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Review

Industry 4.0 and Lean Six Sigma Integration: A Systematic Review of Barriers and Enablers

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Abstract: In recent years, Industry 4.0 (I4.0) has been a recurrent theme in the literature on Lean Six Sigma (LSS), given the synergies that can arise from their combination. However, their joint implementation presents several challenges. In this article, a systematic literature review (SLR) of research on I4.0 and LSS integration was performed. This review involved five database platforms and included seventy-four articles providing state-of-the-art knowledge on the topic, focusing on the barriers to and enablers of integration. As a result, 20 integration barriers were identified, highlighting the high implementation cost, long learning curve, and technology incompatibility as the main barriers. Seventeen enablers were found to facilitate and guarantee implementation success, highlighting investment in IT infrastructure and employee training, stakeholder involvement, and top management support. In addition, the article discusses actions to facilitate I4.0 and LSS integration in practice, determined by connecting the identified enablers to their corresponding barriers. Finally, the SLR identifies several avenues for future research.

Keywords: automation; barriers; enablers; Industry 4.0; integration

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1. Introduction

Companies are increasingly looking to improve their operations, especially during challenging financial times [1]. In this context, it has been reported that companies can improve their performance by adopting digital technologies under the "umbrella" of Industry 4.0 (I4.0) [2]. Another way to improve operations is adopting Lean Six Sigma (LSS), which is a well-known approach to maximise shareholder value by reducing costs and improving speed, the quality of products (or services), and customer satisfaction [3,4]. In recent years, integrating I4.0 and LSS has become a vibrant research field. This study aims to examine the key factors that make such integration possible.

I4.0 was initially introduced in 2011 to describe the German government's strategy to boost its productive sector's competitiveness [5]. However, over the years, it has become an umbrella term loosely describing the many current and emerging technologies for improving manufacturing operations. For instance, in [6], I4.0 was specifically related to Internet use, production flexibility, and process virtualisation. However, there is no consensus on these technologies or the definition of I4.0 [7].

LSS, on the other hand, is a methodology used to improve organisational processes [1]. The term was introduced in the early 2000s to describe the fusion of two well-established practices: Lean manufacturing (L) and Six Sigma (SS) [8]. While both seek process improvement, they differ in their approaches. L focuses on eliminating waste and non-value-added activities [9], while SS mainly focuses on process variability reduction and superior quality [10].

I4.0 and LSS are approaches that help companies be competitive and respond quickly to changing market demands [11]. Moreover, I4.0 has gradually developed into a topic of significant interest for practitioners and academics interested in L and LSS. As shown in Figure 1, the number of publications investigating the relationship between I4.0 and these methodologies has grown significantly in recent years. However, most studies have only focused on the relationship between I4.0 and L [10]. The literature has indicated the need for more studies addressing the integration between I4.0 and LSS [12].

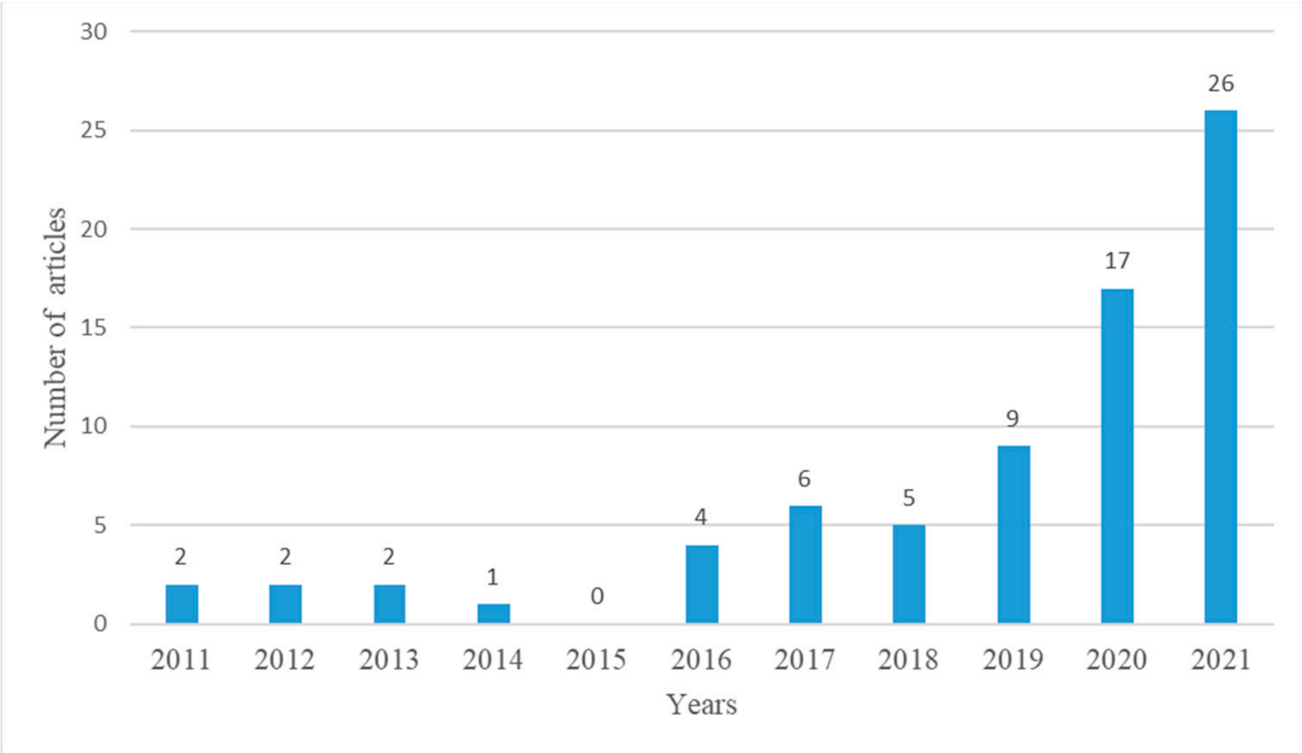

Figure 1. Journal articles on I4.0 and LSS integration per year.

Despite the growing interest in integrating I4.0 and LSS, only a few studies have attempted to synthesise and assess the related body of knowledge using standalone literature reviews [10,13–16]. For example, in [16], a systematic literature review (SLR) was performed to identify the contact points (CPs) between I4.0 and LSS. They identified 13 CPs in total and their corresponding technical requirements. More recently, in [10], a scoping review (SR) based on a combination of bibliometric and qualitative content analysis was conducted to encapsulate the literature on the combination of I4.0 and LSS and orient future research. In particular, they identified the synergies emerging from this combination, some success factors for implementation, and KPIs that may experience an improvement.

While these reviews provide significant value to the field, their focus has mainly been on assessing the relationships and synergies between I4.0, L, and LSS, identifying technologies and techniques involved in integration, and highlighting possible effects on performance. However, some critical aspects of the integration process still need to be comprehensively reviewed, synthesised, and assessed. In fact, one of the 'gaps' is related to the conditions that facilitate or hinder the integration process between I4.0 and LSS in companies. In this regard, the first research question (RQ1) to be addressed by this study is as follows: What are the main barriers and enablers when integrating I4.0 and LSS? Another aspect that requires attention in the literature is how the enablers of integration can be deployed independently (or together) to address the obstacles to integration. Consequently, the second research question (RQ2) to be addressed is: What are the possible approaches to facilitate the integration of I4.0 with LSS? Finally, although several authors have conducted case studies showing the Industry 4.0 technologies used in conjunction with LSS, a systematic review of these, which would allow for identifying the most used technologies in the context of integration, is lacking. Therefore, this article will address this gap by answering the following question (RQ3): What I4.0 technologies and LSS techniques/tools are commonly involved in integration?

