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One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study

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ABSTRACT
Production research literature and industry practice have started to pay increasing attention to the Industry 4.0 (I4.0) phenomenon. Scholars and practitioners identified a strong link between this paradigm and the well-known Lean Production (LP) paradigm. Most studies consider LP as a prerequisite of I4.0 and I4.0 as a tool to overcome LP limits and boost its practices. However, so far, these effects have been studied only at a high level, without an in-depth and comprehensive pairwise analysis at a practice-technology level. Moreover, few empirical studies have been carried out on this topic. Our paper attempts to fill these gaps by conducting a multiple case studies research to explain the one-to-one relationships between LP techniques and I4.0 technologies, and vice versa. More specifically, the one-to-one analysis examines the enabling effect of LP on I4.0 and the empowering effect of I4.0 on LP. Based on the empirical analyses, we propose a framework on the relationships between the two paradigms structured into six areas drawn from previous research (i.e. manufacturing equipment and processes, shop-floor management, workforce management, new product development, supplier relationships, customer relationships). Such representation clarifies the interdependence of the two paradigms in the whole supply chain.

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Industry 4.0; lean; multiple case studies; empirical research; smart factory

1. Introduction

The last four decades of operations management and production research literature have been characterised by an increasing interest in the lean production (LP) phenomenon (Ciano et al. 2019). On one hand, LP has been proved to eliminate wastes, reduce set-up and lead times, reduce inventories, and improve performance (Pozzi et al. 2018; Kovács 2020; Tortorella, Fettermann, et al. 2020; Sancha et al. 2020). On the other hand, it can improve the employees' morale and satisfaction, communication, and decision-making attitude (Jasti and Kodali 2015; Hopp 2018; Ciano et al. 2019).

All these LP benefits lead to costs and efforts reduction and contribute to reaching customer satisfaction (Jasti and Kodali 2015; Kovács 2020). However, nowadays, the market is increasingly competitive and requires companies to improve rapidly; moreover, it is challenging the industry with the rapid increase of highly customised products' demand (Kolberg, Knobloch, and Zühlke 2017; Buer, Strandhagen, and Chan 2018). LP is facing several challenges from an integration perspective; indeed, the acquisition of exact customer needs is getting more and more complex, pull production must face rapid changes in scheduling, and often the set-up time reduction is based exclusively on human experience (Sanders, Elangeswaran, and Wulfsberg 2016). The current context implies complex systems and a consequent high-volume data that call for the adoption of new solutions able to exploit the potential of information and communication technologies (Kolberg, Knobloch, and Zühlke 2017; Buer, Strandhagen, and Chan 2018; Yin, Stecke, and Li 2018).

The literature considers the potentialities of Industry 4.0 (I4.0) able to overcome the LP's limits in facing the aforementioned issues (Kolberg and Zühlke 2015; Kolberg, Knobloch, and Zühlke 2017). Indeed, I4.0 is seen as the 'usage of intelligent products and processes, which enables autonomous data collection and analysis as well as the interaction between products, processes, suppliers, and customers through the internet' (Buer, Strandhagen, and Chan 2018). Several studies demonstrate that I4.0 technologies significantly improve industrial performance, most of all, flexibility, productivity, delivery time, cost, and quality (Moeuf et al. 2018, 2020). Furthermore, I4.0 is attracting many companies since these benefits

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can be translated into the promise of an individual and customised production at the same cost of mass production (Wang et al. 2016). Indeed, the integration of smart machines and components into a digital network, at the basis of I4.0, creates a so-called cyber-physical system that enables a modular and changeable production (Kolberg, Knobloch, and Zühlke 2017), as the prerequisite of an individual single-item production (Matt and Rauch 2013; Kolberg and Zühlke 2015).

However, I4.0 does not mean the sunset of lean. On the contrary, literature recognises a strong interdependency between the two paradigms (e.g. Sanders, Elangeswaran, and Wulfsberg 2016; Buer, Strandhagen, and Chan 2018; Tortorella and Fettermann 2018; Kamble, Gunasekaran, and Dhone 2020; Rossini et al. 2019; Rosin et al. 2020). Indeed, on the one hand, the LP's high streamlined process orientation with defined tasks and times, its standardisation of work and places, and its emphasis on visual control and transparency facilitate the implementation of the I4.0 information sharing and automation (Kolberg and Zühlke 2015; Dombrowski, Richter, and Krenkel 2017). On the other hand, several studies pointed out that I4.0 technologies can boost LP practices (Buer, Strandhagen, and Chan 2018). For instance, factory integration, sensors, and IoT technologies can improve Kanban, shorten cycle time, and make milk-runs more efficient (Hofmann and Rüsch 2017). Moreover, these technologies allow the real-time collection of data that can empower the value-stream-mapping and fasten the wastes' detection (see among others: Meudt, Metternich, and Abele 2017; Mrugalska and Wyrwicka 2017).

The investigation of the mutual support between the two paradigms is however still characterised by some gaps. Even though scholars agree on the enabling effect of implementing LP before I4.0, so far this effect has been studied just at a high level, without investigating the specific LP practices that cause it (Buer, Strandhagen, and Chan 2018). Moreover, there is still a lack of an in-depth and comprehensive pairwise analysis at a practice-technology level, able to clarify the roles of both paradigms in a LP-I4.0 transformation (Rossini et al. 2019). These gaps are also related to the general scarcity of empirical studies about the topic (Buer, Strandhagen, and Chan 2018; Pagliosa, Tortorella, and Ferreira 2019). Indeed, according to a recent review, only 14 percent of the studies in the field are empirical and actually verified how the relationships occur (Pagliosa, Tortorella, and Ferreira 2019).

All these aspects led to the lack of a holistic integration framework (Buer, Strandhagen, and Chan 2018), especially of one considering the link between I4.0 technologies and LP practices according to the entire value chain (Pagliosa, Tortorella, and Ferreira 2019).

This paper aims to fill these gaps by distinguishing and characterising the possible effects of the two paradigms on each other in enabling, i.e. the creation of opportunities for something to become able or competent, and/or empowering, i.e. the achievement of a sense of self-efficacy and of best version (Dunst, Trivette, and Deal 1988). Given their definitions, and the fact that an empowering effect implies that its objectives are already present or possible (Dunst, Trivette, and Deal 1988), we consider the effect of LP on I4.0 enabling, and the effect of I4.0 on LP empowering. The analysis of these effects is conducted in a one-to-one way, answering the following research questions:

> RQ1: How do LP techniques and practices enable I4.0 technologies and characteristics?
>
> RQ2: How do I4.0 technologies and characteristics empower LP techniques and practices?

More in detail, the aim of our paper is theory building on the relationship between Industry 4.0 and Lean production, i.e. identifying the key concepts of these two paradigms and their interrelationships (Gioia and Pitre 1990; Corley and Gioia 2011).

The results are obtained through the analysis of eight case studies conducted in manufacturing companies that apply both paradigms.

Our paper significantly contributes to both production research theory and practice. Indeed, it fills the content gaps depicting a detailed picture of the relationship between LP and I4.0 in both directions. Moreover, the results lead to the formalisation of an integration framework that encompasses all the areas of the value chain. The disclosure of the practice-technology relationship and the insights given by the companies can help practitioners in understanding the requirements and in anticipating the effects of the specific directions of the LP-I4.0 transformation.

The article is organised as follows: Section 2 defines the domain of LP and I4.0 and outlines their relationship through a literature review. Section 3 describes the research method and the analysed sample. The results from the case studies are presented in section 4. Section 5 discusses the main findings in light of extant literature, while section 6 summarises and concludes the article.

2. Background

This section aims first to explain the main concepts of both LP and I4.0 paradigms and to collect the key techniques and technologies to be investigated. Then, it aims to depict the state of the art of the scientific production that focuses on the effect of LP on I4.0 and the effect of I4.0 on LP.

2.1. Main concepts

2.1.1. Lean production practices and techniques

In over forty years of study, the body of knowledge on LP has expanded considerably to include dedicated journals, various special issues and many literature reviews on it. According to the high recognised reviews by Bhamu and Sangwan (2014) and by Jasti and Kodali (2015), in literature LP is generally addressed from two points of view, namely from a theoretical perspective related to guiding principles and general goals (Womack and Jones 1996; Spear and Bowen 1999), or from the practical perspective of a set of practices and techniques that can be observed directly (Shah and Ward 2003). The scope of this study leads to deepening the understanding of LP practices and techniques, the tools through which LP helps companies to achieve all the above-mentioned benefits, and to strive towards operational excellence (Möldner, Garza-Reyes, and Kumar 2020).

LP practices have been extensively adapted and implemented in several sectors with the general expectation that by adopting the same set of practices, the companies can obtain similar benefits that will distinguish them in their businesses (Tortorella, Fettermann, et al. 2020).

In literature, the LP practices were often categorised into bundles (Sancha et al. 2020; Bevilacqua, Ciarapica, and De Sanctis 2017). Flynn, Sakakibara, and Schroeder (1995) focused on the practices related to Just-in-Time (JIT) and Total Quality Management (TQM). Sakakibara et al. (1997) divided the practices into infrastructure practices (quality management, workforce management, manufacturing strategy, organisational characteristics, product design) and JIT practices (set-up time reduction, schedule flexibility, maintenance, equipment layout, kanban and JIT supplier relationships). For McLachlin (1997), LP practices can be associated to the JIT flows, Human Resource Management (HRM) and empowerment, Total Productive Maintenance (TPM) and equipment management, and TQM. According to Van Assen and de Mast (2019), these four bundles of practices are still the most addressed by literature.

