Lean 4.0: a systematic literature review on the interaction between Lean Production and Industry 4.0 pillars

Abstract

Purpose: The interaction between Lean Production and Industry 4.0 has been discussed and investigated since 2011 ever since the term "fourth industrial revolution" was born. The purpose of this paper is to understand how the interaction between the two paradigms unfolds and whether it is synergetic.

Design/methodology/approach: The research relies on a systematic literature review of peer reviewed articles from Scopus and Web of Science discussing the interaction between the two paradigms. The final set of the articles pertaining to the topic was analysed.

Findings: The research shows that the interaction between the two paradigms is manifested through the pillars of house of lean interacting with the I4.0 nine technological pillars. There is a consensus on the synergetic nexus among the pillars and the positive impact they bring on operational performance. We also show through Sankey charts the weights of the interactions between the two paradigms and the operations management areas where this interaction takes place.

Practical implications: The Sankey charts show the expectations concerning the extent of synergy in the one-to-one relationship between the pillars of LP and I4.0. The thickness of the links between the pillars shown in the Sankey charts reflects the extent by which previous researchers through their studies, theoretical and empirical, is discussing the one-to-one interaction. Our research indicates that companies should invest in IoT and Cyber-physical systems as they hold the largest weight of interactions.

Originality: With the rise of discussion on the interaction between the two paradigms, there is still an opportunity for understanding the specificity of the interaction. This research contributes into further investigating such specificity and better understanding the relationship governing LP and I4.0 through delineating the interaction state among the pillars of the two paradigms and its relevant importance. The research constitute the starting point for future researchers to formulate hypotheses and test them through empirical research

Keywords: Lean Production, Industry 4.0, Lean manufacturing, interaction, literature review, Lean 4.0, smart, digital

Paper type: Literature Review

1. Introduction

Lean Production (LP) and Industry 4.0 (I4.0) are two paradigms governing the manufacturing world to face the challenges imposed by the growing complexity of the market. They contribute to lowering production costs, increasing productivity and process efficiency (Buer et al., 2018b; Mayr et al., 2018; Rosin et al., 2020). LP is a set of management practices, tools, or techniques that can be observed directly (Shah & Ward, 2003) while aiming at value creation and eliminating wastes (Mayr et al., 2018; Shah and Ward, 2007). Industry 4.0 aims at optimizing production processes making them more efficient and effective, but also more flexible to reach the conditions needed to implement mass customization or product personalization approach (Culot et al., 2020; Moeuf et al., 2020).

In 2011, the German government introduced I4.0 as a technology-driven paradigm as part of its vision to incorporate technological advancements in the manufacturing world (Osterrieder et al., 2020). The paradigm advocates the factory of the future where the various resources inside the factory are interconnected in real-time and are aware and capable of adapting to any changes in the process (Jerman *et al.*, 2020). I4.0 is widely discussed in the literature as a disruptive paradigm. It is gaining more attention requiring researchers to delve into its characteristics and understand how it can be implemented (Liao *et al.*, 2017).

LP is a diffused management approach, born in the 1950s as a culture and a set of practices based on "respect for people" and improvement in processes (Ohno, 1988). The cultural aspect of LP renders it, to date, a very relevant paradigm worth the discussion. Though coined to production, hence the name "Lean Production", Lean strives for continuous improvement across the supply chain and all areas of operations management (Womack *et al.*, 1990). LP has been in deliberation in the literature for decades and it has proven to be a widely accepted manufacturing paradigm that highly impacts companies' improvement goals (Holweg, 2007).

The interaction between the two paradigms has gained the attention of researchers and the discussion is still ongoing.

Buer et al., (2018) created a conceptual model describing a supportive bidirectional relationship between I4.0 and LP where LP facilitates the implementation of I4.0 technologies and I.0 adds the technological capabilities to LP tools. They also state that when applied together they contribute to performance improvement with an emphasis on environmental factors. Such interaction was explained on a conceptual level and did not detail the interaction between the pillars of the two paradigms. Some researchers have attempted to draw the interactions between LP tools and I4.0 technologies through literature review (Pagliosa *et al.*, 2019) and case studies (Ciano *et al.*, 2020). Others studied the interaction on a more functional level, studying the various digital aspects I4.0 offers to LP bundles (Sanders *et al.*, 2016a) investigating Value Stream Mapping VSM 4.0 (Hartmann *et al.*, 2018; Lugert, Völker, *et al.*, 2018) or e-Kanban (Houti *et al.*, 2017; Svirčević *et al.*, 2013) with various use cases and applications (see Powell *et al.*, 2018; Romero, Gaiardelli, *et al.*, 2018a).

Some researchers have a different perspective as they highlighted some incompatibilities between the two paradigms While LP is a low-tech philosophy aiming at simplicity, I4.0 is a technology-driven approach that might increase the complexity of the system (Kolberg *et al.*, 2017; Romero and Flores, 2019; Rosin *et al.*, 2020). Moreover, LP entails a human integration focused on efficiency, while high levels of automation introduced by I4.0 might cause a secondary role of people within the system (Pagliosa *et al.*, 2021).

Lean 4.0 is where I4.0 and LP meet but understanding how it unfolds is still a challenge. There exists a body of knowledge discussing the interaction between the two paradigms. However, there is still a lack of consensus and a comprehensive understanding of the nature of such interaction (Buer et al., 2018b; Pagliosa et al., 2021). Therefore, the research contributes to the body of knowledge and provides more analysis on how Lean 4.0 unfolds and how it impacts the manufacturing world. Our research contributes to the body of knowledge by presenting the current literature on the topic through a systematic literature review (SLR). It identifies how and where this interaction takes place in a manufacturing context and the operational performances it impacts on. It aims at helping future researchers in formulating their hypotheses necessary for empirical studies base on our findings.

The remainder of the paper is organized as follows. Section 2 introduces the background. Section 3 describes the research methodology followed by the results in section 4. The results are discussed in section 5 before concluding with section 6.

2. Theoretical Background

2.1. Lean Production

LP is generally described from two points of view, either from a philosophical perspective related to guiding principles and overarching goals (Spear & Bowen, 1999), or from the practical perspective of a set of management practices, tools, or techniques that can be observed directly (Shah & Ward, 2003). It aims at systematically and continuously reducing non-value-adding activities and aligning processes to customers' expectations (Holweg, 2007) represented by The House of Lean (HoL). The roof of the HoL is about creating customer value with the highest quality, reached through the lowest cost and shortest lead time. Just in Time (JIT) and Jidoka are the building blocks of the HoL. Under the umbrella of JIT lies the continuous flow and the pull production practices while Jidoka entails error-proofing and error reduction. The foundation of the HoL instead relies on "stability and standardization" , which includes Total Productive maintenance, 5S, and Kaizen. At the center, people are the main actors, empowered by Lean to contribute to process improvement through teamwork and cross-training (Holweg, 2007).

