Unleashing Industry 4.0: Leveraging Lean Practices to Overcome Implementation Barriers

Stefano Frecassetti, Matteo Rossini, and Alberto Portioli-Staudacher

Abstract—**Digitalization is underway and is a new way to make companies more competitive. However, it is a tortuous road where failure often arises. Lean management has been shown to be a significant element in the success of digitalization, particularly in driving and directing companies on their digital technologies implementation journey. Despite this, there is limited evidence of how Lean Management can facilitate the implementation of Industry 4.0 technologies. Intending to understand this facilitating role, this article investigates the relationship between different Lean practices and the most common Industry 4.0 implementation barriers. Relying on expert opinions, through the use of the interpretive ranking process methodology, a specific relationship between Lean practices and barriers has been depicted, showing that some practices have a major impact in reducing some specific barriers. In particular, the ones related to the elimination of waste and continuous improvement bundle are expected to be the most prominent. The implications of this study are both practical and theoretical, adding knowledge on how Lean can facilitate firms' digital transformation and set the base for further research.**

Index Terms—**Barriers, digital technologies, interpretive ranking process (IRP), Industry 4.0, Lean.**

I. Introduction

In recent years, many events have impacted the global economy, which has affected several companies' competitiveness and performance. Disruptive events, such as COVID-19, have completely changed how companies compete, forcing them to move toward new paradigms, such as digitalization [1]. Companies must adapt and evolve to stay relevant and competitive in todays' constantly changing business landscape [2]. Evidence shows how being up to date, both from a managerial and technological perspective, enhances companies' competitiveness and facilitates their survival during disruptive events [3]. In this sense, using the latest technologies is fundamental because it can strengthen resilience and improve firms' performance [4]. In recent years, increasing interest has been given to the paradigm of Industry 4.0, which includes several innovative digital technologies. We can observe the Internet of Things (IoT), blockchain, augmented reality (AR), autonomous robots, and simulation and cloud computing [5]. When fairly implemented, these technologies can substantially benefit firms' performance, both from an operational level and from a business and financial one [6]. However, several issues that companies can face throughout the implementation process can lead to longer implementation, time, failure to meet expected results, or lack of performance improvement [6]. These facts can happen due to nonoptimal and structured implementation processes [7] and some implementation barriers, which can hamper fulfilling the objectives mentioned above [6], [8]. Those barriers can have different characteristics; they can be operational [6], [9], [10], financial [6], [9], or cultural [6], [9]. Knowing these barriers and their effect is of fundamental importance for companies and managers to drive the digitalization process and successfully implement the selected technologies [11]. Among the others, one of the main aspects managers should focus on is the cultural one, which is deemed one of the most relevant ones to guarantee the success of any firms' digital transformation [12]. For instance, an organization that is used to continuously changing and adapting to the external environment and market needs could be one in which the digital transformation will go smoothly [11]. In contrast, companies which are less adaptive and more keen on the as-is are the ones in which the cultural aspect can play a significant negative role [7]. In this sense, using the right managerial practices and levers plays a fundamental role [13]. In fact, there is evidence of how some practices facilitate the digital transformation process, especially in the manufacturing environment [14]. Among the others, Lean Management is a case in point [7]. The term Lean was coined in the nineties to identify and share the management paradigm used in Toyota [15], also known as Toyota Production System (TPS). Based, among others, on the continuous improvement philosophy [16], the bottom-up approach and the pull production system, Lean Management is well known [17] and applied worldwide, giving, in many cases, beneficial outcomes [18]. Lean Management has evolved throughout the years, and its practices, such as value stream mapping (VSM) [19], have been integrated and improved with digital technologies. This fact has become even more relevant with Industry 4.0, where it has been noticed that Lean companies have greater benefits from the Industry 4.0 technologies implementation rather than non-Lean ones [21], [22]. Notably, from an operational perspective, researchers see Lean as a fundamental prerequisite to implementing and exploiting Industry 4.0 technologies [22], [23]. Also, from a

Manuscript received 2 October 2023; revised 9 February 2024; accepted 25 April 2024. Date of publication 3 May 2024; date of current version 5 June 2024. Review of this manuscript was arranged by Department Editor J. Antony. *(Corresponding author: Stefano Frecassetti.)*

The authors are with the Department of Management, Economics and Industrial Engineering, Politecnico di Milano, 20156 Milano, Italy (e-mail: stefano.frecassetti@polimi.it).

Digital Object Identifier 10.1109/TEM.2024.3396448

more managerial perspective, some studies highlighted how Lean companies face a more simple and successful digital transformation process [14]. This could be justified by the embedded features of Lean organizations, which are usually prone to change [25]. Even though there is some evidence [24], why and how Lean supports the digital transformation process is still an open debate [26]. This article aims to contribute to this body of literature investigating how Lean practices (LPs) could help firms' digital transformation overcome Industry 4.0 implementation barriers. By knowing these facts, this study seeks to answer the following research question: "Can Lean Practices break down Industry 4.0 barriers?" This article will showcase the relationship between a selected set of LP and the most relevant Industry 4.0 barriers performing an interpretive ranking process (IRP) analysis. The rest of this article is organized as follows. A theoretical background on the two domains will be presented in Section II, followed by a detailed explanation of the chosen methodology in Section III. Then, in Section IV, the findings will be shown and discussed in Section V. Finally, Section VI concludes this article, with the limitations and the proposed future research lines.

II. Theoretical Background

A. Industry 4.0

Technological evolution has profoundly marked the course of global industries and economies in the contemporary era. This phenomenon represents a crucial turning point, where digital technologies, artificial intelligence, the IoT and advanced connectivity come together to transform production processes and the nature of work radically [27]. The proliferation of new technologies has created an increasingly interconnected world, leading to the fourth industrial revolution, Industry 4.0 [28]. Industry 4.0 was first defined at the Hannover Fair in Germany in 2011 [29]. It describes an industry characterized by connected machines, intelligent products and systems, and interconnected solutions [29]. The adoption of this paradigm by firms allows the integration of cyber and physical systems, leading to the emergence of the so-called smart factories [30]. This revolution stands out as an element of change and renewal capable of redesigning production assets, resource management, the value chain, and the competitive dynamics of companies [31]. In this respect, Industry 4.0 strives for dynamic and autonomous production, which embeds information and communication technologies (ICT) to meet the typology of todays' market demand, i.e., mass customization [32]. Sony [30], stated that in terms of effectively addressing customer expectations, Industry 4.0 will have a significant long-term and short-term strategic influence on global markets for manufacturing and services. The roots of this transformation lie in the digitalization process that has marked the last decades, enabling the collection, sharing, and analysis of huge amounts of data. When properly processed, such data proves to be a key infrastructure for the emergence of increasingly intelligent and efficient production processes [27]. The pervasive connectivity provided by the IoT enables real-time communication between machines, systems, and devices, paving the way for a new era of continuous monitoring, control, and adaptation of industrial activities [33]. In parallel, artificial intelligence and machine learning enable machines to learn from data and make autonomous decisions [34], accelerating process automation and improving operational accuracy [5], [35]. These characteristics directly impact digitalized manufacturers, i.e., to maintain and create a sustainable competitive advantage in operations management and manufacturing productivity [3]. Industry 4.0 has been one of the most often debated subjects among practitioners and academics in recent years. Nevertheless, there has yet to be an official definition of the paradigm, not allowing companies to adopt a univocal process for adopting the latter [28]. Hermann et al. [36] provided six design concepts that might assist firms in finding potential pilot projects to close that gap, i.e.,

1) interoperability;
2) virtualization;
3) decentralization;
4) real-time capability;
5) service orientation;
6) modularity.

However, the transformation linked to Industry 4.0 is not limited to technology; it also penetrates the economic and social framework. The interconnection of production elements on a global scale makes it possible to create highly flexible and efficient production and distribution networks, breaking down geographical barriers and opening up new frontiers for collaboration between companies [37]. Digital transformation affects both production modalities and the nature of human work, requiring adaptation of skills and favouring new perspectives for human–machine interaction [38]. With a broader vision, [39] defines three kinds of integration in the Industry 4.0 paradigm, i.e., 1) horizontal integration, 2) vertical integration, and 3) end-to-end engineering integration. Horizontal integration involves integrating value networks to facilitate collaboration across businesses or organizations in the value chain [40]. Vertical integration merges several hierarchical subsystems to establish a flexible and changeable production system [30]. Through end-to-end engineering integration, customized goods and services may be produced at every value chain stage [41], [42].

B. Industry 4.0 Barriers

In the current turbulent environment, the application of Industry 4.0 is considered an appropriate solution to address contemporary issues, such as shortened technology and innovation cycles, increasing customization, and enhanced demand volatility [43]. In addition, Industry 4.0 in the literature is promised to improve efficiency and flexibility and decrease time-to-market and excess production. However, Kagermann et al. [29] also identified implications for changing workforce qualifications, data security concerns, and expiring business models. However, the benefits and impacts of adopting Industry 4.0 still need to be improved due to the contradictory outcomes of researchers, consultants, politicians, and practitioners [43]. Indeed, the research made by McKinsey and Company [44] highlighted that six out of ten manufacturers interviewed face implementation barriers for Industry 4.0. These barriers have proved to be largely relevant in that manufacturers' progress achieved in one year is limited or nonexistent. In addition, they demonstrated that there are some barriers specific to manufacturers with no or limited progress in Industry 4.0 (e.g., lack of necessary talent and cybersecurity concerns when working with third-party providers). Additional barriers are mentioned by more advanced manufacturers, such as concerns about data ownership challenges with integrating data from disparate sources to enable Industry 4.0 applications. Moreover, Leipzig et al. [45] found out that, although most companies have recognized the importance of digitalizing, some challenges are inhibiting companies from starting or benefitting from the digital transformation journey [46]. Specifically, the Industry 4.0 barriers that are the most mentioned by the companies interviewed include insufficient IT structures, lack of technical skills, inadequate business processes, and high implementation risks and costs [45]. From these works, it is clear how the barriers are many and different: They can be internal barriers, which means inside the firm's boundaries or external ones. Among the internal barriers, it is possible to find different categories, such as shortage of resources [43], [47], [48], [49], organizational resistance [11], technology risks [11], [43], lack of managerial support [11], and lack of knowledge/skills [11], [43], [44]. On the other hand, the external barriers are still important because they can greatly impact the firms' digital transformation. Among them, we can find three main categories: security-related risks [11], [43], [44], technology integration [39], [43], [50], and environmental ones [43], [44]. Many researchers, consultants, politicians, and practitioners agree that the environment in which all the companies compete is changing. In this regard, Horvath and Szabo [11] pointed out that the intense market competition and pressure from competitors characterizing the market nowadays are additional driving forces for adopting Industry 4.0. Specifically, they suggest that the market share and the competitive advantage could be increased through innovative developments based on Industry 4.0 technologies. Consequently, it is extremely important to understand the barriers that prevent companies from adopting Industry 4.0 technologies in their processes and how to cope with them.