The remainder of this paper is organised as follows. Section 2 presents the theoretical background of this study. Section 3 presents the study's research methodology and questions. Section 4 discusses the results of the review process. Section 5 identifies the main gaps and directions for future research. Finally, Section 6 presents the conclusions, implications, and limitations of the study.

2. Theoretical Background

2.1. Industry 4.0 Technology

Since its introduction in 2011, multiple authors have attempted to conceptualise Industry 4.0 [17]. However, to date, there has been no consensus on its definition. This fact makes it challenging to conduct academic studies on the topic [18] and has given rise to the incorrect assumption that I4.0 covers almost every technology. To shed light on this issue, we begin by reviewing some of the most cited articles that provide descriptions of I4.0. We then analyse these descriptions and identify a set of technologies that enable their implementation.

Table 1 summarises the descriptions of I4.0, listed chronologically, to show how this notion has been shaped over the years. From a pure technology perspective, these descriptions show that, at a fundamental level, I4.0 is characterised by the confluence of the concepts of the Internet of Things (IoT) and cyber–physical systems (CPSs) [5]. The IoT focuses on the interconnectivity of physical objects, allowing their communication and collaboration [19]. In this regard, wireless communication technologies can be seen as enablers of this concept. Cyber–physical systems are integrations of physical objects, cloud technology, and algorithms, which allow the analysis and control of physical processes [20]. In this regard, technologies that allow data collection from physical objects, such as radio-frequency identification (RFID) tags and sensors, can be seen as enablers of such integrations (i.e., CPSs). A similar argument can be made in favour of technologies that facilitate data storage from physical objects (in the cloud) and technologies that allow data analysis. Examples of the latter include (but are not limited to) Big Data and Analytics (BDA), machine learning, artificial intelligence, simulation, and digital twins [21]. Furthermore, the control dimension of the CPSs means that the "computations" can affect the physical objects being monitored (and vice versa) [22], leading to a need for actuators as part of such cyber–physical systems.

From the perspective of deployment, according to [5], I4.0 may be implemented in organisations through a combination of horizontal and vertical integrations, as well as the integration of engineering from beginning to end along the full value chain. Horizontal integration relates to the cooperation of information technology (IT) systems at different stages of the value chain, as well as their cooperation with the IT systems of other companies' value chains. Such cooperation entails security issues related to data and information sharing [23]. In this regard, technologies that enable secure data sharing, such as blockchain, are usually considered enablers of I4.0. In contrast, vertical integration relates to the hierarchical integration of IT systems, which requires the actuator and sensor signals to be fully integrated digitally across all levels, all the way up to the ERP level [5]. In this regard, systems for supervisory control and data acquisition (SCADA), manufacturing execution systems (MES), and enterprise resource planning modules (ERP modules) can be considered as part of the baseline technological infrastructure for I4.0 implementation.

Table 1. A summary of relevant works.

Authors	Description	Year	Article Citations
[5]	Industry 4.0, or the fourth stage of industrialisation, is a technological evolution in the manufacturing domain enabled by cyber-physical systems (CPSs) and the Internet of Things and Services.	2013	3825
[24]	"Industry 4.0 collectively refers to a wide range of current concepts, whose clear classification concerning a discipline as well as their precise distinction is not possible in individual cases. [...] Fundamental concepts are: Smart Factory, Cyber-physical systems, self-organization, new systems in distribution and procurement, adaptation to human needs, and corporate social responsibility".	2014	3806
[20]	"The term Industry 4.0 refers to the fourth industrial revolution and is often understood as the application of the generic concept of cyber-physical systems (CPSs) to industrial production systems (cyber-physical production systems)."	2015	139
[19]	Industry 4.0 is based on the principles of interconnection (i.e., a collaboration between physical objects and humans), information transparency (i.e., availability of digital data of the physical world and their exploitation using analytics), decentralised decisions (enabled by CPSs), and technical assistance.	2017	708
[25]	"I4.0 is aimed at creating intelligent factories where manufacturing technologies are upgraded and transformed by Cyber-physical systems (CPSs), Internet of Things (IoT), and cloud computing".	2017	1728
[26]	"Industry 4.0 represents the current trend of automation technologies in the manufacturing industry, and it mainly includes enabling technologies such as the cyber-physical systems (CPSs), Internet of Things (IoT) and cloud computing".	2018	1990

From a design perspective, in [19], I4.0 was characterised using the principles of interconnection, information transparency, decentralised decisions, and technical assistance. According to these authors, the latter characteristic is based on the notion that, in the "Smart Factory", the staff needs (1) technologies aggregating and displaying data for decision-making, such as smartphones and other wearables (e.g., augmented/virtual reality glasses) and (2) technologies automating time-consuming or safety-critical activities, such as robots.

The literature also shows that, despite not being technologies themselves, the IoT and CPSs are recurrently considered as such. Following a convention previously adopted in [21], in this research, we refer to the IoT as a "technology" for the sake of generality and refer to CPSs in terms of constituent technologies.

2.2. Lean Six Sigma

The origins of LSS date back to the early 2000s, when the principles of Lean (L) began to be integrated into Six Sigma (SS) [1]. While the emphasis of SS has been on variability minimisation and defect eradication, mainly in manufacturing [27], the primary focus of L has been on removing all Muda, or waste, from all places and processes inside the system [28]. Hence, both approaches can be considered complementary.

Different LSS implementation frameworks have been proposed in the literature, but so far, there has been no agreement on this or a definition [8,29]. However, there appears to be a consensus that, at a basic level, LSS implies adopting the problem-solving approach DMAIC (Define–Measure–Analyse–Improve–Control) and incorporating L and SS techniques in each phase of this approach [30,31].

Multiple tools and techniques are used as part of Lean and SS. According to the work in [23], the Lean techniques and tools with the highest synergistic connection with I4.0 technologies are value stream mapping (VSM), Lean office, visual management, just-in-time (JIT), heijunka, 5Ss, jidoka, kanban, cellular manufacturing, single-minute exchange of die

(SMED), total productive maintenance (TPM), and poka-yoke. Furthermore, according to [27], SS involves the use of the DMAIC approach for achieving operational excellence and DMADV (Define–Measure–Analyse–Design–Verify) for achieving excellence in the design process of new products and services (an area known as Design For Six Sigma), as well as the use of statistical tools, such as statistical process control (SPC), regression, design of experiments (DOE), failure mode and effects analysis (FMEA), and management tools, such as SIPOC (Suppliers-Inputs-Process-Outputs-Customers), Critical to Quality (CTQ) trees, or the Voice of the Customer (VOC), to name a few.

2.3. I4.0 and LSS Integration

Two recurrent ideas in the literature on integration are that (1) LSS creates the conditions for I4.0 implementation, and (2) I4.0 and LSS support each other during their respective deployments. Regarding the first idea, LSS tools and techniques facilitate the adoption of I4.0 technologies through process standardisation and human error reduction [32,33], as well as through process variability reduction [23]. Furthermore, using LSS techniques, such as VSM, can help select I4.0 technologies for a company, as these facilitate the identification of areas where these technologies can contribute the most [33]. Regarding the second integration perspective, I4.0 technologies can, for example, reduce the required effort to maintain L [34] and benefit SS by enabling the collection and analysis of large volumes of data in a shorter time [35,36]. Likewise, LSS can boost the performance of I4.0 during its execution by providing practical uses for the data collected (through I4.0 technologies) and facilitating their interpretation and analysis (see [10,37]).