2.2. Industry 4.0

I4.0 was coined by the German Federal Government in 2011, referring to the fundamental block of their strategy for digitalizing the industry (Kagermann *et al.*, 2013), essentially describing their vision of the future of manufacturing where humans and machines are interconnected and can communicate with each other through large networks (Santos *et al.*, 2017). This results in the improvement of productivity, speed, flexibility, and quality throughout the whole value chain (Qin *et al.*, 2016; Tortorella and Fettermann, 2018). Given the complexity of the concept and the constant evolution of its understanding, commonly addressed topics include its definition, scope, and characteristics, and the identification of its key technologies (Culot *et al.*, 2020; Oztemel and Gursev, 2020).

Several publications have attempted to define the term I4.0 through different methodologies; however, to date, no given definition has gained consensus (Oztemel and Gursev, 2020). Emerging technologies have been part of its definition, with Kagermann *et al.* (2013) focusing on their impact in manufacturing systems, while subsequent publications described I4.0 in terms of the combination of convergent technologies that enable it (Drath and Horch, 2014; Frank *et al.*, 2019; Monostori, 2014). Rubmann et al., (2015) identified the nine I4.0 “pillars” (see table 1) that were used in previous studies (Ciano *et al.*, 2020; Culot *et al.*, 2020; Liao *et al.*, 2017).

2.3. Lean Production and Industry 4.0: the interaction conversation

Lean automation term surged in the end of the 20th century as a representation for automation solutions in lean environments. The introduction of the fourth industrial revolution added to this stream of research and called for investigating the relation between the two paradigms (Kolberg *et al.*, 2017; Kolberg and Zühlke, 2015). Indeed, it is argued that I4.0 is not a cancellation factor to the established lean paradigm but rather a support that could be used to strengthen it (Rüttimann and Stöckli, 2016). Through survey-based research, some researchers found out that companies implementing industry 4.0 technologies are most likely to have implemented lean operations as well (Rossini, Costa, Tortorella, *et al.*, 2019; Tortorella, Giglio, *et al.*, 2019). This indicated that I4.0 relies on lean operations for it to be implemented in the organization. Researchers have also shown the positive impact that the interaction between LP and Industry 4.0 implementation levels has on operational performances in underdeveloped context (Tortorella and Fettermann, 2017) and developed context (Rossini, Costa, Tortorella, et al., 2019).

Table 1: Industry 4.0 pillars

Industry 4.0 pillar (Rubmann *et al.*, 2015)	**Characteristics or associated technologies**	**Explanation**	**Sources**
Autonomous Robots	Collaborative robots Automated guided vehicles (AGV) Autonomous mobile robots (AMR)	"Being possible for the worker and the robot to work alongside each other in collaboration, the worker's productivity is enhanced, while her/his stress and fatigue are reduced"	(Villani et al., 2018)
Simulation	Digital Twin (DT) Real-time data and synchronization	"Automated guided vehicles (AGVs) are mobile robots which are extensively used in the industry to transport goods from A to B."	(de Ryck et al., 2020)
Horizontal, Vertical and end-to end System Integration	Integration across the value chain Integration within the organization	"AMRs can provide many services beyond mere transport and material handling operations, such as patrolling and collaborating with operators. Combined with the ability to take autonomous decisions, these mobile platforms can offer flexible solutions."	(Fragapane et al., 2021)

Industrial Internet of Things (IIOT)	Cyber-Physical Systems Sensors and actuators Auto ID and data capture (RFID, NFC, DMC, etc.)	"These are digital representations (…) to reflect the current status of the system and to perform real-time optimizations, decision making and predictive maintenance according to the sensed conditions."	(Negri et al., 2017)
Cybersecurity	Encryption, obfuscation, patching, vulnerability scans, firewalls, quarantines, etc.	"In an Industry 4.0 context, the collection and comprehensive evaluation of data from many different sources (…) will become standard to support real-time decision making."	(Rubmann et al., 2015)
Cloud computing	Cloud systems for data storage, processing, and analysis.	"Horizontal integration of the factory with external suppliers to improve the raw material and final product delivery in the supply chain, which impact on operational costs and delivery time" "Factory's vertical integration comprises advanced ICT systems that integrate all hierarchical levels of the company (…) helping decision-making actions to be less dependent of human intervention."	(Frank et al., 2019)

Additive Manufacturing	3D printing	" Radio frequency identification system (RFID) is an automatic technology and aids machines or computers to identify objects, record metadata or control individual target through radio waves (…) RFID is often seen as a prerequisite for the IOT".	(Jia et al., 2012)
Virtual Reality (VR) and Augmented Reality (AR)	Computer-generated Digital environment or digital contents	"The IIoT (…) consists of sensors, controllers, and actuators interconnected by independent local area networks"	(Sisinni et al., 2018)
Big Data and Analytics	Artificial intelligence AI Machine learning ML	" Internet of Things (IoT) is a computing concept describing ubiquitous connection to the Internet, turning common objects into connected devices."	(Sisinni et al., 2018)
		"(…) enable efficient interaction between the physical world and its digital counterpart, i.e., what is usually addressed as a cyber-physical system (CPS)".	(S 20
		"Cybersecurity aims at protecting the cyberspace (which includes both information and infrastructures) from any cyber threat or cyber-attack."	(L 20
		"The main thrust of Cloud computing is to provide on-demand computing services with high reliability, scalability and availability in a distributed environment."	(X

		"Additive manufacturing is able to 3D print small quantities of customised products with relatively low costs."	(N
		"VR as a simulation tool [has] many different forms (…) from 2D monitor-based to 3D immersive and sophisticated set up such as the CAVE (…) AR is a novel human-computer interaction tool that overlays computer-generated information on the real scene."	(N 20
		"The ML and AI are two compelling tools that are emerging as solutions for managing large amounts of data, especially for making predictions and providing suggestions based on the data sets. (…) There exists a succession of evolution in big data analytics, starting from descriptive analytics to diagnostic analytics to predictive analytics, and (…) towards prescriptive analytics"	(K 20

3. Research Methodology

The novelty of the I4.0 topic and the maturity of LP in the industrial field direct the research methodology towards conducting a Systematic Literature Review (SLR) of peer-reviewed articles (**Figure *1***). A SLR is replicable, relies on specific steps, and lays out the basis for sound future research based on extant research and gap identification. It is a consistent and reliable methodology that allows to surveying authors' opinions and expertise in both fields (Watson and Webster, 2020). This SLR follows the method "Systematic Search

Flow" (SSF) introduced by Ferenhof and Fernandes (2016) which involves four steps: Research protocol definition, Analysis, Synthesis and Writing.