Looking at the tradition of LP literature, Jasti and Kodali (2015) affirmed that it can be classified into four research streams, i.e. lean manufacturing, lean product development, lean supply chain management and lean enterprise. The first three streams concern the application of LP in the related fields, the last one emphasises the application of LP across the entire value chain of a company (Womack and Jones 1994). Indeed, a lean enterprise is a company that selects the best practices in all functional areas and the management of external relationships (Karlsson and Åhlström 1996).

Based on this last concept, the seminal study by Panizzolo (1998) suggested a scheme for classifying the LM practices composed of six areas of intervention of LP that encompass all the internal and the external pivotal aspects: the manufacturing area, other internal areas such as product design and development and human resources, and relationships with external actors belonging to the supply chain, namely suppliers and customers. Later, this scheme was recalled by Doolen and Hacker (2005) and by Bai, Satir, and Sarkis (2019); both studies updated the techniques and practices corresponding to the six areas identified by Panizzolo (1998). In particular, the recent study of Bai, Satir, and Sarkis (2019) included the findings of many works attempting to classify LM practices, namely Bortolotti, Boscari, and Danese (2015); Sezen, Karakadilar, and Buyukozkan (2012); Saurin, Marodin, and Ribeiro (2011); Pettersen (2009); Shah and Ward (2007); Shah and Ward (2003); Cua, McKone, and Schroeder (2001). The general classification brought by Panizzolo (1998) and the following studies adopting his view assign to the area *manufacturing equipment and process*, all the techniques related to the set-up and cycle time reduction, to the work standardisation and the pursuit of quality. Another area, devoted to the *shop floor management,* includes the techniques regarding the pull flow, the lot size reduction, and the production scheduling. The external actors belonging to the supply chain, i.e. suppliers and customers, have two distinct areas, i.e. *supplier relationships* and *customer relationships*. The internal relationships with the workforce were characterised by a set of LP practices referring to their commitment and their organisation, like multifunctional teamwork. Finally, the area about *new product development* included the techniques concerning the standardisation of the components and the design for manufacturing.

Nowadays, in addition to internal LP practices within individual manufacturing organisations, existing studies and industry pay attention to LP practices in the context of manufacturing supply chains (Meng 2019). Therefore, to adopt a comprehensive value chain perspective, considering both internal and external areas, this study refers to a list of LP techniques and practices classified into the related impact areas, drawn from Panizzolo (1998), Doolen and Hacker (2005), Buer, Strandhagen, and Chan (2018), Bai, Satir, and Sarkis (2019), and their main references, as reported in Table 1.

Table 1. LP practices and techniques classified into six impact areas.

Areas	LP practices and techniques	Sources
Manufacturing Equipment and Processes	Value Stream Mapping (VSM) Process Mapping Set-up time reduction – SMED Andon Poka-Yoke Standardised Work Statistical Process Control Total Productive Maintenance (TPM) Elimination of Waste 5S and Visual Management (VM) Lean Layout	Bai, Satir, and Sarkis (2019); Buer, Strandhagen, and Chan (2018); Bortolotti, Boscari, and Danese (2015); Sezen, Karakadilar, and Buyukozkan (2012); Saurin, Marodin, and Ribeiro (2011); Pettersen (2009); Shah and Ward (2007); Doolen and Hacker (2005); Shah and Ward (2003); Cua, McKone, and Schroeder (2001); Panizzolo (1998)
Shop-Floor Management	Kaizen Kanban/ Pull Strategy Heijunka One-Piece-Flow Just-in-Time (JIT) Takt Time Jidoka	
Supplier Relationships	Long-term Supplier Supplier Involvement	
Customer Relationships	Customer Involvement	
Workforce Management	Multifunctional Team Employee Commitment	
New Product Development	Standardisation of Components Design for Manufacturing	

2.1.2. Industry 4.0 technologies and characteristics

I4.0 is a label referred to the cyber-physical production system based on the integration, the transparency and the availability of heterogeneous knowledge, for meeting the market's requirements (Lu 2017). I4.0 is not limited to direct manufacturing in the company, but it concerns the whole value chain (Lu 2017; Rojko 2017; Tortorella and Fettermann 2018; Frank, Dalenogare, and Ayala 2019). Moreover, it can track and support the entire lifecycle of systems and products introducing new business and services (Rojko 2017; Dalenogare et al. 2018). Furthermore, I4.0 significantly affects production dynamics; its technologies can indeed substitute the conventional forecast based production planning with real-time planning together with dynamic self-optimisation (Moeuf et al. 2020; Sanders, Elangeswaran, and Wulfsberg 2016).

The concept of I4.0 is very complex and comprehensive, and literature does not provide a univocal definition (Buer, Strandhagen, and Chan 2018; Piccarozzi, Aquilani, and Gatti 2018; Culot et al. 2020). Among the many, Pan et al. (2015) focused on the fact that I4.0 represents the ability of industrial components and actors to communicate. This focus on the link between elements was highlighted by Kovács and Kot (2016) as well; they argued that the core point of I4.0 is the introduction of network-linked intelligent systems able to realise a self-regulating production. Burritt and Christ (2016), Lu (2017), Frank, Dalenogare, and Ayala (2019), Bai, Satir, and Sarkis (2019) and many other authors proposed a definition of I4.0 based on its combining nature, considering I4.0 as an umbrella term to describe a group of connected technological advances for increasing the digitisation of the business.

This last aspect was underlined by the key work in the I4.0 formalisation developed by Rüßmann et al. (2015), who identified nine technological 'pillars' of I4.0: (i) *Autonomous Robots*, (ii) *Simulation*, (iii) *Horizontal and Vertical Integration*, (iv) *Industrial Internet of Things (IIoT)*, (v) *Cybersecurity*, (vi) *Cloud*, (vii) *Additive Manufacturing*, (viii) *Augmented Reality*, and (ix) *Big Data and Analytics*. The pillars are also confirmed by the review of I4.0 definitions performed by Culot et al. (2020), as well as by other reviews on Industry 4.0 (i.e. Liao et al. 2017; Machado, Winroth, and Ribeiro da Silva 2020; Parente et al. 2020).

Autonomous Robots include: *Collaborative Robots*, that perform repetitive and non-ergonomic tasks in direct collaboration with the operator (Romero et al. 2016); *Automated Guided Vehicles (AGV),* that realise decentralised coordination of supplies (Stock and Seliger 2016); and *Smart Machines* that communicate with robots and products and make consequent decisions (Davenport and Kirby 2016).

Simulation can leverage real-time data to mirror the physical world in a virtual model (Rüßmann et al.2015), a concept that also leads to the *Digital Twin (DT)* (Uhlemann, Lehmann, and Steinhilper 2017). *DT* represents an achievement even for maintenance; indeed, training or scenarios simulations can be performed in a safe context replicating the 'real' environment (Tuegel et al. 2011; Negri, Fumagalli, and Macchi 2017; Liu, Meyendorf, and Mrad 2018).

Horizontal and Vertical System Integration guarantees the truly automated value chain (Rüßmann et al. 2015). Horizontal Integration, across the whole value chain, and Vertical Integration, within the company, are possible due to MES/ERP software, sensors and IIoT for data sharing (Lasi et al. 2014; Ivanov, Dolgui, and Sokolov 2019). This might also allow to enhancing the ripple effect control along supply chains (Ivanov, Dolgui, and Sokolov 2019). *IIoT* allows the interconnection at the basis of the integration enriching some devices with embedded computing. Some examples of IIoT are RFID, sensors, tags, global positioning systems (Shrouf, Ordieres, and Miragliotta 2014), real-time scanning through smartphones (Xu, Xu, and Li 2018), and smart bins (Thürer et al. 2016).

With interconnection, companies need protection from cyber-attacks. Some *Cybersecurity* systems listed in literature are encryption, cryptography, virus scanners, signature scanner, ICT Anomaly Detection/IDS (Flatt et al. 2016).

Data sharing and data analytics can be facilitated by the adoption of *Cloud*-based software. Indeed, cloud computing enables ubiquitous and on-demand network access to a shared collection of resources (Mell and Grance 2011).

Additive Manufacturing, a layer-by-layer build-up of parts (Herzog et al. 2016), such as 3D Printings, allows a quickly customised single-item or small batches production. In this regard, smart material with shape memory can be used to achieve the desired characteristics (Dilberoglu et al. 2017).

Augmented Reality (AR), as *an* overlap of computer-generated sensory input in a physical real-world, and *Virtual Reality (VR),* as a completely artificial environment created by software (Chavan 2014), might be applied for different purposes, like warehouse management, layout testing, operators' training, and remote maintenance (Rüßmann et al. 2015; Büttner et al. 2017).

Big Data collected in the smart factory allows process optimisation. *Data Analytics* divides into *Descriptive, Predictive* and *Prescriptive*. Descriptive Analytics describes the current situation and helps in the diagnosis of the problems; Predictive Analytics predict future events; while Prescriptive Analytics concerns decision-making mechanisms (Nguyen et al. 2018). *Artificial Intelligence* can exploit the collected data to make the system self-aware, self-adaptive, proactive and prescriptive (Kibria et al. 2018).

Various studies argue that Industry 4.0 offers unique opportunities to redesign production processes as well as business models, this way significantly enhance firm performance (Moeuf et al. 2020; Hahn 2020; Culot et al. 2020).

