Aggarwal et al. 2019; Sevinç, Gür, et Eren 2018)
Intelligent and clean processes and products	(Pieroni, McAloone, et Pigosso 2021; D. Skalli, Charkaoui, et Cherrafi 2022; Amjad, Rafique, et Khan 2021)	Poor readiness and maturity level	(Angreani, Vijaya, et Wicaksono 2020; Edwin Cheng et al. 2022; Schumacher, Erol, et Sihn 2016)
Fast-changing customer needs	(Antony et al. 2018; Cherrafi et al. 2016; Raji et Rossi 2019; Michael Sony et al. 2021; Stentoft et al. 2021; Touriki et al. 2021)	High investment and implementation cost	(Angreani, Vijaya, et Wicaksono 2020; Edwin Cheng et al. 2022; Schumacher, Erol, et Sihn 2016)
Resources optimization	(de Sousa Jabbour et al. 2018; Nagy et al. 2018; Szalavetz 2017)	Data privacy issues and cyber security risks	(A. Al-Futaih et Demirkol 2020; Kumar, Singh, et Dwivedi 2020)
Support to Sustainability	(Edwin Cheng et al. 2022; de Sousa Jabbour et al. 2018; M. Sony 2019; Govindan et Hasanagic	Shortage of workforce competencies and skills	(Nagy et al. 2018; Saniuk, Grabowska, et Grebski 2022)

Increased process optimization, and quality control	2018; Kristoffersen et al. 2020) (Amjad, Rafique, et Khan 2021; Dounia Skalli et al. 2023; Michael Sony et al. 2021; Pieroni, McAloone, et Pigosso 2021)	Resistance to change	(Singh et Bhanot 2020)
		Lack of a unified roadmap	(Nagy et al. 2018; Saniuk, Grabowska, et Grebski 2022)

3 Research methods

This study uses a two-pronged approach to minimize the biases likely to be present with a one-pronged approach. It relies, therefore, on both a systematic literature review and semi-structured interview-based case studies, to make the study more exhaustive, structured, robust and significant. Figure 3 shows the research design. We first carried out a systematic literature review, the results of which are presented in the preceding sections. An exploratory qualitative method was perfectly suited to our research topic, as it allows new learning, and rich and in-depth analysis of an under-studied issue (Yin 2009) without the need for numerical data (Rowley 2002). Interviews are a very effective way to collect extensive empirical data (Korpjuweit et al., 2019). Indeed, to collect data and build theory, the semi-structured interview was preferred as it allows for practical insights from multiple sources (Eisenhardt 1989), hence participants can respond to questions freely and openly, allowing for a better understanding of the topic and better results (Eisenhardt 1989; Voss, Tsikriktsis, et Frohlich 2002). Figure 3 illustrates the research design phases of this study.

3.1 Case selection

We targeted large and medium-sized multinational manufacturing companies located in Morocco that have experience with the LSS improvement process and have adopted digital and circular transformation within the framework of CE practices and I4.0 technologies. We followed the company size classifications defined by the European Union, considering companies with 50 to 249 employees as medium-sized companies, and those with more than 250 employees as large companies (Belhadi et al. 2020b). In approaching the prospective manufacturing companies, we provided them with a brief overview of CE, LSS, and I4.0 and the study aims and ensured that the companies had implemented all three paradigms at least 18 months ago. Table 3 illustrates the characteristics of the case studies. Prospective interviewees were selected based on three criteria as cited by (Gibbert, Ruigrok, et Wicki 2008): (1) Position and role, (2) Year of Experience and (3) Expertise and knowledge. All participants had a high managerial position, more than 10 years of experience and were experienced with LSS and involved in I4.0 and CE deployment projects. They were approached using several ways: through the authors' professional network, by using the snowball technique and by contacting the companies' experts via LinkedIn. The company represents the unit of analysis. Following

the purposive sampling (B. G. Glaser et Strauss 2010), we targeted 18 manufacturing companies from various sectors to allow for theoretical representativeness (Miles et Huberman 1994).

Figure 3 appears here

Table 3. Characteristics of companies involved in the study

Company Code	Industry Sector	Firm size	Respondent role	Experience in years
C1	Construction industry	Large	Quality manager	13
C2	Fast-Moving Consumer Goods (FMCG) Industry	Large	Technology and business modeling director	11
C3	Hygiene, care and cosmetic products	Medium	General director	16
C4	Electronics industry	Large	Operational excellence director	12
C5	Food industry	Medium	Head of production and optimization department	10
C6	Automotive industry	Large	Operational excellence executive manager	13
C7	Automotive industry	Large	Production manager	12
C8	FMCG	Large	Digital transformation project manager	14
C9	Aeronautic industry	Large	Digital Business Development Manager	18
C10	Oil and Gaz	Large	Operations Manager	20
C11	FMCG	Medium	General manager	10
C12	Chemicals industry	Large	Area Operations and Digital transformation director	22

3.2 Data collection

One senior manager involved in CLSS4.0 implementation projects was the representative for each case study in the semi-structured interview. The twelve semi-structured interviews were performed digitally via Microsoft Teams and lasted between 68 and 90 minutes. Two researchers were involved in conducting the interviews using an interview guide and a defined protocol (see Appendix 3). The use of a case study protocol positively contributes towards reliability (Yin 2009). The interview guide was elaborated based on previous literature and tested with six senior academics and four practitioners (2 operations managers, 1 Information Technology director, and 1 quality, security and

environment manager). Their feedback was used to refine the questionnaire. A study briefing protocol including the background and purpose of the study, estimated duration of the interview, confidentiality conditions, the consensus form, and contact information for the principal interviewer and associated research team was emailed to all respondents to get well-informed and prepared for the interview. To address ethical issues, there was no reference to any participant's details and a consent form was provided to be signed by the interviewees. All interviews were recorded and transcribed for further analysis. After completing 12 interviews, we realized that the information collected from the last 2 interviews was similar to the previous ones and that no new insights emerged from the 10th interview. Therefore, according to (B. Glaser et Strauss 2017), we assumed that data saturation was reached, for which the data collection was then followed (Bakhtawar 2020). We extended our data collection with information from additional available internal documentation (policies and procedures) and public sources (website and annual reports) (website, flyers, and documentation). In total, we examined twelve firms, exceeding (Eisenhardt 1989; 2022) the suggestion of four to ten cases.

3.3 Data analysis

All semi-structured interviews were recorded and then data were transcribed and analyzed by two researchers using inductive thematic analysis based on Nvivo software (Braun et Clarke 2006). We used both within and cross-case analysis based on the grounded theory approach (Eisenhardt 1989; Miles et Huberman 1994). We conducted a thematic analysis of transcripts and documented data for each interview (within-case approach) to identify key findings (Eisenhardt 1989) and then a cross-case analysis by grouping and categorizing the data into common patterns and clusters and subsequently matching them to the literature to increase external validity (Yin 2009). Interviewees were made anonymous to avoid bias and to increase the reliability of the results. For construct validity, we adopted a triangulation approach (Yin 1994). The present research used interview insights as a primary source of data, additional data were extracted from internal documents (policies and procedures) and public documentation (website and annual reports) to help build theory. For better data reliability and results accuracy (Ardichvili, Page, et Wentling 2003), the data summary was returned to the participants for validation. Thus, minor comments were received and included in our analysis. We closed the coding and discussion process once all authors agreed.

4. Results

Through an inductive data analysis, codes were generated and grouped into main factors, and main themes, and then reported to dimensions. Accordingly, twenty-nine drivers' factors and thirty-one barriers factors were identified and categorized into six dimensions namely operational, organizational, technological, economic, financial and regulatory. Figure 4 summarizes the detailed thematic analysis. This section presents answers to the research questions outlined in the introduction in four subsections: Section 4.1 presents the main driving factors, Section 4.2 the main barriers, and Section 4.3 the actions taken or proposed by manufacturers to mitigate the different challenges and Section 4.4 presents a proposal CLSS4.0 framework.

4.1 Perceived drivers for CLSS4.0

Based on a Pareto analysis, 10 driving factors were considered to be the most critical driver factors (see Figure 4). The majority of respondents were confident that the CLSS4.0 approach has great potential to increase their operational and economic performance and improve their environmental and social impacts, as it could reduce energy, water and raw material consumption and boost competitiveness and profitability. Hence, Strategies for cost saving, resource optimization, waste reduction and productivity increase are highly appreciated by manufacturers and represent the common driver for all cases. The findings show that achieving operational excellence, sustainable manufacturing performance, developing manufacturing capabilities such as flexibility, agility, resilience, and promoting brand image and labels were the relevant motivations for the adoption of the CLSS 4.0 approach.

“The potential benefits and capabilities afforded by the integrated CLSS4.0 approach motivated us to take the plunge” C1

“We launched the digitalization of our operations to boost customer satisfaction and process efficiency” C3

“We look forward to expected benefits such as quality defects and cost reduction, energy and waste reduction, traceability and flexibility.” C10

“We have a long-term experience with LSS, so adopting advanced technologies with quality improvement tools such as lean and six sigma have helped us eliminate non-value added activities and generate better results and superior operational excellence in a short time. In addition, by applying sensors, data analytics and machine learning

algorithms, we are now able to detect errors, and deviations in real-time and react rapidly to quality issues by 40% lower cost” C4.

"The connection between LSS and I4.0 has allowed us to accelerate our operational excellence and reduce energy consumption. In our case, we have implemented sensors connected to the plant manager's smartphone, which allows him to monitor critical process parameters in real-time and react immediately, avoiding process variability that causes quality problems while saving time, cost and resources” C8.

“As LSS, CE and Industry 4.0 coexist, they can support each other to create better products and processes with greater efficiency, accuracy, and sustainability” C11

All cases emphasized the need for adopting digital innovative technologies of I4.0 to achieve efficient process monitoring and enhance decision-making. Digital capabilities primarily connectivity, transparency and communication are vital capabilities highly appreciated by manufacturers.

“Digital transformation in Industry 4.0 has become an irresistible force as it makes our business more competitive and responsive to market demand and turns our operations and supply chain more agile and resilient than before” C2.

“the new channels of communication offered by the advanced technologies have been of great support in covid-19 as it has allowed us to maintain our activities and to exchange with the world in a very fluid and easy way and has thus created an approach of proximity innovative” C6.

All respondents agree on the potential I4.0 technologies benefits in terms of high connectivity and communication between man and machine, task automation and more efficient and safer work.

“Acquisition of digital innovative technologies of industry4.0 remain not nice to have but a must have to sustain in the disruptive and networked market” C4.

Most respondents mentioned at least one driver factor under the regulatory dimension, making it the third most cited driver after operational excellence.

“the driving force behind the development of renewable feedstock products is the joint interest in reducing CO2 emissions resulting from the global and European legislation on CO2 emission reduction that we adhere to” C1.

"Our products are regulated by law, so compliance with national and international laws and standards related to the production, transportation of petroleum products and its derivatives and the control of their impact on the environment is an imperative and part of our performance" C10.

In contrast, C6 has declared that internal corporate policies are driving forces to adopt CE practices: “We have a global plan called Cap50, whose objective is to reduce CO2 emissions by 45% in 2030, and achieve neutrality in 2050. This plan is broken down into several actions carried out internally and also with suppliers and service providers. Industry technologies have been of great help to us in deploying it, so the commitment and dedication of all staff and general management have been the key to our success in this 5-year-old strategy”.

C10 and C12 share the same thoughts:

“Global banks, funding institutions and insurance companies are embracing new ways of financing based on circular business achievements.”