Multiple examples of I4.0-LSS solutions have been proposed in the literature; however, most research has focused on I4.0 technologies that may support L techniques and tools [36,38–43]. For instance, [44] pointed out that the IoT is beneficial in conjunction with poka-yoke and Andon, ensuring “zero defects” in production. RFID tags and sensors may allow real-time data collection from the production process to feed the VSM [45]; in [43], the impact of JIT was stressed by integrating it with RFID, cloud technologies, BDA, and augmented reality (AR). With the help of these technologies, JIT can reduce inventory in production processes by monitoring materials and enabling accurate delivery within the system [41]. Furthermore, a study with 46 companies in India found that Machine Learning can effectively identify the correct level of manufacturing flexibility to guarantee a lean operation [46]. Regarding SS techniques, in [47], the benefit of integrating BDA with SPC was studied. According to the authors, it can quickly address quality and delivery issues by enabling data tracking. BDA and SS integration was also discussed in [35] and [48]. They pointed out its potential to handle data variability and complexity, and provide in-depth process knowledge, helping to improve decision-making accuracy. Finally, regarding Design-for-Six-Sigma, in [49], the authors showed how Artificial Neural Networks (ANN) could be used to enhance the performance of the DMADV approach through a case study. The reader is referred to [23] for more examples of I4.0–LSS solutions.

Other aspects of the integration that have received little or moderate attention in the literature include the contact points between I4.0 and LSS [16], reference architectures to enable integration [50], and the combined impact of I4.0, LSS, and Quality Management Systems (e.g., ISO 9001) on organisational performance [51]. Furthermore, in a review in [13], themes such as motivations, challenges, benefits, and critical success factors were identified as recurrent in the literature on I4.0 and LSS integration. However, in most cases, these themes have been addressed only from the I4.0 and L integration perspective or have appeared in the I4.0 and LSS integration literature as ancillary topics (as opposed to core topics), implying a need for a systematic review of them. To the best of our knowledge, only the benefits of integration have been addressed in recent work by [10]. Encouraged by this research gap, we propose a research design to systematically assess the literature on enablers of and barriers to I4.0 and LSS integration in the next section.

3. Methodology

This section describes the systematic literature review (SLR) approach used to answer the research questions. The SLR is based on a procedure that aims to ensure high levels of objectivity, precision, and clarity during the review process [52]. It consists of four stages adapted from the work reported in [53]: (1) research scope, (2) search limit setting, (3) article selection, and (4) result analysis and reporting, as shown in Figure 2.

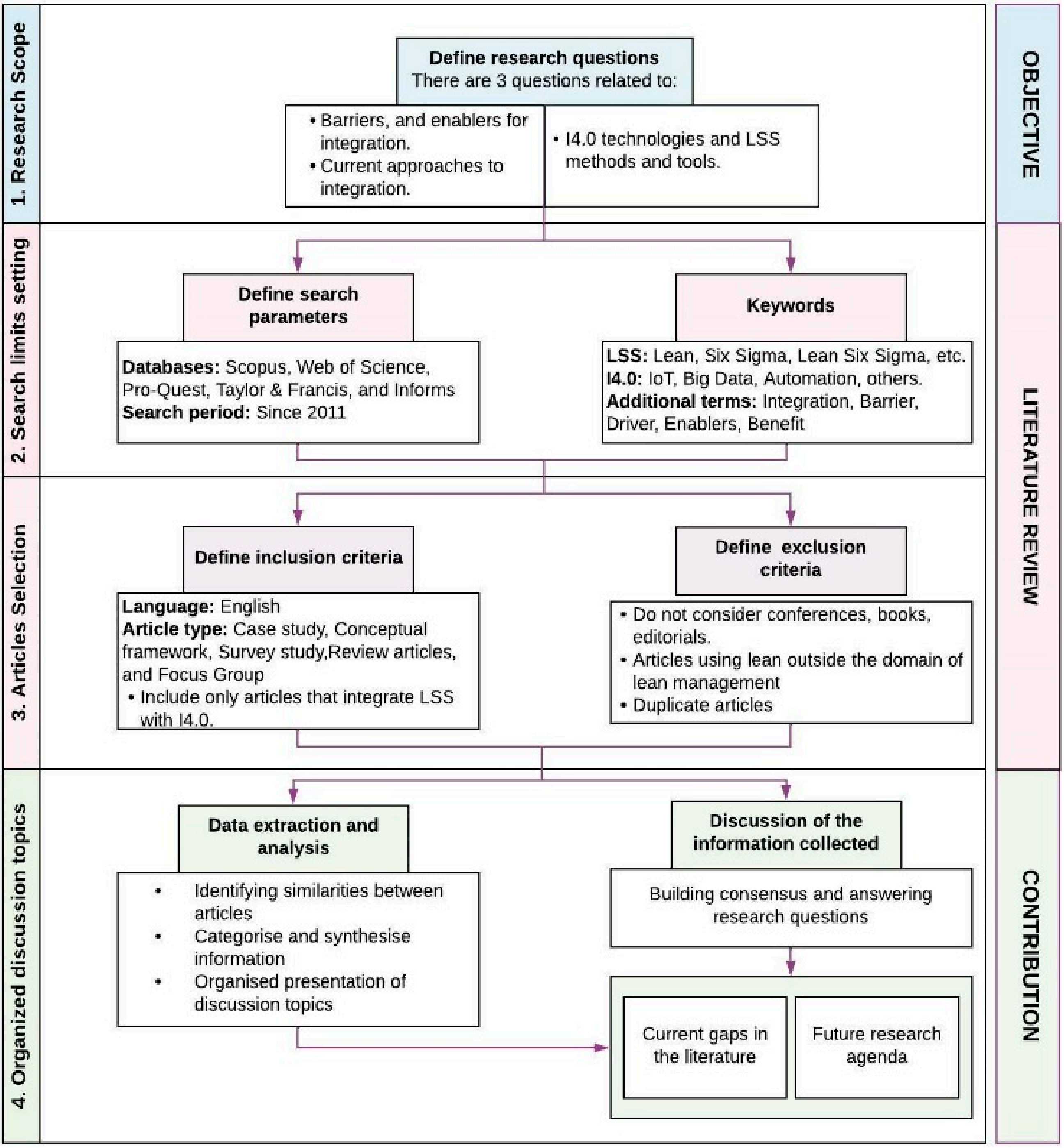

Figure 2. Literature review structure.

Scopus, Web of Science, Pro-Quest, Taylor & Francis, and Informs were selected for this study. Although LSS emerged around 2000 [8], I4.0 began in 2011 at the Hannover Fair [6,54]. For this reason, only peer-reviewed papers published since 2011 were considered.

Three groups of keywords were identified within the research scope. The first corresponds to the terms relating to I4.0 [11,44,55,56]. The second refers to LSS methods and tools [57,58]. The third category includes key terms that would help answer the research questions, as detailed in Table 2.

Table 2. Descriptions of research keywords.

Characteristics	Keywords
Industry 4.0	TITLE ("Industry 4.0" OR "the fourth industrial revolution" OR "I4.0" OR "Lean 4.0" OR "Smart manufacturing" OR "Smart maintenance" OR "Smart factory" OR "Cyber physical systems" OR "CPS" OR "Big Data" OR "automation" OR "RFID" OR "Cloud" OR "Simulation" OR "Artificial intelligence" OR "AI" OR "Internet of Things" OR "IoT" OR "IIoT" OR "Digital Twin" OR "Blockchain" OR "Robotic" OR "Autonomous systems" OR "System integration" OR "Cybersecurity" OR "Additive manufacturing" OR "3D printing" OR "Augmented Reality" OR "Manufacturing 4.0" OR "Quality 4.0" OR "Supply chain management 4.0" OR "SCM 4.0" OR "Data science" OR "Data analytics" OR "Data mining" OR "Data warehouse" OR "Predictive" OR "Digital transformation" OR "Logistics 4.0").
Lean Six Sigma	TITLE ("Lean" OR "six sigma" OR "lean six sigma" OR "lean manufacturing" OR "lean tools" OR "lean practices" OR "5S" OR "SMED" OR "TPM" OR "VSM" OR "Just in time" OR "JIT" OR "poka yoke" OR "heijunka" OR "andon" OR "one piece flow" OR "kanban" OR "SPC" OR "visual management" OR "Lean distribution" OR "Lean warehousing" OR "Lean transportation" OR "Lean logistics" OR "Lean SCM").
Additional terms	TITLE-ABS-KEY ("Integration" OR "Barrier" OR "Driver" OR "Enabler" OR "Success factor" OR "Benefits").