3.1. Research Protocol Definition

In this step, all four researchers and authors discussed through meetings the aim of the research and the preparation phases of the search. For the choice of the keywords, we opted for "Lean Manufacturing" and "Lean Production" following the seminal works of (Buer et al., 2018; Pagliosa et al., 2019). As suggested by Boell and Cecez-Kecmanovic (2015), to have an extensive literature review of emerging phenomena, it is useful to use additional keywords like paraphrases or specific terms related to the main concept. Therefore, we adopted the keywords of Liao et al. (2017) that provided an exhaustive view on the most relevant I4.0 keywords. We referred to English documents in the Scopus and Web of Science (WoS) databases for the areas of investigation: "Engineering" and "Business, Management, and Accounting". The databases were chosen due to their high coverage and ability to statistically dissect results based on time, publication, language, the topic covered, and article type (Falagas *et al.*, 2008). LP has been in deliberation in the industrial world since the 1980s, but since I4.0 has emerged in 2011, it was decided to restrict the timeline to 2011 onward including all types of documents. All retrieved documents were organized into a spreadsheet to develop a database to be later used for the statistical analysis. Through the search query (fig.1), a total of 589 documents were identified, which were reduced to 280 after eliminating duplicates, as shown in fig. 1. Two researchers conducted the abstract analysis, where 147 articles not pertinent to I4.0 and LP and not pertinent to manufacturing such as health, medicine, and construction were excluded. The second screening phase involved thoroughly reading the full text of the article. Articles heavily focusing on one paradigm while briefly mentioning the other without thorough discussion regarding their interaction were excluded. The other two researchers then reviewed the work of their colleagues and discussions were had to maintain a solid work. A final set of 120 papers has been analysed and synthesized.

3.2. Analysis

A bibliometric analysis was performed to have a statistical overview over the extracted data from documents timeline, to country and authors distribution. Also a preliminary overview on the distribution of the various pillars of the paradigms was performed.

3.3. Synthesis

In this phase, all information is presented through tables and graphs. This is done according to the three main areas of investigation: the interaction between I4.0 and LP pillars, the place of interaction and the impact of the interaction.

3.4. Writing

The writing phase consisted of reporting discussions regarding the literature to be able to cater to the research objective and provide the proper insights.

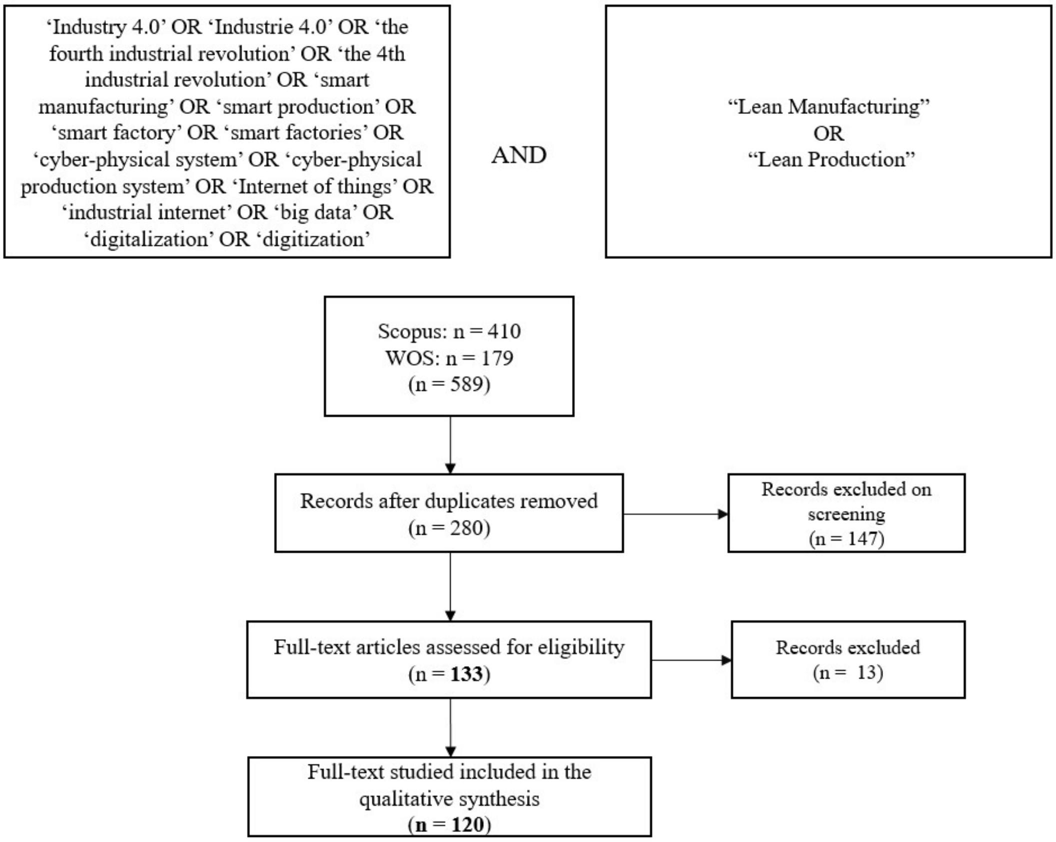

Figure 1: Literature review PRISMA chart

4. Research Results

4.1. Bibliometric Results

This section introduces the various bibliometric analyses performed, from the timeline of publications to the network of co-authorship and the distribution of the keywords (fig.2).

This research theme is considerably novel and the number of publications rising exponentially indicates an increase in the interest by researchers in investigating it.