The high competitiveness, disruptive marketplace and fast-growing global market is most frequently identified as determinant driving manufacturers toward CLSS4.0 transformation.

"In adopting this integrated approach, we were motivated by the need to anticipate and respond to technological advances and environmental protection concerns, which is necessary to remain competitive in today's market."

The respondent from company 10, an aerospace company, claimed that digitization helps to respond to increased demand and attract new customers with higher profits. In addition, the respondent added that digitized processes and adherence to environmental protection strategies represent an important business opportunity to improve the company's image and compete in overseas markets with rigorous requirements.

Under market disruptions, C7 stated:

"COVID-19 resulted in the suspension of our daily debriefing meeting, training, and travel to the subsidiaries." Similarly, C9 noted, "CE and I4.0 are driven by our perspective and awareness of the need to sustain our business after the pandemic".

C3 reported “the COVID-19 pandemic and its global impact have resulted in unprecedented disruption to our global operational systems and supply chains, particularly in response to customer demands, generating big losses”, and explains that "given these constraints and in response to future disruptive market happenings, we have embraced digital technologies to increase our resilience and agility." C4 noted that “The advent of the pandemic, disrupted supply chains, political instabilities and a growing shortage of raw materials, all of these factors among others, have prompted us to rethink our business strategy as a post-Covid action plan to account for digital

technologies and circular practices for cost reduction, market increase and customer satisfaction while improving agility and resilience process capabilities.”

Some firms have mentioned that customers have high expectations for custom products and a growing demand for sustainable products. Looking at sustainable environmental performance, the perceived benefits are waste reduction, energy saving, optimization of resources consumption, monitoring all negative emissions and environmental impacts, and improved lifestyle for future generations which are supported by the literature. Overall, all interviewees reported that Sustainability has become a core value to maintain the manufacturing systems. The company's strong position in the market can influence the willingness for LSS, I4.0 and CE adoption benefits.

Respondents also noted the ability of CLSS4.0 adoption to advance their brand image. In light of our analysis, three novel drivers have emerged that were not reported in the literature, namely: bank and financial institutions' requirements, insurance pressure, and subsidiaries' policies and instructions. Figure 4 illustrates the driver factors identified by the interview respondents.

Figure 4 appears here

4.2 Barriers to CLSS4.0 implementation

Similar to the drivers, we focused on understanding the factors that hinder the adoption of CLSS4.0. Based on PARETO, 10 barrier factors were considered to be the most critical factors to impede the successful implementation of CLSS4.0 as presented in Fig 6. Resistance to change, lack of knowledge, fear of failure, lack of roadmap, lack of standardization and supportive policies were identified as the common factors among all firms.

All cases mentioned the critical role of workforce skills and competencies in the adoption of CLSS4.0. Technical skills are required to embrace this initiative.

“Human resource profiles and skills, both operational and managerial, such as software engineers, automation, digital business market, artificial intelligence, big data analysts, with academic background and approved experience, are very limited, making us very dependent on external vendors and consultants. We need skilled talent with knowledge

of I4.0 to collaborate with suppliers. It's not acceptable to rely only on vendors' recommendations to make our decisions.” C5

The lack of skilled workforce, expertise and graduates people was addressed by all interviewees.

"BDA requires specific skills and knowledge on the use of complex techniques, mainly machine learning and artificial intelligence". C1.

“Insufficient number of digital graduates for recruitment” C2

C3 explained that "the complexity and novelty of I4.0 have created new skilled jobs and functions". Similarly, C9 added that "it is time to redefine the university's curriculum to accommodate training in I4.0 technologies". C10 stated that "we faced the shortage of experienced consultants and digital project managers to lead our digital transformation because our managing directors lacked expertise". The lack of knowledge of advanced technologies and CE practices is a huge impediment to such an approach.

C8 added “the complexity of the operations involved in CE practices including re-engineering, remanufacturing, reusing, recycling and refurbishing models requires training in new operations and processes, as well as new skills and competencies”. We had difficulty finding a highly qualified consultant and trainers”. C10 reported "the lack of specialists is an obstacle to the accelerated development of digital technologies". Also, all firms confirmed that top management support and involvement, from multiple dimensions (organizational, financial, operational) is essential as this act as an enabler, barrier, and critical success factor.

"Leadership is the best driver for all forms of changes in organizations." C5

The role of leaders is to provide leadership so that managers and employees follow it. A corporate culture and employee mindset must be developed to drive the transition to CLSS4.0.

"Going down to the site and following the production and teams closely is one of the ways our general manager has used to get people to more involved in the projects” C10

C1 added, "as leaders and managers we are engaged in our firm's culture and that's pushed us move towards CE but believe it is important to bring co-workers on board with the corporate culture and keep it simple”.

Cyber security represents a big challenge for almost all firms’ cases. The risk of over-reliance on systems and hacking risks associated with digitization is the most discussed barriers related to cyber security. C4 said, “most information is stored and shared on clouds and if systems fail, all the data will be lost”.

All respondents mentioned the lack of an integration roadmap as a barrier impeding the successful CLSS4.0 implementation. Manufacturing companies need well-defined, tested and validated guidelines to apply. Moreover, the absence of standards hinders many firms to commit in this initiative. High initial capital costs, lack of cost/gain estimates, training, expertise and consulting expenses, and maintenance/repair budgets as barrier factors under financial dimensions. CE practices and I4.0 technologies appear to be exceptionally expensive. C2 said, “Cost is consistently a challenge for us”. Managers should find a trade-off between investments in CE and digital technologies and revenues. The key factor that can hinder the organization in its journey towards digitization and CE, especially SMEs, are the financial constraints related to technology and equipment acquisition, maintenance and repair costs, training costs, and consulting services. Interestingly, C3, C5, and C11, as SMEs, stated that they had engaged in CLSS4.0 through pilot projects and that there were plans to extend it to all business processes, but that they remained challenged by the high investment cost, In this way C10 said ‘There is an expected high cost for hardware and software upgrading’. C5 suggested, “Cost is often the first and biggest concern in the implementation of any project, change or implementation.”

Figure 5 appears here

“Investments concerns not only technology infrastructure but moreover knowledge acquisition through the hiring of new skills and development of necessary knowledge through training” C5. "We suffer from the availability of consultants and high cost of training providers” C6. “we are currently facing difficulties to find maintenance service providers in our geographical proximity".C11

C10 and C12 both large companies shared the same thoughts:

“As far as we are concerned, we are using our funds to invest in this CLSS4.0 project because the Moroccan government is not yet ready to invest in this field and government funding is a long-term process. Our customer market is based in developed economies so we need to align with their advanced and rigorous requirements. We believe that it is worth investing in this project because the return on investment is very high.”

As for complexity, this factor was mentioned by seven interviewees who had experienced technical trouble in changing their plant to a smart plant.

“Our experienced difficulty in changing toward smart operations management is the complexity of both technologies and process”. C5

The use of new I4.0 technologies for the circular economy can make the implementation of the circular economy more complex. In addition, C3 commented, “New technologies are complexes”.

Regarding support, the respondents mostly expressed the need for fiscal support, as well as assistance with technology, training, and consulting.

“We were initially unprepared and unsuccessful in adopting I4.0 and CE because we had to recruit new staff, which was a big challenge given the scarcity of qualified and experienced people, and we needed government support and invoicing to make this project successful, and so staff were reluctant.” C12

Unlike literature, we noted emerging barriers from participants: ‘organizational changes management’, ‘designing digital management functions’, ‘deficit in the availability of job-ready university graduates’, ‘lack of information-sharing platforms’, ‘poor cooperation between academics and manufacturers’, ‘inadequate and inexperienced service and technology providers’, ‘lack of government support and tax incentives’, ‘evolution gap between university education against the economy and industry progress’ and ‘difficulty in recruiting new staff due to the scarcity of required skills’. Figure 6 summarizes the major barrier factors revealed by interviewees.

Figure 6 appears here

4.3 Actions to mitigate barriers

In response to RQ2, we identified several ongoing or proposed actions by interviewees to mitigate the various barriers listed in the previous section. Based on the results of section 4.2, statistically 50% of the barriers were related to people (e.g. lack of skills, knowledge, awareness, management commitment, employees and stakeholders' commitment and resistance to change). To achieve the full potential of the CLSS4.0 approach, it is recommended that businesses fully engage their workforce, establish an open communication channel, and prioritize sustainability.

All of the proposed actions addressed organizational barriers, as they were the most significant and common to all sectors.

Table 5 Summary of the participants' recommendations

N°	Action	Barriers
1	Introduce CE and I4.0 learning in academic programs (Support from academic institutions)	Scarcity of required skills
2	Develop collaboration between universities and industry.	Lack of available graduates' skills Recruitment of new staff issues
3	Visits and benchmarking with leading companies in this field could motivate leaders.	Lack of management involvement
4	Participate in workshops and learning experiences	
5	Launch an awareness and training campaign among employees and other stakeholders.	Lack of skills and competencies
6	Reward employees for innovative ideas.	Lack of workforce motivation
7	Embedding CLSS4.0 initiatives in organizational objectives	Lack of workforce commitment
8	Develop an extensive and reliable networking system to massively expand the circularity facility.	Lack of a proximity ecosystem
9	Take the pioneering role to conduct cooperative operations and form industry ecosystems	
10	Share experience by creating a digital platform	Lack of platforms for
11	Develop close circular economy and digital ecosystems to encourage supplier and partner participation.	information exchange

4.4 Framework

In the present volatile, disruptive and complex world, there is tremendous pressure to address resource scarcity, energy consumption and waste generation through the use of environmentally friendly operational practices. Despite considerable progress in both the literature and practical applications regarding the drivers, barriers, and implementation framework for each approach, there appears to be a lack of a well-defined implementation model related to an integrated and holistic approach which could practically guide manufacturers to a successful CLSS4.0 implementation. We developed a framework for integrating CE practices and digital technologies into LSS projects to promote digital and circularity improvements in all dimensions of the DMAIC (Define, Measure, Analyze, Improve, and Control) project cycle. The proposed framework illustrated in Fig 7 highlighted the theoretical aspects of such integration mainly driving and impeding factors to help practitioners develop viability and sustainability. A clear assessment of

these factors would contribute to management's increased knowledge of how to successfully implement CLSS4.0. We first consider the factors that drive firms to adopt the three manufacturing strategies, as well as the barriers that may impede this combination. Indeed, companies can consider this combination to improve their operational and financial performance, while strengthening their digital and sustainable business capabilities. Process efficiency and eco-friendly manufacturing were widely perceived by respondents as one of the most important driving factors in the success of CLSS4.0 implementation. However, a number of barriers such as a lack of knowledge and skills, an unfavorable organizational culture, along with specific technical issues, need to be addressed. The lack of expertise and skills is one of the most significant barriers to CLSS4.0. This factor appears to be more important to practitioners than it was in the literature. To support the implementation of the CLSS4.0 initiative, a specific skillset should be developed for employees working at the management and non-management levels. Industry 4.0 digital technologies enable real-time monitoring and better decision-making based on the analysis of machine-generated data. In other words, using the relevant technologies requires specific skills and competencies. In practice, possessing the right work skills and knowledge required within the workforce are important. On the other hand, a clear and comprehensive assessment of the complementarity between the three concepts of CLSS4.0 is a crucial step in our integration model. The model illustrates the relationship between the paradigms. LSS represented by DMAIC represents the core of our model with a close link to CE practices and I4.0 main technologies and a purpose of unlocking some of the trade-offs between the three. Given that Lean, CE, I4.0 and Six Sigma are complementary, accordingly, each method has the potential to minimize the drawbacks of the others. Building on the results of our study and considering the theoretical implications, the implementation of this integrated approach will lead to sustainable and viable achievements in a globally competitive environment. Companies can achieve better dynamic capabilities by applying LSS, CE and Industry 4.0. Finally, we find sustainability and viability at the bottom of the scale, which is the result of this combination, providing a good understanding of how to successfully implement the CLSS4.0 method.