C. Lean Management

Within the context of production and business management strategies, the concept of Lean Management emerges with clear relevance as one of the most influential managerial philosophies of recent times, aimed at maximizing efficiency, eliminating waste, and optimizing resources [17], [18], [25], [51], [52]. Initially born at the end of the twentieth century as part of the TPS [53], it has been the dominant manufacturing paradigm in the previous decades in the United States of America and Europe. Lean Management quickly transcended the boundaries of the automotive industry, spreading across multiple manufacturing sectors and becoming a cornerstone of modern operations management [18], [54]. Lean has been defined as a set of management principles and techniques geared toward eliminating waste in the manufacturing process and increasing the flow of activities that, from the customers' perspective, add value to the product [55]. These different techniques, also known as Lean management practices, encompass a collection of methods to enhance productivity and decrease manufacturing expenses [27], minimize ecological footprints [56], [57], and improve social sustainability [58], [59]. This perspective is echoed in many works such as the one by Kamble et al. [33]. Shah and Ward [25] defined ten underlying dimensions starting from 48 items representing Lean. The application of Lean Management practices was initially considered only within the production boundaries; however, more recently, it has been widened throughout different industries [60] and the whole supply chain [61]. In this sense, the extension of Lean principles and practices to the supply chain has been called Lean supply chain [61]. Therefore, due to the benefits provided to manufacturing environments, incorporating Lean principles and practices into the supply chain has culminated in differentiated results along the supply chain, surpassing those already achieved by the organizations individually [62]. According to this definition, other researchers tried identifying the most relevant LPs from a more holistic perspective. Jasti and Kodali [63] identified a framework in which eight pillars were depicted. From this, some authors [64], [65] selected the 22 LPs most cited in the studied literature and created and validated four bundles of interrelated and internally consistent LPs. These four bundles are as follows:

1) customer-supplier relationship management (CSRM);
2) logistics management (LOM);
3) elimination of waste and continuous improvement (EWCI);
4) top management commitment (TMC).

Given the increased competition in recent years, implementing LPs at a wider level has become fundamental [66], [67]. The competition is moving from a firm level to a supply chain one; thus, it is not enough anymore to be efficient only inside the boundaries of a single company [68], [69]. Rather, the whole supply chain needs to be efficient to be competitive in the market. Hence, implementing LPs has become a relevant competitive advantage and an effective way to improve performance. Besides this, applying LPs as a standalone managerial paradigm has resulted in being confined to the business scenario [70]. Therefore, implementing Lean along the supply chain needs to be complemented with further concepts or tools, such as the triple bottom line or the Industry 4.0 paradigm.

D. Lean Management and Industry 4.0

In the ever-evolving landscape of manufacturing methodologies and technologies, amalgamating traditional practices and emerging innovations often leads to transformative outcomes. Its core principles have proven effective across industries, driving enhanced productivity, flexibility, and innovation [17], [18], [25], [51], [52]. Lean management initially stood in contrast to ICT dependency. However, the relentless march of progress in ICT solutions has triggered a paradigm shift. Researchers have begun exploring the potential synergy between Lean principles and advanced ICT, driven by the common overarching goals of heightened productivity and flexibility [31]. Throughout the years, Lean management has continuously embraced collaborations with other technologies. This integration has continuously evolved from material requirements planning [71], [72] to early digital solutions. The emergence of Industry 4.0 has reinvigorated this synergy, amplifying its transformative potential. The concept of Industry 4.0, characterized by its intelligent automation and data exchange, aligns seamlessly with Lean principles to drive efficiency and adaptability. This union goes beyond operational performance enhancement, extending its positive impact on working conditions and innovation across industries. Contrary to misconceptions, Industry 4.0, a revolution marked by the fusion of digital technologies, the IoT, and cyber-physical systems, is not a replacement for Lean Management. Instead, it enhances the maturity of Lean programs within firms [28], [73]. In the literature, three different schools of thought were identified [28], which were related to Lean Management and Industry 4.0. First, many studies [74], [75], [76] have considered Industry 4.0 and Lean as mutually supportive, where Lean methods are seen as facilitators of Industry 4.0, whereas Industry 4.0 is analyzed as a factor strengthening Lean. In this sense, Lean and Industry 4.0, despite with different approaches, can and should be complementary since they have the same goal of reducing costs and increasing productivity for companies. Therefore, as Industry 4.0 technologies unfold, Lean automation or Lean 4.0 concepts emerge as a significant aspect of this transformation. As studied by Tortorella and Fettermann [32], manufacturing companies have integrated Industry 4.0 and Lean principles. This integration signifies a dynamic shift toward smarter and more efficient manufacturing processes. Lean tools find a harmonious connection with Industry 4.0, as highlighted by Shahin et al. [77]. This integration does not negate the essence of Lean principles; instead, it complements and enhances them, aligning the operational philosophy with the technological revolution.

On the other hand, the second branch argues that digitalization significantly impacts the implementation of Lean along the supply chain [27], [78]. The convergence of these two paradigms facilitates LPs to flourish alongside advanced technologies. Sanders et al. [27] emphasized that Industry 4.0 is an enabler for Lean Management, with its research activities fostering performance improvements. Frecassetti et al. [79] highlighted how simulation can be used to evaluate the impact of LPs before their implementation, thus leading to an improved and eased implementation phase. Pagliosa et al. [38] reinforced this perspective, showcasing the positive association between LPs and Industry 4.0 technologies. The third group of authors claim that Lean could become a facilitator in the implementation process of Industry 4.0 since the Lean work environment creates a culture more receptive to new technologies [80], [81]. Even though, according to Mayr et al. [82], the existing body of research acknowledges the potential advantages of integrating Lean and Industry 4.0, they have yet to deeply investigate how Lean Management facilitates the implementation of Industry 4.0 technologies. In fact, some studies have explored the link between specific practices and technologies from a high perspective [26]; others instead used a very narrow perspective focusing on specific implementation cases [83], [84]. Other authors pointed out that they confirmed this facilitating relationship from a theoretical perspective. However, on the other hand, they hypothesized an effect on the implementation barriers reduction, suggesting further empirical cases to validate that effect [24]. Therefore, this article aims to investigate the punctual interactions between the LPs and Industry 4.0 barriers. In particular, with this article, the authors will try to answer the following research question: "Can Lean Practices break down Industry 4.0 barriers?" By using the IRP methodology, this article will investigate the externalities, mainly positive, that the implementation of one paradigm produces on the other by looking at how and which LP can break down the Industry 4.0 implementation barriers.

III. Methodology

This section will provide all the relevant information related to the methodology used for answering the research question and fill the literature gap explained above. All the methodological steps will be thoroughly explained, along with the data collection and analysis procedures.

A. *Interpretive Ranking Process*

The methodology chosen for filling the highlighted gap is the IRP analysis. Developed by Sushil [85], "the IRP is a novel ranking method that combines the analytical logic of the rational choice process with the strengths of the intuitive process at the elemental level" [85]. It uses an interpretative matrix as a basic tool and compares the matrix elements pairwise. Thus, this technique builds on the strengths of pairwise comparison approaches to minimize cognitive overload [85], [86], [87], [88], [92]. As a ranking method, the IRP combines the rational choice process's analytical logic with the intuitive process's strengths at the elemental level [85]. As some authors [85], [89] pointed out, the IRP creates new knowledge during the ranking process. This new knowledge is useful for future decision-making because ranking variables to certain criteria is crucial to any management decision-making. Other classical classification ranking techniques, such as analytic hierarchical process, analytic network process, and interpretive structural modeling (ISM), do not have this capability. Indeed, contrary to the traditional paired-comparison analytic hierarchy process [90], wherein the interpretations of the experts' judgments are not explicit to the implementer, IRP requires that the dominance of one factor on another is exclusively interpreted, and thereby mitigates the possibility of biased judgments [91]. In addition, through the IRP technique, it is possible to identify three characteristics for each variable analyzed. Specifically, rank, driving power, and dependence power could be identified for each variable to determine and prioritize the most impacting variables. The IRP technique has additional advantages over other ranking methods. Indeed, the IRP method can rank one variable according to another [85], [92], whereas other ranking methods only rank one variable. In addition, IRP makes it easy to compare the interaction of variables to a set of performance parameters or different sets of variables rather than to compare the variables abstractly [85], [92].

B. *Interpretive Ranking Process Steps*

A sequence of steps required to deploy the IRP successfully is explained in detail below, while the graphical scheme is provided in Fig. 1.

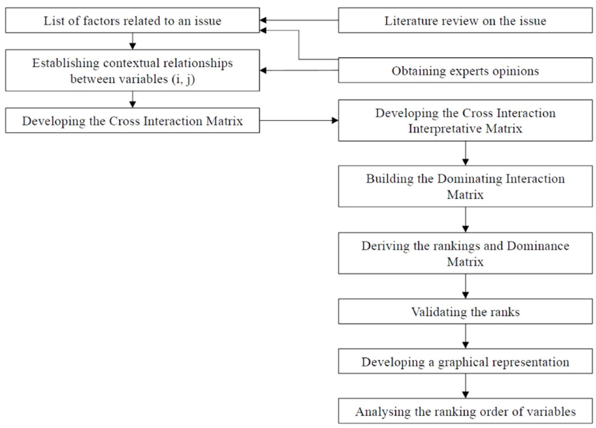


Fig. 1. IRP methodological steps.

1) *Step 1:* Identification of variables. The first step to implement the IRP technique is to list the two sets of variables that should be investigated. Indeed, it is necessary to rank one set of variables with the other [92].
2) *Step 2:* Definition of the contextual relationship. The further step in the IRP method is to identify the contextual relations between the two sets of variables identified in the previous step. Specifically, this step should work closely with experts to discuss and clarify these contextual relations.
3) *Step 3:* Development of cross-interaction matrix based on the experts' opinions. A cross-interaction matrix is developed using one set of variables as rows and the other as columns. The population of the matrix could be obtained using binary numbers according to the following:
 - 0 if the variable in the row does not impact the variable in the column;
 - 1 if the variable in the row impacts the variable in the column.
4) *Step 4:* Development of cross-interaction interpretative matrix. Once the cross-interaction matrix has been developed, there is the need to interpret the relationships identified in the matrix by the binary number 1. This interpretation should be made with experts [93] that could provide interpretations based on their practical experiences and rich knowledge. When there are different opinions about the interpretation of a relationship, several rounds of discussions occur until a consensus is reached. No action is required for the relationship in the cross-interpretative matrix characterized by the binary number 0. Indeed, the empty cells of the cross-interaction interpretative matrix correspond to the cells with a value of 0 in the cross-interaction matrix.
5) *Step 5:* Development of the Dominating Interaction Matrix. The interpretative matrix serves as the base to compare the factors regarding the reference variables [10] to identify the level of importance. The interpretive logic of dominating interactions between each pair of factors with the different criteria parameters is applied in this step. The pairwise comparison conducted here is different in that the variables in the rows are not compared directly. Rather, their interactions with the variables in the columns are compared. More specifically, the pairwise comparison determines the more important variables in the rows and the less important ones in each variable in the columns. The dominating interaction matrix summarizes the dominating interactions thus obtained.
6) *Step 6:* Development of rankings and dominance matrix. The dominance matrix summarizes the dominating interactions. Each matrix cell contains the number of variables or cases for which a variable dominates or is dominated by another variable. The sum along each row provides the total cases for which a variable dominates other variables. In contrast, the sum along each column provides the total cases for which the others dominate a variable. The difference between the corresponding row total and column total gives the net dominance for each variable. Then, the variables are ranked according to descending net dominance.
7) *Step 7:* Validation of ranks. This step requires a dominance system graph for each variable on the columns. The first set of variables in each of these graphs must be represented and connected with arrows, each representing a dominating relationship. The validation criterion assesses that each graph's flow is unidirectional with transitive relationships among arrows. When this is not respected, a loop has been created. Therefore, there must be an intransitive arrow between these variables. In the case of a loop, the dominating relationship between the two variables needs to be revised and modified. Based on such modification, dominating interaction matrix and dominance matrix need to be modified, and the new ranks are to be elaborated.
8) *Step 8:* Development of a graphical representation. The obtained ranking is represented diagrammatically as an interpretive ranking model.
9) *Step 9:* Analysis of ranking order of variables. The ranking order is interpreted for recommending actions.