Search strings were created considering the terms shown in Table 2. Additionally, synonyms, alternative terms, and abbreviations were included in the search to avoid limiting the results. Once the articles were identified, a spreadsheet list was prepared to identify and eliminate duplicates.

The content of the selected articles was carefully examined to ensure that they met the inclusion and exclusion criteria. A thorough reading of the title, abstract, and keywords was performed to obtain a list of articles relevant to this research.

Two inclusion criteria were considered:

1. The paper must be in English and peer-reviewed. In addition, it must pertain to business case studies, review articles, survey studies, conceptual frameworks, and focus groups;
2. Articles must focus on applying I4.0 technology with an LSS tool or method.

The excluding criteria were as follows:

1. Exclude conferences and non-peer-reviewed articles, such as books and editorials;
2. Articles were excluded when "Lean" was used in a field other than the lean management domain;
3. Articles that considered technologies unrelated to I4.0 were excluded.

The snowballing technique was used to expand the results. In other words, the articles obtained from the search strings in Table 2 were examined for new relevant references (i.e., articles), and those meeting the inclusion criteria were added to the list of selected publications [59]. The resulting number of articles is shown in Figure 3.

The results of the SLR are divided into two sections presented below. Section 4 discusses the selected articles' main characteristics, the identified enablers of and barriers to I4.0 and LSS integration, and the proposed actions to help practitioners to achieve this goal. Finally, Section 5 identifies a set of 'gaps' in the literature, which may help to guide future research efforts on I4.0 and LSS integration.

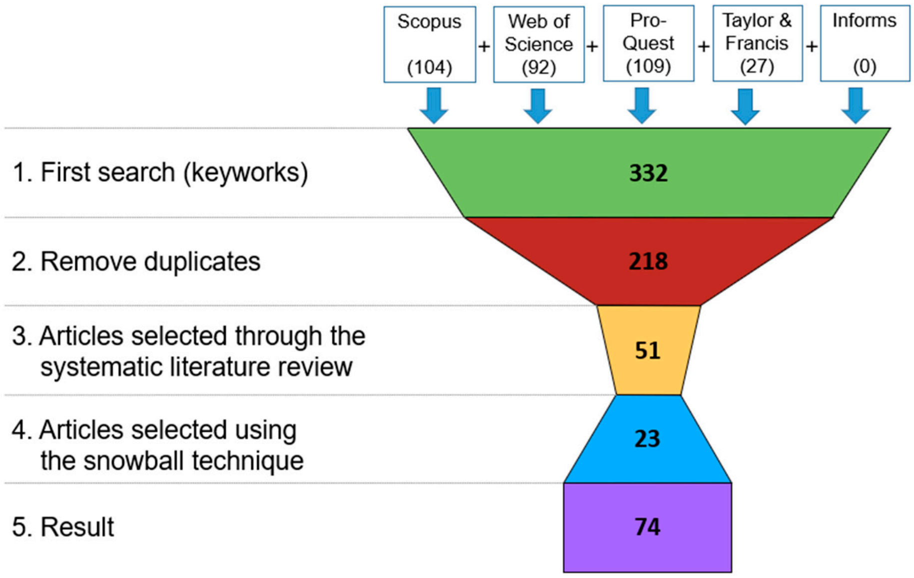

Figure 3. Search results summary.

4. Review and Discussion

Fifty-one articles containing information on integrating I4.0 and LSS were identified using the SLR. This result was expanded using the snowball technique, obtaining twenty-three additional articles, totalling seventy-four from 2011 to 2021, which served as the foundation for this study and are presented in Appendix A.

4.1. Analysed Papers' Main Features

In total, academic contributions from 22 countries were identified, as shown in Figure 4. The findings show that studies on I4.0 and LSS integration have mainly been carried out in Germany, Brazil, Italy (eight articles each), the United States (six articles), and China (five articles). In the case of Oceania, an analysis in [60] found that, from 2017 onwards, I4.0 has started to gain attention in companies; however, no journal article has addressed its integration with LSS in the industries of this continent so far, as shown in Figure 4.

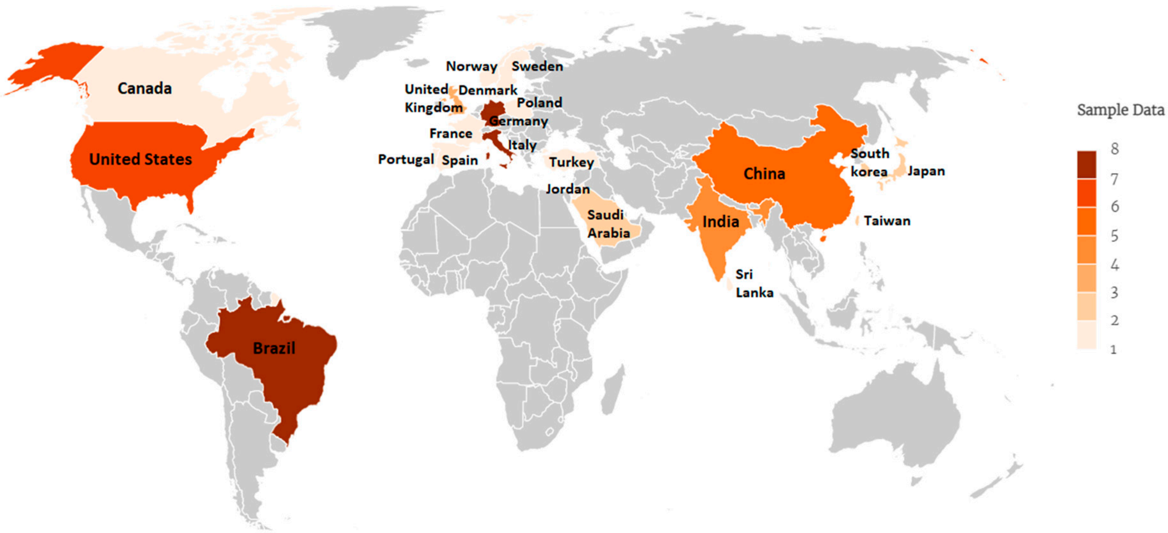

Figure 4. I4.0 and LSS integration research by countries.

Additionally, the industries concentrating most of the research on I4.0 and LSS were identified. As shown in Figure 5, metal mechanical (33.8%) and automotive (25.7%) are the two most addressed sectors, followed by food and beverage (17.6%) and construction (16.2%). The automotive sector is familiar with Lean manufacturing because of its origins with the Toyota car manufacturer [61], which places it in a favourable position to become a primary research source for I4.0 and LSS integration. Other sectors are grasping the importance of this integration in their organisations. One example is the healthcare sector, where integrating I4.0 and LSS may help improve patient flow and enhance supply chain performance, especially in high-demand scenarios [62]. Twenty-four industrial sectors were identified, with some papers addressing more than one (hence, percentages in Figure 5 do not add up to one). Nevertheless, 29.7% of the research did not mention the sector in their study.