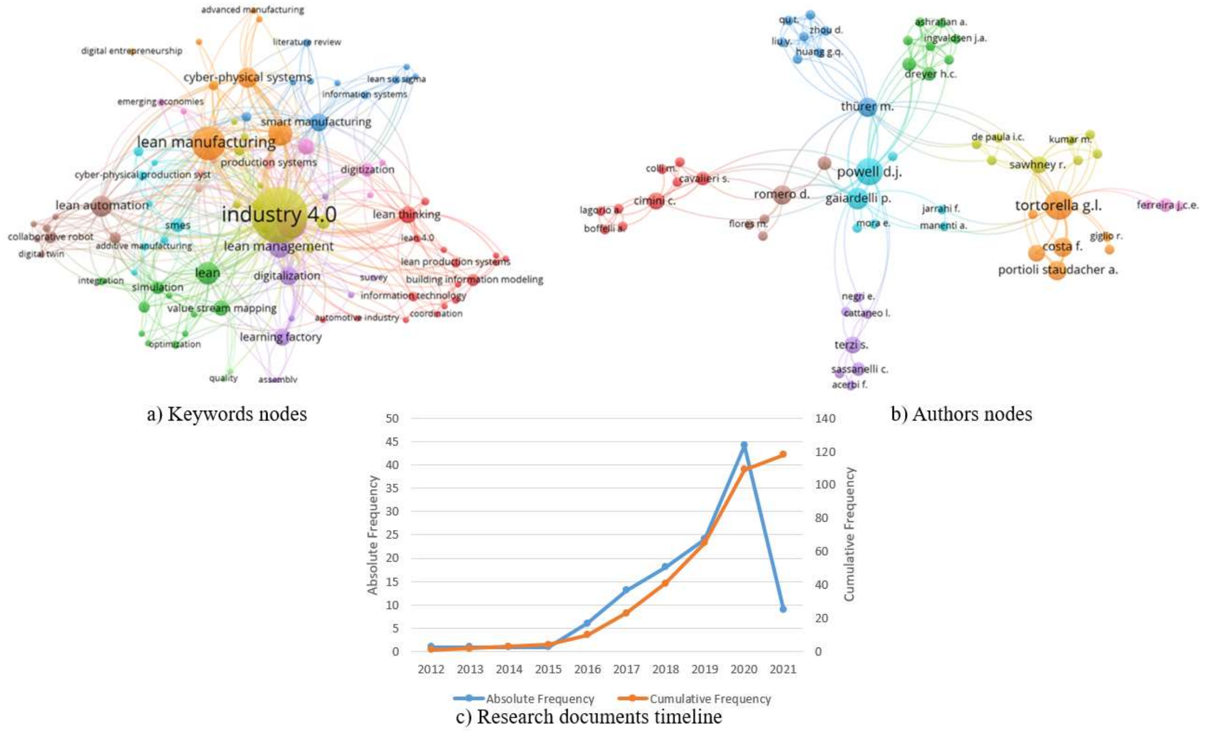

Figure 2: Keywords and Authors collaboration concentration nodes

I4.0 brings with it the digital aspect coming from the third industrial revolution. This might explain the difference between the nodes of “digitalization” and “industry 4.0”. We might infer that “industry 4.0” is beyond the term “digital”. The “lean 4.0” node size is outweighed by “lean automation” as researchers still associate automation with I4.0. The keywords related to the human factor are not shown in the network which signals a promising opportunity for future researchers to tackle this aspect.

Guilherme Tortorella and Daryl Powell. are the most active authors with a large network of co-authorship. Tortorella is conceptually oriented, he drafts the interaction with I4.0 technologies mainly through surveys and other methodologies. Powell is practice-oriented; he relies on the implementation of lean digital tools. This could indicate, to future researchers, possible collaborators based on the methodology to address the topic.

4.2 Lean 4.0 research results

From the general point of view, IIOT has the highest occurrences. IIOT contains technologies that have already been introduced by previous industrial revolutions (Huxtable and Schaefer, 2016). Figures 4.a and 4.b show the distribution of the discussion of I4.0 and LP pillars in the extant literature of the interaction.

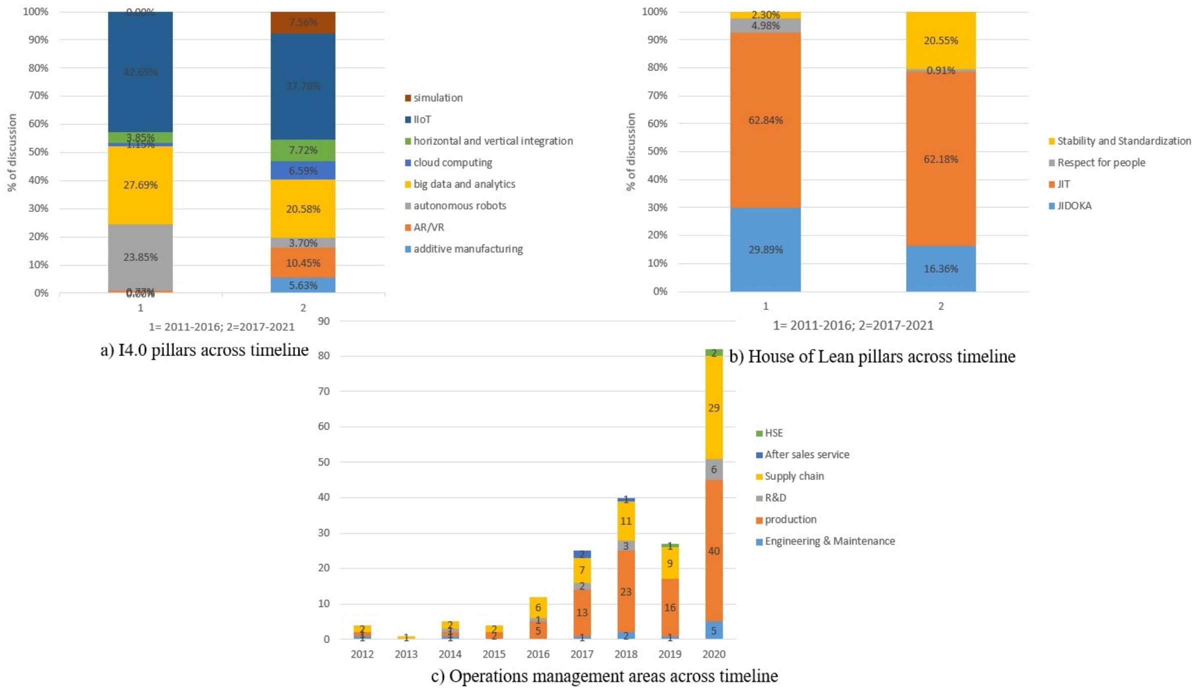

Figure 3: Analysis of pillars and areas across timeline

IIOT and Big data are the I4.0 pillars with the highest rate of discussion. There is an increase in the occurrences of AR-VR, additive manufacturing, simulation, and cloud computing, and a relative decrease for autonomous robots. This indicates a sort of maturity in understanding how the implementation of IIOT and Big data can be of use to LP and vice versa, and it highlights the pillars to investigate how they interact with LP.