C. Variables Selection

1) LPs Selection: LPs and, in general, Lean Management are very well-known and studied topics, and it is possible to consider these topics as mature ones. Knowing this, the authors decided to start from already known and sound papers in the literature. This could also lead to more understandable, reliable and robust practice selection and study results. Second, this allowed the authors to select the most relevant practices and keep only an adequate number of them, given the embedded limitations of the chosen methodology. Specifically, it has been decided to start from the analysis conducted by Tortorella et al. [64], in which they selected the most relevant LPs. In the articles they analyzed, 22 were the LPs most quoted in the literature. Considering the final aim of this article, the characteristics of the four different bundles, and the limitations of the methodology, the authors have obtained 13 LPs. Hence, to be coherent with the interaction of the barriers to the implementation of the Industry 4.0 technologies, two bundles were more related to the operational features of the

Lean paradigm (LOM and EWCI). Consequently, CSRM and TMC are more related to the strategic one; thus, they were not included in the analysis. The largest amount of the selected LPs belong to the LOM bundle [64], which are as follows:

P1 - Efficient and continuous replenishment: [61];
P2 - Material handling systems: [61];
P3 - Standardized work procedures to assure quality achievement: [61], [94];
P4 - Open-minded and in-depth market research conducted jointly: [95];
P5 - Inbound vehicle scheduling: [96];
P6 - Outbound transportation: [61];
P7 - Establishment of distribution centers: [97];
P8 - Functional packaging design: [64], [65].
The remaining part of the selected LPs belong to the EWCI bundle are as follows:
P9 - Kanban or pull system: [61];
P10 - Leveled scheduling or Heijunka: [61], [98];
P11 - Consignment stock: [99];
P12 - Win-win problem-solving methodology: [98];
P13 - Value chain analysis or VSM: [100].

2) Industry 4.0 Barriers Selection: Contrary to LPs, the Industry 4.0 paradigm and its technologies are a more recent domain, and studies related to barriers can be considered emerging; even though there are many studies on Industry 4.0, only some can be considered as potential reference papers, especially if we refer to studies related to Industry 4.0 barriers. Thus, for this part, the authors decided to perform a literature review and a criterion-based selection to identify the most relevant barriers to be included in this study. To do that, the authors have sought in the literature which are the criteria applied for this purpose. Indeed, some researchers [101], [102] argued that any criterion becomes more important when cited in articles. Therefore, the appropriate method to identify the barriers to be considered in the analysis is the number of citations in the literature [103], [104]. Alongside this, experts' opinions have been considered to validate the selection conducted. After the literature review and selection, 10 main barriers were selected by the authors. This number has been considered an appropriate one since it enables to obtain realistic and relevant results.

D. Matrix Development and Data Collection

Since the IRP technique requires quantitative information as input, creating a punctual and clear tool to collect data is paramount to avoid misinterpretation. Specifically, the authors created a 2-D matrix, that has been distributed via email (shown in Appendix 1). In this matrix, the rows contain the 13 selected LP, whereas the 10 chosen barriers are included in the columns. The respondents were asked to fill in the matrix using either a 0 or a 1, depending on the relationship they thought to be existent between each LP and barrier. A cell value of 0 indicates that there is no relationship between the specific LP and the corresponding Industry 4.0 barrier, whereas a cell value of 1 attests to an existing relationship [104]. Besides this, the reliability of the results is strictly connected with the characteristics of the respondents. Therefore, the authors have carried out specific research to identify the appropriate interviewees, all deemed experts in both Lean and Industry 4.0 since the research comprises both paradigms. The authors have chosen to send the email to 36 European experts belonging to both academic and practitioner domains. This sample included experts in different European countries who have active relationships with various European universities. Among them, 15 replied, representing a 41.7% response rate, which can be considered a fair value, similar to previous expert-based studies [6], [105]. Also, the overall number of respondents can be regarded as acceptable since it is slightly higher than prior studies using the same methodology [104], [106]. The authors have decided to collect data from different clusters of respondents with different seniority, geographical locations, and areas of expertise to achieve a more comprehensive dataset. This choice should enhance the quality of the replies, ensuring a more reliable analysis. Also, the authors decided to balance the heterogeneity between the academic and manufacturing worlds; this was done to give a uniform representation of both. Thus, the respondents belonged to universities, manufacturing companies, and consultancy companies. The specific distribution of the professional roles of the respondents is shown in Fig. 2.

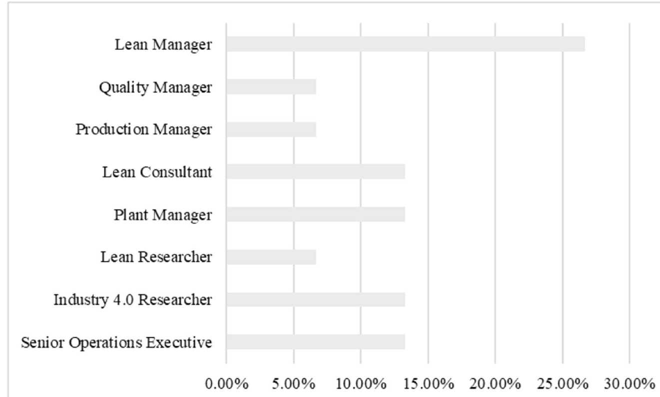


Fig. 2. Respondents profile.

IV. Findings

This section investigates the links between the LPs and the Industry 4.0 paradigms by matching the practices with the barriers. In particular, it studied how and to what extent the LPs can break down the Industry 4.0 barriers. The ranking method provided by the IRP has been used to investigate the relationships mentioned above. This methodology perfectly fits the problem under analysis since it allows us to compare the interaction of variables—practices in this case—with respect to another set of variables, barriers. From the review of the fifteen matrices returned from the experts, no anomalies have emerged; therefore, all of them have been considered eligible for the analysis.

	Practice
P1 (LOM)	Efficient and continuous replenishment
P2 (LOM)	Material handling systems
P3 (LOM)	Standardized work procedures to assure quality achievement
P4 (LOM)	Open-minded and in-depth market research conducted jointly
P5 (LOM)	Inbound vehicle scheduling
P6 (LOM)	Outbound transportation
P7 (LOM)	Establishment of distribution centers
P8 (LOM)	Functional packaging design
P9 (EWCI)	Kanban or pull system
P10 (EWCI)	Levelled scheduling or heijunka
P11 (EWCI)	Consignment stock
P12 (EWCI)	Win-win problem solving methodology
P13 (EWCI)	Value chain analysis or value stream mapping

Fig. 3. Selected LPs.

	Barrier
B7	Lack of financial resources
B8	Organizational resistance
B9	Lack of management commitment and leadership
B10	Lack of training and skills
B11	Uncertain profitability and economic business benefit
B12	Lack of planning skills and activities
B13	Concerns about cybersecurity
B14	Need a flexible interface to synchronize different languages
B15	Standardization problems
B16	Difficulty of coordination across organizational units

Fig. 4. Selected Industry 4.0 barriers.

	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
P1	0	0	0	0	0	1	0	0	0	0
P2	0	0	0	0	0	0	0	0	0	0
P3	0	0	0	1	0	0	0	0	0	0
P4	1	0	0	0	1	0	0	0	0	0
P5	0	0	0	0	0	1	0	0	0	0
P6	0	0	0	0	0	0	0	0	0	0
P7	1	0	0	0	0	0	0	0	0	0
P8	0	0	0	0	0	0	0	0	0	0
P9	0	1	0	0	0	0	0	0	1	1
P10	0	0	0	0	0	1	0	0	1	1
P11	1	0	0	0	0	1	0	0	0	1
P12	0	0	0	0	0	0	0	0	0	0
P13	0	1	0	1	0	0	0	0	0	0

Fig. 5. Cross-interaction matrix.

A. Procedure

The following paragraph reviews the steps conducted to deploy the IRP analysis and the results obtained.

1) *Step 1:* Identification of variables. The list of the two sets of variables used for the analysis is provided in Figs. 3 and 4. The purpose of the analysis has been to rank the set of practices to the set of barriers.
2) *Step 2:* Definition of contextual relationship. Starting from the two sets of variables listed in Figs. 3 and 4, a matrix has been developed, placing the practices on the rows and the barriers on the columns. The result was a 13×10 table, and the experts were required to fill the ij cell with a 1 if they believed that the i practice could break down the j barrier and a 0 otherwise. The structure of the matrix is provided in Appendix A.
3) *Step 3:* Development of cross-interaction matrix. The results of the fifteen tables collected from the experts have been averaged to obtain a unique table for the analysis (Appendix B). According to the structure of the starting matrix, the values of the resulting table range from 0 to 1. Therefore, to obtain the cross-interaction matrix made up of 0 and 1 shown in Fig. 5, a threshold of 0,7 has been set, meaning that cells that show values equal to or higher than 0,7 have been filled with a 1, whereas the ones that show an average lower than 0,7 have been filled with a 0. The results obtained using different thresholds discarded according to the expert opinion are provided in Appendix C.
4) *Step 4:* Development of cross-interaction interpretative matrix. A deep analysis of the cross-interaction matrix is necessary to interpret the relationships identified. To do so, the cross-interaction interpretative matrix has been developed. In particular, for the cells of the cross-interaction matrix that contain a 1, an explanation of the relationship has been searched with the collaboration of an expert and reported in the cross-interaction interpretative matrix (see Fig. 6). At the same time, no actions have been necessary for the cells characterized by a 0.
5) *Step 5:* Development of the dominating interaction matrix. Then, the practices have not been pairwise compared directly; rather, their interaction with the barriers and the variables in the columns have been compared. For instance, since the cell corresponding to the intersection between P4 and B11 contains a 1, P14 has been individually compared to all the other practices. Therefore, concerning B11, it became the dominating practice since no other practice intersects the column of B11 with a 1. A more complex process is needed in case there are multiple 1 values on a specific barrier column. In this case, it is necessary to consider the matrix resulting from averaging the experts' opinions before setting the threshold (Appendix B) and rounding the values to 1 or 0. In particular, if in the same column:
   a) If the average value of two practices is the same, then there is not an absolute dominant practice;
   b) If the average value of one practice is higher than that of another, then the first practice is the dominant one.