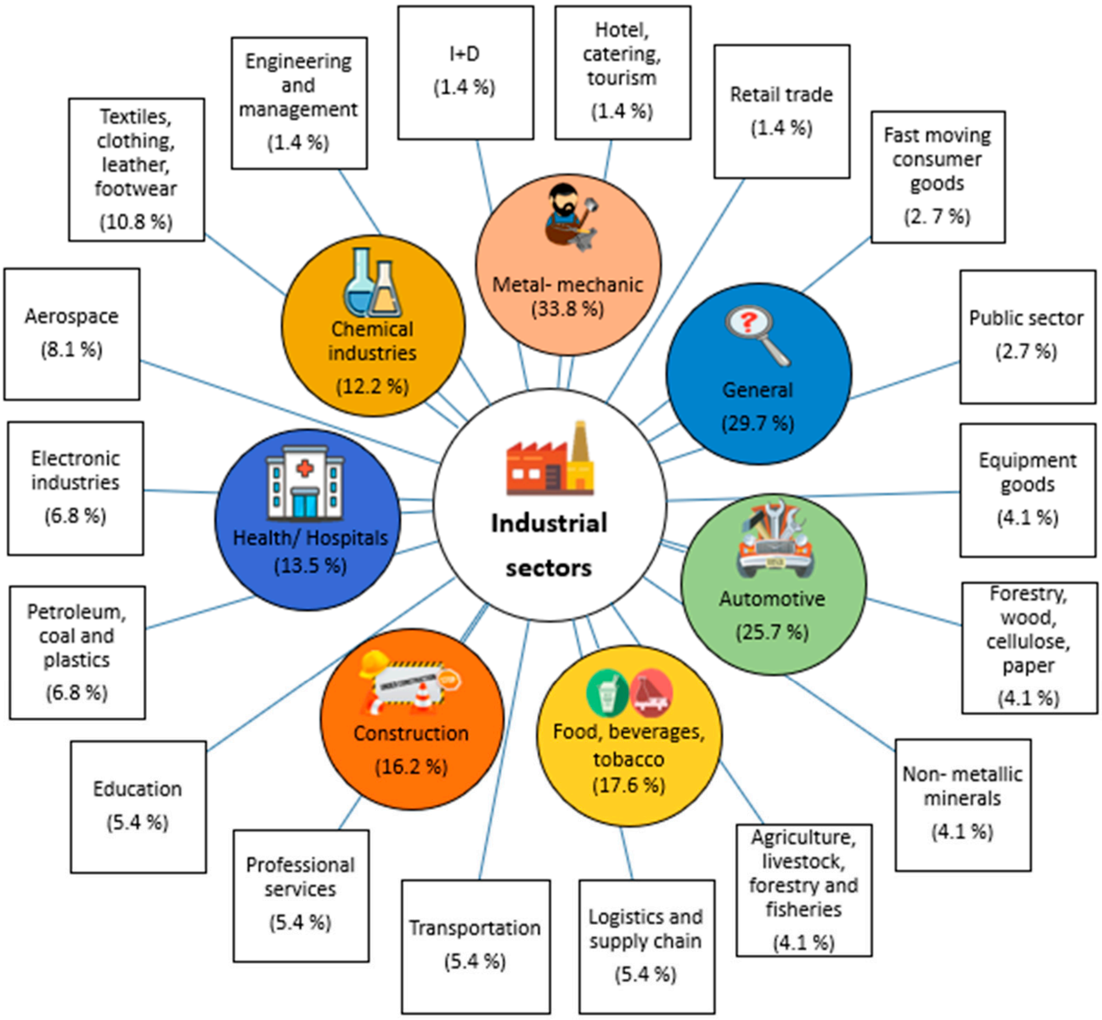

Figure 5. Primary industries identified by the reviewed articles.

Another aspect of interest is the type of research conducted in the reviewed papers. Case studies accounted for 39.2% of the research. For example, in [63], JIT and robotics in the automotive industry were analysed to optimise the cycle time in a hybrid (human–robot) assembly line system. It was found that 23.0% of the authors used the review method to address the interaction between I4.0 and LSS. Some studies assessed integration feasibility through surveys (21.6%) with the application of structural equation methods [35,40] and correlation and regression analyses [62,64]. Finally, 16.2% used conceptual frameworks and focus groups, as shown in Figure 6.

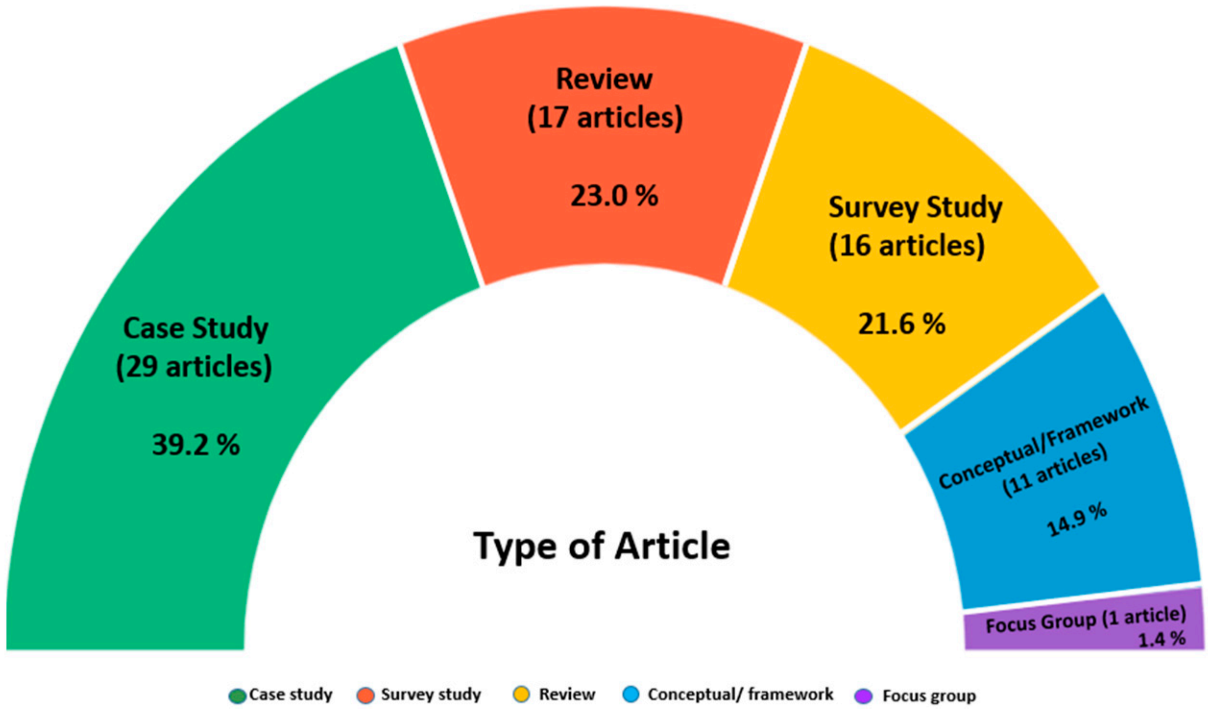

Figure 6. Primary industries identified by the reviewed articles.

4.2. Integration Enablers

This section discusses the enablers of the LSS and I4.0 integration. By enablers, we mean facilitators or factors that make integration possible [65]. Table 3 presents the categories of enablers determined through a literature review. These categories are discussed below.

Table 3. I4.0 and LSS integration enablers.

Category	Integration Enablers	Articles Considering the Enabler (%)
Collaborative culture	Involvement of employees and other stakeholders	22%
	Top management support and commitment	18%
	Availability and openness of company staff	4%
Strategic orientation	Investment in staff training	27%
	Investment in IT infrastructure	16%
	Integration of implementation approach with the business strategy	8%
	Mature understanding of I4.0 and Lean Six Sigma	4%
	High level of company maturity in the use of I4.0 and L	3%
	Availability of implementation patterns for integration	1%
Efficient operations	Simplified processes	5%
	Standardised processes	4%
External stakeholders' support	Regulations for the protection and security of company data	4%
	Subsidies and seed funding	1%
Interconnected IT systems	Interoperability of IT systems	14%
	Availability of reference architecture models	3%
	Flexibility of IT systems	1%
	Timely and accurate data availability	1%

Efficient operations—Although companies can directly implement I4.0 in their operations, the reviewed literature suggests improving process efficiency first [66]. This can be achieved by implementing L and SS tools/techniques before integration with I4.0 [33,67,68] and conducting process standardisation [23,33]. As a result, no inefficiencies in the process are automated, and no money is wasted [66].