The proposed model (figure 7) serves as a framework where companies can assess the driving forces and barriers to implementing CLSS4.0 and appreciate the interplay between these concepts. It is a way to improve sustainability and gain a competitive advantage, which is the most common concern of a company.

Figure 7 appears here

5. Results discussion and implications

5.1 Discussion

The study addresses the literature gaps on the lack of knowledge and a holistic assessment of CLSS4.0 drivers and barriers. The authors have mapped driving and impeding factors of CLSS4.0 adoption based on qualitative data. Discussing the results, we provided an overview of the key drivers and inhibitors of the CLSS4.0 approach.

Our findings are consistent with the literature. Executives emphasized that they were seeking benefits such as improved operational and environmental performance, increased productivity and profitability, and high performance in a highly competitive and rapidly changing business environment. Findings highlight that increasing environmental concerns and continuous pressure from customers, stakeholders, government and institutional organisms (Cherrafi et al. 2022) related to resources depletion, energy consumption and climate change are the major's drivers of CLSS4.0 adoption. Corporate customers from the international side are encouraging manufacturers to implement the CLSS4.0 (S. A. R. Khan et al. 2021). Also, promoting connectivity, transparency, process visualization, human-machine communication and data exchange in real-time represents the driving forces pushing companies to embrace such an approach. Several novel driving factors such as corporate policies and guidelines, pressure from financial institutions, insurance, and non-governmental institutions, corporate image, and customer specifications, were cited as new factors that have not been sufficiently explored in the literature and not reported in previous studies (Govindan et Hasanagic 2018; Tura et al. 2019; Ghobakhloo et al. 2022; Hina 2022), which could be explained by the specific country study context.

As for the barriers that may hinder the successful implementation of CLSS4.0, the main factors highlighted by respondents are the lack and scarcity of both tangible (human resources, financial constraints, equipment) and intangible (standards, techniques, skills and methods) resources, which is consistent with the findings in the existing literature (Singh et Bhanot 2020; Stentoft et al. 2021; Govindan et Hasanagic 2018; S. M. Ali et al. 2020). Also, data privacy and cyber security issues represent the potential barriers impeding manufacturing companies. Different from the literature, participants noted the difficulty of changing the culture, attitude, and mindset of staff, hence the need

for change management. Fear of change, lack of proximity ecosystems and knowledge-sharing platforms, and availability of consultants and providers with expertise are new barriers that were found but not reported in previous studies. These factors may be related to the specific context of a country studied.

In terms of best practices to mitigate barriers, collaboration with academic institutions, support from universities, creation of a local ecosystem and exchange platforms have emerged as interesting results. By collaborating with universities, companies can save the cost of recruitment by creating training courses tailored to their specific needs.

Universities should incorporate new courses designed for I4.0-CE skills and knowledge. Universities can go hand in hand with the industrial revolution and market progress to adapt their curricula to offer new graduates who can easily integrate into companies. No previous study has mentioned the role of collaboration between universities, government and industries in accelerating digital transformation and awareness of CE principles and potential benefits. Companies have great difficulty recruiting qualified graduates in new digital technologies. We, therefore, suggest that companies work with universities to define the skills required and adapt the educational programs to future digital careers. Recruitment, training, technology acquisition, and maintenance require a high level of investment, so government funding and institutional support are needed.

Although most of the drivers and barriers identified in this study are consistent with the literature, the remaining new factors identified by respondents, which were absent in previous empirical studies in European countries, can be explained by the country-specific context.

In light of the gaps in the literature related to the lack of a holistic integrated model and based on the knowledge gathered, we developed a theoretical framework. The proposed model, illustrated in Figure 7, is based on a clear understanding of the drivers and barriers factors to initiate a CLSS4.0 approach in a company.

By following the model outlined in Fig 7, organizations can create a culture of continuous improvement and achieve long-term success while contributing to environmental sustainability efforts. The proposed model outlines key considerations for manufacturing companies seeking to adopt CLSS4.0. The model suggests that the identified drivers will motivate manufacturers to consider CE and I4.0 technologies in conjunction with LSS and may push them forward, while the identification of barriers is

strongly recommended to assess the ability of companies to adopt CLSS4.0 and overcome them.

By integrating drivers and barriers, the proposed model offers an innovative approach for building the decision-making arena toward CLSS4.0 adoption to promote sustainability.

One of the key factors that differentiates our study from previous works is the integration of CLSS4.0 with a sustainability perspective, specifically in the context of an emerging economy in North Africa. Unlike previous studies, which have explored the CLSS4.0 integrated framework in developed economies, our research goes beyond by conducting a thorough analysis of the factors that impact its successful implementation. By examining the unique characteristics, challenges, and opportunities of the Moroccan context, this study offers comprehensive insights into the specific drivers and barriers of CLSS4.0 adoption in Morocco's industrial landscape, which may differ from other contexts. It identifies the key drivers that motivate organizations to adopt CLSS4.0, sheds light on the barriers they may encounter, and offers guidance for policymakers and industry leaders to formulate strategies and initiatives that support the implementation of CLSS4.0 practices. By addressing this research gap, our study offers a holistic understanding of sustainable manufacturing practices, incorporating a comprehensive and integrated approach that considers the entire system as a whole, rather than focusing on isolated aspects or individual components. Furthermore, our study employs an exploratory approach, uncovering new insights and identifying previously unexplored dimensions. The study's findings can inform policymakers, industry leaders, and decision-makers in Morocco about the potential of CLSS4.0 adoption. This can contribute to the overall sustainability and competitiveness of Morocco's industrial sector. Furthermore, the study enriches the global understanding of CLSS4.0 by incorporating a Moroccan perspective, stimulating further research and exploration of sustainable practices in developing regions and contributing to the advancement of theory.

5.2 Implications

5.2.1 Theoretical implications

Our study provides a strong contribution to different theories by bridging continuous improvement theory (underpinning LSS), technical-social system interface theory (underpinning I4.0) and sustainability theory (underpinning CE). This research contributes to the advancement of several theoretical implications. First, this study is one of the first empirical studies conducted in a developing economy to investigate the drivers

and barriers to the successful adoption of CLSS4.0, thus adding new and significant insights into the academic CLSS4.0 research field. Second, we conducted an exploratory study of motivators and barriers to an integrated CLSS4.0 approach as they have not been identified in the prior literature. The research field did not receive enough scholarly attention. The authors proposed a CLSS4.0 model and a holistic view of the specific theoretical elements (drivers and barriers) making a significant theoretical contribution to the literature. To the best of the author's knowledge, this research is one of the first studies to discuss the drivers and barriers of LSS, CE, and I4.0 as an integrated approach, as well as define a holistic model for implementing CLSS4.0. Third, the strength of our study lies in the novel combination of these concepts that have not previously been linked in the literature. This work promotes a new vision of sustainability and viability. Finally, this study is conducted in a manufacturing context that is a major source of environmental problems (air emissions, energy consumption and waste production, resource depletion) providing novel insights and building academic research.

5.2.2 Practical implications

The proposed CLSS4.0 integrated approach will help organizations improve their organizational and environmental effectiveness. This study inspires practitioners to adopt the CLSS4.0 integrated approach by drawing on theoretical evidence about the key drivers and barriers to CLSS4.0 and empirical evidence from case studies in emerging economies. We suggest that the proposed model will guide practitioners in their efforts to implement sustainable manufacturing. The proposed framework provides holistic guidelines for practitioners to execute this approach. This research will motivate manufacturers to rethink their operations and resources to move toward sustainability methods. The study provides guidance to practitioners on how to implement CLSS 4.0 more effectively.

5.3 Limitations and future research perspectives

Beyond research implications, this study entails some limitations that can serve as potential perspectives and directives for future research. First, since we used qualitative research, which is often vulnerable to subjective biases, including those of the researcher team's interpretations and the participants' opinions, it is important to consider the limitations of this approach. Future research could explore the perspectives of a more diverse range of participants, as well as the potential impact of contextual factors on the findings. By addressing these limitations, future research can build on the insights gained

from this study and provide a more comprehensive understanding of the topic. Second, the small sample size of the study could limit the generalizability of the findings. While theoretical saturation was reached, it is possible that a larger sample size could have provided additional insights or revealed different perspectives. Therefore, it is important to consider the limitations of the sample size when interpreting the findings of the study. Further empirical research with larger sample sizes could help to validate the findings and provide a more comprehensive understanding of the topic. Additionally, it may be beneficial to explore the perspectives of participants from a wider range of backgrounds and industries to increase the generalizability of the findings. Finally, the results obtained are valid for Moroccan companies representing multinationals that adhere to international regulations and corporate policies. As such, the results of the study need to be supported by further studies in other emerging country contexts to confirm the outcomes of our research.

This study contributes to the theoretical understanding by providing scholars with directions for further research. Given the qualitative design of our study and the limited sample size, we propose that further quantitative studies should be conducted to complement and validate our results and improve the generalization of the model proposed. The efforts initiated in this research can be further investigated to find how CLSS4.0 may support resilience in the post-COVID-19 era, and explore what technologies are useful and suitable for each DMAIC step and CE practice. Additionally, the main focus was on Moroccan manufacturing companies as a hence we invite scholars to conduct the same study scope in other developing economies' geographical contexts to validate our findings. The drivers and barriers are partly determined by the size of the company, the sector and the geographical region in which the companies operate. In this context, we highlight the need for conducting a similar study in the context of developed economies to obtain a cross-comparison of results and then provide a holistic understanding of the drivers and barriers of CLSS4.0. Scholars may extend our findings to the service sector. Also as our topic is a growing research field that is in an early stage, a well-defined framework and agreed stepwise roadmap for CLSS4.0 implementation are still missing. Scholars are invited to refine the proposed integration framework, develop a detailed model and present empirical evidence on its validation. Lastly, it is suggested to study the impact of the CLSS4.0 integration on the improvement of staff development and environmental performance and to assess the role of the workforce in the success of

CLSS4.0 implementation and estimate and explore trade-offs between deployed resources to implement CLSS4.0 and potential financial savings generated.

6. Conclusions

The article examines CLSS4.0 as an enabler of sustainability. Its main purpose is to identify potential drivers and barriers regarding the implementation of CLSS4.0 in manufacturing companies. The results will benefit production and transformation managers. Given that various internal and external motivations and challenges from cultural, organizational, financial and technical perspectives influence the deployment of CLSS4.0, its deployment in developing economies appears to be limited. Given these limitations, decision-makers should be well aware of these challenges, hence the value and contribution of our study, which aims to shed light on the various drivers and barriers to be considered for any CLSS4.0 project.

Given the limited study exploring the drivers and barriers for a CLSS4.0 approach, we deployed a qualitative research design to generate in-depth knowledge in this field. We have explored the drivers and barriers for the transition towards a CLSS4.0 in manufacturing industries by studying twelve multinational companies based in Morocco. Our study provides a clear knowledge of the various drivers and barriers required to be undertaken for a successful CLSS4.0 implementation. Since the LSS approach is considered a well-known practice for manufacturers to eliminate waste and process variability while reducing costs and improving operational performance, the drivers are very familiar and the barriers are now impeded, hence the respondents have focused on CE and I4.0 concepts as they are still novel and not well known.