   To better explain this procedure, considering the column of B10, the intersection with both P3 and P13 in the cross-interaction matrix is characterized by a 1. However, looking at the matrix resulting from averaging the collected data, it is possible to observe that the intersection P3-B10 is 0,786 whereas P13-B10 is 0,714. Therefore, in this case, P3 will dominate all the other practices, including P13, since $0{,}714 < 0{,}786$, whereas P13 will dominate all the other practices except P3. This procedure has been conducted for each pair of practice. It has allowed us to identify the most and least important practices and build the dominating interaction matrix presented in Fig. 7.
6) *Step 6:* Development of rankings and dominance matrix. The dominating interaction matrix has been subsequently used to develop the dominance matrix by substituting the identifiers of the barriers in each cell with the number of the barriers in each cell. Then, the dominating (D) and the dominated value (B) were calculated by summing up the

	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
P1	-	-	-	-	-	An up and running efficient and continuous replenishment system reduces the planning needs and activities.	-	-	-	-
P2	-	-	-	-	-	-	-	-	-	-
P3	-	-	-	The presence of standardized work procedures drastically reduces the training need.	-	-	-	-	-	-
P4	Conducting jointly open-minded and in-depth market research reduces the need of financial resources for the implementation of the Industry 4.0	-	-	-	A deep and detailed market research carried out following the Lean logic can help to better understand the tangible and intangible benefits that can derive from the implementation of Industry 4.0 technologies.	-	-	-	-	-
P5	-	-	-	-	-	A appropriate inbound vehicle scheduling system reduces the planning needs.	-	-	-	-
P6	-	-	-	-	-	-	-	-	-	-
P7	The establishment of distribution centers reduces the need of financial resources for the implementation of the Industry 4.0	-	-	-	-	-	-	-	-	-
P8	-	-	-	-	-	-	-	-	-	-
P9	-	The development of apull system allows to build a flexible organizational structure that allows the information to flow and support the introduction of new technologies that would otherwise meet resistance.	-	-	-	-	-	-	The adoption of kanban increases the standardization of the information in the business, thus reducing the related problem.	The implementation of kanban allows to create a continuous flow of infomation between the organizational units, facilitating the coordination.
P10	-	-	-	-	-	Being levelled scheduling a sort of planning strategy, if a firm is pursuing that approach, it means that it already acquired the planning skills needed.	-	-	The adoption of levelled scheduling increases the standardization of the information in the business, thus reducing the related problem.	The implementation of heijunka allows to create a continuous flow of infomation between the organizational units, facilitating the coordination.
P11	The implementation of consignment stock reduces the need of financial resources for the implementation of the Industry 4.0	-	-	-	-	The adoption of consignment stock with the physical movement of the stock to the warehouses reduces the planning needs.	-	-	-	The adoption of consignment stock with the movement of the stock to the warehous of the following tier of the chain and so outside the firm reduces the need of coordination across the
P12	-	-	-	-	-	-	-	-	-	-
P13	-	The analysis of the value stream allows to build a flexible organizational structure that allows the information to flow and support the introduction of new technologies that would otherwise meet resistance.	-	A proper analysis of the value chai allows also to map the competences available and needed and to allocate the right people to the right tasks, thus reducing the training needs.	-	-	-	-	-	-

Fig. 6. Cross-interaction interpretive matrix.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
P1	-	B12	B12	B12	-	B12	B12	B12	B12	-	-	B12	B12
P2	-	-	-	-	-	-	-	-	-	-	-	-	-
P3	B10	B10	-	B10	B10	B10	B10	B10	B10	B10	B10	B10	B10
P4	B7, B11	B7, B11	B7, B11	-	B7, B11	B7, B11	B11	B7, B11	B7, B11	B7, B11	B11	B7, B11	B7, B11
P5	-	B12	B12	B12	-	B12	B12	B12	B12	-	-	B12	B12
P6	-	-	-	-	-	-	-	-	-	-	-	-	-
P7	B7	B7	B7	-	B7	B7	-	B7	B7	B7	-	B7	B7
P8	-	-	-	-	-	-	-	-	-	-	-	-	-
P9	B8, B15, B16	B8, B15, B16	B8, B15, B16	B8, B15, B16	B8, B15, B16	B8, B15, B16	B8, B15, B16	B8, B15, B16	-	B8, B15, B16	B8, B15	B8, B15, B16	B15, B16
P10	B12, B15, B16	B12, B15, B16	B12, B15, B16	B12, B15, B16	B12, B15, B16	B12, B15, B16	B12, B15, B16	B12, B15, B16	B12	-	B12, B15	B12, B15, B16	B12, B15, B16
P11	B7, B16	B7, B12, B16	B7, B12, B16	B12, B16	B7, B16	B7, B12, B16	B12, B16	B7, B12, B16	B7, B12	B7, B16	-	B7, B12, B16	B7, B12, B16
P12	-	-	-	-	-	-	-	-	-	-	-	-	-
P13	B8, B10	B8, B10	B8	B8, B10	B8, B10	B8, B10	B8, B10	B8, B10	B10	B8, B10	B8, B10	B8, B10	-

Fig. 7. Dominating interaction matrix.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	Dominating (D)
P1	0	1	1	1	0	1	1	1	1	0	0	1	1	9
P2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P3	1	1	0	1	1	1	1	1	1	1	1	1	1	12
P4	2	2	2	0	2	2	1	2	2	2	1	2	2	22
P5	0	1	1	1	0	1	1	1	1	0	0	1	1	9
P6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P7	1	1	1	0	1	1	0	1	1	1	0	1	1	10
P8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P9	3	3	3	3	3	3	3	3	0	3	2	3	2	34
P10	3	3	3	3	3	3	3	3	1	0	2	3	3	33
P11	2	3	3	2	2	3	2	3	2	2	0	3	3	30
P12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P13	2	2	1	2	2	2	2	2	1	2	2	2	0	22
Dominated (B)	14	17	15	13	14	17	14	17	10	11	8	17	14	

Fig. 8. Dominance matrix.

rows and columns, respectively. The resulting dominance matrix is presented in Fig. 8.

Subsequently, by calculating D-B, the net dominance of each practice has been derived, and the practices have been ranked according to descendent values of D-B. An additional step is required if some practices have the same value of D-B since the IRP methodology does not allow more practices to be in the same ranking level. In order to solve this issue, the authors have compared the ranking results with the threshold chosen, 0,7, with the one that they would have obtained using the threshold 0,6. According to this, it has been possible to determine which practice should have precedence in the final ranking. The resulting table, including the net dominance and the final ranking, is shown in Fig. 9.

7) *Step 7:* Validation of ranks. A dominance system graph has been created for each barrier on the column in which all the practices are represented and connected according to the dominance relationships found, as shown in Appendix D. Then, to validate the rank, the authors carefully checked for the intransitivity of the relationships and the absence of transitive loops. No loops have been identified, supporting the validity and the solidity of the opinions collected from the experts.
8) *Step 8:* Development of a graphical representation. The results of applying the IRP are shown in Fig. 10.

The last step of the methodology, Step 9 – analysis of the ranking order of variables, will be addressed in the next paragraph to provide a complete and extensive interpretation of the results obtained.

	Net Dominance (D-B) with threshold 0,7	Rank with threshold 0,7	Net Dominance (D-B) with threshold 0,6	Rank with threshold 0,6	Final rank
P1	−5	VII	14	III	VIII
P2	−17	VIII	−36	XIII	XIII
P3	−3	V	13	IV	VI
P4	9	III	−5	VII	IV
P5	−5	VII	−9	IX	IX
P6	−17	VIII	−25	XI	XI
P7	−4	VI	−8	VIII	VII
P8	−17	VIII	−34	XII	XII
P9	24	I	46	I	I
P10	22	II	37	II	II
P11	22	II	12	V	III
P12	−17	VIII	−10	X	X
P13	8	IV	5	VI	V

Fig. 9. Net dominance and ranking determination.

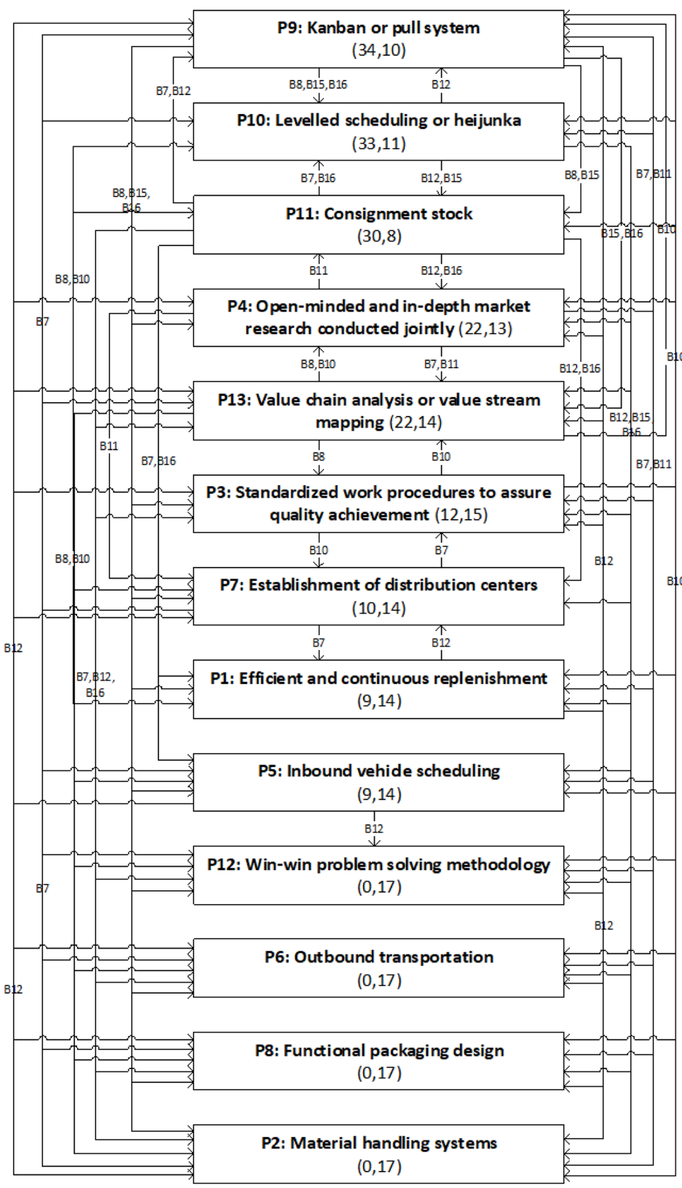


Fig. 10. IRP graphical representation.

B. Results Interpretation

Starting from the crucial elements of the IRP analysis, the net dominance and the final rank developed in Step 6, the authors decided to begin from the first element, the net dominance, and to classify the practices according to the value of D-B as follows:

1) *Net dominance (D-B) > 0:* The practices that present positive net dominance, in descendent rank order, are Kanban or pull system (P9), leveled scheduling or Heijunka (P10), consignment stock (P11), open-minded and in-depth market research conducted jointly (P4) and value chain analysis or VSM (P13). Looking at the D-B values, it has been observed that P9, P10, and P11 are significantly above P4 and P13 and present net dominance values near each other. In addition, most of these practices belong to the EWCI bundle.
2) *Net dominance (D-B) < 0:* The LPs characterized by negative values of net dominance are, in descendent rank order, standardized work procedures to assure quality achievement (P3), establishment of distribution centers (P7), efficient and continuous replenishment (P1), inbound vehicle scheduling (P5), win-win problem-solving methodology (P12), outbound transportation (P6), functional packaging design (P8), and material handling systems (P2). Analyzing the net dominance values, the first four practices, P3, P7, P1, and P5, present values near zero, whereas the remaining ones, P12, P6, P8, and P2, have D-B strongly unbalanced toward the negative and cannot provide support to the reduction of any of the Industry 4.0 barriers.

Summing up this preliminary analysis, the LPs that can mostly support the reduction of the Industry 4.0 barriers are Kanban or pull system (P9), leveled scheduling or Heijunka (P10), consignment stock (P11), and to a lesser extent, open-minded and in-depth market research conducted jointly (P4), and value chain analysis or VSM (P13). The inclusion of a pull system as a positively supporting element can appear surprising at first glance due to its traditional association with high-volume, repeatable manufacturing rather than low-volume, highly customized products. However, Saxby et al. [81] suggest that the high computerization levels in Industry 4.0 could facilitate efficient automated pull systems.

Moreover, it is possible to notice that most of these practices belong to the EWCI bundle; therefore, they have a managerial orientation rather than an operative one, and P4, even if associated with the LOM bundle, shares the same direction. This finding could be expected a priori because the spectrum of influence of actions carried out at the management level is usually way larger than that of operative measures. To have a

Practice	Ranking	Net Dominance	Most impacted barriers
Kanban or pull system (P9)	I	24	B8, B15, B16
Levelled scheduling or heijunka (P10)	II	22	B12, B15, B16
Consignment stock (P11)	III	22	B7, B12, B16
Open-minded and in-depth market research conducted jointly (P4)	IV	9	B7, B11
Value chain analysis or value stream mapping (P13)	V	8	B8, B10
Standardized work procedures to assure quality achievement (P3)	VI	−3	B10
Establishment of distribution centers (P7)	VII	−4	B7
Efficient and continuous replenishment (P1)	VIII	−5	B12
Inbound vehicle scheduling (P5)	IX	−5	B12
Win-win problem solving methodology (P12)	X	−17	-
Outbound transportation (P6)	XI	−17	-
Functional packaging design (P8)	XII	−17	-
Material handling system (P2)	XIII	−17	-

Fig. 11. IRP results summary.

complete view to analyze the results of the IRP, Fig. 11 has been developed.