Collaborative culture—An organisational culture involving employees, suppliers, and customers is a crucial enabler for I4.0 and LSS integration. According to [64], this can boost the workforce's empowerment and collaboration in problem-solving activities. In addition, employee empowerment, regardless of job position, is a crucial aspect that helps employees to engage in improvements and offer solutions based on their expertise [42,64]. Another factor that may facilitate I4.0 and LSS integration is management support. Indeed, [69,70] indicated that when top management creates a supportive learning and proactive working environment, it builds trust and loyalty in the work team.

Strategic orientation—Several strategic elements favouring the integration process have been suggested in the literature. For instance, in [23], the importance of implementation patterns for I4.0 and LSS integration was addressed. These patterns provide companies with information, for example, on I4.0 technologies to enhance the performance of LSS tools and techniques, and vice versa, as well as critical aspects to consider during the integration process. Another element that may facilitate overall integration is a solid understanding of I4.0 and L among company management [41,66,71]. This is an inherited enabler from the literature on Lean automation, encompassing aspects such as knowledge of I4.0 concepts, awareness of its related technologies, and understanding of the individual benefits of I4.0 and L. Furthermore, a high level of maturity in both approaches has been identified as an advantage for their integration [12]. Other critical factors favouring integration include linking the implementation approach to business strategies [39,42,72], investing in staff training [73] and IT infrastructure [72].

External stakeholders' support—According to [74], the policymakers' role is crucial in moving from a traditional production model to an innovative and sustainable one. In addition, external organisations can facilitate the integration process through initiatives to provide financial support for technology acquisition [75], and governments can help by issuing laws that guarantee the protection and security of company data [76].

Interconnected IT systems—From the work in [23] investigating the integration of I4.0 with LSS in Italian manufacturing companies, two characteristics of the IT infrastructure can be inferred as crucial enablers: interoperability and flexibility. By interoperability, we mean the capacity of the IT systems in the company's value chain to exchange and share data [77], whereas flexibility means their capacity to adjust to changes in the environment [78]. In particular, we consider these two measures as part of the features of a highly connected IT environment. Furthermore, from an IT system design perspective, another factor that appears to favour integration is the availability of reference architectures for I4.0 [23,50,79]. Reference architecture models are crucial for successfully developing IT system architectures because they provide well-organised templates with standardised terminology [80].

In addition to the five enablers discussed above, our review identified the I4.0-enabling technologies studied in the context of integration with LSS tools and techniques. These technologies can also be considered enablers of integration. The identified technologies are listed in Table 4 according to the percentage of case study articles and surveys that mention them. Although beyond the scope of this study, it is worth noting that, in the broader field of factory digitalisation, the additive manufacturing technology cluster was mentioned in relation to LSS in 27% of the articles reviewed [40–42,81].

Table 4. List of technologies enabling I4.0 and LSS integration.

I4.0 Enabling Technologies	(%)
Big Data	51%
Internet of Things (IoT)	43%
Cloud Computing Systems	35%
Radio-Frequency Identification (RFID)	35%
Digital twin/Simulation/CAD/BIM	27%
Robots/Automation	19%
Enterprise Resource Planning (ERP)	19%
Augmented Reality (AR)	18%
Digital Autonomation/Sensors	15%
Artificial Intelligence (AI)	9%
Virtual Reality (VR)	7%
Blockchain	1%
Wireless Sensor Networks (WSNs)	1%

4.3. Integration Barriers

Three barriers to integration were identified as the most recurrent in the literature: high implementation costs [32,44,45,82], technological incompatibility [36,83–85], and extended learning curves [75,86–88]. Other relevant barriers were identified and are listed in Table 5. The identified barriers were organised into the four major categories discussed below.

Table 5. I4.0 and LSS integration barriers.

Category	Integration Barriers	Articles Considering the Enabler (%)
Cultural suitability	Resistance to change	8%
	Insufficient management support	5%
	Short-term vision of company goals	4%
	Insufficient organisational communication	1%
	Low employee involvement	1%
Financial plausibility	High implementation costs	28%
	Lack of awareness of potential benefits	4%
	Long implementation time	4%
Operational viability	Long learning curve	16%
	Poorly structured, non-standardised processes	8%
	Insufficient data privacy/security	8%
	Data loss issues	8%
	Low level of experience and skills in LSS/I4.0	7%
	Significant changes in production processes	4%
	Workforce instability	1%
Technological feasibility	Technology incompatibility	18%
	Insufficient IT design and infrastructure	9%
	Matching and integration between different data sources	8%
	Massive volume of data to be managed	3%
	Lack of common communication protocols	3%

Cultural suitability—The literature highlights several barriers related to organisational culture, namely resistance to change [48,76,81], insufficient management support [61,87,88], and short-term vision [86,89]. Usually, the resistance to change during the integration process comes from the fact that an increase in automation is sometimes perceived as a threat to job stability [90]. In addition, changing the company KPIs in connection with the new data collected by I4.0 technologies is not always well received by staff [23]. As for the other two barriers in this category, their importance comes from the fact that, for the effective implementation of I4.0, a long-term vision, clear plans, and objectives must be set early on in the process [89], hence requiring significant management attention.

Financial plausibility—The high implementation cost associated with integrating I4.0 and LSS appears to be the most critical barrier, with 28% of the reviewed articles mentioning it. Adopting innovative technologies represents a considerable capital cost, and some companies may refrain from acquiring them [12]. Technology investments are critical, especially in sectors where products or services do not compensate for the (capital) costs generated [12]. Another aspect contributing to high costs is the length of the implementation process [23,91], which may depend on multiple factors, such as the size of the company, its current level of technology adoption, and the target level of integration, among others. A third obstacle is the lack of awareness of the potential benefits of integration [32,69,76], which manifests as uncertainty regarding the economic value of this process, making it difficult to justify the integration initiative financially.

Operational viability—Several process barriers to LSS and I4.0 integration have been mentioned in the literature. The first is the long learning curve [64,79]. The integration process implies using technologies and concepts for which the company staff may have little knowledge and experience, thus requiring a long training period. Furthermore, barriers such as workforce instability and frequent changes in production processes [43,89] may contribute to management's perception of this training period as costly and unworthy. The lack of process standardisation is a second component that appears to pose a challenge [12,23]. When processes are not standardised, it is well known that they are more likely to be inaccurate and unreliable [59,81], leading to financial waste. However, the lack of standardisation sometimes responds to the need for job flexibility and quality [92] which cannot be entirely avoided. Finally, companies' data privacy and security issues are also significant concerns [44,89]. These issues can be seen as a downside of the expected data availability, sharing, and transparency increases resulting from implementing I4.0 [93].

Technological feasibility—Barriers in this category include technical aspects affecting IT systems' horizontal and vertical integration in the context of I4.0 and their cooperation with LSS tools and techniques [81,83]. In this regard, insufficient or poorly designed IT infrastructure can be seen as the primary obstacle to this purpose [26,32,45,86]. As for horizontal/vertical integration, technology incompatibility is, by far, the most recurrent issue in the related literature [94,95]. Among the causes of this issue are the progressive adoption in manufacturing companies of IT systems from different software providers that cannot easily communicate with each other [23] and the absence of standard communication protocols between technology components [89]. Data integration appears to be a second technology barrier connected to the previous one [23,71,86,87]. Given the amount and variety of information sources that may be available in the context of I4.0 (e.g., machines, products, and software), combining the data so that they can be accessed anywhere and shared is a challenge that may affect a company's ability to collaborate with supply chain partners. The third challenge comes from the massive volume of data collected by I4.0 technologies. As noted in [23], some companies using LSS face the challenge of extracting insights from large volumes of data captured from their manufacturing processes. In this context, traditional statistical techniques are limited in their capacity to analyse data [14], implying a limitation in conventional SS applications that may make integration with I4.0 technologies impractical.