This paper highlights ten key drivers and ten barriers to the application of CLSS4.0 in the manufacturing industry. Our approach was to systematically review the literature, and then identify and analyze the drivers and barriers of CLSS4.0 from a practical perspective. We, therefore, used both quantitative and qualitative methods to better understand the drivers and barriers of the integrated CLSS4.0 approach. We found that the main driving forces behind implementing CLSS4.0 are increased operational excellence, sustainability, high market pressure, regulations and corporate strategies and policies. Management's expectation to improve the company's image and comply with regulations and label requirements can be a powerful driver for CLSS4.0 adoption. By implementing CLSS4.0, business leaders can simultaneously improve operational and environmental performance, ensure compliance with customer and stakeholder requirements, and

develop digital capabilities and sustainable practices. The results of our research converge with the literature in that CLSS4.0 adoption presents several barriers factors. The most significant barriers factors include a lack of understanding of the technology, implementation difficulties due to resource constraints, and the cost and complexity associated with implementation. Among the rising obstacles, aspects relating to standardization, management and leadership, as well as the lack of skills and competencies, are also important. Standardization refers to the need for organizations to establish consistent practices and processes for implementing and managing change. Management and leadership involve the need to ensure that leaders have the skills and competencies to effectively guide their teams and organizations through change initiatives. Leadership skills such as communication, motivating others, setting expectations and making tough decisions, as well as knowledge of change management principles and practices, are essential to the success of change initiatives. The absence of these skills and competencies can lead to costly mistakes, poor communication and delays in the implementation process. In addition, a lack of sufficient resources to undertake change initiatives can also be a problem, as organizations may not have the budget or personnel to complete the process.

By understanding the benefits of the CLSS4.0, consulting with stakeholders, and providing education and training, a company can promote a smoother transition towards CLSS4.0 and contribute to superior sustainable performance

The authors have identified several challenges that could be taken into account in future research. First, the range of organizations that were implementing CE was very limited, and given the focus of this study on Moroccan manufacturing companies, it was difficult to find the right candidate for the interview, with expertise in LSS and experience in both I4.0 and CE implementation. Second, while CE is an emerging concept, it is not yet well-known among manufacturers and practitioners, and its implementation is still limited. The effective move towards a circular business model and CE practices in manufacturing companies vary between cases. The discussion of common drivers and barriers to CLSS4.0 requires further research to provide additional clarification of the various internal and external facets of this new paradigm.

Data availability statement:

The data that support the findings of this study are available on request from the corresponding author, [A.Sh]. The data are not publicly available due to restrictions.

Acknowledgements

We would like to thank all the company managers who have participated in our interviews for their engagement and contributions as well as Mrs H.Aijjou and MH. Alaoui for their support and enlightenment.

References

- A. Al-Futaih, Abdulmalek, et İsa Demirkol. 2020. « The Relationship Between Industry 4.0 and Lean Production: An Empirical Study on Bursa Manufacturing Industry ». *Journal of Business Research - Turk* 12 (2): 1083-97. <https://doi.org/10.20491/isarder.2020.897>.
- Acerbi, Federica, et Marco Taisch. 2020. « A Literature Review on Circular Economy Adoption in the Manufacturing Sector ». *Journal of Cleaner Production* 273 (novembre): 123086. <https://doi.org/10.1016/j.jclepro.2020.123086>.
- Aggarwal, P.K., Shalika Vyas, Philip Thornton, Bruce Morgan Campbell, et Martin Kropff. 2019. « Importance of considering technology growth in impact assessments of climate change on agriculture ». *Global Food Security* 23 (avril). <https://doi.org/10.1016/j.gfs.2019.04.002>.
- Akdil, Kartal, Alp Ustundag, et Emre Cevikcan. 2018. « Maturity and Readiness Model for Industry 4.0 Strategy ». In , 61-94. https://doi.org/10.1007/978-3-319-57870-5_4.
- Alexander, Paul, Jiju Antony, et Elizabeth Cudney. 2021. « A Novel and Practical Conceptual Framework to Support Lean Six Sigma Deployment in Manufacturing SMEs ». *Total Quality Management & Business Excellence*, juillet, 1-31. <https://doi.org/10.1080/14783363.2021.1945434>.
- Alfutaih, Abdulmalek, et İsa Demirkol. 2020. « The Relationship Between Industry 4.0 and Lean Production: An Empirical Study on Bursa Manufacturing Industry ». *Journal of Business Research - Turk* 12 (juin): 1083-97. <https://doi.org/10.20491/isarder.2020.897>.
- Ali, Syed Mithun, Md. Anwar Hossen, Zuhayer Mahtab, Golam Kabir, Sanjoy Kumar Paul, et Zia ul Haq Adnan. 2020. « Barriers to Lean Six Sigma Implementation in the Supply Chain: An ISM Model ». *Computers & Industrial Engineering* 149 (novembre): 106843. <https://doi.org/10.1016/j.cie.2020.106843>.
- Ali, Yousaf, Ahsan Younus, Amin Ullah Khan, et Hamza Pervez. 2021. « Impact of Lean, Six Sigma and Environmental Sustainability on the Performance of SMEs ». *International Journal of Productivity and Performance Management* 70 (8): 2294-2318. <https://doi.org/10.1108/IJPPM-11-2019-0528>.
- Amjad, M.S., M.Z. Rafique, et M.A. Khan. 2021. « Leveraging Optimized and Cleaner Production through Industry 4.0 ». *Sustainable Production and Consumption* 26: 859-71. <https://doi.org/10.1016/j.spc.2021.01.001>.
- Angreani, Linda Salma, Annas Vijaya, et Hendro Wicaksono. 2020. « Systematic Literature Review of Industry 4.0 Maturity Model for Manufacturing and Logistics Sectors ». *Procedia Manufacturing, System-Integrated Intelligence – Intelligent, Flexible and Connected Systems in Products and Production* Proceedings of the 5th International Conference on System-Integrated Intelligence (SysInt 2020), Bremen, Germany, 52 (janvier): 337-43. <https://doi.org/10.1016/j.promfg.2020.11.056>.

- Antony, Jiju, Sandeep Gupta, Vijaya Sunder M., et E.V. Gijo. 2018. « Ten Commandments of Lean Six Sigma: A Practitioners' Perspective ». *International Journal of Productivity and Performance Management* 67 (6): 1033-44. <https://doi.org/10.1108/IJPPM-07-2017-0170>.
- Antony, Jiju, Olivia McDermott, Daryl Powell, et Michael Sony. 2022. « The Evolution and Future of Lean Six Sigma 4.0 ». *The TQM Journal*, mai. <https://doi.org/10.1108/TQM-04-2022-0135>.
- Ardichvili, Alexander, Vaughn Page, et Tim Wentling. 2003. « Motivation and Barriers to Participation in Virtual Knowledge-sharing Communities of Practice ». *Journal of Knowledge Management* 7 (1): 64-77. <https://doi.org/10.1108/13673270310463626>.
- Bag, S., A.K. Sahu, P. Kilbourn, N. Pisa, P. Dhamija, et A.K. Sahu. 2022. « Modeling Barriers of Digital Manufacturing in a Circular Economy for Enhancing Sustainability ». *International Journal of Productivity and Performance Management* 71 (3): 833-69. <https://doi.org/10.1108/IJPPM-12-2020-0637>.
- Bakhtawar, Barira. 2020. *An Introduction to Qualitative Research (Flick, U. (2014). An introduction to qualitative research. Sage.) Book Review for Academic Consultation*. <https://doi.org/10.13140/RG.2.2.11809.22887>.
- Bauer, Harald, Felix Brandl, Christopher Lock, et Gunther Reinhart. 2018. « Integration of Industrie 4.0 in Lean Manufacturing Learning Factories ». *Procedia Manufacturing* 23: 147-52. <https://doi.org/10.1016/j.promfg.2018.04.008>.
- Belhadi, Amine, Sachin S. Kamble, Karim Zkik, Anass Cherrafi, et Fatima Ezahra Touriki. 2020a. « The Integrated Effect of Big Data Analytics, Lean Six Sigma and Green Manufacturing on the Environmental Performance of Manufacturing Companies: The Case of North Africa ». *Journal of Cleaner Production* 252 (avril): 119903. <https://doi.org/10.1016/j.jclepro.2019.119903>.
- . 2020b. « The Integrated Effect of Big Data Analytics, Lean Six Sigma and Green Manufacturing on the Environmental Performance of Manufacturing Companies: The Case of North Africa ». *Journal of Cleaner Production* 252 (avril): 119903. <https://doi.org/10.1016/j.jclepro.2019.119903>.
- Bhattacharya, A., A. Nand, et P. Castka. 2019. « Lean-green integration and its impact on sustainability performance: A critical review ». *Journal of Cleaner Production* 236. <https://doi.org/10.1016/j.jclepro.2019.117697>.
- Bittencourt, V.L., A.C. Alves, et C.P. Leão. 2021. « Industry 4.0 triggered by Lean Thinking: insights from a systematic literature review ». *International Journal of Production Research* 59 (5): 1496-1510. <https://doi.org/10.1080/00207543.2020.1832274>.
- Braun, Virginia, et Victoria Clarke. 2006. « Using Thematic Analysis in Psychology ». *Qualitative Research in Psychology* 3 (2): 77-101. <https://doi.org/10.1191/1478088706qp0630a>.
- Bucea-Manea-țoniș, R., V. Prokop, D. Ilic, E. Gurgu, R. Bucea-Manea-țoniș, C. Braicu, et A. Moanță. 2021. « The relationship between eco-innovation and smart working as support for sustainable management ». *Sustainability (Switzerland)* 13 (3): 1-17. <https://doi.org/10.3390/su13031437>.
- Buer, Sven-Vegard, Jan Ola Strandhagen, et Felix T. S. Chan. 2018. « The Link between Industry 4.0 and Lean Manufacturing: Mapping Current Research and Establishing a Research Agenda ». *International Journal of Production Research* 56 (8): 2924-40. <https://doi.org/10.1080/00207543.2018.1442945>.
- Burggräf, P., C. Lorber, A. Pyka, J. Wagner, et T. Weißer. 2020. « Kaizen 4.0 Towards an Integrated Framework for the Lean-Industry 4.0 Transformation ». *Advances*

in Intelligent Systems and Computing.