Fig. 11 shows that the number of affected barriers decreases from the top to the bottom of the ranking. Furthermore, the practices belonging to the groups identified inside the bundles of positive and negative D-B impact the same number of barriers. Changing the perspective and focusing on the Industry 4.0 barriers, three different groups can be identified as follows.

1) Barriers that can be reduced through the implementation of some LPs are lack of planning skills and activities (B12), lack of financial resources (B7), and difficulty of coordination across organizational units (B16);
2) Barriers can hardly be reduced by implementing LPs since they require the implementation of some specific practices to be impacted. In particular, they are organizational resistance (B8), lack of training and skills (B10), standardization problems (B15), and uncertain profitability and economic business benefit (B11);
3) Barriers that cannot be reduced or cut down through the application of any LPs, specifically lack of management commitment and leadership (B9), concerns about cybersecurity (B13), and need for a flexible interface to synchronize different languages (B14).

Starting from lack of planning skills and activities (B12), the practices that can help to cut down this barrier are efficient and continuous replenishment (P1), inbound vehicle scheduling (P5), and consignment stock (P11), but mostly leveled scheduling or Heijunka (P10). In fact, leveled scheduling is a planning strategy; thus, if a company pursues that approach, planning skills are already acquired in the business. Regarding the lack of financial resources (B7) from the research, it can be reduced through the implementation of open-minded and in-depth market research conducted jointly (P4), establishment of distribution centers (P7), and consignment stock (P11). The difficulty of coordination across organizational units (B16) can be weakened by applying some practices related to the EWCI, in particular, Kanban or pull system (P9), leveled scheduling or Heijunka (P10), and consignment stock (P11). Indeed, implementing Kanban and Heijunka allows a continuous flow of information between the organizational units, facilitating coordination. Organizational resistance (B8) could be weakened through the implementation of a Kanban or pull system (P9) and value chain analysis or VSM (P13). The value stream analysis and the pull system's development foster the creation of a flexible organizational structure that allows the information to flow and supports the introduction of new technologies that would otherwise meet resistance. Coherently with what is expected, these last two organizational barriers (B16 and B8) can benefit from applying managerial EWCI practices rather than more operative practices belonging to the LOM bundle. Lack of training and skills (B10) could be reduced by implementing value chain analysis or VSM (P13) and mostly standardized work procedures to assure quality achievement (P3). The presence of specific work procedures drastically reduces the training need. Standardization problems (B15) can be removed through the implementation of Kanban or pull system (P9) and leveled scheduling or Heijunka (P10). Deploying these two EWCI practices that are the basis of Lean, it is possible to increase the standardization of the information in the business. This contributes to decreasing the standardization problem concerning the implementation of Industry 4.0. However, the standardization problem regarding the interface cannot be solved through the implementation of these practices. Uncertain profitability and economic business benefit (B11) can be lessened from accurate, open-minded, in-depth market research conducted jointly (P4). Indeed, deep and detailed market research following the Lean logic can help better understand the tangible and intangible benefits that can be derived from implementing Industry 4.0 technologies. Lack of management commitment and leadership (B9), concerns about cybersecurity (B13), and the need for a flexible interface to synchronize different languages (B14) cannot be reduced or eliminated through the implementation of LPs. Lack of management commitment and leadership (B9) can be indirectly weakened by shooting down other barriers to Industry 4.0. Concerns about cybersecurity (B13) represent a problem by itself, so it cannot benefit from implementing any LP. The need for a flexible interface to synchronize different languages (B14) can be reduced through technological improvements. At the same time, Lean cannot help in this sense, given its holistic view of the processes. Concluding this IRP analysis, companies that seek to reduce the barriers that they are facing in the implementation of Industry 4.0 should focus on properly applying the LP that addresses the EWCI, in particular, Kanban or pull system (P9), leveled scheduling or Heijunka (P10), and consignment stock (P11). Through these, achieving significant benefits in reducing Industry 4.0 barriers is possible.

V. Discussion

Being digital is no longer a fashion for manufacturing; rather, it is a matter of maintaining competitiveness and surviving. That is why a structured process to embark on the digital journey is fundamental nowadays. First, this can significantly influence the outcome of the digital transformation, such as operational performance improvement. Second, the decisions related to the possibility of investing in specific technologies are crucial in current times. Companies should optimize their investment to keep the digital transformation short in time and costs. Previous studies showcased that having a strong managerial culture or using specific managerial practices can strongly affect this. These outcomes were very general and at an exploratory level. With this study, we wanted to highlight the most relevant practices that allow firms to create an eased environment where companies can face fewer barriers while transforming digitally. The findings section showed the possible interactions between LPs and Industry 4.0 barriers by highlighting the potential relationships and showcasing the practices that can lower the presence and the impact of the Industry 4.0 implementation barriers. To better understand what has been obtained and position these outcomes in the literature, it is necessary to assume two different points of view, focusing first on the practices, presenting which LPs are the most powerful to reduce the Industry 4.0 barriers, and then on the barriers, deriving which and to which extent can be slaughtered through the adoption of some LPs. Starting from the practices, it was discovered that the LPs that can mostly support the reduction of the Industry 4.0 barriers are Kanban or pull system, leveled scheduling or Heijunka, consignment stock, and, to a lesser extent, open-minded and in-depth market research conducted jointly, and value chain analysis or VSM. Most of these practices belong to the EWCI bundle and, in general, have a high-level managerial orientation that allows them to have a larger spectrum of influence with respect to more operative practices. Assuming now the perspective of the barriers, it was found that lack of planning skills and activities, lack of financial resources and difficulty of coordination across organizational units are the barriers that can be most easily slaughtered through implementing some LPs. Instead, other obstacles require implementing specific LPs and punctual actions to be reduced. Then, it is worth evidence that lack of management commitment and leadership, concerns about cybersecurity, and the need for a flexible interface to synchronize different languages cannot be reduced or reduced by applying any LP. For instance, the cybersecurity concern represents a problem by itself, so it cannot benefit from implementing any LP, but the related Industry 4.0 practice can address it. For the need for a flexible interface to synchronize different languages, Lean cannot help since this problem can be tackled through technological improvements. Lack of management commitment and leadership can be faced easily by using practices related to other bundles, such as the TMC or by establishing a strong Lean culture in the firm. Thus, this study confirms Lean's fundamental role in guiding the firms' digital transformation [14]. Particularly, it demonstrates how it can help reduce barriers and drive companies to a smoother implementation of digital technologies [7]. Further, this is even more relevant for companies seeking to advance toward Industry 5.0 [22]. On the track to human-centric digitalization, companies should promote technologies which foster an enhancement of social conditions [23] and put the workers at the center of the technology implementation [22]. In this sense, Lean can have a pivotal role and contribute to successfully driving companies throughout this path.

A. *Theoretical Implications*

Considering the research objective of this article, this article advances the current knowledge regarding Lean and Industry 4.0 [107], particularly those indicating a facilitating effect of LPs toward Industry 4.0 [14]. The findings can be properly located in this stream of literature, particularly contributing to the discussion pointed out by other authors [7], [28]. Accordingly, the authors have provided academicians with an analytical framework based on a robust procedure that can determine the relation between these two paradigms. Moreover, each relationship that exists between these two paradigms and the detailed explanation of these connections can be further analyzed by academicians. The insights provided by this article provide for the first time a detailed overview of the LPs that foremost contribute to the Industry 4.0 barriers break-down; indeed, the existing research [7], [21], [24], [28], [108], and [109] just highlighted the facilitating effect of Lean towards Industry 4.0 implementation, without relating the effect on the barriers. This article enhances the related state of the art, which mainly focuses on this effect, considering a very aggregated and holistic view of Lean. Even though other authors pointed out this effect, only some of them tried to deeply investigate this and relate specific aspects of Lean with specific elements of Industry 4.0 [110]. For instance, Ciano et al. [26] considered the relationship between practices and technologies but from a qualitative perspective without explicitly stating which were the most prominent relationships. Others instead had a very narrow view of implementation cases, where a detailed description of how a single practice was used to facilitate the implementation of a specific technology. Thanks to using the IRP methodology, we pointed out the relationship using a wide range of practices and barriers and added a more quantitative component. Also, to the best of the authors' knowledge, no one before related specific LPs with Industry 4.0 barriers. From a more holistic perspective, this study brings another element to the change-management debate on how companies can facilitate the implementation of digital technologies and how they can address the dramatic changes that digitalization as a phenomenon is bringing. On top of contributing to the ongoing discussion on these two topics, this research can be considered a starting point for other researchers. For instance, other research can be done to confirm empirically the experts' opinions represented here. Also, extensions to different practices and barriers can be done following the example provided here.

B. *Practical Implications*

Aside from the theoretical contributions, this work is not exempt from practical contributions. Given Lean's positive effect on implementing Industry 4.0 technologies, this study provides further information. There are better environments for technology implementation than inefficient and nonstandardized production processes. However, only some of the LPs can provide the same barrier reduction benefits. This article outlines which practices are the most suitable to face and cope with the selected barriers and guides managers, practitioners, and companies in this direction. Each company could face different barriers; thus, this article ranks the most relevant practices and their impact on specific barriers, if any.

VI. Conclusion

Prior research in the literature has demonstrated how LPs can facilitate the implementation of Industry 4.0 technologies. However, there is a notable gap in the existing research, as it has yet to delve deeply into this subject, limiting our current understanding of this phenomenon. To fill this gap, our study set out to provide a more comprehensive perspective on the interplay between these practices and the barriers. To achieve this, the authors of this study carefully selected a specific set of practices and barriers. Through the IRP methodology, we examined the connections between Lean principles and the Industry 4.0 paradigm. This approach allowed us to move beyond the fragmented view presented in previous research, which had explored these concepts from an aggregate and high-level viewpoint and instead provided a detailed account of how these practices directly influence the barriers. Our findings revealed that companies aiming to mitigate the barriers they face in adopting Industry 4.0 should prioritize the proper implementation of certain LPs, particularly those focused on waste reduction and continuous improvement. Specifically, practices such as Kanban or the pull system (P9), leveled scheduling or Heijunka (P10), and consignment stock (P11) were found to be effective in this regard. Conversely, most LPs related to LOM bundles exhibited a negative net dominance, suggesting that they should not be the primary focus when seeking to alleviate barriers to Industry 4.0 implementation. This research contributes significantly to the discourse surrounding the drivers of Lean and Industry 4.0, particularly by emphasizing the importance of specific practices in overcoming particular barriers. Our findings highlight the varied relationships between these practices and barriers, enriching the understanding of this phenomenon.

A. Limitations

Considering the interrelations between Lean and Industry 4.0 obtained from the framework analyzed in detail, the discussed results have enhanced the knowledge in this field regarding theoretical and practical implications, as mentioned above. Nevertheless, this article is not exempt from limitations, as any other research. First, given the huge number of variables, both barriers and practices, considered in the analyses developed, the results may suffer from biases due to the computational limitations of IRP methodology. Despite this, the extensive set of factors has allowed the authors to achieve relevant outcomes, giving future readers the starting point for further research in this field. Starting from this robust and structured research, different criteria to select fewer variables could be applied. On the other hand, other practices and barriers the authors did not select could have an interaction not investigated here; thus, this could represent an additional limitation. In addition, the quality and the reliability of the results obtained are affected by several aspects. Furthermore, the IRP methodology heavily relies on experts' opinions and not on field application. Thus, there could be a bias due to the respondents' personal opinions. Nevertheless, the authors have ensured great content validity, given the variety of experts. The model validation through other methodologies could further extend this work. Finally, the thresholds identified for applying the IRP techniques have been decided by the authors, who have discussed them with experts. Given the arbitrariness of the threshold, different limits may bring slightly different results.