4.4. Approaches Facilitating Integration

This section discusses various ways to deal with I4.0 and LSS integration challenges. Based on the method introduced in [96], the approaches result from linking the enablers identified in Section 4.2 of this study to their corresponding barriers in Section 4.3, as shown in Figure 7. Following the convention adopted in [97], the arrows in the figure show which enabler categories have an advantageous effect on which barrier categories and the numbers on the lines correspond to the numerical identifier of each paper in Appendix A, directly or indirectly supporting such connections.

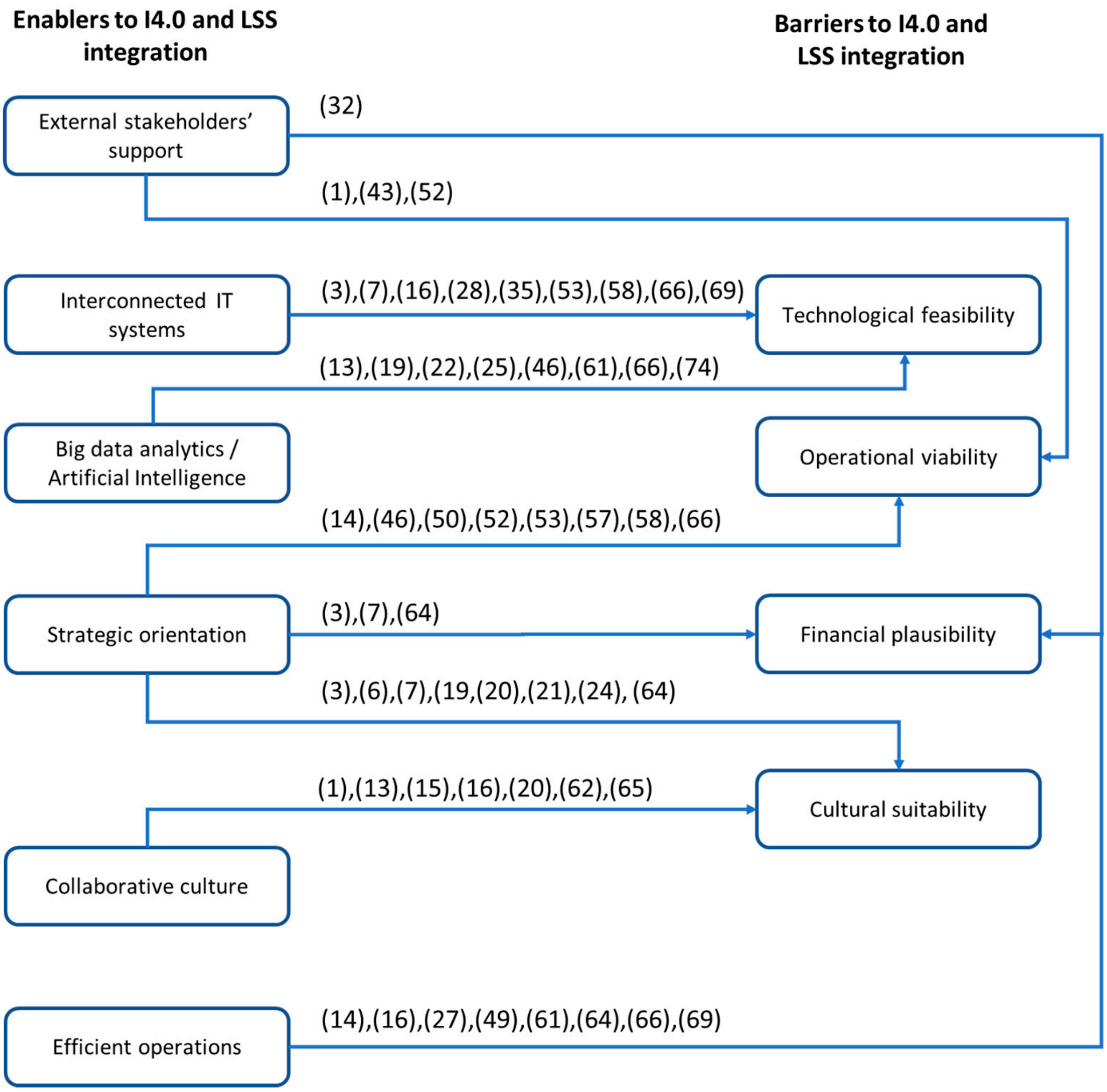

Figure 7. Connecting enablers to barriers for I4.0 and LSS integration (articles in Appendix A).

Cultural suitability issues are mitigated by employee involvement, training, and a good understanding of I4.0 and LSS. Solid knowledge of both approaches allows company management to understand the potential benefits of each in operational performance [41,66], which may increase their willingness to support the integration process. Moreover, it may help company management to understand the importance of a long-term vision when working with I4.0 and the value of employee training in the integration process. The latter, in particular, may boost empowerment and collaboration in the workforce [64], hence increasing employee involvement during the process. Furthermore, investing in staff training and good project management may reduce resistance to change during the integration process [91,98].

Operational viability issues are mitigated by taking a strategic orientation during the integration process. This can be achieved, for example, by linking the implementation approach to the business strategy [39,42,72] so that strategic actions (e.g., significant changes in production processes) can be considered as part of the I4.0 and LSS integration roadmap to avoid any adverse effects on the process. Regarding the low level of experience and skills in LSS and I4.0, integration patterns that show how other companies have managed the integration process can be valuable tools to address this limitation. An example of an integration pattern describing implementation considerations and examples of I4.0-based LSS solutions can be found in [23]. Another obvious mitigation action is investing in staff training, which can increase the administrative skill level inside the organisation and tackle the knowledge limitation [99]. Moreover, investing in staff training can help to reduce the learning curve. This barrier may also be mitigated by reducing the technical expertise required to deploy and run digital solutions [99]. Stakeholders outside the company can also help to tackle operational viability issues. For instance, regulatory norms from governments and other organisations may mitigate data-related challenges, such as misuse and confidentiality, which might affect the deployment of crucial technologies in I4.0, such as BDA [76].

Technological feasibility issues during integration can be reduced through actions aimed at building interconnected IT systems, which usually have characteristics such as flexibility and interoperability. For instance, the technology incompatibility barrier can be anticipated and avoided by building flexibility into the IT infrastructure since its conception so that it can adapt to future modifications in the working environment [78]. However, this may only sometimes be feasible in practice. In fact, as identified in [23], integrating I4.0 and LSS may require reconfiguring IT modules to share and exchange information. In this context, flexibility can be achieved, for instance, by adopting a modular reference architecture when developing I4.0-based LSS solutions. Modularity refers to the ability to break down a unit into parts that can be joined to create numerous configurations [77]. As a result, companies can more easily add new features (e.g., components) to the I4.0-based LSS solutions or combine them with other standalone digital solutions in an affordable way. Examples of reference architectures studied in the broad context of I4.0 and LSS integration can be found in [50,79]. On the other hand, integration issues between different data sources can be addressed by building interoperability within an IT system. This can be achieved, for example, by agreeing on a common set of communication standards [89], which can occur at the beginning of the I4.0 and LSS integration process. Examples of standards include, but are not limited to, constrained application protocols (CoAPs), message queue telemetry protocols (MQTT), and open platform communication–unified architecture (OPC-UA), with the latter receiving acceptance in I4.0 solutions [100]. Regarding the issues related to the analysis of the massive amount of data collected by I4.0, technologies such as big data analytics (BDA) and artificial intelligence appear to be valuable options when traditional statistical tools are not suitable [35,40,91,101].