Table 2 provides an overview of the main I4.0 technologies and characteristics considered by this study, classified into the nine pillars presented above.

Table 2. I4.0 technologies or characteristics.

I4.0 pillar (Rüßmann et al. 2015)	Technologies or characteristics	Sources
Autonomous Robots	Collaborative Robots	Romero et al. 2016
	Automated Guided Vehicles	Stock and Seliger 2016
	Smart Machines	Davenport and Kirby 2016
Simulation	Of Product Of Process	Rüßmann et al. 2015
	Digital Twin	Uhlemann, Lehmann, and Steinhilper 2017; Tuegel et al. 2011; Negri, Fumagalli, and Macchi 2017; Liu, Meyendorf, and Mrad 2018
Horizontal and Vertical System Integration	Interconnection between machines and MES/ERP Data Sharing between Suppliers, Company and Customers	Lasi et al. 2014
The Industrial Internet of Things	RFID, Sensors, Tags, Global Positioning Systems	Shrouf, Ordieres, and Miragliotta 2014
	Real-Time scanning through Smartphone	Xu, Xu, and Li 2018
	Smart Bin	Thürer et al. 2016
Cybersecurity	Encryption, cryptography, virus scanners, signature scanner, ICT Anomaly Detection/IDS	Flatt et al. 2016
Cloud	Cloud systems for data sharing or for analytics application	Mell and Grance 2011
Additive Manufacturing	3D Printing	Dilberoglu et al. 2017; Herzog et al. 2016
	Smart Materials	Dilberoglu et al. 2017
Augmented Reality	Augmented Reality Virtual Reality	Büttner et al. 2017; Chavan 2014
Big Data e Analytics	Descriptive (and diagnostic) Predictive Prescriptive	Nguyen et al. 2018
	Artificial Intelligence	Kibria et al. 2018

2.2. *The effect of lean production on Industry 4.0*

The history of LP is characterised by a tendency towards autonomation since its early stages; indeed, its founder, Taiichi Ohno, stated that repetitive value-adding processes should be automated to improve the information flow and meet the market demands (Kolberg, Knobloch, and Zühlke 2017). In this regard, Ohno adopted the term 'autonomation' (Ohno 1988). Since autonomy is a crucial theme in I4.0, LP can be considered as its precursor.

According to Wang et al. (2016), a production process already based on LP can be an easier environment for the introduction of I4.0. Other papers stated or demonstrated the same concept (Parente et al. 2020). Kolberg and Zühlke (2015) and Dombrowski, Richter, and Krenkel (2017) highlighted the need for the LP process orientation and defined tasks and times to implement the I4.0 autonomation and information exchange and to lower the risks of integration. Indeed, only standardised processes allow the identification of errors and the consequent troubleshooting, essential for a valuable synchronisation of the various processes (Butollo, Jürgens, and Krzywdzinski 2018). Evidence by Tortorella and Fettermann (2018) proved that the success of I4.0 is significantly associated with the level of LP adoption. Pessl, Sorko, and Mayer (2017) confirmed the importance of LP suggesting its adoption as a fundamental strategy in a roadmap for I4.0 implementation. Erol et al. (2016) pointed out that LP as a basic competence should be transferred as well to the technical level. Mayr et al. (2018) added that LP enables I4.0 even because of the competencies that a LP decision-maker has in considering customer value and in avoiding wastes. They also highlighted the potential of LP reduction of product and process complexity to enable the efficient and economic use of I4.0 technologies. Even the more recent paper by Rossini et al. (2019) emphasises the need for a previous LP adoption to successfully introduce I4.0. Pagliosa, Tortorella, and Ferreira (2019) highlighted that VSM can be potentially beneficial for the adoption of I4.0 since it provides a structured approach to identify improvement opportunities.

Therefore, literature seems to consider LP as a prerequisite to the I4.0 implementation (Ciano et al. 2019). Nevertheless, Buer, Strandhagen, and Chan (2018) identified a lack of investigation about the facilitating effect of LP on I4.0. Indeed, even if scholars agree on the general enabling effect of I4.0 on LP, the knowledge of how it happens is still immature (Wagner, Herrmann, and Thiede 2017; Buer, Strandhagen, and Chan 2018; Rossini et al. 2019).

2.3. The effect of Industry 4.0 on lean production

Literature focusing on the effect of I4.0 on LP is richer than the one focused on the opposite direction. However, few articles considered a comprehensive set of technologies or practices (see Mayr et al. 2018; Rosin et al. 2020; Pagliosa, Tortorella, and Ferreira 2019). Indeed, most studies considered limited and specific aspects. For instance, Kietzmann, Pitt, and Berthon (2015) highlighted that 3D Printers can be considered a new form of Kanban, as they can intervene in the inventory management replicating JIT items on-demand. Lu, Li, and Tian (2015) stated that the adoption of 3D Printing helps in equipment maintenance, re-manufacturing and on-site maintenance. Regarding SMED, Feldmann and Gorj (2017) argued that, since Additive Manufacturing is not product-specific, the set-up time for selection, search and adjustment of pieces and tools are avoided.

According to Negahban and Smith (2014), Simulation empowers JIT, because it allows to test and optimise the AGV's routes. Rosin et al. (2020) found that the ability of Simulation to detect bottlenecks ensures JIT continuous flow. Simulation can be also used for the identification of ideal Kanban parameters like stock, delivery frequency and lot size (Goienetxea Uriarte, Ng, and Urenda Moris 2020). DT, instead, can reproduce realistic production plants helpful in maintenance activities (Mayr et al. 2018).

JIT, and especially One-Piece-Flow, can be promoted by Collaborative Robots included in lean assembly lines allowing the increase of production capacity and hence productivity (Gil-Vilda et al. 2017).

According to Rosin et al. (2020), the majority of the studies about the support of I4.0 on LP focus on IIoT. Indeed, they are essential to retrieve information, identification and assignment of spaces, materials, pieces and tools (Mayr et al. 2018). Literature particularly focuses on the benefits that IIoT and Cyber-Physical Systems can bring to VSM (Buer, Strandhagen, and Chan 2018; Pagliosa, Tortorella, and Ferreira 2019; Kamble, Gunasekaran, and Dhone 2020), Continuous Flow, Pull/Kanban strategy, and VM (Rosin et al. 2020). Real-time data collected by IIoT can bring to the so-called VSM 4.0 (Meudt, Metternich, and Abele 2017), a dynamic picture of the shop floor (Buer, Strandhagen, and Chan 2018; Tortorella, Pradhan, et al. 2020). The JIT continuous flow and the Pull/Kanban strategy are ensured by the IIoT ability to track products in real-time and to send instant progress updates (Rosin et al. 2020). Smart Bins recognise in real-time their filling level and the system sends a virtual Kanban to trigger replenishments (Kolberg and Zühlke 2015). IIoT can empower VM thanks to the visual monitoring information available to employees (Rosin et al. 2020). The studies by Kolberg and Zühlke (2015), Ma, Wang, and Zhao (2017), and Kolberg, Knobloch, and Zühlke (2017) focused on the role of Integration and IIoT for the empowerment of Jidoka, especially Andon. The latter study underlined the positive effect of IIoT and Integration on JIT, Heijunka and Continuous Improvement.

Other papers focus on the importance of IIoT devices to collect data for the prediction and the prescription of maintenance programmes (e.g. Lee et al. 2015; Khoshafian and Rostetter 2015; Sanders et al. 2017; Kipper et al. 2020).

Mayr et al. (2018) highlighted the importance of Big Data and Analytics in JIT, indeed the analysis of real-time process information provides insights into parameters, trends, and rules for the production system. In this direction, Huo, Zhang, and Chan (2020) propose a fuzzy control system that uses real-time data made available by Industry 4.0 technology to determine when to rebalance an assembly line and how to adjust production rates to achieve higher utilisation of machines and lower buffer levels.

Mayr et al. (2018) stated that AR and VR are important for JIT, TPM, SMED, VSM and Poka-Yoke. They mainly focused on the possibility of AR to replace physical boards to guide operators and on the use of VR to train operators for maintenance objectives. Similarly, Mourtzis et al. (2019) report on an AR-based maintenance system that provided an increased capacity to a robotics company.

Considering the supply chain level, Núñez-Merino et al. (2020) investigated by using a Systematic Literature Review (SLR) the relationships between Information and Digital Technologies (IDT) of Industry 4.0 and Lean Supply Chain Management. According to the authors, when extended to the supply chain level, a large number of IDT of Industry 4.0 and several Lean practices are used at the same time. As an example, IoT use in Lean Supply Chain Management usually occurs together with RFID, Cyber-Physical System (CPS), Cloud Computing and Big-Data affecting positively different LP practices. These benefits cover agility, flexibility, information sharing, collaboration, coordination, reduced costs, faster deliveries, reduced inventory levels as well as errors, enabling traceability and inventory control, reduced risk, improved service quality as well as customer satisfaction (Núñez-Merino et al. 2020).

Among the others, Buer, Strandhagen, and Chan 2018 pointed out that one underexplored aspect in literature is the effect of I4.0 on the so-called 'soft' LP techniques, namely the ones regarding Workplace and VM and Human Resources.