B. Future Research

Given the novelty of the findings, this piece of work could be considered a preliminary analysis for further advanced research regarding the relationships between Lean and Industry 4.0. Therefore, the authors have identified several improvements for future complementary studies. Similar studies should be implemented to validate the results obtained, adopting the same methodology or adding similar ones, such as Decision-Making Trial and Evaluation Laboratory (DEMATEL) [6], [111] or ISM [112], [113]. Since these three methodologies heavily rely on the experts' opinions, the results could be validated or denied with a different cluster of experts. Indeed, with proper validation, the reliability of results obtained through specific methodologies is enhanced. In addition, to increase the knowledge in the literature, relevant results could be obtained considering only firms currently applying LPs and want to start the journey with Industry 4.0. In this scenario, a case study could be developed to understand the practical implications of applying both paradigms and validate the theoretical results obtained. Starting from the variables identified through the literature review performed here, the same analysis can be performed again, considering different clusters of variables. Indeed, the authors have adopted a specific criterion for selecting barriers, but several other criteria could be applied; thus, other barriers could be considered. Regarding the selection of LPs, future researchers could focus their attention on the more strategic bundles—CSRM and TMC—rather than the operative ones—LOM and EWCI, to understand whether the results could slightly or heavily change. According to these suggestions, it would be possible to compare the results obtained in this research. Another possible future step can involve the application of the framework of analysis developed here on specific situations, i.e., considering a particular industry, company size or geographical location. Indeed, considering an small and medium-sized enterprise (SME) or a large enterprise could bring different outcomes in adopting LPs and Industry 4.0. Finally, due to the novelty of the topic and the significant importance that this argument is achieving nowadays, these types of analysis would need to be replicated after a few years since new technologies and barriers could arise.

APPENDIX A
MATRIX USED TO COLLECT EXPERTS' OPINION

Please, with a binary number, identify if the Lean Practices in the rows of the table can have an impact on the Industry 4.0 barriers in the columns in the relative cross-intersection cells according to: 0 - the practice has no impact on barrier 1 - the practice has some impact on the barrier.

Can Lean Practices break down Industry 4.0 barriers?	B7: Lack of financial resources	B8: Organizational resistance	B9: Lack of management commitment and leadership	B10: Lack of training and skills	B11: Uncertain profitability and economic business benefit	B12: Lack of planning skills and activities	B13: Concerns about cybersecurity	B14: Need a flexible interface to synchronize different languages	B15: Standardization problems	B16: Difficulty of coordination across organizational units
P1: Efficient and continuous replenishment										
P2: Material handling systems										
P3: Standardized work procedures to assure quality achievement										
P4: Open-minded and in-depth market research conducted jointly										
P5: Inbound vehicle scheduling										
P6: Outbound transportation										
P7: Establishment of distribution centers										
P8: Functional packaging design										
P9: Kanban or pull system										
P10: Levelled scheduling or heijunka										
P11: Consignment stock										
P12: Win-win problem solving methodology										
P13: Value chain analysis or value stream mapping										

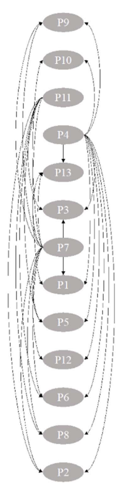
APPENDIX B
CROSS-INTERACTION MATRIX WITHOUT THRESHOLD

	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
P1	0,643	0,429	0,357	0,500	0,571	0,714	0,071	0,643	0,571	0,643
P2	0,429	0,500	0,286	0,357	0,286	0,286	0,071	0,500	0,286	0,143
P3	0,357	0,643	0,500	0,786	0,571	0,571	0,071	0,571	0,643	0,643
P4	0,714	0,429	0,429	0,429	0,786	0,286	0,214	0,214	0,500	0,357
P5	0,357	0,357	0,429	0,357	0,071	0,714	0,286	0,571	0,500	0,643
P6	0,429	0,357	0,357	0,286	0,071	0,643	0,286	0,429	0,429	0,429
P7	0,714	0,500	0,571	0,143	0,643	0,429	0,286	0,286	0,429	0,571
P8	0,429	0,214	0,286	0,214	0,214	0,143	0,000	0,143	0,500	0,357
P9	0,571	0,786	0,643	0,643	0,571	0,643	0,071	0,357	0,929	0,786
P10	0,429	0,571	0,643	0,643	0,286	0,857	0,000	0,500	0,714	0,714
P11	0,714	0,429	0,429	0,357	0,500	0,714	0,286	0,286	0,500	0,786
P12	0,357	0,643	0,643	0,500	0,214	0,571	0,143	0,429	0,357	0,357
P13	0,571	0,786	0,571	0,714	0,571	0,643	0,286	0,357	0,500	0,357

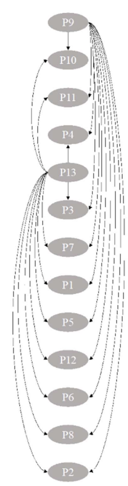
APPENDIX C
IRP RESULTS SUMMARY WITH 0,6 THRESHOLD

Practice	Ranking	Net Dominance	Most impacted barriers
Kanban or pull system (P9)	I	46	B8, B9, B10, B12, B15, B16
Levelled scheduling or heijunka (P10)	II	37	B9, B10, B12, B15, B16
Efficient and continuous replenishment (P1)	III	14	B7, B12, B14, B16
Standardized work procedures to assure quality achievement (P3)	IV	13	B8, B10, B15, B16
Consignment stock (P11)	V	12	B7, B15, B16
Value chain analysis or value stream mapping (P13)	VI	5	B8, B10, B12
Open-minded and in-depth market research conducted jointly (P4)	VII	–5	B7, B11
Establishment of distribution centers (P7)	VIII	–8	B7, B11
Inbound vehicle scheduling (P5)	IX	–9	B12, B16
Win-win problem solving methodology (P12)	X	–10	B8, B9
Outbound transportation (P6)	XI	–25	B12
Functional packaging design (P8)	XII	–34	-
Material handling system (P2)	XIII	–36	-

APPENDIX D
DOMINANCE GRAPHS

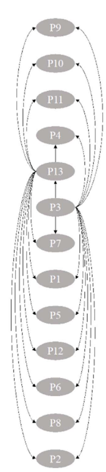


Dominance system graph for Lack of financial resources (B7)

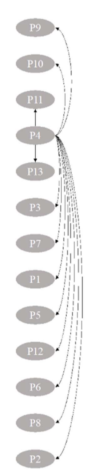


Dominance system graph for Organizational resistance (B8)

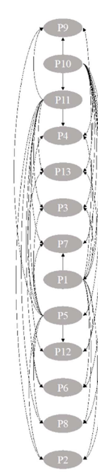
Dominance system graph for Lack of management commitment and leadership (B9)



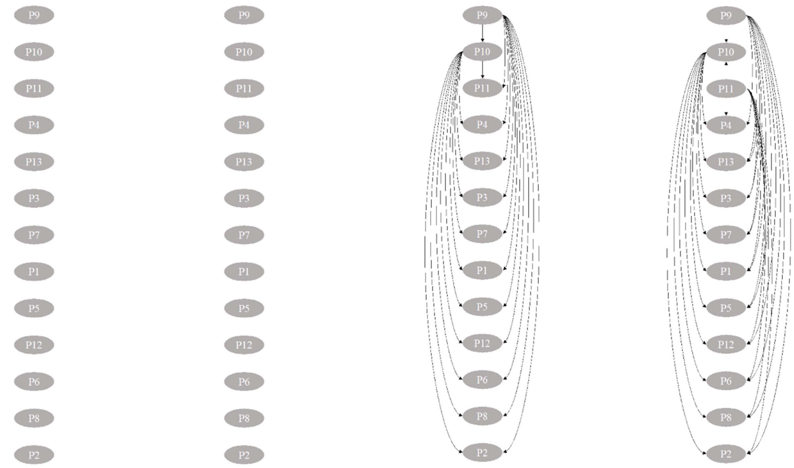
Dominance system graph for Lack of training and skills (B10)



Dominance system graph for Uncertain profitability and economic business benefit (B11)



Dominance system graph for Lack of planning skills and activities (B12)



Dominance system graph for Concerns about cybersecurity (B13)

Dominance system graph for Need a flexible interface to synchronize different languages (B14)

Dominance system graph for Standardization problems (B15)

Dominance system graph for Difficulty of coordination across organizational units (B16)

ACKNOWLEDGMENT

The authors would like to thank all the experts and professionals who participated in this study for giving them their precious time and valuable opinions.

REFERENCES

[1] N. Abidi, M. E. Herradi, and S. Sakha, "Digitalization and resilience during the COVID-19 pandemic," *Telecommun. Policy*, vol. 47, no. 4, 2023, Art. no. 102522.

[2] F. Almeida, J. D. Santos, and J. Monteiro, "The challenges and opportunities in the digitalization of companies in a Post-COVID-19 world," *IEEE Eng. Manag. Rev.*, vol. 48, no. 3, pp. 97–103, Sep. 2020.

[3] M. Ghobakhloo and M. Fathi, "Corporate survival in Industry 4.0 era: The enabling role of lean-digitized manufacturing," *J. Manuf. Technol. Manage.*, vol. 31, no. 1, pp. 1–30, 2019.

[4] A. Miceli, B. Hagen, M.P. Riccardi, F. Sotti, and D. T. S. -Blundo, "Not just surviving in changing times: How sustainability, agility and digitalization intertwine with organizational resilience," *Sustainability*, vol. 13, 2021, Art. no. 2052.

[5] Y. Liao, F. Deschamps, E. de F. R. Loures, and L. P. Ramos, "Past, present and future of Industry 4.0 - A systematic literature review and research agenda proposal," *Int. J. Prod. Res.*, vol. 55, no. 12, pp. 3609–3629, 2017.

[6] A. Raj, G. Dwivedi, A. Sharma, A. B. L. de S. Jabbour, and S. Rajak, "Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective," *Int. J. Prod. Econ.*, vol. 224, 2020, Art. no. 107546.

[7] S. Frecassetti, A. Presciuttini, M. Rossini, and A. P.-Staudacher, "Lean and digital strategy role in achieving a successful digital transformation," in *Proc. Int. Conf. Adv. Prod. Manage. Syst.. Prod. Manage. Syst. Responsible Manuf., Serv., Logistics Futures*, 2023, vol 689, pp. 157–170.

[8] G. Orzes, E. Rauch, S. Bednár, and R. Poklemba, "Industry 4.0 implementation barriers in small and medium sized enterprises: A focus group study," in *Proc. 2018 IEEE Int. Conf. Ind. Eng. Eng. Manage. (IEEM)*, 2018, pp. 1348–1352. [Online]. Available: https://doi.org/10.1109/ieem.2018.860747

[9] F. Costa, S. Frecassetti, M. Rossini, and A. P. -Staudacher, "Industry 4.0 digital technologies enhancing sustainability: Applications and barriers from the agricultural industry in an emerging economy," *J. Cleaner Prod.*, vol. 408, 2023, Art. no. 137208.