[https://www.scopus.com/inward/record.uri?eid=2-s2.0-](https://www.scopus.com/inward/record.uri?eid=2-s2.0-85075668773&doi=10.1007%2f978-3-030-32523-7_52&partnerID=40&md5=5dfb297de920aa78b82aa84b3f6ddad6)

[85075668773&doi=10.1007%2f978-3-030-32523-](https://www.scopus.com/inward/record.uri?eid=2-s2.0-85075668773&doi=10.1007%2f978-3-030-32523-7_52&partnerID=40&md5=5dfb297de920aa78b82aa84b3f6ddad6)

[7_52&partnerID=40&md5=5dfb297de920aa78b82aa84b3f6ddad6.](https://www.scopus.com/inward/record.uri?eid=2-s2.0-85075668773&doi=10.1007%2f978-3-030-32523-7_52&partnerID=40&md5=5dfb297de920aa78b82aa84b3f6ddad6)

- Chaouni Benabdellah, Abla, Kamar Zekhnini, et Anass Cherrafi. 2021. « Sustainable and Resilience Improvement Through the Design for Circular Digital Supply Chain ». In *Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems*, édité par Alexandre Dolgui, Alain Bernard, David Lemoine, Gregor von Cieminski, et David Romero, 550-59. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-85910-7_58.
- Chauhan, Chetna, Vinit Parida, et Amandeep Dhir. 2022. « Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises ». *Technological Forecasting and Social Change* 177 (avril): 121508. <https://doi.org/10.1016/j.techfore.2022.121508>.
- Cherrafi, Anass, Andrea Chiarini, Amine Belhadi, Jamal El Baz, et Abla Chaouni Benabdellah. 2022. « Digital Technologies and Circular Economy Practices: Vital Enablers to Support Sustainable and Resilient Supply Chain Management in the Post-COVID-19 Era ». *The TQM Journal* 34 (7): 179-202. <https://doi.org/10.1108/TQM-12-2021-0374>.
- Cherrafi, Anass, Said Elfezazi, Andrea Chiarini, Ahmed Mokhlis, et Khalid Benhida. 2016. « The Integration of Lean Manufacturing, Six Sigma and Sustainability: A Literature Review and Future Research Directions for Developing a Specific Model ». *Journal of Cleaner Production* 139 (décembre): 828-46. <https://doi.org/10.1016/j.jclepro.2016.08.101>.
- Cherrafi, Anass, Said Elfezazi, Kannan Govindan, Jose Arturo Garza-Reyes, Khalid Benhida, et Ahmed Mokhlis. 2017. « A Framework for the Integration of Green and Lean Six Sigma for Superior Sustainability Performance ». *International Journal of Production Research* 55 (15): 4481-4515. <https://doi.org/10.1080/00207543.2016.1266406>.
- Cherrafi, Anass, Jose Arturo Garza-Reyes, Amine Belhadi, Sachin S. Kamble, et Jamal Elbaz. 2021. « A Readiness Self-Assessment Model for Implementing Green Lean Initiatives ». *Journal of Cleaner Production* 309 (août): 127401. <https://doi.org/10.1016/j.jclepro.2021.127401>.
- Ciano, M.P., P. Dallasega, G. Orzes, et T. Rossi. 2021. « One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study ». *International Journal of Production Research* 59 (5): 1386-1410. <https://doi.org/10.1080/00207543.2020.1821119>.
- Cimini, Chiara, Roberto Pinto, Giuditta Pezzotta, et Paolo Gaiardelli. 2017. « The Transition Towards Industry 4.0: Business Opportunities and Expected Impacts for Suppliers and Manufacturers ». In *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing*, édité par Hermann Lödding, Ralph Riedel, Klaus-Dieter Thoben, Gregor von Cieminski, et Dimitris Kiritsis, 513:119-26. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-66923-6_14.
- Cui, Yongfeng, Wei Liu, Pratibha Rani, et Melfi Alrasheedi. 2021. « Internet of Things (IoT) Adoption Barriers for the Circular Economy Using Pythagorean Fuzzy SWARA-CoCoSo Decision-Making Approach in the Manufacturing Sector ».

- Technological Forecasting and Social Change* 171 (octobre): 120951.
<https://doi.org/10.1016/j.techfore.2021.120951>.
- de Sousa Jabbour, Ana, Charbel Chiappetta-Jabbour, Moacir Filho, et David Roubaud. 2018. « Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations ». *Annals of Operations Research* 270 (novembre). <https://doi.org/10.1007/s10479-018-2772-8>.
- Dixit, Ankur, et Rajiv Chaudhary. 2020. « Sustainability: an Essential Concept for Current and Upcoming Technological Practices ». *IOP Conference Series: Materials Science and Engineering* 804 (juin): 012023.
<https://doi.org/10.1088/1757-899X/804/1/012023>.
- Edwin Cheng, T. C., Sachin S. Kamble, Amine Belhadi, Nelson Oly Ndubisi, Kee-hung Lai, et Manoj Govind Kharat. 2022. « Linkages between Big Data Analytics, Circular Economy, Sustainable Supply Chain Flexibility, and Sustainable Performance in Manufacturing Firms ». *International Journal of Production Research* 60 (22): 6908-22. <https://doi.org/10.1080/00207543.2021.1906971>.
- Eisenhardt, Kathleen M. 1989. « Building Theories from Case Study Research », 20.
 ———. 2022. « Building Theories from Case Study Research », 20.
- El Baz, Jamal, Sunil Tiwari, Temidayo Akenroye, Anass Cherrafi, et Ridha Derrouiche. 2022. « A Framework of Sustainability Drivers and Externalities for Industry 4.0 Technologies Using the Best-Worst Method ». *Journal of Cleaner Production* 344 (avril): 130909. <https://doi.org/10.1016/j.jclepro.2022.130909>.
- Elkington, John. 1994. « Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development ». *California Management Review* 36 (2): 90-100. <https://doi.org/10.2307/41165746>.
- Farrukh, Amna, Sanjay Mathrani, et Aymen Sajjad. 2021. « A natural resource and institutional theory-based view of green-lean-six sigma drivers for environmental management ». *Business Strategy and the Environment* 31 (novembre). <https://doi.org/10.1002/bse.2936>.
- Gandhi, Nevil S., Shashank J. Thanki, et Jitesh J. Thakkar. 2018. « Ranking of Drivers for Integrated Lean-Green Manufacturing for Indian Manufacturing SMEs ». *Journal of Cleaner Production* 171 (janvier): 675-89.
<https://doi.org/10.1016/j.jclepro.2017.10.041>.
- Garza-Reyes, Jose Arturo. 2015. « Lean and Green – a Systematic Review of the State of the Art Literature ». *Journal of Cleaner Production* 102 (septembre): 18-29.
<https://doi.org/10.1016/j.jclepro.2015.04.064>.
- Gatto, M. 1995. « Sustainability: Is it a Well Defined Concept? » *Ecological Applications* 5 (4): 1181-83.
- Geissdoerfer, Martin, Paulo Savaget, Nancy M.P. Bocken, et Erik Jan Hultink. 2017. « The Circular Economy – A New Sustainability Paradigm? » *Journal of Cleaner Production* 143 (février): 757-68.
<https://doi.org/10.1016/j.jclepro.2016.12.048>.
- Ghaithan, Ahmed M., Yasser Alshammakhi, Awsan Mohammed, et Khwaja Mateen Mazher. 2023. « Integrated Impact of Circular Economy, Industry 4.0, and Lean Manufacturing on Sustainability Performance of Manufacturing Firms ». *International Journal of Environmental Research and Public Health* 20 (6): 5119. <https://doi.org/10.3390/ijerph20065119>.
- Ghobakhloo, Morteza, Masood Fathi, Mohammad Iranmanesh, Parisa Maroufkhani, et Manuel E. Morales. 2021. « Industry 4.0 Ten Years on: A Bibliometric and Systematic Review of Concepts, Sustainability Value Drivers, and Success

- Determinants ». *Journal of Cleaner Production* 302 (juin): 127052. <https://doi.org/10.1016/j.jclepro.2021.127052>.
- Ghobakhloo, Morteza, Mohammad Iranmanesh, Mantas Vilkas, Andrius Grybauskas, et Azlan Amran. 2022. « Drivers and Barriers of Industry 4.0 Technology Adoption among Manufacturing SMEs: A Systematic Review and Transformation Roadmap ». *Journal of Manufacturing Technology Management* 33 (6): 1029-58. <https://doi.org/10.1108/JMTM-12-2021-0505>.
- Gibbert, Michael, Winfried Ruigrok, et Barbara Wicki. 2008. « What Passes as a Rigorous Case Study? » *Strategic Management Journal* 29 (13): 1465-74. <https://doi.org/10.1002/smj.722>.
- Glaser, Barney G., et Anselm L. Strauss. 2010. *The Discovery of Grounded Theory: Strategies for Qualitative Research*. 5. paperback print. New Brunswick: Aldine Transaction.
- Glaser, Barney, et Anselm Strauss. 2017. *Discovery of grounded theory: Strategies for qualitative research*. *Discovery of Grounded Theory: Strategies for Qualitative Research*. <https://doi.org/10.4324/9780203793206>.
- Govindan, Kannan, et Mia Hasanagic. 2018. « A Systematic Review on Drivers, Barriers, and Practices towards Circular Economy: A Supply Chain Perspective ». *International Journal of Production Research* 56 (1-2): 278-311. <https://doi.org/10.1080/00207543.2017.1402141>.
- Gupta, S., S. Modgil, et A. Gunasekaran. 2020. « Big data in lean six sigma: a review and further research directions ». *International Journal of Production Research* 58 (3): 947-69. <https://doi.org/10.1080/00207543.2019.1598599>.
- Hina, Maryam. 2022. « Drivers and Barriers of Circular Economy Business Models: Where We Are Now, and Where We Are Heading ». *Journal of Cleaner Production*, 18.
- Horváth, D., et R.Z. Szabó. 2019. « Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? » *Müller* 146: 119-32. <https://doi.org/10.1016/j.techfore.2019.05.021>.
- Ivanov, Dmitry, Christopher S. Tang, Alexandre Dolgui, Daria Battini, et Ajay Das. 2021. « Researchers' Perspectives on Industry 4.0: Multi-Disciplinary Analysis and Opportunities for Operations Management ». *International Journal of Production Research* 59 (7): 2055-78. <https://doi.org/10.1080/00207543.2020.1798035>.
- Jeschke, Sabina, Christian Brecher, Tobias Meisen, Denis Özdemir, et Tim Eschert. 2017. « Industrial Internet of Things and Cyber Manufacturing Systems ». In *Industrial Internet of Things*, édité par Sabina Jeschke, Christian Brecher, Houbing Song, et Danda B. Rawat, 3-19. Springer Series in Wireless Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-42559-7_1.
- Jesus, Ana de, et Sandro Mendonça. 2018. « Lost in Transition? Drivers and Barriers in the Eco-Innovation Road to the Circular Economy ». *Ecological Economics* 145 (mars): 75-89. <https://doi.org/10.1016/j.ecolecon.2017.08.001>.
- Joshi, Sudhanshu, Manu Sharma, Shalini Bartwal, Tanuja Joshi, et Mukesh Prasad. 2022. « Critical challenges of integrating OPEX Strategies with I4.0 technologies in Manufacturing SMEs: A few pieces of evidence from developing economies ». *TQM Journal*, octobre. <https://doi.org/10.1108/TQM-08-2022-0245>.