In conclusion, it can be argued that the relationship between the two paradigms has been studied mostly at a high level, with a poor investigation at a practice-technology level (Rossini et al. 2019). As can be seen, some studies deepened the relationship but referring to specific and limited aspects. The studies by Mayr et al. (2018), Rosin et al. (2020) and Pagliosa, Tortorella, and Ferreira (2019) attempted to conduct a comprehensive pairwise investigation. However, the first two studies focused just on the effect of I4.0 on LP, a research area that has more contribution than the one referring to the opposite direction (Buer, Strandhagen, and Chan 2018). Pagliosa, Tortorella, and Ferreira (2019) proposed synergy levels in both directions, but referring to LP they explained only the ones of VSM and Takt-Time on the general paradigm of I4.0.

3. Research method

3.1. Case study approach and sampling

Driven by the goal of our paper (theory building) and the nature of the RQs (i.e. 'how' questions, see the Introduction section), we adopted a multiple case study methodology. This research methodology, 'oriented towards exploration, discovery, and inductive logic' (Patton 2002), is indeed suited to the development of data grounded testable theories (Eisenhardt 1989; Voss, Tsikriktsis, and Frohlich 2002).

Our unit of analysis is the company within a manufacturing value chain. Considering the focus of our study (i.e. the relationship between I4.0 and LP) the population of interest consists of companies that have adopted both these paradigms. We adopted a theoretical sampling method (Eisenhardt 1989; Patton 2002) and selected heterogeneous cases in terms of firm size (both SMEs and large companies[1]), manufacturing industries (e.g. manufacture of fabricated metal products, electromechanical and electronic components, pumps, cableways, and sealing solutions), and level of adoption of I4.0 (both 'normal' adopters and lighthouse plants) and homogeneous cases in terms of country (Italy). The sampled companies consist of different players of the manufacturing value chain (e.g. case D is a supplier of case H, and case C is a provider of MES and other I4.0 technologies). Despite the focus on the manufacturing value chain and a single country might reduce the possibility to generalise findings, it ensures that variation is not caused by extraneous or confounding variables (e.g. Saunders, Lewis, and Thornhill 2003).

Table 3 provides data about the sampled companies, using code names to protect identity. Appendix A shows in detail the specific LP principles and techniques as well as I4.0 technologies adopted by each company.

3.2. Data collection

Data were mainly collected through face-to-face semi-structured interviews. Archival data (e.g. annual reports, websites, and internal documents on LP or I4.0 implementation projects) were also used to triangulate the empirical evidence.

Based on the review of the relevant literature (see section 2), we defined an interview protocol organised in four main sections: (1) general information about the company and the interviewee; (2) adoption of LP principles and techniques; (3) adoption of I4.0 technologies; (4) relationships between LP and I4.0. In section 2, we provided to the interviewees a detailed list of LP principles and techniques classified into six impact areas (see Table 1) and asked them whether, when, and in which department each technique was adopted. In section 3, we provided instead to the interviewees a detailed list of I4.0 technologies or characteristics (see Table 2) and asked them whether, when, and in which department/activity each technology was adopted. Finally, in section 4, we asked to the interviewees to identify and explain all possible one-to-one links between LP practices and I4.0 technologies (in both directions), i.e. whether and how

Table 3. Sampled companies.

Code	Sector/products	Employees	Turnover (euro)	Size	Note
Case A	Manufacture of fabricated metal products	60	9,5 M	SME	
Case B	Manufacture of electromechanical and electronic components	36	10,5 M	SME	
Case C	Manufacture of electromechanical and electronic components	240	43 M	SME	Manufacturing lighthouse (The World Economic Forum)
Case D	Manufacture of electromechanical components	102	25 M	SME	
Case E	Manufacture of pumps	250	100 M	LARGE	
Case F	Manufacture of cableways	3500*	1,21 B*	LARGE	
Case G	Manufacture of health care sealing solutions	270	45 M	LARGE	
Case H	Manufacture of electrical equipment	5.869*	2,344 B*	LARGE	Lighthouse plant of the cluster 'Fabbrica Intelligente' (Italian Ministry of Economic Development)

*Since data of the manufacturing company were not available for this case, we reported here data of the entire group.

each LP technique/practice has enabled the adoption of each I4.0 technology/characteristics and whether and how each I4.0 technology/characteristic has empowered each LP technique and practice. The interview protocol is reported in Appendix B.

In each company, we interviewed at least two managers (including the production and operations manager) to enhance validity (Yin 2003) and reliability of the collected data (Voss, Tsikriktsis, and Frohlich 2002). Each interview lasted 90–120 min. All interviews were recorded and transcribed verbatim.

3.3. Data analysis

We created a database for each case consisting of the interview transcripts, field notes, and archival data. As suggested by Eisenhardt (1989) and Voss, Tsikriktsis, and Frohlich (2002), we then analysed the data following a two-step procedure (i.e. within-case analysis and cross-case analysis). Due to length limitation, we however reported in the paper only the results of the cross-case analysis.

In the within-case analysis, we developed for each case two tables, following the suggestions of Miles and Huberman (1994) for qualitative data analysis. In the first one, we put in the lines the LP practices/techniques mentioned by the interviewees, in the columns the I4.0 technologies mentioned, and in the intersections the explanation of the enabling effects of LP practices on I4.0 technologies provided by the interviewees (if any) (an excerpt of this table can be found in Appendix C – Table C.1). In the second table, we put instead in the lines the I4.0 technologies mentioned by the interviewees, in the columns the LP practices/techniques mentioned, and in the intersections the explanation of the empowering effects of I4.0 technologies on LP practices/techniques. Coding and data analysis were conducted manually by two authors to ensure inter-coder reliability (Duriau, Reger, and Pfarrer 2007). These two authors and an additional one who was assigned the role of 'resident devil's advocate' discussed and resolved any disagreements.

In the cross-case analysis, we then combined the above-mentioned tables into two summary tables with the results of all analysed cases concerning (a) the

Table 4. The enabling effect of LP practices and techniques on I4.0 technologies or characteristics.

Area	LP practices and techniques	Enabling effect on I4.0	I4.0 Technology or characteristic	Cases
Manufacturing Equipment and Processes	Value Stream Mapping	(i) It allows the identification of the pivotal areas in which invest with I4.0 technologies		C; E; F; G; H
		(ii) It allows the definition of the value-adding tasks to be standardised in electronic Job Element Sheets (JES) visualised on monitors at the working stations. The electronic JES allow the operator to insert information up to date in the MES and ERP promoting the integration	Vertical Integration	B; C; E; F; G; H
	Process Mapping	(i) It allows the identification of the process flow, and therefore of the materials, WIP and information flows, essential to the design of the MES/MOM for the integration or to integrate to the ERP	Vertical Integration	A; B; C; D; E; F; G; H

(*continued*)

Table 4. Continued.

Area	LP practices and techniques	Enabling effect on I4.0	I4.0 Technology or characteristic	Cases
	Set-up time reduction – SMED	No direct effect identified		
	Andon	No direct effect identified		
	Poka-Yoke	No direct effect identified		
	Standardised Work	No direct effect identified		
	Statistical Process Control	(i) The Overall Equipment Effectiveness (OEE) concept defines data to be collect and analysed, namely all the data related to availability, performance, and quality	Descriptive Analytics	B; C; E; F; G; H
	TPM	No direct effect identified		
	Elimination of Waste	(i) PDCA and A3 to design new tools able to facilitate the introduction of I4.0 technologies (e.g. in case G A3 were used to design new carts able to facilitate collaborative robots in picking plaques from the shearing machine)	Autonomous Robots	G
	5S and Visual Management	(i) The standardisation and optimisation of the warehouse facilitates the adoption of smartphones to manage materials: without rules and standards the smartphones would identify more inconsistencies than matches	Real-time Scanning with Smartphone	E; H
		(ii) The standardisation and optimisation of the warehouse facilitates the adoption of AR glasses to manage materials: without rules and standards the smartphones would identify more inconsistencies than matches	Augmented Reality	H
		(iii) Standardisation and optimisation of the workstations and the warehouse facilitate Autonomous AGV in the material handling	Autonomous AGV	E; H
	Lean Layout	(i) In case E. a Lean Re-Layout in a straight-line cell facilitated the route of the autonomous AGV	Autonomous AGV	E; D
		(ii) In case D, the introduction of a Collaborative Robot in the U-shape cell made the flow more balanced and continuous.		
Shop-Floor Management	Kaizen	(i) Kaizen events facilitate the acceptance of I4.0 implementation by the workers and create shared occasion to bring new ideas (e.g. in case G, a multifunctional team designed the new cart above-described during a kaizen event)		C; E; F; G; H
	Kanban/ Pull Strategy	No direct effect identified		
	Heijunka	No direct effect identified		
	One-Piece-Flow	(i) It facilitates tracking and tracing of pieces in real-time increasing transparency	Vertical Integration	C; E; F; H
	Just-in-Time	(i) It facilitates tracking and tracing of pieces in real-time increasing transparency	Vertical Integration	C; E; H
	Takt Time	No direct effect identified		
	Jidoka	No direct effect identified		
Supplier Relationships	Long-term Supplier Supplier Involvement	(i) The relationship with suppliers based on lean practices enables the Horizontal Integration, indeed companies can trust suppliers in sharing platforms about the real-time status of the material consumption and in letting them manage electronic Kanban. On the other hand, involved suppliers are more willing to give such service.	Horizontal Integration	E; H
Customer Relationships	Customer Involvement/ Customisation	No direct effect identified		
Workforce Management	Multifunctional Team Employee Commitment	(i) Problem Solving conducted in multifunctional team and contests for innovative ideas enable the choice and the introduction of I4.0 solutions		G; H
New Product Development	Standardisation of Components	No direct effect identified		
	Design for Manufacturing	No direct effect identified		

Table 5. The empowering effect of I4.0 technologies or characteristics on LP practices or techniques.