[10] C. Shuvabrata, S. Ankit, and V. S. Omkarprasad, "Achieving sustainable operational excellence through IT implementation in indian logistics sector: An analysis of barriers," *Resour., Conservation Recycling*, vol. 152, 2020, Art. no. 104506.

[11] D. Horvath and R. Z. S. Szabo, "Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?," *Technological Forecasting Social Change*, vol. 146, pp. 119–132, 2019.

[12] C. M. -Flores and J. O. -Nadal, "Enablers and inhibitors for IoT implementation," in *Proc. Int. Ser. Manage. Sci./Operations Res.*, 2021, pp. 25–48.

[13] A. Hanelt, R. Bohnsack, D. Marz, and C. Marante, "A Systematic review of the literature on digital transformation: Insights and implications for strategy and organizational change," *J. Manage. Stud.*, vol. 58, no. 5, pp. 1159–1197, 2020.

[14] R. Matteo, C. Fabiana, K. Bassel, C. Federica, and P. Alberto, "Being lean: How to shape digital transformation in the manufacturing sector," *J. Manuf. Technol. Manage.*, vol. 32, pp. 239–259, 2021, doi: 10.1108/JMTM-12-2020-0467.

[15] J. F. Krafcik, "Triumph of the lean production system," *Sloan Manage. Rev.*, vol. 30, pp. 41–52, 1988.

[16] J. Bicheno and M. Holweg, *The Lean Toolbox*. Buckingham, U.K.: PICSIE, 2009.

[17] J.P. Womack, D.T. Jones, and D. Ross, *The Machine That Changed the World*. New York, NY, USA: MacMillan/Rawson Associates, 1990.

[18] M. Holweg, "The genealogy of lean production," *J. Oper. Manage.*, vol. 25, no. 2, pp. 420–437, 2007.

[19] B. P. Sullivan, P. G. Yazdi, A. Suresh, and S. Thiede, "Digital value stream mapping: Application of UWB real time location systems," *Procedia CIRP*, vol. 107, pp. 1186–1191, 2022.

[20] G. L. Tortorella, M. Rossini, F. Costa, P. A. Staudacher, and R. Sawhney, "A comparison on Industry 4.0 and lean production between manufacturers from emerging and developed economies," *Total Qual. Manage. Bus. Excellence*, vol. 32, no. 11–12, pp. 1249–1270, 2021.

[21] M. Rossini, F. Costa, G. Tortorella, and A. P. -Staudacher, "The interrelation between Industry 4.0 and lean production: An empirical study on European manufacturers," *Int. J. Adv. Manuf. Technol.*, vol. 102, pp. 3963–3976, 2019, doi: 10.1007/s00170-019-03441-7.

[22] R. Souza, H. Ferenhof, and F. Forcellini, "Industry 4.0 and Industry 5.0 from the lean perspective," *Int. J. Manage., Knowl. Learn.*, vol. 11, pp. 145–155, 2022.

[23] A. Alves, "Lean thinking: An essential mindset," *IEEE Eng. Manage. Review.*, vol. 50, no. 4, pp. 127–133, Dec. 2022.

[24] M. Rossini, D. Powell, and K. Kundu, "Lean supply chain management and Industry 4.0: A systematic literature review," *Int. J. Lean Six Sigma*, vol. 14, pp. 253–276, 2022.

[25] R. Shah and P. T. Ward, "Defining and developing measures of lean production," *J. Operations Manage.*, vol. 25, no. 4, pp. 785–805, 2007.

[26] M. Ciano, P. Dallasega, G. Orzes, and T. Rossi, "One-to-one relationships between Industry 4.0 technologies and lean production techniques: A multiple case study," *Int. J. Prod. Res.*, vol. 59, no. 5, pp. 1386–1410, 2020, doi: 10.1080/00207543.2020.1821119.

[27] A. Sanders, C. Elangeswaran, and J. P. Wulfsberg, "Industry 4.0 implies lean manufacturing: Research activities in Industry 4.0 function as enablers for lean manufacturing," *J. Ind. Eng. Manage.*, vol. 9, no. 3, pp. 811–833, 2016.

[28] S. V. Buer, J. O. Strandhagen, and F. T. Chan, "The link between Industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2924–2940, 2018.

[29] H. Kagermann, W. Wahlster, and J. Helbig, "Securing the future of german manufacturing industry: Recommendations for implementing the strategic initiative INDUSTRIE 4.0," Final Report of the INDUSTRIE 4.0 Working Group, vol. 4, 2013.

[30] M. Sony, "Industry 4.0 and lean management: A proposed integration model and research propositions," *Prod. Manuf. Res.*, vol. 6, no. 1, pp. 416–432, 2018.

[31] S. V. Buer, M. Semini, J. O. Strandhagen, and F. Sgarbossa, "The complementary effect of lean manufacturing and digitalisation on operational performance," *Int. J. Prod. Res.*, vol. 59, no. 7, pp. 1976–1992, 2021.

[32] G. L. Tortorella and D. Fettermann, "Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2975–2987, 2018.

[33] S. Kamble, A. Gunasekaran, and N. C. Dhone, "Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies," *Int. J. Prod. Res.*, vol. 58, no. 5, pp. 1319–1337, 2020.

[34] E. Moretti, E. Tappia, V. Limère, and M. Melacini, "Exploring the application of machine learning to the assembly line feeding problem," *Oper. Manage. Res.*, vol. 14, pp. 403–419, 2021.

[35] A. C. Pereira, C. J. Dinis, A. C. Alves, and P. Arezes, "How Industry 4.0 can enhance lean practices," *FME Trans.*, vol. 47, pp. 810–822, 2019, doi: 10.5937/fmet1904810P.

[36] M. Hermann, T. Pentek, and B. Otto, "Design principles for Industrie 4.0 scenarios," in *Proc. 49th Hawaii Int. Conf. Syst. Sci. HICSS*, 2016, pp. 3928–3937. [Online]. Available: https://doi.org/10.1109/HICSS.2016.488

[37] D. Santos et al., "Industry 4.0 collaborative networks for industrial performance," *J. Manuf. Technol. Manage.*, vol. 32, no. 2, pp. 245–265, 2021, doi: 10.1108/JMTM-04-2020-0156.

[38] M. Pagliosa, G. Tortorella, and J. C. E. Ferreira, "Industry 4.0 and lean manufacturing: A systematic literature review and future research directions," *J. Manuf. Technol. Manage.*, vol. 32, no. 3, pp. 543–569, 2021.

[39] S. Wang, J. Wan, D. Li, and C. Zhang, "Implementing smart factory of Industrie 4.0: An outlook," *Int. J. Distrib. Sens. Netw.*, vol. 12, 2016, Art. no. 3159805.

[40] H. Foidl and M. Felderer, "Research challenges of Industry 4.0 for quality management," in *Proc. 4th Int. Conf. Innov. Enterprise Inf. Syst. Manage. Eng.*, 2016, vol. 245, pp. 121–137.

[41] E. Moretti, E. Tappia, M. Mauri, and M. Melacini, "A performance model for mobile robot-based part feeding systems to supermarkets," *Flexible Serv. Manuf. J.*, vol. 34, pp. 580–613, 2021.

[42] A. Napoleone, E. Moretti, M. Macchi, and M. Melacini, "Synchronisation of material flows in mass-customised production systems: A literature-based classification framework and industrial application," *Prod. Plan. Control*, pp. 1–19, 2023. [Online]. Available: https://doi.org/10.1080/09537287.2023.2214529

[43] D. Kiel, J. Muller, C. Arnold, and K.-I Voigt, "Sustainable industrial value creation: Benefits and challenges of Industry 4.0," *Int. Soc. Professional Innov. Manage.*, vol. 21, 2017, Art. no. 1740015.

[44] Mckinsey and Company, *Industry 4.0 After the Initial Hype*. Mckinsey Digital, 2016. [Online]. Available: https://www.mckinsey.com/capabilities/operations/our-insights/industry-40-looking-beyond-the-initial-hype

[45] T. v. Leipzig et al., "Initialising customer-orientated digital transformation in enterprises," *Proc. Manuf*, vol. 8, pp. 517–524, 2017.

[46] Massachusetts Institute of Technology, *The Nine Elements of Digital Transformation MIT Sloan Management Review*. MIT Sloan Management, Jan. 7, 2014, [Online]. Available: https://sloanreview.mit.edu/article/the-nine-elements-of-digital-transformation

[47] S. Erol, A. Jäger, P. Hold, K. Ott, and W. Sihn, "Tangible industry 4.0: A scenario-based approach to learning for the future of production," *Procedia CiRp*, vol. 54, pp. 13–18, 2016.

[48] D. Kiel, C. Arnold, and K.-I. Voigt, "The influence of the industrial Internet of Things on business models of established manufacturing companies – A business level perspective," *Technovation*, vol. 68, pp. 4–19, 2017.

[49] J. Muller and K.-I Voigt, "Industrie 4.0 fur kleine und mittlere Unternehmen," *Prod. Manag.*, vol. 3, pp. 28–30, 2016.

[50] B. Zhou, "Lean principles, practices, and impacts: A study on small and medium-sized enterprises (SMEs)," *Ann. Oper. Res.*, vol. 241, no. 1/2, pp. 457–474, 2016.

[51] G. Marodin, A. G. Frank, G. L. Tortorella, and T. Netland, "Lean product development and lean manufacturing: Testing moderation effects," *Int. J. Prod. Econ.*, vol. 203, pp. 301–310, 2018.

[52] J. P. Womack and D. T. Jones, *Lean Thinking*. New York, NY, USA: Simon and Schuster, 1996.

[53] T. Ohno, *Toyota Production System: Beyond Large-Scale Production*. Tokyo, Japan: Diamond Inc., 1988.

[54] T. R. Browning and S. D. Treville, "A lean view of lean," *J. Oper. Manage.*, vol. 67, no. 5, pp. 640–652, 2021.

[55] J. P. Womack and D. T. Jones, "Beyond Toyota: How to root out waste and pursue perfection," *Harvard Bus. Rev.*, vol. 74, no. 5, pp. 140–151, 1996.

[56] A. Chiarini, "Sustainable manufacturing-greening processes using specific lean production tools: An empirical observation from European motorcycle component manufacturers," *J. Cleaner Prod.*, vol. 85, pp. 226–233, 2014.

[57] R. M. Torielli, R. A. Abrahams, R. W. Smillie, and R. C. Voigt, "Using lean methodologies for economically and environmentally sustainable foundries," *China Foundry*, vol. 8, no. 1, pp. 74–88, 2011.

[58] J. G. de Freitas, H. G. Costa, and F. T. Ferraz, "Impacts of lean six sigma over organizational sustainability: A survey study," *J. Cleaner Prod.*, vol. 156, pp. 262–275, 2017, doi: 10.1016/j.jclepro.2017.04.054.

[59] W. P. Wong and K. Y. Wong, "Synergizing an ecosphere of lean for sustainable operations," *J. Cleaner Prod.*, vol. 85, pp. 51–66, 2014.

[60] B. R. Staats, D. J. Brunner, and D. M. Upton, "Lean principles, learning, and knowledge work: Evidence from a software services provider," *J. Operations Manage.*, vol. 29, no. 5, pp. 376–390, 2010.

[61] G. Anand and R. Kodali, "A conceptual framework for lean supply chain and its implementation," *Int. J. Value Chain Manage.*, vol. 2, no. 3, pp. 313–357, 2008.

[62] K. A.-U.-Zaman and A. Ahsan, "Lean supply chain performance measurement," *Int. J. Productiv. Perform. Manage.*, vol. 63, no. 5, pp. 588–612, 2014.

[63] N. Jasti and R. Kodali, "A critical review of lean supply chain management frameworks: Proposed framework," *Prod. Plan. Control*, vol. 26, no. 13, pp. 1051–1068, 2015.