- Kamble, Sachin, Angappa Gunasekaran, et Ncelkanth C. Dhone. 2020. « Industry 4.0 and Lean Manufacturing Practices for Sustainable Organisational Performance in Indian Manufacturing Companies ». *International Journal of Production Research* 58 (5): 1319-37. <https://doi.org/10.1080/00207543.2019.1630772>.
- Kaswan, Mahender Singh, Rajeev Rathi, Jennifer Cross, Jose Arturo Garza-Reyes, Jiju Antony, et Vishwas Yadav. 2023. « Integrating Green Lean Six Sigma and Industry 4.0: A Conceptual Framework ». *Journal of Manufacturing Technology Management* 34 (1): 87-121. <https://doi.org/10.1108/JMTM-03-2022-0115>.
- Khan, Ateeq, et Klaus Turowski. 2016. « A Survey of Current Challenges in Manufacturing Industry and Preparation for Industry 4.0 ». In *Proceedings of the First International Scientific Conference "Intelligent Information Technologies for Industry" (IITI'16)*, édité par Ajith Abraham, Sergey Kovalev, Valery Tarassov, et Václav Snášel, 450:15-26. Advances in Intelligent Systems and Computing. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-33609-1_2.
- Khan, Syed Abdul Rehman, Asif Razzaq, Zhang Yu, et Sharon Miller. 2021. « Industry 4.0 and Circular Economy Practices: A New Era Business Strategies for Environmental Sustainability ». *Business Strategy and the Environment* 30 (8): 4001-14. <https://doi.org/10.1002/bse.2853>.
- Khin, Sabai, et Daisy Mui Hung Kee. 2022. « Factors influencing Industry 4.0 adoption ». *Journal of Manufacturing Technology Management* 33 (3): 448-67. <https://doi.org/10.1108/JMTM-03-2021-0111>.
- Kiel, Daniel, Julian M. Müller, Christian Arnold, et Kai-Ingo Voigt. 2017. « SUSTAINABLE INDUSTRIAL VALUE CREATION: BENEFITS AND CHALLENGES OF INDUSTRY 4.0 ». *International Journal of Innovation Management* 21 (08): 1740015. <https://doi.org/10.1142/S1363919617400151>.
- Kristoffersen, Eivind, Fenna Blomsma, Patrick Mikalef, et Jingyue Li. 2020. « The Smart Circular Economy: A Digital-Enabled Circular Strategies Framework for Manufacturing Companies ». *Journal of Business Research* 120 (novembre): 241-61. <https://doi.org/10.1016/j.jbusres.2020.07.044>.
- Kumar, Ravinder, Rajesh Kr. Singh, et Yogesh Kr. Dwivedi. 2020. « Application of Industry 4.0 Technologies in SMEs for Ethical and Sustainable Operations: Analysis of Challenges ». *Journal of Cleaner Production* 275 (décembre): 124063. <https://doi.org/10.1016/j.jclepro.2020.124063>.
- Kurdve, M., et M. Bellgran. 2021. « Green lean operationalisation of the circular economy concept on production shop floor level ». *Journal of Cleaner Production* 278. <https://doi.org/10.1016/j.jclepro.2020.123223>.
- Kurpjuweit, Stefan, Dagmar Reinerth, Christoph G. Schmidt, et Stephan M. Wagner. 2019. « Implementing Visual Management for Continuous Improvement: Barriers, Success Factors and Best Practices ». *International Journal of Production Research* 57 (17): 5574-88. <https://doi.org/10.1080/00207543.2018.1553315>.
- Lasi, Heiner, Peter Fettke, Hans-Georg Kemper, Thomas Feld, et Michael Hoffmann. 2014. « Industry 4.0 ». *Business & Information Systems Engineering* 6 (4): 239-42. <https://doi.org/10.1007/s12599-014-0334-4>.
- Leipold, Sina, Anna Petit-Boix, Anran Luo, Hanna Helander, Machteld Simoens, Weslyne Ashton, Callie Babbitt, et al. 2021. « Lessons, Narratives and Research Directions for a Sustainable Circular Economy ». Preprint. In Review. <https://doi.org/10.21203/rs.3.rs-429660/v1>.

- Liu, Qinglan, Adriana Hofmann Trevisan, Miying Yang, et Janaina Mascarenhas. 2022. « A Framework of Digital Technologies for the Circular Economy: Digital Functions and Mechanisms ». *Business Strategy and the Environment* 31 (5): 2171-92. <https://doi.org/10.1002/bse.3015>.
- Lobo, A., A.H. Trevisan, Q. Liu, M. Yang, et J. Mascarenhas. 2022. « Barriers to Transitioning Towards Smart Circular Economy: A Systematic Literature Review ». *Smart Innovation, Systems and Technologies* 262 SIST: 245-56. https://doi.org/10.1007/978-981-16-6128-0_24.
- Luthra, Sunil, Anil Kumar, Edmundas Kazimieras Zavadskas, Sachin Kumar Mangla, et Jose Arturo Garza-Reyes. 2020. « Industry 4.0 as an Enabler of Sustainability Diffusion in Supply Chain: An Analysis of Influential Strength of Drivers in an Emerging Economy ». *International Journal of Production Research* 58 (5): 1505-21. <https://doi.org/10.1080/00207543.2019.1660828>.
- Mangla, Sachin Kumar, Kannan Govindan, et Sunil Luthra. 2017. « Prioritizing the Barriers to Achieve Sustainable Consumption and Production Trends in Supply Chains Using Fuzzy Analytical Hierarchy Process » 151 (mai): 509-25. <https://doi.org/10.1016/j.jclepro.2017.02.099>.
- Mangla, Sachin Kumar, Sunil Luthra, Nishikant Mishra, Akshit Singh, Nripendra P. Rana, Manoj Dora, et Yogesh Dwivedi. 2018. « Barriers to Effective Circular Supply Chain Management in a Developing Country Context ». *Production Planning & Control* 29 (6): 551-69. <https://doi.org/10.1080/09537287.2018.1449265>.
- Mhatre, Purva, Rohit Panchal, Anju Singh, et Shyam Bibyan. 2021. « A Systematic Literature Review on the Circular Economy Initiatives in the European Union ». *Sustainable Production and Consumption* 26 (avril): 187-202. <https://doi.org/10.1016/j.spc.2020.09.008>.
- Miles, Matthew B., et A. Michael Huberman. 1994. *Qualitative data analysis: An expanded sourcebook, 2nd ed.* Qualitative data analysis: An expanded sourcebook, 2nd ed. Thousand Oaks, CA, US: Sage Publications, Inc.
- Missimer, Merlina, Karl-Henrik Robèrt, et Göran Broman. 2016. « A Strategic Approach to Social Sustainability - Part 1: Exploring the Social System ». *Journal of Cleaner Production* 140 (avril). <https://doi.org/10.1016/j.jclepro.2016.03.170>.
- Morelli, John. 2011. « Environmental Sustainability: A Definition for Environmental Professionals ». *Journal of Environmental Sustainability* 1 (novembre). <https://doi.org/10.14448/jes.01.0002>.
- Müller, Julian Marius, Oana Buliga, et Kai-Ingo Voigt. 2018. « Fortune Favors the Prepared: How SMEs Approach Business Model Innovations in Industry 4.0 ». *Technological Forecasting and Social Change* 132 (juillet): 2-17. <https://doi.org/10.1016/j.techfore.2017.12.019>.
- Müller, Julian Marius, Daniel Kiel, et Kai-Ingo Voigt. 2018. « What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability ». *Sustainability* 10 (1): 247. <https://doi.org/10.3390/su10010247>.
- Nagy, Judit, Judit Oláh, Edina Erdei, Domician Mate, et Jozsef Popp. 2018. « The Role and Impact of Industry 4.0 and the Internet of Things on the Business Strategy of the Value Chain—The Case of Hungary ». *Sustainability* 10 (septembre): 3491. <https://doi.org/10.3390/su10103491>.
- Nascimento, D.L.M., O.L. Goncalvez Quelhas, R.G. Gusmão Caiado, G.L. Tortorella, J.A. Garza-Reyes, et L. Rocha-Lona. 2019. « A lean six sigma framework for

- continuous and incremental improvement in the oil and gas sector ». *International Journal of Lean Six Sigma* 11 (3): 577-95. <https://doi.org/10.1108/IJLSS-02-2019-0011>.
- Ojha, Ravindra. 2022. « Lean in industry 4.0 is accelerating manufacturing excellence – A DEMATEL analysis ». *The TQM Journal* ahead-of-print (ahead-of-print). <https://doi.org/10.1108/TQM-11-2021-0318>.
- Pieroni, Marina P. P., Tim C. McAloone, et Daniela C. A. Pigosso. 2021. « Developing a Process Model for Circular Economy Business Model Innovation within Manufacturing Companies ». *Journal of Cleaner Production* 299 (mai): 126785. <https://doi.org/10.1016/j.jclepro.2021.126785>.
- Psarommatis, Foivos, Gökan MAY, Paul-Arthur Dreyfus, et Dimitris Kiritsis. 2019. « Zero defect manufacturing: state-of-the-art review, shortcomings and future directions in research ». *International Journal of Production Research* 58 (avril): 1-17. <https://doi.org/10.1080/00207543.2019.1605228>.
- R, Vigneshvaran, et S. Vinodh. 2020. « Development of a structural model based on ISM for analysis of barriers to integration of leanwith industry 4.0 ». *The TQM Journal* ahead-of-print (ahead-of-print). <https://doi.org/10.1108/TQM-07-2020-0151>.
- Raj, Alok, Gourav Dwivedi, Ankit Sharma, Ana Beatriz Lopes de Sousa Jabbour, et Sonu Rajak. 2020. « Barriers to the Adoption of Industry 4.0 Technologies in the Manufacturing Sector: An Inter-Country Comparative Perspective ». *International Journal of Production Economics* 224 (juin): 107546. <https://doi.org/10.1016/j.ijpe.2019.107546>.
- Raji, I.O., et T. Rossi. 2019. « Exploring industry 4.0 technologies as drivers of lean and agile supply chain strategies ». In *Proceedings of the International Conference on Industrial Engineering and Operations Management*, 292-303. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85079284808&partnerID=40&md5=ba23d23aee897cd0dc186b28bad7eb17>.
- Rajput, Shubhangini, et Surya Prakash Singh. 2019. « Connecting Circular Economy and Industry 4.0 ». *International Journal of Information Management* 49 (décembre): 98-113. <https://doi.org/10.1016/j.ijinfomgt.2019.03.002>.
- Ranta, Valtteri, Leena Aarikka-Stenroos, Paavo Ritala, et Saku J. Mäkinen. 2018. « Exploring Institutional Drivers and Barriers of the Circular Economy: A Cross-Regional Comparison of China, the US, and Europe ». *Resources, Conservation and Recycling* 135 (août): 70-82. <https://doi.org/10.1016/j.resconrec.2017.08.017>.
- Rowley, Jennifer. 2002. « Using Case Studies in Research ». *Management Research News* 25 (1): 16-27. <https://doi.org/10.1108/01409170210782990>.
- Sanders, A., C. Elangeswaran, et J. Wulfsberg. 2016. « Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing ». *Journal of Industrial Engineering and Management* 9 (3): 811-33. <https://doi.org/10.3926/jiem.1940>.
- Saniuk, Sebastian, Sandra Grabowska, et Wieslaw Grebski. 2022. « Knowledge and Skills Development in the Context of the Fourth Industrial Revolution Technologies: Interviews of Experts from Pennsylvania State of the USA ». *Energies* 15 (avril): 2677. <https://doi.org/10.3390/en15072677>.
- Schumacher, Andreas, Selim Erol, et Wilfried Sihn. 2016. « A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises ». *Procedia CIRP* 52: 161-66. <https://doi.org/10.1016/j.procir.2016.07.040>.