I4.0 pillar	Technologies or characteristics	Empowering effect on LP	LP principle or technique	Cases
Autonomous Robots	Collaborative Robots	(i) They speed up One-Piece-Flow (e.g. in case H, a YuMi® robot is included in the production line for assembling disconnect switches one by one faster than human workers used to do allowing a more balanced line)	One-Piece-Flow	E; H
		(ii) They relieve workers from repetitive and alienating tasks (e.g. in case A collaborative robots substitute human workers in the repetitive action of picking metal sheet from the press)	Employees Commitment	A; E; G; H
	Autonomous AGV	(i) They empower the supply of materials to workstations and supermarket managed through Kanban	Kanban	E; H
		(ii) They allow an itinerant pre-assembly that reduce machine tooling and promote JIT production. Indeed, the AGV visits all the stations of the supermarket according to the identified route for the specific product and the workers add every time a sequential component to the work in progress	SMED JIT	H
	Smart Machines	(i) They can track the material consumption empowering Kanban system	Kanban	C; D; E; F; H
		(ii) They can detect and separate products with defects (e.g. in case D, the operator cannot throw a good piece into the wastebasket and vice versa because the machine to mount clips on filter units recognises the defect through a camera and opens only the gate of the wastebasket. Moreover, the machine does not allow to go on until the wrong piece is discarded)	Poka-Yoke	D; H
		(iii) They can detect anomalies in the process through sensors or cameras and call for repair via an alarm on smartphones, smartwatches or screens	Andon	A; B; C; D; E; F; G; H
		(iv) They receive information about different materials, products, or work phase and prepare the right set-up of the machine's parameters (e.g. in case D, a smart machine represents the last and single station for the packaging phase. It recognises different orders with barcode scanning and gives workers the right components for the manual assembly)	SMED	A; B; C; D; E; F; G; H
		(v) They receive information about different work phases and displays the relative electronic JES on monitors	Standardised Work	A; B; C; D; E; F; G; H

(*continued*)

Table 5. Continued.

I4.0 pillar	Technologies or characteristics	Empowering effect on LP	LP principle or technique	Cases
Simulation	Product Simulation	(i) It allows to understand if standardised components and modularity strategy can meet the customer requirements	Modularity Customisation	A; B; C; D; E; F; H
		(ii) It allows to understand which configuration allows to reduce scraps, material consumption, and processing phases meeting the LP motto 'do more with less'	Kaizen	A; B; C; D; E; F; G; H
	Process Simulation	(i) It allows configuring the layout such as to empower the process flowIn some cases, the process flow to empower is a One-Piece-Flow	Lean layout One-Piece-Flow – JIT	C; D; E;G; HC; D; E; H
		(ii) Scheduling Simulation is adopted to respect the JIT principle	JIT	E; H
	Digital Twin	(i) It creates a virtual Obeya-Room in different plants to share information and work in Multifunctional Teams from distant plants	Obeya-Room Multifunctional Team	H
		(ii) Machine DT Simulation allows to try different maintenance solutions in a safe condition and to forecast future maintenance (e.g. in case H, it is possible to replicate in VR electric panel for these purposes)	TPM	H
Horizontal and Vertical system Integration	Machines integrated with MES, ERP	(i) The integration allows real-time information record and sharing that empower:		
		(a) Kanban system: material consumption is always recorded and I. in case of warehouse integration, it triggers pick-to-light systems (with smartphones or lights in the shelf) II. in case of autonomous AGV adoption, it directs the material handling	Kanban	C; E; H
		(b) JIT: the flow is transparent and there is real-time awareness of the machine's capacity and availability that allows to better react to plan deviations	JIT	C; D; E; H
		(c) Immediate communication of anomalies or breakdowns (in case C and H communicated also through wearable smartwatches)	Andon	A; B; C; D; E; G; H
		(d) Data collection to calculate real-time KPIs (especially all the components of the OEE, namely availability, performance, and quality)	Statistical Process Control	B; C; E; G; H
	Data shared with suppliers and/or partners through IIoT systems	(i) A shared platform of real-time data empowers the supplier involvement (shared warehouse and KPIs situation)	Supplier involvement	E; G; H
		(ii) A shared platform of real-time data allows the supplier of transport and logistics to better plan its deliveries	Supplier involvement	G; H
		(iii) A shared platform of real-time data empowers the Kanban system directly managed by the supplier	Kanban	H

(*continued*)

Table 5. Continued.

I4.0 pillar	Technologies or characteristics	Empowering effect on LP	LP principle or technique	Cases
The Industrial Internet of Things	RFID, sensors, tags, global positioning systems	(i) RFID adoption allows to recognise the die and set all the relative parameters up	SMED	G
		(ii) An RFID based tool management system avoids that the wrong tool is used by the machine and thus that the tool or the workpiece is damaged.	Poka-Yoke	A; F; H
		(iii) RTLS can map movement creating spaghetti charts or can create heat maps that give information about the need for re-layout	Lean Layout	D; G; H
	Real-time scanning with smartphone	(i) It allows the Pick-to-light in the warehouse	Kanban	E
		(ii) It allows the real-time control of machines' KPIs just pointing them with a tablet or a smartphone	Statistical Process Control	C; H
Cybersecurity	encryption, cryptography, virus scanners, signature scanner, ICT Anomaly Detection/IDS	No effect identified		
Cloud	Cloud	No direct effect identified		
Additive Manufacturing	3D Printing	(i) It allows the production of small customised pre-series	Customisation	E
		(ii) It allows the production of prototypes to test if modular and standardised elements can meet customers requirement	Modularity Customisation	A; B; C; D; E; F; H
		(iii) It allows the production of Poka-yoke tools (jig and clamps)	Poka-Yoke	A; E; H
Virtual / Augmented Reality	Augmented Reality	(i) AR glasses are adopted for interactive maintenance instruction	TPM	A (project); H
	Virtual Reality	(i) It allows a virtual walk through a simulated layout to test if the configuration allows a fluid process and comfortable motions	Lean layout	G; H
Big Data and Analytics	Descriptive (e diagnostic)	(i) It provides real-time KPIs calculation, essential for the statistical control of the process (especially for calculating OEE)	Statistical Process Control	B; C; E; F; G; H
		(ii) This analysis helps in detecting defects, weaknesses and wastes	Kaizen	B; C; E; F; G; H
		(iii) Due to this analysis, it is possible to display real-time information in the visual board and discuss them during the 5 min meeting	Employee Commitment Waste Reduction	B; C; E; F; G; H
	Predictive	(i) It allows predicting maintenance actions	TPM	H
	Prescriptive	(i) It allows to prescript a maintenance plan	TPM	H
	Artificial Intelligence	(i) Genetic algorithm is adopted to optimise Heijunka (multi-objective genetic algorithm for levelling the workstations workload according to the Heijunka principle)	Heijunka	H

enabling effects of LP practices on I4.0 technologies (RQ1) (an excerpt of this table can be found in Appendix C – Table C.2) and (b) the empowering effect of I4.0 technologies on LP practices/techniques (RQ2). Finally, we combined the findings of the different cases and developed two summary cross-case analysis tables that are reported in Tables 4 and 5. Two I4.0 technologies initially considered (i.e. *smart bins* and *smart materials*) were then removed from the list since none of the analysed cases implemented them (see Appendix A).

3.4. Validity and reliability

Various strategies suggested by Yin (2003) and Eisenhardt (1989) were adopted to enhance the validity and reliability of the results. To ensure *construct validity*, we triangulated empirical evidence from different sources, mainly interviews and archival data (such as annual reports, websites, and internal documents provided by the sampled companies), and from multiple respondents (see Section 3.2). Furthermore, the coding and data

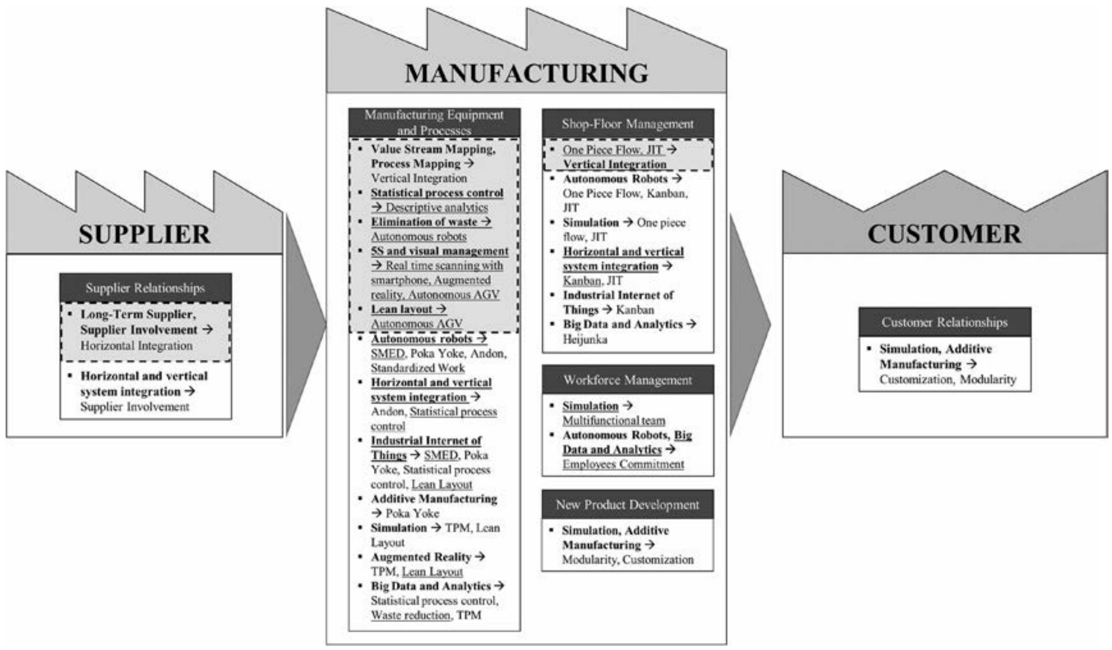

Figure 1. One-to-one relationships between LP techniques and I4.0 technologies.