There is a high and steady contribution of JIT with a decrease of that of JIDOKA and small importance of "Respect for people" (fig.4.a). The steadiness exhibited by JIT is rather expected as it is the core of the lean genealogy (Holweg, 2007).

The "Respect for people" falls short because of the intrinsic technological nature of I4.0 and the debate around human contribution in the new era still in its infancy (Flores *et al.*, 2020).

There is a great interest in investing in this interaction across the areas of operations management that include: Production, Supply Chain (SC), R&D, Engineering and Maintenance, After Sales Services, and Health, Safety, and Environment (HSE). Figure 4.c shows the major areas of the interaction (i.e. the concurrent use of the pillars of both paradigms, or the use of one pillar for the benefit of the other). The trajectory of the discussion on Lean 4.0 follows the same path of Lean, the focus starts on production, and then it expands to the areas beyond it. Lean was indeed born for production before expanding into the SC (Ohno, 1988).

5 Discussion

The interaction between LP and I4.0 is prevalently bidirectional and synergetic. The surveyed literature shows that the interaction mostly takes place at the tactical level, i.e. the level of the pillars of the two paradigms. This section discusses this level and explains where such interaction takes place and touches on the impact it has on operational performances.

The research relied on the various Sankey charts to show the various interactions between I4.0 and LP. Figure 4.a for example shows the interactions among the four pillars of HoL and I4.0 pillars. The link between the two sides is strictly related to the existence of the interaction that is an I4.0 pillar make use of LP pillar and vice versa. The thickness of the link corresponds to the weight of the interaction which is the number of occurrences across the extant literature (the thicker the link, the greater the interest of researchers in discussing the interaction). A summary of the main interactions and benefits is reported in Table 2. We formulate a list of findings delineating the various interactions based on those charts and proceed into explaining them. Cybersecurity is excluded as no interaction was found between this pillar and any other LP pillars which is aligned with (Ciano *et al.*, 2020).

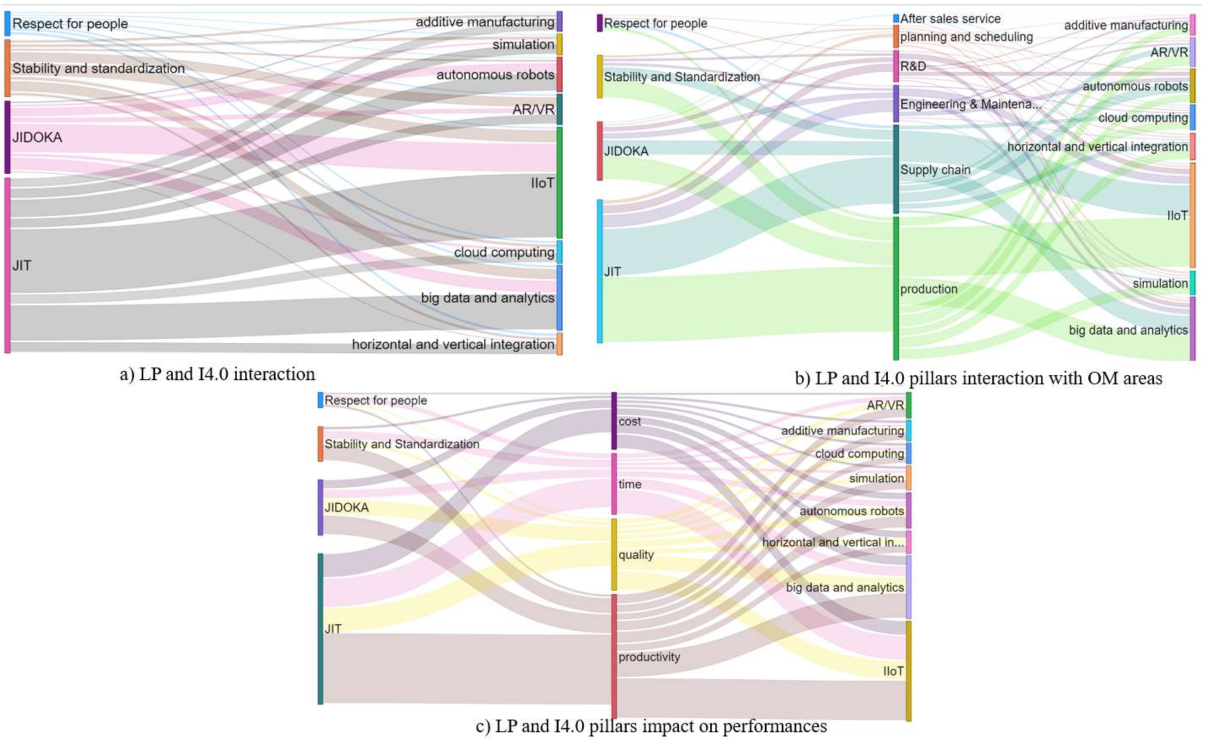

Figure 4: Analysis of interactions through Sankey charts

Though some researchers raise some doubts about the nature of the interactions, there is a prevalent synergetic relationship between LP pillars and I4.0 pillars, and it contributes to improving operational performances across all areas of operations management.

5.1 Lean 4.0: the common ground

LP and I4.0 have common characteristics. To begin with, they can be applied across all levels of organization and the value chain. Moreover, they both bring similar benefits (Marodin and Saurin, 2013) from reducing costs to flexibility and improving productivity (Alves, 2022; Sanders *et al.*, 2016b) Such benefits are due to both paradigms promoting standardized and easily integrated modules (Buer, Fragapane, *et al.*, 2018; Kolberg *et al.*, 2017; Kolberg and Zühlke, 2015).

5.2 Lean 4.0: The Interaction between LP and I4.0

5.2.1 Lean 4.0: I4.0 impact on LP and its pillars

The literature puts a great emphasis on this direction of interaction both from theoretical and empirical points of view.

Finding 1: I4.0 technologies empower potentials on LP tools and practices.

This stream of research shows several applications of lean tools leveraged by the potentials of I4.0 technologies such as the shift from Kanban to e-kanban (see Sanders et al., 2016b) and from VSM to real-time VSM (Anosike *et al.*, 2021). The implementation of I4.0 solutions will be eased in companies that have applied the standardization of processes and waste elimination, typical of the LP approach (Kolberg and Zühlke, 2015; Nicoletti, 2013; Tortorella *et al.*, 2021; Wyrwicka and Mrugalska, 2017).