Financial plausibility issues can be reduced by combining several of the enablers mentioned above. First, adopting LSS tools and techniques may eliminate non-value-added activities and variability in operations so that financial resources are not spent on automating process inefficiencies [23,66]. Second, costs in the horizontal and vertical integration of I4.0 technologies into the existing IT infrastructure (or with LSS solutions) may be reduced by building flexibility as discussed before, but also by using inexpensive technology components when developing digital solutions [99], such as those arising from integrating I4.0 and LSS. Examples of low-cost technologies and their combination to create solutions in the broader field of digital manufacturing can be found in [102,103]. Third, a solid understanding of I4.0 and LSS in company management may increase awareness of the integration's potential benefits, facilitating the project's economic justification (e.g., cost–benefit analysis) and viability [87,104,105]. Finally, external support in the form of funding for technology acquisition can help further reduce the barrier of high implementation costs, especially in Small-and-Medium-Sized Enterprises (SMEs) [75,99].

5. Identified Gaps and Directions for Future Research

5.1. Little Attention Has Been Paid So Far to the Integration of I4.0 Technologies and SS Techniques

Despite the growing number of publications linking the concepts of I4.0 and LSS, our review found that the vast majority have focused mainly on integration with Lean. As shown in Table 6, with the exception of SPC and DMAIC, most of the SS techniques, including FMEA, DOE, CTQ, SIPOC, and QFD, have received little attention in the context of integration with I4.0. Therefore, we see a significant opportunity for future research in this direction. For instance, it might be worth investigating how methods such as QFD and the Taguchi loss function might interact with digital twins, or how process capability and root–cause analyses could benefit from using sensors and microcomputers installed in the production process.

Table 6. LSS techniques and tools that integrate with I4.0, according to reviewed articles.

I4.0 Technologies	(%)
Just-in-Time (JIT)	49%
Value-Stream Mapping (VSM)	39%
Kanban	31%
Total Productive Maintenance (TPM)	30%
Flow Continuous	24%
Low Setup	24%
Pull	20%
Involved Customers	20%
Kaizen/Continuous Improvement	20%
Poka-Yoke	20%
Statistical Process Control (SPC)	19%
5S	19%
Developing Suppliers	18%
Involved Employees	15%
Jidoka	15%
Andon	14%
Define–Measure–Analyse–Improve–Control (DMAIC)	14%
Heijunka	12%
Supplier Feedback	11%
Total Quality Management (TQM)	9%
Visual management	9%
Failure Modes Effect Analysis (FMEA)	7%
5 Whys	5%
Human Resource Management (HRM)	4%
Controlled processes	4%
Design of Experiments (DOE)	4%
Critical to Quality (CTQ)	4%
Plan–Do–Check–Act –PDCA)	4%
Cellular Manufacturing	4%
Constant Work in Process (CONWIP)	1%
Suppliers–Inputs–Process–Outputs–Customers (SIPOC)	1%
Quality Function Deployment (QFD)	1%
Gemba	1%

5.2. Lack of a Case Study Quantifying the Benefits of the Integration

Although our review identified research focused on measuring the effect of I4.0 and LSS integration on company performance through surveys, future work could investigate the impact of such integration through case studies in the industry to complement previous findings. Of the twenty-nine case study articles from our literature search on integrating both concepts, twenty-six focused solely on I4.0 and Lean, excluding SS techniques. Thus, the economic value of a more comprehensive integration remains to be determined. Furthermore, case study research could evaluate the impact of such integration on the social and environmental dimensions of sustainability. Lastly, future case studies could help better understand the barriers and enablers by industry type and company size to gain a more specific perspective of the key factors involved in the integration process.

5.3. Studies on Implementation Patterns of I4.0 and LSS Integration Are Rare

Except for the work in [23], our review did not find any research addressing implementation patterns for I4.0 and LSS integration. Future research in this direction could address patterns in companies that have significantly progressed in the horizontal integration of I4.0 as part of the value chain, that is, towards the collaboration/cooperation of cyber-physical systems involving LSS tools and techniques. Similarly, it could address companies successfully deploying an end-to-end engineering approach in the value chain and the potential synergies of this with DMADV and DMAIC. Furthermore, given the difficulties associated with the vast volumes of data collected through I4.0 technologies, future studies on implementation patterns could also cover algorithms for data analyses currently used by companies in the context of integration between I4.0 and SS and practical uses of the information.

6. Conclusions

This article addressed the integration of I4.0 and LSS and the approaches that facilitate it. By conducting a systematic review of the literature, this article has attempted to capture the key barriers and enablers that need to be considered by practitioners during the integration process, as well as research gaps that require attention from academics. In order to operationalise the research findings, the enabling factors identified were linked to barriers to determine managerial actions that facilitate integration. In addition, a range of I4.0 technologies enabling the integration was identified, with BDA, IoT, cloud computing, and RFID as the four most recurrent in the reviewed literature. Consequently, this work offers significant opportunities for the LSS community.

On the other hand, the growing interest in this topic is interesting to observe. For example, we identified several articles illustrating how companies are combining L tools with I4.0 technologies and how some of these tools have been digitalised or automated. Similarly, we identified a few examples of SS techniques assisted by I4.0 technologies, with BDA being the most recurrent. As for examples of the integration of the I4.0, L, and SS, most case studies have been limited to incorporating L and I4.0 technologies within the stages of the DMAIC approach of SS. Therefore, combining I4.0 technologies with the tools/techniques of L and SS into unified solutions (e.g., a cyber–physical system) appears to be a reasonable next step.

Developing a clear notion of I4.0 and LSS integration is critical for this field. We see with optimism how the research has recently started determining patterns for the successful joint deployment of I4.0 and LSS, which will help to shape the notion of integration. However, we share the view of other researchers that a complete conceptualisation of this process and its benefits is still in the early stages. From a theoretical perspective, the notion of I4.0 and LSS integration is affected by legacy issues, such as the lack of agreement on the technologies that define I4.0, limitations in reference architecture models, and the absence of a universally accepted model of LSS, to name a few. Therefore, new conceptual developments in I4.0 and LSS may significantly impact the notion of integration. Furthermore, from an application perspective, case studies that show broader I4.0 horizontal integrations among the stages of a value chain (and among value chains) operating with LSS could greatly help companies to achieve process synchronisation. Finally, from a sustainability perspective, some aspects related to the economic, social, and environmental benefits of integrating I4.0 and LSS remain unexplored and need to be added to the future research agenda.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Final list of papers included in the literature review.

No.	Bibliographic Information
1	Ciliberto, C., Szopik-Depczyńska, K., Tarczyńska-Łuniewska, M., Ruggieri, A., & Ioppolo, G. Enabling the Circular Economy transition: A sustainable lean manufacturing recipe for Industry 4.0, 2021, 10.1002/BSE.2801
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5	Boudella, M. E. A., Sahin, E., & Dallery, Y. (2018). Kitting optimisation in Just-in-Time mixed-model assembly lines: Assigning parts to pickers in a hybrid robot–operator kitting system. International Journal of Production Research, 56(16). https://doi.org/10.1080/00207543.2017.1418988
6	Erkayman, B. Transition to a JIT production system through ERP implementation: A case from the automotive industry, 2019, 10.1080/00207543.2018.1527048
7	Parra, B. B., Cerra, P. P., & Peñín, P. I. Á. Combining ERP, Lean Philosophy and ICT: An Industry 4.0 Approach in an SME in the Manufacturing Sector in Spain, 2021, 10.1080/10429247.2021.2000829
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15	Sanders, A., Elangeswaran, C., & Wulfsberg, J. Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing, 2016, 10.3926/jiem.1940
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Table A1. *Cont.*

No.	Bibliographic Information
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25	Goh, M., & Goh, Y. M. Lean production theory-based simulation of modular construction processes, 2019, 10.1016/j.autcon.2018.12.017
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