analysis were carried out by two researchers/authors separately and then compared (see Section 3.3); the few disagreements in the initial coding/analyses were widely discussed until a final agreed decision was reached. *Internal validity* was instead enabled by pattern matching, i.e. we iteratively compared the findings of the within-case analysis with the proposed model (whose final version is reported in Figure 1), until when theoretical saturation was reached. To increase *external validity* (i.e. the generalizability of the results) we adopted a theoretical sampling method (Eisenhardt 1989; Patton 2002), explained in detail in Section 3.1, and we identified commonalities and differences in the analysed cases (Section 3.3). Finally, *reliability* was ensured by defining and following a case study protocol during field research and analysis (see Section 3.2 and 3.3) as well as by creating a case study database containing interview transcripts, field notes, and archival data.

4. Results

The results of the case studies are presented below in two paragraphs corresponding to the two possible directions of the relationship between LP and I4.0. Tables 4 and 5 summarise their characteristics. LP practices and techniques and I4.0 technologies or characteristics not adopted by any of the companies (see Appendix A) have been excluded from the analysis and are not present in the tables. If none of the companies recognised an enabling/empowering effect of a specific item of a paradigm on a specific one of the other paradigm, the relevant row shows the entry 'no direct effect identified.'

4.1. The enabling effect of LP practices and techniques on I4.0 technologies

All the case studies investigated in this work confirmed the agreed statement of LP as a prerequisite of I4.0. Supporting this view, in all the cases LP has been in general adopted before I4.0. However, Case A reported a particular situation in which a premature introduction of I4.0 technology called for a step back to the LP techniques. Indeed, the company introduced Smart Machines and Collaborative Robots that increased productivity. Still, the layout was neither optimised nor standardised, so the increased production was often addressed to the wrong place, work-in-progress were piled up disorderly, and different lots were mixed up. Therefore, the company understood the need for the application of LP techniques for workplace and plant standardisation, namely *5S* and *VM*.

Case D, E, and H understood that *Lean Layout* could be the basis in which including I4.0, indeed they applied cell design and then introduced Autonomous Robots or Smart Machines such as to facilitate the flow. For instance, Case D introduced Collaborative Robots in the U-shape cell in the position in which the line could be more balanced and the flow more continuous.

In summary, all the interviewees argued something similar to the statement of the manager of case H: 'If a company does not apply LP before introducing technologies and digital innovations, the results would be just a digitalisation of existing wastes.'

Considering RQ1, the cases provided deep insights about the one-to-one enabling effects of LP techniques on I4.0 technologies. These enabling effects are summarised in Table 4 and presented in detail below.

Some LP techniques can have an enabling effect on the introduction of I4.0 in general. First examples are represented by *VSM* and *Kaizen* (see cases C, E, F, G, and H). Indeed, *VSM* can be adopted to identify the pivotal areas within the value stream in which invest with any I4.0 for boosting the performance. For instance, case G, belonging to the pharmaceutical industry, stated that 'through VSM, we understood the crucial point in our process (i.e. the cleanroom) and applied I4.0 technologies to optimise order recognition as well as set-up activities, speeding up the entire phase'.

Kaizen events, instead, involve people and facilitate their acceptance of I4.0 implementation creating shared occasions to bring in new ideas. *Kaizen* events are characterised by *Multifunctional Teams* that can adopt different *Problem Solving* and *Elimination of Waste* techniques to solve an inefficiency or to improve an area. This is what happened in case G, in which, during a *Kaizen* event, a *Multifunctional Team* adopted *PDCA* and *A3* to design new carts for facilitating collaborative robots in picking plaques from shearing machines.

Kaizen and *Multifunctional Team* are often considered 'soft' LP techniques (Buer, Strandhagen, and Chan 2018), however the analysed case studies prove that their contribution to I4.0 can be very effective. Buer, Strandhagen, and Chan (2018) classified as 'soft' also *5S* and VM. However, also these other 'soft' techniques are proven to have strong enabling effects on I4.0. Indeed, according to case E:

> The principle of everything at the right place, the so-called 'set in order' of 5S, is necessary for the picking and the supply of materials and products in an automated way. Searching for specific items in a chaotic warehouse trying to use real-time scanning with smartphones would lead to find more inconsistencies than matches.

Case H supported and confirmed this statement. This company also adopted AR via smartphones for managing the warehouse and therefore found the need for *5S* and *VM* for this technology. Referring to the need for *5S* and *VM* rules and standardisation, case E added: 'Otherwise, the automation would not be efficient; for instance, an AGV in a not-standardised environment would have to perform every time a reroute.' Case E found out that also a *Lean* Re-*Layout* in a straight-line cell enables the adoption of Autonomous AGV facilitating their routes.

In cases C, E, F, and H *JIT* and *One-Piece-Flow* were fundamental practices for enabling tracking and tracing of pieces in real-time, contributing to the transparency aimed by Vertical Integration, and, if present, Horizontal Integration. Indeed, as stated by case F:

> The One-Piece-Flow principle and the connection of machines to the ERP-system both enable the introduction of a production flow that facilitates the I4.0 tracking and tracing of pieces in real-time. This increases transparency allowing to identify quality errors in early phases and consequently to reduce reworks and/or scraps.

Regarding Vertical Integration, all the cases highlighted the need to *Map Processes*, not necessarily in a *Value Stream* view, but at least in a process flow view, to identify the flow of the materials, WIP and information, essential to the design of the MES/MOM.

In cases B, C, E, F, G, and H, *VSM*, instead enabled Vertical Integration. Indeed, it allowed defining the value-adding tasks to be standardised in electronic *Job-Element-Sheets* (*JES)* visible on monitors at the working stations. The electronic *JES* allow the operator to insert up-to-date information in the MES and ERP promoting the integration. Skipping from a phase to the following one after completion, the system can record the employed time. If workers stop the station because of defects or tools breakage, the system will record the machine downtime and its causes allowing the updating of KPIs and related root cause analyses.

In the same cases, KPIs to be calculated with Descriptive Analytics are defined by the LP concept of *Overall Equipment Effectiveness* (*OEE*). *OEE* defines data to be collected, namely the ones related to availability, performance, and quality. Case C took advantage of I4.0 creating a new business division that provides other companies with new software for the shop floor integration whose several monitoring parameters are based on this LP parameter.

Regarding Horizontal Integration, case E and H identified in the practices of keeping *long term* relationships with *suppliers* and *involving* them as a fundamental basis. Indeed, companies can trust suppliers in sharing platforms about the real-time status of material consumption and in letting them manage electronic *Kanban*. On the other hand, involved suppliers are more willing to give such services.

4.2. The empowering effect of I4.0 technologies or characteristics on LP techniques

Unlike the previous analysis, the cases proved that almost all the I4.0 technologies or characteristics have specific empowering effects on LP practices or techniques (Table 5). Only *Cybersecurity* is excluded. *Cloud* has no empirical evidence to empower LP, but some interviewees recognised that it might empower the techniques belonging to the shop-floor management area and the relationships with suppliers and customers due to the on-demand shared data availability (case C, E, G, H).

All the cases identified the empowering effects of *Smart Machines* on Andon, SMED, and Standardised Work and the one of *Product Simulation* on Kaizen.

Smart Machines can detect anomalies in the process through sensors or cameras and call for repair via smartphones, smartwatches, or screens empowering Andon.

They can also receive information about materials, products, or work phase and prepare the right set-up of the machines empowering SMED. For instance, in case D, a Smart Machine represents the last and single station for the packaging phase. It recognises different orders with barcode scanning, and it gives workers the right components for the manual assembly of the boxes, drastically reducing the time for picking the right component.

Receiving information corresponding to the precise product and work phase allows displaying the relative JES on monitors. These virtual JES can be easily updated if any product changes configuration or if the line balancing finds a new configuration.

Product Simulation meets the purposes of continuous improvement; indeed, it allows to understand which configuration can reduce scraps, material consumption, and phases.