Finding 2: JIT has the largest weight of synergy with I4.0 pillars, and IIOT has the largest weight of synergy with LP pillars

With RFID, every product in the order note is tagged (Wagner, et al., 2017) and IoT uses integrated devices to manage data and track the movements of products as they move along the SC. This leads to delivering the right product at the right time in the right quantity to the right customer (Ben-daya *et al.*, 2017; Sanders *et al.*, 2016a). Smart products can communicate directly with the machines about their process steps through the cloud, which allows machines to self-adjust and adapt to the product in line resulting in quicker changeover and SMED applications (Lugert, Batz, *et al.*, 2018; Pecas *et al.*, 2022; Satoglu *et al.*, 2018)

Jidoka is the second pillar with the largest interaction with I4.0 technologies. The key component of Jidoka is Andon and error-proofing. IIOT plays an important role in reducing production errors and preventing them (Kolberg *et al.*, 2017; Ma *et al.*, 2017; Tripathi *et al.*, 2021). In addition, error-proofing tools could be 3d printed (Kietzmann *et al.*, 2014).

Regarding the "Respect for people" pillar, I4.0 technologies act on the physical as well as social aspects. From AGV and robots to virtual reality, workers no longer have to perform repetitive tasks (Giuliani *et al.*, 2010). The simulation tool could be also used to test various scenarios and therefore empower the critical thinking of operators for efficient problem-solving (Abd Rahman *et al.*, 2020; Ferreira *et al.*, 2022; Negahban and Smith, 2014). It is an educational tool that supports the employees in understanding the changes on the production lines before implementing a new project (Uriarte *et al.*, 2018).

5.1.2 Lean 4.0: LP facilitates the implementation of I4.0 pillars

The lean culture favours the implementation of I4.0 technologies in a manufacturing company. By providing a waste-free process, companies are ready to welcome new technologies on the shop floor without the risk of being caught up in the spiral of understanding where to use those technologies. Companies implementing LP are more open to radical changes in their processes (Moyano-Fuentes *et al.*, 2012). An LP process is more likely to be modelled and controlled through automatization (Rüttimann and Stöckli, 2016). This has led some researchers to claim that LP implementation must be necessarily seen as a prerequisite for a successful I4.0 transformation. If we digitize an inefficient process, this yields an inefficient digitized process (Nicoletti, 2013), therefore they need to implement LP. Based on a survey in European and Brazilian manufacturing companies, Tortorella et al. (2019) and Rossini et al. (2019a), showed that companies implementing LP are more likely to implement I4.0 technologies so they advocate that LP is an ideal foundation when shifting towards I4.0.

In addition, Garner et al. (2017) show that implementing I4.0 in a manufacturing company is a mere continuation of the improvement path LP is on. The I4.0 journey is similar to that of LP, so they suggest adopting the same steps to ensure the proper implementation of I4.0 technologies.

This stream of thought is mainly theoretical with some empirical attempts. This suggests ample room for future research to deeply investigate in an empirical way how a company might not benefit from I4.0 if a lean culture is not instilled.

JIT is the pillar with the biggest weight of interaction with the I4.0 pillars (fig. 4.a). IIOT and Big Data show the highest synergetic interaction with JIT.

Finding 3: The foundation of LP could be the same as I4.0.

Finding 4: Though "Stability and Standardization" and "Respect for people" have the smallest weight of interactions with I4.0 pillars, they interact with all I4.0 pillars equally.

It is expected to have equal weights of synergetic relationship for "Stability and Standarization" because "An inefficient process that is automated is still inefficient" (Buer, Strandhagen, *et al.*, 2018) . 5S and visual management contribute to the standardization of shop floors and warehouses. This was proven empirically through the work of Ciano et al. (2020) where companies had to adapt their shop floors and warehouses to guarantee efficient automation. AGV for example would avoid reworks having made sure all items are in place and in order. They also showed that empowering teamwork enables idea creation for deciding the corresponding investments in technologies.

There was scarce evidence of the synergetic impact of the rest of the LP pillars on I4.0 technologies. Ciano et al. (2020) demonstrated empirically that kaizen events mitigate resistance to change and help operators understand I4.0 and its importance. Kaizen events offered a space of shared vision and ideas creation for problem-solving where digitalization is introduced, hence lessening workers' resistance to technological advancements adoption. They also demonstrated that companies applying LP and I4.0 pillars use VSM to map the process and individualize for future state areas of improvements through digitalization.

Unlike the first direction of the interaction, the literature approaches the impact of LP on the implementation of I4.0 technologies, mainly with a theoretical lens and with less profundity and breadth. It might be inferred that the cultural nature of LP drives this non-holistic investigation by researchers. Kolberg et al. (2015, 2017) consider the digital feature as an add-on to LP from automation in the 90s till the concept of I4.0. Furthermore, this might be supported by the lack of proof that I4.0 technologies could function well alone without the need for a lean culture. Rossini et al. (2021) highlighted two digital transformation patterns for *high* lean and *low* lean adopters. Though there was no discussion on the effectiveness of the use of the technologies but rather the approach in which they are implemented, the low lean adopters still hold some level of lean adoption.

5.3 Lean 4.0 Areas and positive impact on operational performances

Finding 5: The Lean 4.0 interactions follow the same pattern as Lean; they take place mostly in the production area followed by the SC.

The production floor is the area where most of the interactions (fig. 4.b), followed by the SC. Bhamu and Sangwan (2014) presented an extensive literature review on Lean and showed that the association of Lean with the production area was more extensively used in the definitions of Lean in comparison to the SC area. The current literature on Lean 4.0 is mainly focused on production followed by SC which suggests that Lean 4.0 follows the same genealogy of Lean when first encountered in literature and practice.

Finding 6: Lean 4.0 interactions improve all operational performances and Productivity is the performance targeted the most by them (see fig. 5.c)

The production system benefits from real-time availability to track products on the floor. Managers can monitor all production steps, the production process, and its performance and make optimal reactive decisions when necessary (Ben-Daya *et al.*, 2019; Buer, Strandhagen, *et al.*, 2018; Javaid *et al.*, 2022; Moeuf *et al.*, 2018).

Smart machines are capable through embedded sensors and CPS to actively suggest task arrangements and adjust operational parameters to maximize productivity and product quality(Hoellthaler *et al.*, 2018; Lee *et al.*, 2015). Furthermore, the production process can self-maintain and self-adjust whenever faced with internal changes such as machine breakdowns. In a dynamic production, decisions are postponed, allowing for a real-time reactive production system (Meissner, et al., 2017; Qin, et al., 2016; Quintanilla, et al., 2012;). This confirms that smart machines could empower Andon and Jidoka (Ciano *et al.*, 2020). It allows for the reduction of wastes in material consumption, in workers ' non-value-added times, and eventually the reduction of lead time.