- Seuring, Stefan, et Martin Müller. 2008. « From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management ». *Journal of Cleaner Production* 16 (15): 1699-1710. <https://doi.org/10.1016/j.jclepro.2008.04.020>.
- Sevinç, Ali, Şeyda Gür, et Tamer Eren. 2018. « Analysis of the Difficulties of SMEs in Industry 4.0 Applications by Analytical Hierarchy Process and Analytical Network Process ». *Processes* 6 (12): 264. <https://doi.org/10.3390/pr6120264>.
- Sharma, M., S. Joshi, M. Prasad, et S. Bartwal. 2023. « Overcoming Barriers to Circular Economy Implementation in the Oil & Gas Industry: Environmental and Social Implications ». *Journal of Cleaner Production* 391. <https://doi.org/10.1016/j.jclepro.2023.136133>.
- Singh, Rajdeep, et Neeraj Bhanot. 2020. « An Integrated DEMATEL-MMDE-ISM Based Approach for Analysing the Barriers of IoT Implementation in the Manufacturing Industry ». *International Journal of Production Research* 58 (8): 2454-76. <https://doi.org/10.1080/00207543.2019.1675915>.
- Skalli, D., A. Charkaoui, et A. Cherrafi. 2022. « Assessing Interactions between Lean Six-Sigma, Circular Economy and Industry 4.0: Toward an Integrated Perspective ». *IFAC-PapersOnLine* 55 (10): 3112-17. <https://doi.org/10.1016/j.ifacol.2022.10.207>.
- Skalli, Dounia, Abdelkabar Charkaoui, et Cherrafi Anass. 2022. « The Integration of Industry 4.0 in Operations Management: Toward Smart Lean Six Sigma ». In , 3-11. https://doi.org/10.1007/978-3-031-01942-5_1.
- Skalli, Dounia, Abdelkabar Charkaoui, Anass Cherrafi, Jose Arturo Garza-Reyes, Jiju Antony, et Alireza Shokri. 2023. « Industry 4.0 and Lean Six Sigma integration in manufacturing: A literature review, an integrated framework and proposed research perspectives ». *Quality Management Journal* 0 (0): 1-25. <https://doi.org/10.1080/10686967.2022.2144784>.
- Sony, M. 2019. « Implementing sustainable operational excellence in organizations: an integrative viewpoint ». *Production and Manufacturing Research* 7 (1): 67-87. <https://doi.org/10.1080/21693277.2019.1581674>.
- Sony, Michael. 2018. « Industry 4.0 and Lean Management: A Proposed Integration Model and Research Propositions ». *Production and Manufacturing Research-an Open Access Journal* 6 (1): 416-32. <https://doi.org/10.1080/21693277.2018.1540949>.
- Sony, Michael, Jiju Antony, Olivia Mc Dermott, et Jose Arturo Garza-Reyes. 2021. « An Empirical Examination of Benefits, Challenges, and Critical Success Factors of Industry 4.0 in Manufacturing and Service Sector ». *Technology in Society* 67 (novembre): 101754. <https://doi.org/10.1016/j.techsoc.2021.101754>.
- Stentoft, Jan, Kent Aadsbøll Wickstrøm, Kristian Philipsen, et Anders Haug. 2021. « Drivers and Barriers for Industry 4.0 Readiness and Practice: Empirical Evidence from Small and Medium-Sized Manufacturers ». *Ghobakhloo* 32 (10): 811-28. <https://doi.org/10.1080/09537287.2020.1768318>.
- Szalavetz, A. 2017. « The environmental impact of advanced manufacturing technologies: Examples from Hungary ». *Central European Business Review* 6 (2): 18-29. <https://doi.org/10.18267/J.CEBR.177>.
- Ting, Lim Sin, Suhaiza Zailani, Noor Zahirah Mohd Sidek, et Mohd Rizaimy Shaharudin. 2023. « Motivators and Barriers of Circular Economy Business Model Adoption and Its Impact on Sustainable Production in Malaysia ». *Environment, Development and Sustainability*, mai. <https://doi.org/10.1007/s10668-023-03350-6>.

- Tortorella, G.L., M. Rossini, F. Costa, A. Portioli Staudacher, et R. Sawhney. 2019. « A comparison on Industry 4.0 and Lean Production between manufacturers from emerging and developed economies ». *Total Quality Management and Business Excellence*. <https://doi.org/10.1080/14783363.2019.1696184>.
- Touriki, Fatima Ezahra, Imane Benkhati, Sachin S. Kamble, Amine Belhadi, et Said El fezazi. 2021. « An Integrated Smart, Green, Resilient, and Lean Manufacturing Framework: A Literature Review and Future Research Directions ». *Journal of Cleaner Production* 319 (octobre): 128691. <https://doi.org/10.1016/j.jclepro.2021.128691>.
- Trevisan, A.H., A. Lobo, D. Guzzo, L.A.D.V. Gomes, et J. Mascarenhas. 2023. « Barriers to Employing Digital Technologies for a Circular Economy: A Multi-Level Perspective ». *Journal of Environmental Management* 332. <https://doi.org/10.1016/j.jenvman.2023.117437>.
- Tura, Nina, Jyri Hanski, Tuomas Ahola, Matias Ståhle, Sini Piiparinen, et Pasi Valkokari. 2019. « Unlocking Circular Business: A Framework of Barriers and Drivers ». *Journal of Cleaner Production* 212 (mars): 90-98. <https://doi.org/10.1016/j.jclepro.2018.11.202>.
- Vinodh, S., et Somishang A. Shimray. 2022. « Analysis of barriers for implementation of integrated Lean Six Sigma and Industry 4.0 using interpretive ranking process ». *The TQM Journal* ahead-of-print (ahead-of-print). <https://doi.org/10.1108/TQM-04-2022-0121>.
- Voss, Chris, Nikos Tsikriktsis, et Mark Frohlich. 2002. « Case Research in Operations Management ». *International Journal of Operations & Production Management* 22 (2): 195-219. <https://doi.org/10.1108/01443570210414329>.
- Wagner, Tobias, Christoph Herrmann, et Sebastian Thiede. 2017. « Industry 4.0 Impacts on Lean Production Systems ». In *Manufacturing Systems 4.0*, édité par M. M. Tseng, H. Y. Tsai, et Y. Wang, 63:125-31. Amsterdam: Elsevier Science Bv.
- Xiao, Yu, et Maria Watson. 2019. « Guidance on Conducting a Systematic Literature Review ». *Journal of Planning Education and Research* 39 (1): 93-112. <https://doi.org/10.1177/0739456X17723971>.
- Yin, Robert K. 1994. « Discovering the Future of the Case Study. Method in Evaluation Research ». *Evaluation Practice* 15 (3): 283-90. <https://doi.org/10.1177/109821409401500309>.
- . 2009. *Case Study Research: Design and Methods*. SAGE.
- Yüksel, Hilmi. 2022. « Industry 4.0 transformation: factors affecting adoption and impacts on companies ». *International Journal of Industrial Engineering and Operations Management* 4 (3): 63-89. <https://doi.org/10.1108/IJIEOM-06-2022-0020>.
- Zekhnini, Kamar, Anass Cherrafi, Imane Bouhaddou, Abla Chaouni Benabdellah, et Surajit Bag. 2021. « A model integrating lean and green practices for viable, sustainable, and digital supply chain performance ». *International Journal of Production Research* 0 (0): 1-27. <https://doi.org/10.1080/00207543.2021.1994164>.

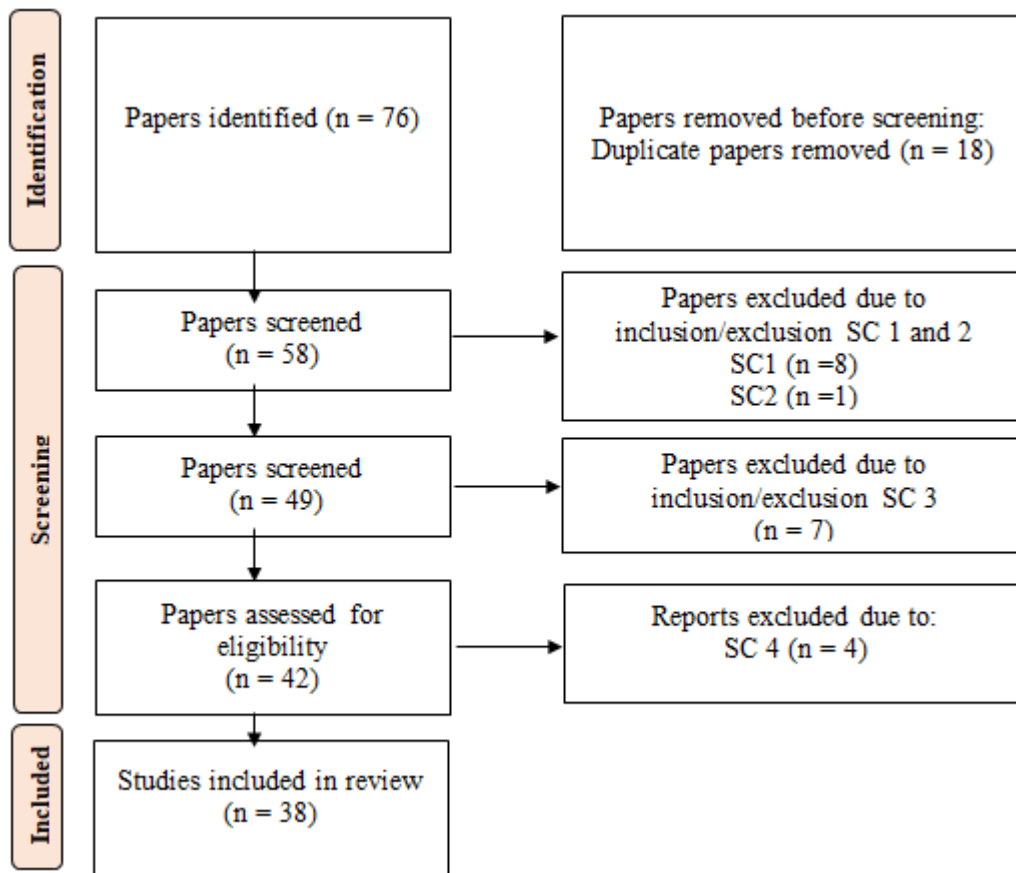
Appendix 1: List of articles on the drivers and barriers to CLSS4.0, detailing the methodologies used.

Author	Used methodology	Source
--------	------------------	--------

1.	(Horváth et Szabó 2019)	Semi-structured interviews	Technological Forecasting and Social Change
2.	(Müller, Buliga, et Voigt 2018)	Interviews	Technological Forecasting and Social Change
3.	(Joshi et al. 2022)	Experts panel Multi-Criteria Decision Methods” (MCDM) and Interpretative structural modeling (ISM)	TQM journal
4.	(Stentoft et al. 2021)	Survey	Production Planning & Control
5.	(Ghobakhloo et al. 2022)	Literature review and content analysis	Journal of Manufacturing Technology Management
6.	(Govindan et Hasanagic 2018)	Literature review	International Journal of Production Research
7.	(Dounia Skalli et al. 2023)	Literature review	Quality management journal
8.	(Tura et al. 2019)	Literature review	Journal of cleaner production
9.	(Hina 2022)	Literature review	Journal of cleaner production
10.	(de Jesus et Mendonça 2018)	Literature review	Ecological Economics
11.	(El Baz et al. 2022)	Experts’ surveys and the Best-Worst Method.	Journal of cleaner production
12.	(Farrukh, Mathrani, et Sajjad 2021)	Multiple case study	Business Strategy and the Environment
13.	(Ghobakhloo et al. 2021)	Literature review	Journal of cleaner production
14.	(Luthra et al. 2020)	Literature review, experts panel and Grey DEMATEL	International Journal of Production Research
15.	(Ranta et al. 2018)	Multiple case study	Resources, Conservation and Recycling
16.	(Mhatre et al. 2021)	Literature review	Sustainable Production and Consumption
17.	(S. M. Ali et al. 2020)	Literature review, experts panel and ISM model	Computers & Industrial Engineering
18.	(Singh et Bhanot 2020)	Literature review, experts panel and DEMATE-MMDE--ISM model	International Journal of Production Research