Regarding the other pillars, *Autonomous Robots* have an empowering effect on several LP techniques. *Collaborative Robots* can speed up One-Piece-Flow (cases E and H). For instance, in case H, a YuMi® robot is included in the production line for assembling disconnect switches one by one faster than human workers used to do, allowing a more balanced line. They can also empower employees' commitment by handling all the repetitive and alienating activities they used to do (case A, E, G, and H). For instance, in case A *Collaborative Robots* substituted human workers in the repetitive action of picking metal sheets from the press. Only cases E and H adopted *Autonomous AGV*. Both the cases noticed an empowering effect on the supply of materials to workstations and supermarkets managed through Kanban. Case H adopted them also for the itinerant pre-assembly, which allows reducing machine tooling, empowering SMED and JIT production. Indeed, the *AGV* visits all the stations of the supermarket according to the identified route for the specific product, and the workers add every time a sequential component to work in progress. Furthermore, cases C, D, E, F, and H proved the empowering effect of *Smart Machines* on a Kanban system. This effect is due to the real-time track of the material consumption that makes instantly the Kanban system aware of the need for replenishment. Cases D and H identified in similar ways an empowering effect of *Smart Machines* on Poka-Yoke practices. Case D argued that:

> The machine to mount clips on filter units recognizes the defect through a camera and opens only the gate of the wastebasket. Moreover, the machine does not allow to go on until the wrong piece is discarded. Once human errors were normal and understandable, now they do not happen anymore.

In addition to the effect on Kaizen, *Product Simulation* can empower modularity and customisation, testing if standardised components and modularity strategy can meet the customer requirements (cases A, B, C, D, E, F and H).

Process Simulation, instead, allows trying different layout configurations for choosing the one that better facilitates the process flow (cases C, D, E, G, H), or even One-Piece-Flow (cases C, D, E, H). Often, the company can have a virtual walk within the simulated environment for testing if the configuration allows a fluid process (cases G and H). It also allows for finding the right scheduling to respect JIT practices (cases E and H).

Case H is the only one that adopts *DT* (appendix A). The company identified an interesting empowering effect of *DT* on a multifunctional team, especially on teams with people located in different plants that share ideas and monitor the development of strategies and new products in a virtual simulated Obeya-Room. The company also highlighted an empowering effect of *DT* on TPM. Indeed, with machine *DT Simulation*, it is possible to try different maintenance solutions in a safe condition and thus allowing to forecast future maintenance. For instance, the company replicates an electric panel in VR for these purposes.

Machines integrated with MES/ERP allow real-time information record and sharing that empower Kanban (cases C, E, and H), JIT (cases C, D, E, and H), Andon (cases A, B, C, D, E, G, H), and Statistical Process Control (cases B, C, E, G, and H). Considering Kanban, material consumption is always recorded, and, in case of warehouse integration, it triggers pick-to-light systems (with smartphones or lights in the shelf). In the case of *Autonomous AGV* adoption, it directs the material handling. Due to this *Vertical Integration*, the flow is transparent, and there is real-time awareness of the capacity and availability of the machines that allow reacting better to plan deviations empowering JIT. The Real-Time Tracking can identify and immediately communicate anomalies or brake-downs respecting the Andon principle. In cases C and H, this Andon 4.0 also communicates through wearable smartwatches. Finally, data collection allowed by *Vertical Integration* allows calculating real-time KPIs (especially all the components of the OEE, namely availability, performance, and quality).

The *Horizontal Integration*, implying data shared with suppliers and/or partners through *IIoT systems*, can empower supplier involvement (cases E, G, and H) and the direct management of Kanban by the suppliers themselves (case H).

About *IIoT,* case G adopts *RFID* in presses for recognising the die and setting all the corresponding parameters. This practice reduces set-up time significantly empowering SMED. A similar match is performed by cases A, F, and H for the recognition of the right tool for the right machine, a kind of Poka-Yoke 4.0.

Another *IIoT*, the *RTLS* (real-time location system), is adopted by cases D, G, and H to map movements creating spaghetti charts or heat maps that give information about the need for a re-layout. Case E adopts *pick-to-light* in the warehouse facilitating the picking and hence empowering Kanban. Case C and H adopt *scanning with smartphones* to point machines for monitoring KPIs in real-time. Case C explained that

> by pointing the keyboard of the machine, it is possible to access not only the real-time KPIs, but also the historical ones. So far, we are only displaying KPIs, but this latter aspect could be used in the future for maintenance purposes; indeed, the access to historical breakdowns directly on-site could be useful.

Additive Manufacturing shows an empowering effect on customisation in case E, indeed the company used it for producing small customised pre-series. Most of the cases, namely A, B, C, D, E, F, and H, adopted *3D Printings* only for prototyping purposes to test if modular and standardised elements can meet customers' requirements. Cases A, E, and H, instead, use them to produce specific Poka-Yoke tools, mostly jigs and clamps.

AR is fully adopted only by case H, in which glasses and smartphones give interactive maintenance instruction overlapped to the physical world. Case A has the project of introducing Microsoft HoloLens for receiving maintenance instructions by the machinery constructor.

Six out of the eight case studies, namely cases B, C, E, F, G, and H, perform *Data Analytics*, but only *Descriptive/Diagnostics.* This technology empowers the Statistical Process Control, indeed it provides real-time KPIs' calculation, especially OEE in these cases. The analysis of the defects, the bottlenecks, and wastes promote continuous improvement (Kaizen), as well. All the KPIs and the performed analysis also give the material to display in the visual board during the 5-minutes meetings, empowering the employees' commitment and the waste reduction techniques.

Only case H performs *Predictive* and *Prescriptive Data Analytics* and both to empower TPM's plans. Case H also exploits data adopting a multi-objective *genetic algorithm* for levelling the workstations workload according to the Heijunka principle, fundamental for the company.

The manager of case H highlighted an interesting effect of I4.0 on workers, indeed he stated:

> The first attempts of LP implementation found resistance and mistrust. I4.0, instead, is making all the workers enthusiastic. Tablets, smartwatches, overlapped objects, autonomous AGV, etc. are accepted because everything has the shape of a game. In our company, this 'gaming' effect made the introduction of I4.0 technologies considerably less difficult than the adoption of traditional LP techniques.

Even if only one case reported this aspect, this can suggest interesting possible implications. Indeed, given the interdependence between the two paradigms, perhaps the gaming aspect of I4.0 can drag workers into a new enthusiastic adoption of LP techniques as well.

5. Discussion

This section discusses the results of the one-to-one relationships between I4.0 technologies and LP techniques according to the six LP impact areas. Furthermore, the original results of our paper compared to previous studies are summarised in Section 5.7.

The results of the 8 case studies are summarised and depicted graphically in Figure 1. It follows the structure and symbology of a conventional Vale Stream Map to highlight how an analysis of individual cases has revealed the importance of lean and I4.0 throughout the value chain of a manufacturing company. The upper part of each impact area, coloured in light grey, depicts the enabling effects of LP techniques to I4.0 technologies (RQ1). The lower part with the white background visualises the empowering effects of I4.0 technologies to LP techniques (RQ2).

The underlined enabling or empowering effects represent the original findings not found by previous studies.

5.1. Manufacturing equipment and processes

Considering RQ1, our study gives evidence that *VSM* enables a *Vertical Integration* of manufacturing processes. Moreover, VSM can be considered as a prerequisite to identify the focal areas and processes of a company to support with I4.0 technology. More in detail, VSM allows identifying the value-adding tasks to be standardised in electronic JES. The interaction with them allows information update, as explained in section 4.1. Therefore, VSM sets the basis for the Integration of different processes as well as different information systems (MES and ERP) confirmed by recent works (e.g. Sony 2018; Kolberg, Knobloch, and Zühlke 2017).

Based on our results, *Statistical Process Control* has an enabling effect on *Descriptive Analytics*. This is in line with the outcomes of Jugulum (2016) that highlighted the importance of data quality to perform high-quality analytics.

The cases show that *5S* and *VM* bring rules and standardisation that allow an appropriate implementation of I4.0 technologies used for the management of materials, like *Smartphones*, *AR* as well as *Autonomous Robots* and *AGVs*. On the other hand, literature also reports that *AR* can assist in carrying out *5S* more efficiently (Mayr et al. 2018), confirming mutual support between the two paradigms. Our results show also that a *Lean Layout* can be considered as a fundamental prerequisite to obtaining efficient routing of *Autonomous AGV*.