The impact of Lean 4.0 interactions extends beyond production to logistics and SC. Thanks to CPS and Cloud, this extends to the SC to synchronize suppliers' tasks with production, give them feedback to improve their job as well as improve their performances(Ben-Daya *et al.*, 2019; Nascimento *et al.*, 2022; Sanders *et al.*, 2016a)

Table 2: LP and I4.0 main interactions

LP Pillar	I4.0 Pillar	Interaction Example
JIT (VSM)	Big data + IIoT + Simulation	Data collection in real-time enabled by IoT devices can compensate for the static nature of VSM and turn it into a dynamic and flexible tool due to the highly synchronized flow of digital information (Davis *et al.*, 2020; Garner, Bateman and Martin, 2017; Ilangakoon *et al.*, 2019; Rosin *et al.*, 2020; Tortorella *et al.*, 2020)
JIT	Simulation	Process simulation is an important technique used for the optimization of processes such as scheduling and layout planning (Ciano *et al.*, 2020). Simulations are particularly useful in detecting bottlenecks and are also adopted to potentially improve the results of VSM (Lugert, Batz, *et al.*, 2018).
JIT (Kanban)	IIoT (RFID + sensors)	Electronic kanban or e-kanban systems use RFID technology sensors, and actuators, enabling real-time demand signaling systems for a more efficient production cycle (Kolberg *et al.*, 2017; Romero, Gaiardelli, *et al.*, 2018b)

JIT (heijunka)	Big Data	Big data analytics enhances the scheduling and planning capabilities of Heijunka, making it more reactive to unforeseen changes in production or demand (Ciano *et al.*, 2020; Mayr *et al.*, 2018; Powell *et al.*, 2018).
JIT (Continuous flow)	Additive manufacturing	Additive manufacturing unlocks the capability of producing a high variety of customized products while keeping minimum setup times (Mayr *et al.*, 2018; Tortorella *et al.*, 2020; Yin *et al.*, 2018).
JIT (Continuous flow)	Collaborative robots	The adoption of collaborative robots adds agility to assembly processes and could also increase product mix flexibility (Khanchanapong *et al.*, 2014; Tortorella *et al.*, 2020).
JIDOKA (andon)	IIoT (smart devices + cps)	Operators equipped with smart devices can receive error notifications and locations in real-time regardless of their physical location, thus reducing the time between failure occurrence and failure notification. Once these failures are identified maintenance activities can be triggered automatically (Ciano *et al.*, 2020; Kolberg and Zühlke, 2015; Mrugalska and Wyrwicka, 2017).
JIDOKA (andon)	VR/AR	Devices such as augmented reality head-mounted displays and RFID readers are used to minimize errors during picking and also to prevent errors during assembly operations (Mayr *et al.*, 2018; Mora *et al.*, 2017).
JIDOKA (poka yoke)	IIoT (sensors)	Data collected from machines equipped with sensors are analyzed and can provide insights about avoiding mistakes (Mrugalska and Wyrwicka, 2017; Romero *et al.*, 2019).

		Sensors can also be installed to support processes prone to failure, for instance, by optically identifying components using RFID or QR codes to ensure correct identification and assignment and to quickly detect defective products (Ciano *et al.*, 2020; Kolberg and Zühlke, 2015).
"Respect for People" (stakeholder orientation or empowerment of people).	H/V integration + cloud	Sharing data and information create more synergic cooperation between the manufacturer and all partners in the SC covering the entire product life cycle. Cloud computing can facilitate communication with suppliers, enabling collaborative manufacturing and supply risk mitigation (Ciano *et al.*, 2020; Sanders *et al.*, 2016b).
"Respect for people"	robots	The introduction of collaborative robots can relieve workers from mundane and repetitive tasks (Ciano *et al.*, 2020).
"Stability and Standardization" (TPM)	Big data analytics + IoT	IIoT-connected machines are capable of assessing their health and degradation, and use data from other assets in the network to anticipate potential breakdowns and automatically trigger maintenance activities(Chiarini *et al.*, 2020; Ghobakhloo and Fathi, 2020; Jarrahi *et al.*, 2019; Mora *et al.*, 2017; Sanders *et al.*, 2016b)
"Stability and Standardization" (TPM and KAIZEN)	VR/AR	Head-mounted displays, both augmented and virtual reality, can support operators to follow maintenance instructions and can also facilitate employee training (Mayr *et al.*, 2018; Mora *et al.*, 2017; Rosin *et al.*, 2020; Shahin *et al.*, 2020).

"Stability and Standardization". (TPM)	robots	The implementation of autonomous robots or collaborative robots working along operators supports the standardization of work procedures (Rosin *et al.*, 2020).
"Stability and Standardization" (kaizen)	Big data and analytics	Process data collected during and post-production can be analyzed to drive a continuous improvement process (Kolberg *et al.*, 2017; Kolberg and Zühlke, 2015; Mrugalska and Wyrwicka, 2017).

5.4 Lean 4.0: a different perspective on the interaction

Most of the extant literature confirmed a synergetic positive interaction between LP and I4.0. However, few studies highlighted possible shortfalls in this synergy. Rosin et al. (2020) and Sanders et al, (2016) postulate that while LP emphasizes stability in production and suits better low variability, I4.0 introduces complexity and encourages high variability. Pagliosa et al. (2019) stress the different focus each of the paradigms pays to the human factor; while LP is human-centric, I4.0 is technology-oriented with less interest in human integration. Tortorella et al. (2019) showed that process-related technologies seem to moderate the effect of low setup negatively. However, they explained that this was mainly due to the low adoption of pull practices in the Brazilian context in which the study was carried out.

When we add the synergic combination of LP and I4.0, the benefit is mainly related to the implementation of ad hoc digital LP tools and so general conclusions are more difficult to find. I4.0 as a primarily technical improvement approach cannot replace the LP mentality, however, it can offer many opportunities to take the existing LP systems to the next level of excellence (Meissner *et al.*, 2018). The main limits stated by the literature are related to the organizational implications like cultural change and training needed to embrace new technologies in existing processes (Moeuf et al., 2020). In addition, the majority of these difficulties are faced by SMEs, especially in terms of aversion to change and employee training (Marodin *et al.*, 2016). In an I4.0 environment, the employees' engagement is a 'must'. Indeed, companies must create a "Digital Culture" in which employees should be trained to understand the values of "a new digital way of thinking" (Romero & Flores, 2019). Investments to adapt the competencies of the workers will be needed. Moreover, this is aligned with one of the key principles of the LP paradigm where the person has to grow to maximize individual and team performance (Uriarte *et al.*, 2018).