[64] G. Tortorella, R. Miorando, and G. Marodin, "Lean supply chain management: Empirical research on practices, contexts and performance," *Int. J. Prod. Econ.*, vol. 193, pp. 98–112, 2017.

[65] G. Tortorella, R. Miorando, and D. Tlapa, "Implementation of lean supply chain: An empirical research on the effect of context," *The TQM J.*, vol. 29, no. 4, pp. 610–623, 2017.

[66] G. Tortorella, C. D. Fettermmann, and D. Tlapa, "Lean supply chain practices: An exploratory study on their relationship," *Int. J. Logistics Manage.*, vol. 29, no. 3, pp. 1049–1076, 2018.

[67] G. Tortorella, R. Giglio, and J. L.-Romero, "Supply chain performance: How lean practices efficiently drive improvements," *J. Manuf. Technol. Manage.*, vol. 29, no. 5, pp. 829–845, 2018.

[68] B.B. Flynn, B. Huo, and X. Zhao, "The impact of supply chain integration on performance: A contingency and configuration approach," *J. Operations Manage.*, vol. 28, no. 1, pp. 58–71, 2010.

[69] E.M. Frazzon, A. Albrecht, P.A. Hurtado, S. L. de Silva, and J. Pannek, "Hybrid modelling approach for the scheduling and control of integrated production and logistic processes along export supply chains," *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 1521–1526, 2015.

[70] C. Tasdemir and R. Gazo, "A systematic literature review for better understanding of lean driven sustainability," *Sustainability*, vol. 10, no. 7, 2018, Art. no. 2544.

[71] S. Gupta and S. K. Jain, "A. literature review of lean manufacturing," *Int. J. Manage. Sci., Eng. Manage.*, vol. 8, no. 4, pp. 241–249, 2013.

[72] D. J. Powell, I. Bas, and E. Alfnes, "Integrating lean and MRP: A. taxonomy of the literature," in *Proc. Adv. Prod. Manage. Syst. Sustain. Prod. Serv. Supply Chains: IFIP WG 5.7 Int. Conf.*, 2013, pp. 485–492.

[73] D. Roy, P. Mittag, and M. Baumeister, “Industrie 4.0-einfluss der digitalisierung auf die funf lean-prinzipien-schlank vs. intelligent,” *Productiv. Manage.*, vol. 20, no. 2, pp. 27–30, 2015.
[74] R. Davies, T. Coole, and A. Smith, “Review of socio-technical considerations to ensure,” *Procedia Manuf.*, vol. 11, no. 6, pp. 1288–1295, 2017.
[75] B. Mrugalska and M. K. Wyrwicka, “Towards lean production in Industry 4.0,” *Procedia Eng.*, vol. 182, pp. 466–473, 2017.
[76] A. G. Uriarte, A. H. Ng, and M. U. Moris, “Supporting the lean journey with simulation and optimization in the context of Industry 4.0,” in *Proc. Manuf.*, vol. 25, pp. 586–593, 2018.
[77] M. Shahin, F. F. Chen, H. Bouzary, and K. Krishnaiyer, “Integration of Lean practices and Industry 4.0 technologies: Smart manufacturing for next-generation enterprises,” *Int. J. Adv. Manuf. Technol.*, vol. 107, pp. 2927–2936, 2020.
[78] A. Haddud and A. Khare, “Digitalizing supply chain benefits and impact on lean operations,” *Int. J. Lean Six Sigma*, vol. 11, no. 4, pp. 731–765, 2019.
[79] S. Frecassetti, B. Kassem, K. Kundu, M. Ferrazzi, and A. P. -Staudacher, “Introducing Lean practices through simulation: A. case study in an Italian,” *SME. Qual. Manage. J.*, vol. 30, pp. 1–15, 2023.
[80] V. L. Bittencourt, A. C. Alves, and C. P. Leao, “Industry 4.0 triggered by Lean Thinking: Insights from a systematic literature review,” *Int. J. Prod. Res.*, vol. 59, no. 5, pp. 1496–1510, 2021, doi: 10.1080/00207543.2020.1832274.
[81] R. Saxby, M. C. -Kourouklis, and E. Viza, “An initial assessment of lean management methods for Industry 4.0,” *TQM J.*, vol. 32, no. 4, pp. 587–601, 2020.
[82] A. Mayr et al., “Lean 4. 0–A conceptual conjunction of lean management and Industry 4.0,” *Procedia Cirp*, vol. 72, pp. 622–628, 2018.
[83] S. Frecassetti, A. Ahmadi, I. Khamidov, and A. Staudacher, “The role of lean practices in successful warehouse management system implementation,” in *Proc. Flexible Automat. Intell. Manuf.: Establishing Bridges More Sustain. Manuf. Syst.*, 2023, pp. 372–379.
[84] S. Frecassetti, M. Ferrazzi, and A. P. -Staudacher, “Lean as a facilitator for AGVs implementation: A Case Study,” in *Proc. IFIP Adv. Inf. Commun. Technol.*, 2023, pp. 95–107.
[85] Sushil, “Interpretive ranking process,” *Glob. J. Flexible Syst. Manage.*, vol. 10, no. 4, pp. 1–10, 2009.
[86] V. Sharma, A. Dixit, and M. Qadri, “Analysis of barriers to lean implementation in machine tool sector,” *Int. J. Lean Thinking*, vol. 5, no. 1, pp. 1–25, 2014.
[87] Sushil, “Interpretive matrix: A. tool to aid interpretation of management and social research,” *Glob. J. Flexible Syst. Manage.*, vol. 6, pp. 27–30, 2005.
[88] J. W. Warfield, “Developing interconnected matrices in structural modeling,” *IEEE Trans. Man Cybern.*, vol. SMC-4, no. 1, pp. 81–87, Jan. 1974.
[89] J. Thakkar, A. Kanda, and S. G. Deshmukh, “Interpretive structural modeling (ISM) of ITenablers for Indian manufacturing SMEs,” *Inf. Manage. Comput. Secur.*, vol. 16, no. 2, pp. 113–136, 2008.
[90] T. L. Saaty, *AHP: The Analytic Hierarchy Process*. New York, NY, USA: McGraw-Hill, 1980.
[91] B. E. Narkhede, R. Raut, B. Gardas, H. T. Luong, and M. Jha, “Selection and evaluation of third party logistics service provider (3PLSP) by using an interpretive ranking process (IRP),” *Benchmarking An Int. J.*, vol. 24, pp. 1597–1648, 2017.
[92] A. Haleem, Sushil, M. A. Qadri, and S. Kumar, “Analysis of critical success factors of world- class manufacturing practices: An application of interpretative structural modelling and interpretative ranking process,” *Prod. Plan. Control*, vol. 23, no. 10–11, pp. 722–734, 2012.
[93] S. K. Mangla, P. Kumar, and M. K. Barua, “Risk analysis in green supply chain using fuzzy AHP approach: A case study,” *Resour. Conserv. Recycl*, vol. 104, pp. 375–390, 2015.
[94] K. Vitasek, K. Manrodt, and J. Abbott, “What makes a lean supply chain,” *Supply Chain Manage. Rev.*, vol. 9, no. 7, pp. 39–45, 2005.
[95] R. J. Vokurka, “Supplier relationships: A case study,” *J. Enterprise Resour. Manage.*, vol. 2, pp. 78–83, 2000.
[96] Y. Yusuf, A. Gunasekaran, E. Adeleye, and K. Sivayoganathan, “Agile supply chain capabilities: Determinants of competitive objectives,” *Eur. J. Oper. Res*, vol. 159, pp. 379–392, 2004.
[97] B. C. Arntzen, G. G. Brown, T. P. Harrison, and L. L. Trafton, “Global supply chain management at digital equipment corporation,” *Interfaces*, vol. 21, no. 5, pp. 69–93, 1995.
[98] R. Stratton and R. D. H. Warburton, “The strategic integration of agile and lean supply,” *Int. J. Prod. Econ.*, vol. 85 pp. 183–198, 2003.
[99] R. Cagliano, F. Caniato, and G. Spina, “The linkage between supply chain integration and manufacturing improvement programmes,” *Int. J. Operations Prod. Manage.*, vol. 26, no. 3, pp. 282–299, 2006.
[100] M. Rother and J. Shook, *Learning to See: Value Stream Mapping to Create Value and Eliminate Muda*. Boston, MA, USA: Lean Enterprise Inst., 2003.
[101] G. W. Dickson, “An analysis of vendor selection systems and decisions,” *J. Purchasing*, vol. 2, no. 1, pp. 5–17, 1966.
[102] C. A. Weber, J. R. Current, and W. C. Benton, “Vendor selection criteria and methods,” *Eur. J. Oper. Res.*, vol. 50, no. 1, pp. 2–18, 1991, doi.org/10.1016/0377-2217(91)90033-R.
[103] A. P. Chaple, B. E. Narkhede, M. M. Akarte, and R. Raut, “Interpretive framework for analyzing lean implementation using ISM and IRP Modeling,” *Benchmarking*, vol. 25, no. 9, pp. 3406–3442, 2018.
[104] L. Zhang, B. E. Narkhede, and A. P. Chaple, “Evaluating lean manufacturing barriers: An interpretive process,” *J. Manuf. Technol. Manage.*, vol. 28, no. 8, pp. 1086–1114, 2017.
[105] F. Ullah, S. M. Sepasgozar, J. Thaheem, M. C. Wang, and M Imran, “It’s all about perceptions: A. DEMATEL approach to exploring user perceptions of real estate online platforms,” *Ain Shams Eng. J.*, vol. 12, no. 4, pp. 4297–4317, 2021.
[106] S. J. Thanki and J. Thakkar, “Interdependence analysis of lean-green implementation challenges: A case of Indian SMEs,” *J. Manuf. Technol. Manage.*, vol. 29, no. 2, pp. 295–328, 2018.
[107] G. L. Tortorella, R. Giglio, and D. H. v. Dun, “Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement,” *Int. J. Oper. Prod. Manage.*, vol. 39, no. (6/7/8), pp. 860–886, 2019.
[108] M. Rossini, F. Costa, G. Tortorella, A. Valvo, and A. P.-Staudacher, “Lean production and Industry 4.0 integration: How lean automation is emerging in manufacturing industry,” *Int. J. Prod. Res.*, vol. 60, no. 21, pp. 6430–6450, 2021.
[109] M. Rossini, S. Frecassetti, and A. P.-Staudacher, “Lean supply chain and Industry 4.0: A study of the interaction between practices and technologies,” in *Proc IFIP Adv. Inf. Commun. Technol.*, 2023, pp. 39–53.
[110] G. L. Tortorella, G. Narayanamurthy, and M. Thurer, “Identifying pathways to a high-performing lean automation implementation: An empirical study in the manufacturing industry,” *Int. J. Prod. Econ.*, vol. 231, 2021, Art. no. 107918.
[111] F. Costa, A. D. Granja, A. Fregola, F. Picchi, and A. P. Staudacher, “Understanding relative importance of barriers to improving the customer–supplier relationship within construction supply chains using DEMATEL technique,” *J. Manage. Eng.*, vol. 35, no. 3, May 2019, Art. no. 4019002.
[112] A. P. Sage, *Interpretive Structural Modeling: Methodology for Large-Scale Systems*. New York, NY, USA: McGraw-Hill, 1977.
[113] T. Raj, R. Shankar, and M. Suhaib, “An ISM approach for modelling the enablers of flexible manufacturing system: The case for India,” *Int. J. Prod. Res.*, vol. 46, no. 24, pp. 6883–6912, 2008.

Open Access funding provided by ‘Politecnico di Milano’ within the CRUI CARE Agreement