19.	(Cui et al. 2021)	Literature review, experts panel	Technological Forecasting and Social Change
20.	(Vinodh et Shimray 2022)	Survey	TQM
21.	(Ojha 2022)		TQM
22.	(Müller, Kiel, et Voigt 2018)	Survey	Sustainability
23.	(Liu et al. 2022)	Literature review	Business Strategy and the Environment
24.	(R et Vinodh 2020)	Experts panel	TQM
25.	(Antony et al. 2022)	Literature review	TQM
26.	(Michael Sony 2018)	Literature review	Production and Manufacturing Research
27.	(Bittencourt, Alves, et Leão 2021)	Literature review	International Journal of Production Research
28.	(Khin et Kee 2022)	Interviews	Journal of Manufacturing Technology Management
29.	(Yüksel 2022)	Survey	International Journal of Industrial Engineering and Operations Management
30.	(Ting et al. 2023)	Survey	Environment, Development and Sustainability
31.	(Chauhan, Parida, et Dhir 2022)	Literature review	Technological Forecasting and Social Change
32.	(Lobo et al. 2022)	Literature review	Smart Innovation, Systems and Technologies
33.	(Trevisan et al. 2023)	literature review and multiple case studies	Journal of Environmental Management
34.	(Mangla et al. 2018)	Experts panel and ISM -MICMAC approach	Production Planning & Control
35.	(Ciano et al. 2021)	semi-structured interviews	International Journal of Production Research
36.	(Mangla, Govindan, et Luthra 2017)	Literature review and industrial experts	Journal of Cleaner Production
37.	(Rajput et Singh 2019)	Literature review and focus group	International Journal of Information Management
38.	(Raj et al. 2020)	Literature review and industrial experts	International Journal of Production Economics

Appendix 2: The data collection and screening process following Prisma model



Appendix 3: Interview Instrument

1. Could you please introduce your company (size, sector, products) and your position?
2. Could you briefly describe your company activities, products and eventually your current projects related to CLSS4.0?
3. Could you please describe the digitalization, LSS , CE projects planned, being started or achieved by your company
4. What are your main drivers behind the adoption of the three concepts CE, LSS and I4.0
5. What specific challenges and barriers did you face during your CLSS4.0 implementation project?
6. What were your major leanings?
7. Please describe the measures that you have taken or are considering taking in your organization to mitigate the barriers?



Figure 1 Caption: Literature review process

Figure 1 Alt Text: A 4-steps diagram of the systematic literature review that includes studies selection to extract papers, studies evaluation to process selected studies, papers scanning and analysis and reporting the result



Figure 2 Caption: Theoretical framework of CLSS 4.0drivers and barriers

Figure 2 Alt Text: A simple diagram to show the integration of the circular economy, Lean Six Sigma and Industry 4.0 as a central loop with one square in the left as Drivers and one square in the right as barriers without mentioning any specific driver or barrier.

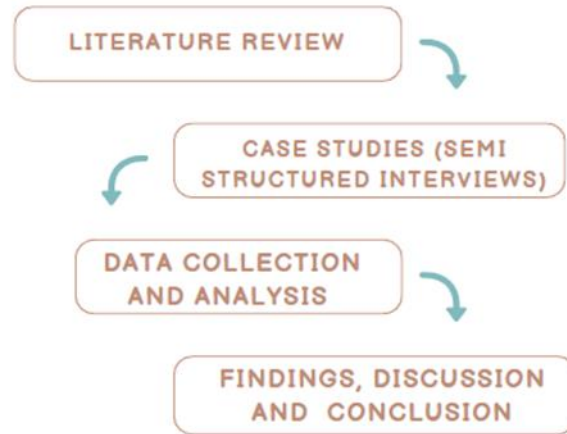


Figure 3 Caption: Research design

Figure 3 Alt Text: A simple diagram to indicate four steps of the research design with literature review as the first step, case study as the second step, data collection and analysis as the third step, and finding, discussion and conclusion as the final step.



Figure 4 Caption: Driving factors of CLSS4.0 adoption

Figure 4 Alt Text: Diagram of ten driving factors of the integration of the circular economy, Lean Six Sigma and Industry 4.0 with each driving factor is connected to the integration in the centre.

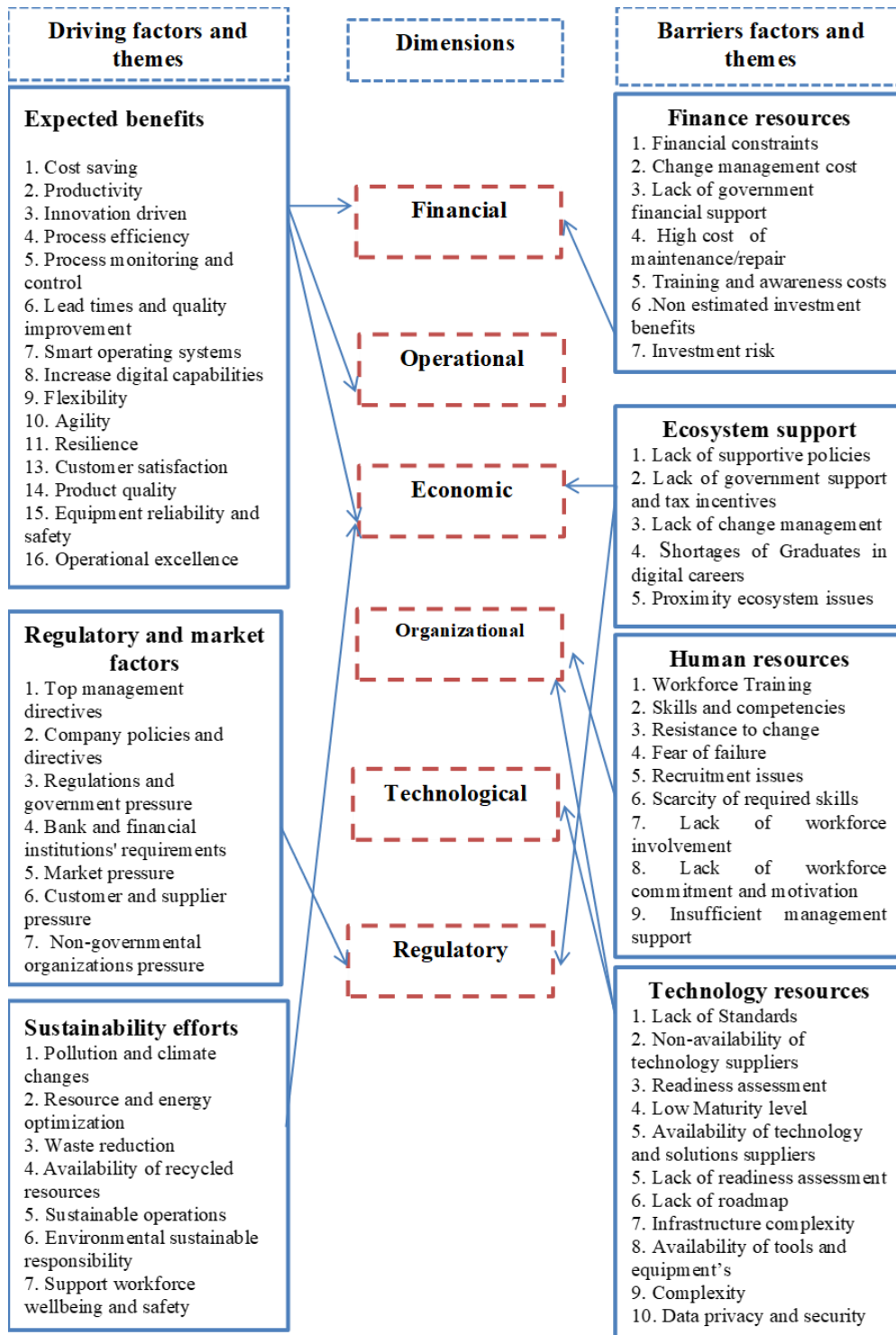


Figure 5 Caption: Summarized thematic analysis

Figure 5 Alt Text: A diagram with having expected benefits, regulatory and market factors and sustainability efforts as driving themes and ecosystem support human resources and technology resources as barriers themes linked to financial, operational, economic, organisational, technological and regulatory dimensions.



Figure 6 Caption: Barriers factors of CLSS4.0 adoption

Figure 6 Alt Text: Diagram of ten barrier factors of the integration of the circular economy, Lean Six Sigma and Industry 4.0 with each driving factor is connected to the integration in the centre.

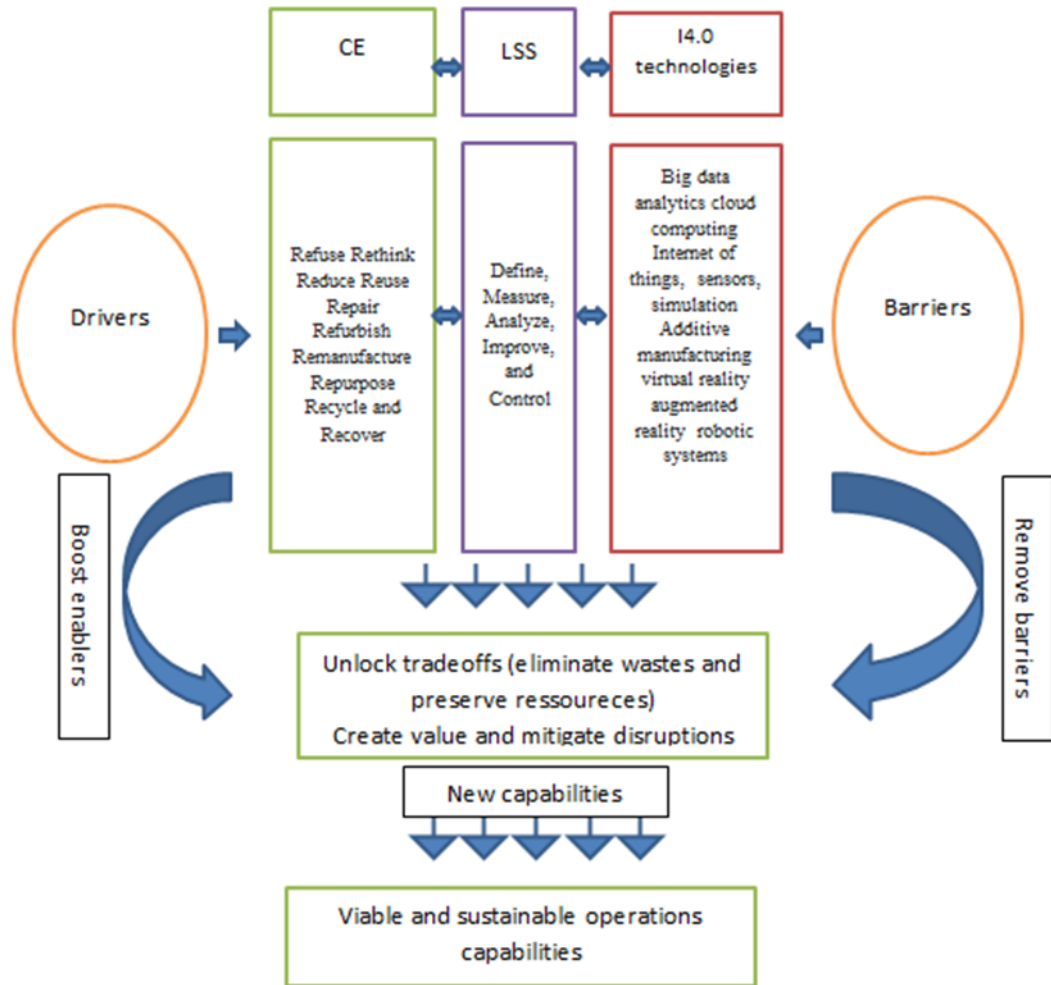


Figure 7 Caption: Conceptual framework supporting CLSS4.0 integrated approach

Figure 7 Alt Text: A framework with circular economy strategies, Lean Six Sigma methodology and Industry 4.0 technologies in the centre with indication of boosting enablers and removing barriers to get viable and sustainable operations capabilities.