These studies gave an idea on possible shortcomings of the synergy, nonetheless they also mainly sustain the consensus on the existence of synergy between the two paradigms and its positive impact on operational performances.

6. Conclusion

6.1. Concluding Remarks

This article explores the extant literature on the interaction between LP and I4.0 and shows how the synergy unfolds between them. Such interaction takes place on the pillars level where the various one-to-one synergetic relationships between the pillars of both paradigms has been explored.

The extant literature reveals a bidirectional relationship between the two paradigms through two research lines. However, such interaction is prevalently dominated by one main research line, that of I4.0 empowering effect on LP tools and practices. Within this context, the extant research considers I4.0 as a collection of advanced technological pillars and sees them as an opportunity to overcome some limitations of LP. Those limitations may not be in terms of the purpose of LP tools and practices but rather in terms of speed in functioning and rendering a more efficient workforce. This research line mostly equates I4.0 with an Add-on to LP, thus shedding more importance on LP rather than on I4.0 as it testifies to the flexibility of LP, a socio-technical paradigm (Shah and Ward, 2003), to continuously adapt to and make use of new technological revolutions, rendering it a "socio-technological" paradigm. LP can use such technologies not only to complement its tools and practices with real-time functioning and improve their effectiveness and thus improve the company's processes but also to support its core resource, the "people". The workforce effort switches from performing repetitive tasks to relying on technologies such as robots to perform those tasks, and on Augmented reality to learn the process and reduce mistakes.

The second less developed research line focuses on I4.0 making use of LP to lay the foundation necessary for the application of its technologies. The foundation of the HoL could be considered as the foundation of I4.0, in the sense that LP is built on standardized and stabilization in processes that pave the way for proper digitalization and implementation of I4.0 pillars. Though the research does not indicate that JIT and Jidoka, the two building blocks of the HoL, have an enabling effect on I4.0 technologies, they are the most empowered by them. The Lean 4.0 paradigm building blocks are JIT 4.0 and Jidoka 4.0. This is due to the enabling power of all I4.0 pillars on IIOT and Big Data.

Within both research lines, research shows that most of the interactions take place in the production area. Lean 4.0 seems to follow the trajectory of LP; they both are implemented heavily in production in addition to SC and other operations management areas.

In addition to highlighting the areas of concentration of Lean 4.0, the research confirms the positive impact the various interactions have on operational performances: productivity, quality, time, and cost. The ceiling of the HoL4.0 is similar to that of LP and, aligned with what I4.0 promises, lean 4.0 is focused on improving productivity, quality, reducing time and cost-related performances.

6.2. Research Implications

Our work contributes to enriching the discussion on the topic of I4.0 and LP and its related body of knowledge. Conversely, the literature is scarce on highlighting how LP tools and practices have enabling power on I4.0 pillars other than “Stability and Standardization and “Respect for people”. Therefore, this area has promising potential for further investigation by researchers. The research shows that Lean 4.0 follows the same trajectory as lean, that is the interactions with I4.0 technologies are extensively used in production areas and then extended in the SC. This highlights that the I4.0 aspect when coupled with LP does not change its intended nature, but rather behaves as an add-on. Such results are aligned with Rossini et al, (2021) where they proved empirically that manufacturing companies that highly adopt LP in their operations, tend to implement I4.0 technologies in the same way it operates, in small batches and based on continuous improvement projects. Lean 4.0 in a sense follows the same trajectory as Lean when LP is coupled with I4.0.

The use of these findings is not only for the research world but also for the managerial one as it entails the following practical implications. The literature shows that LP provides a stable efficient process ready to be digitalized, therefore managers could start the conversation of the leanness of their operations before opting for investing in I4.0 and its technologies. Such conversation could mitigate the possible fallouts of an inefficient digitalized production process with high investments already incurred. The research world tends to focus on specific areas of interaction, and the JIT synergetic relationship with I4.0 is a case in point. The JIT, a key pillar of the lean culture is heavily discussed and presents a solid ground for managers to understand how they can leverage the offerings of I4.0 to empower the use of JIT practices. Furthermore, our research could be used to guide companies in their digitalization journey. Managers operating in companies prevailed by lean operations and are evaluating which I4.0 technologies to invest in, could benefit from our study. The Sankey charts show the expectations concerning the extent of synergy in the one-to-one relationship between the pillars of LP and I4.0. The thickness of the links between the pillars shown in the Sankey charts reflects the extent by which previous researchers through their studies, theoretical and empirical, is discussing the one-to-one interaction. Our research indicates that companies should invest in IoT and Cyber-physical systems as they hold the largest weight of interactions.

6.3. Research Limitations

This research presents some limitations. The work is mainly concentrated on Lean from a manufacturing and production perspective and not the service perspective. This was intended to provide a clear focus of the research, but future work will be dedicated to the service sector. Another limitation is the focus on company's focal firm operations with less focus on the supply chain level. The discussion and conclusions derive from surveying peer-reviewed journal articles and conference proceedings in English. This might have overlooked some important publications written in other languages. Similarly for book chapters, theses and editorials, but such a decision was made in accordance to the research scope. Also, the interaction between the two paradigms does not take into account the company's contextual factors for example, or political conditions and regulations which might contribute to the redefinition of such interaction. Therefore, an expansion of the research in that regard might be helpful as well. We rely on two scientific databases, but they are considered rich in their material and reliable as well. Also, the rigorous steps adopted in conducting the SLR ensured the choosing of the right and most relevant articles to contribute to the extant body of knowledge on the topic. Furthermore, the impact of interactions on operational performances is not measured quantitatively but rather qualitatively. Articles discussing the topic assert positive impact but do not show numerical evidence of such improvement, but rather draw on the usefulness of the interaction between any given two pillars to support such claim.

6.4. Future developments

Future research might benefit from the map of interactions to further develop those who have smaller weights. In addition, we call on researchers to empirically validate the findings put forward in this research. Furthermore, researchers could expand on the work by delineating an implementation process for the various interactions to achieve complete and successful integration between LP and I4.0. Also, cybersecurity is still relatively out of the discussion in this interaction so there is a great potential to deepen this topic. Furthermore, the research for the impact on operational performances needs further developments as there is a lack of empirical evidence and quantitative measures to show such impact in companies' operations. Finally, we suggest expanding the work to Lean Six Sigma as already some authors have studied empirically he interaction between I4.0 and Lean Six sigma (see Chiarini and Kumar, 2021). The study could be also expanded to different sectors and industries as well as different contexts to further contribute to closing the loop.

7. References

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