Considering RQ2, our results reveal that *Autonomous Robots* empower *SMED, Poka-Yoke, Andon* and *Standardised Work*. Considering the early detection of problems and error prevention, our findings confirm that *Smart Machines* can recognise an improper use of equipment in advance and therefore empower the LP concept of *Poka-Yoke* (Li, Ai, and Sun 2013). Similarly, the fact that *Smart Machines* can detect anomalies within the production process in real-time confirms that they empower *Andon* (Ma, Wang, and Zhao 2017). In this direction, our results reveal that *Horizontal and Vertical System Integration* empower *Andon* and *Statistical Process Control*. In particular, machines integrated with MES and ERP systems can immediately communicate anomalies or breakdowns as well as calculate KPIs in real-time. In line with research performed by Kolberg and Zühlke (2015), in case of problems/failures, employees equipped with smartwatches are notified immediately and independently from their location. Similarly, according to our results, *IIoT* empowers *Poka-yoke, SMED* and *Statistical Process Control*. Here, companies reported using *RFID* to avoid the use of a wrong tool by a machine and that the *RFID* tag recognises the die allowing an autonomous set-up of all parameters. This is in line with the research of Mayr et al. (2018), presenting the concept of *Poka-Yoke 4.0*. Besides, in our case studies, *Additive Manufacturing* allows the production of *Poka-Yoke* tools like jigs and clamps, which confirms Lu, Li, and Tian (2015). Considering *Statistical Process Control*, companies reported the use of smartphones for real-time control of machine's KPIs. This confirms Georgakopolous et al. (2016) who outlined the opportunity of *IIoT* to better understand production processes and how to improve them. Based on our results, *Simulation* enables *TPM* through a machine DT that tries different maintenance solutions in a safe environment to forecast optimal maintenance strategies. This is in line with Tuegel et al. (2011), who proposed the use of DT for predicting the life of aircraft structures to assure their structural integrity. In addition, our research reveals that *Process Simulation* allows trying different layout configurations through a virtual walk in the simulated environment reaching a *Lean Layout*. This aspect enriches the research area concerning *Process Simulation* to reach an efficient layout configuration focusing on the evaluation of parameters like machine utilisation, waiting time and throughput obtained from different simulation experiments (Negahban and Smith 2014). Furthermore, our results reveal that global positioning systems like RTLS can map the movement within a factory advising about the need to implement a re-layout. Here, no other scientific works were identified stating this fact. Moreover, VR was found to be used for testing virtually different layout configurations allowing a fluid production flow and comfortable motions. Our results confirmed also the use of *AR* to train and give interactive maintenance assignments facilitating *TPM* (Mayr et al. 2018). Furthermore, *Big Data Analytics* empowers *TPM* by predicting maintenance actions as well as prescribing a maintenance plan. This supports Lee et al. (2013) and Lee et al. (2015), who found that a prediction capability allows maintenance to be more cost-effective. According to Khoshafian and Rostetter (2015), digital prescriptive maintenance is empowered by *Big Data and Analytics*, avoiding potential failures that could have serious consequences for people, environment, and equipment. Moreover, *Big Data and Analytics,* and specifically *Descriptive Diagnostics* empower *Statistical Process Control* by providing a calculation of KPIs in real-time. Our results confirm also the use of the OEE indicator in manufacturing where advanced analytics can be used to pinpoint possible root causes for bottlenecks (Lade, Ghosh, and Srinivasan 2017).

5.2. Shop-floor management

Considering RQ1, our results show that *One-Piece-Flow* and *JIT,* promoting to obtain low levels of WIP, enable a tracking and tracing of products in real-time and hence, the *Vertical Integration* of processes within a company. Moreover, according to our results, continuous improvement processes facilitate the acceptance of I4.0 implementations.

Considering RQ2, our results reveal that *Autonomous Robots* empower *One-Piece-Flow*, *Kanban* and *JIT*. They support Kaspar and Schneider (2015), who stated that *Autonomous AGVs* empower *Kanban* since material supply at the shop floor level can be realised by using a one-container-system without the necessity to refill several containers with the same material. Similarly, the results confirm that *Autonomous AGV* can further contribute to a *JIT* delivery to the workplace because the material to be refilled at the workstation arrives in the exact moment when it is needed, as stated by Mayr et al. (2018). In this direction, scientific works by Kolberg and Zühlke (2015) as well as Kolberg, Knobloch, and Zühlke (2017) showed that *Smart Machines* empower *Kanban* mentioning the example of displays with graphical user interfaces connected to the production line and MES, which can drastically reduce the effort for updating conventional Kanban boards. In addition, our results reveal that *Process Simulation* allows trying different layout configurations through a virtual walk in the simulated environment reaching a *One-Piece-Flow* and even *JIT* production (Aigbedo and Monden 1996; Rosin et al. 2020).

Our research confirms the fact that *Horizontal and Vertical System Integration* and specifically Machines integrated with MES and ERP empower *Kanban* and *JIT* (Kolberg and Zühlke 2015; Kolberg, Knobloch, and Zühlke 2017; Mayr et al. 2018; Rosin et al. 2020*)* by continuously measuring material consumption and by having a real-time awareness of machines capacity and availability.

Similarly, our results confirm that *IIoT* empowers *Kanban* by using smartphones to support pick-to-light in warehouses, as stated by Mayr et al. (2018).

Considering *Big Data and Analytics*, our results identified that Artificial Intelligence is used to level the workstations workload according to the *Heijunka* principle. This was also underpinned by Hou, Katayama, and Hwang (2015) that used Genetic Algorithms to maximise line efficiency and minimise the variation of work overload time in a mixed-model straight/U-shaped assembly line using *Heijunka*.

5.3. Workforce management

Considering RQ1, problem-solving in a multifunctional team and contests for innovative ideas can enable the introduction of I4.0 in general. Here, no other enabling effect of LP on I4.0 were identified.

On the other hand, regarding RQ2, our results reveal that *Simulation* and specifically DT applications allow to create a virtual Obeya-Room to enable *Multifunctional Teams* with people located in different places. Here, no reference from other scientific works was identified that underpins this fact. Moreover, according to our results, *Autonomous Robot*s empower *Employees Commitment* by relieving workers from repetitive and alienating tasks while increasing the level of occupational safety (Giuliani et al. 2010). Similarly, the case study analysis identifies that *Big Data and Analytics* and specifically Descriptive Diagnostics is used to display KPIs updated in real-time on visual boards, which can be used during the 5 min meeting empowering *Employee Commitment*.

5.4. New product development

Similarly, to the previous paragraph, this impact area contributes most to the RQ2. Although the literature identifies potential use of *Additive Manufacturing* for small series favouring Kanban and JIT, the cases mostly demonstrate its use for prototyping in the fields of *Modularity* and *Customisation*. Here, the case studies report the empowering effect of *Additive Manufacturing* for the production of small *Customised* pre-series, in line with Kietzmann, Pitt, and Berthon (2015) who depicted the huge potential of *Additive Manufacturing* in the field of medical prosthetics. Moreover, the case studies adopted *Additive Manufacturing* to manufacture prototypes to test if *Modular* and standardised elements can meet customer requirements. Scientific references also underpin the empowering effect on *Customisation* (Zangiacomi et al. 2020), by substantiating the fact of 3D printers used to create prototypes that test whether standard and modular components can meet customer requirements. Here, especially the application in the field of using 3D printing for producing prosthetics can be mentioned (Bijadi et al. 2017; Hussain et al. 2018).

5.5. Supplier relationships

Based on our results and concerning RQ1, *Long-Term Supplier* relationships as well as *Supplier Involvement* enable a *Horizontal Integration* of supply chains, reporting the examples of shared platforms communicating the status of material consumption in real-time as well as suppliers that manage autonomously electronic Kanban. The companies reported that involved suppliers are more willing to give such a service. In literature, Camarinha-Matos, Fornasiero, and Afsarmanesh (2017) highlight the importance of collaborative organisational structures, processes, and mechanisms as enablers of *Horizontal Integrations* of supply chains.

Considering RQ2, *Horizontal and Vertical System Integration* and specifically data shared with suppliers and/or partners through IIoT systems empower *Supplier Involvement.* The case studies reported examples of electronic platforms that share information about warehouses as well as other KPIs in real-time that allow suppliers to organise in a better way their deliveries. The usage of common knowledge-sharing platforms that favour Horizontal Integration of Suppliers has also be confirmed in literature by Chen (2017).

5.6. Customer relationships

Answering to RQ2, the case study results report that *Simulation* and specifically *Product Simulation* empower *Modularity* and *Customisation* because it allows to understand if standardised as well as customised components meet specific customer requirements. Similarly, as reported in the field of New Product Development, *Additive Manufacturing* empowers the production of *Customised* pre-series and test if *Modular* and standardised prototypical elements can meet customer requirements.

5.7. Summary of original results

Figure 1 summarises the findings of our paper, emphasising the results that, to the best of our knowledge, have not been found by previous studies.

Considering RQ1, the following results have not been found by previous studies. *Statistical Process Control* enables *Descriptive Analytics*. *Elimination of Waste* enables *Autonomous Robots*. *5S* and *VM* enable *Real Time scanning* with *smartphone*, *AR* as well as *Autonomous AGV*. *Lean Layout* enables *Autonomous AGV. One Piece Flow* and *JIT* enable *Vertical Integration*.

Regarding RQ2, the following results have not been found by previous studies. *Autonomous Robots* empower *SMED* and *Standardised Work*. *Horizontal and Vertical System Integration* empower *Statistical Process Control. IIoT* empowers *SMED* and *Lean Layout*. *AR* empowers *Lean Layout*. *Big Data and Analytics* empower *Waste Reduction. Additive Manufacturing* empowers *Modularity. Simulation* empowers *Multifunctional Team*. *Big Data and Analytics* empower *Employees Commitment*.

6. Conclusion

6.1. Contribution to theory

This paper contributes to the production research literature on the relationships between I4.0 and LP in various significant ways.

First, we do a significant theory-building effort and propose a comprehensive framework that shows the one-to-one relationships between I4.0 technologies and lean practices and vice-versa (Figure 1), focusing not only on the company itself but also on the whole value chain (Panizzolo 1998; Hines, Holweg, and Rich 2004; Pagliosa, Tortorella, and Ferreira 2019; Rojko 2017). This pairwise framework for a LP-I4.0 integration at a practice-technology level, which was missing in extant literature (Buer, Strandhagen, and Chan 2018; Rossini et al. 2019), represents in our view a significant theoretical advancement since it highlights in a synthetic but comprehensive way all the relevant constructs (i.e. I4.0 technologies and lean principles and practices) and their interrelationships (Gioia and Pitre 1990; Corley and Gioia 2011). Further research is however needed to further validate the framework, extend it to other geographical and industrial contexts, and empirically test all the hypothesised relationships in a wider, more heterogeneous and statistically significant sample (see Section 6.3).

Second, our paper confirms previous studies that postulate that the relationship between I4.0 technologies and LP is in both directions, i.e. (a) I4.0 affects LP and (b) LP affects I4.0 (e.g. Buer, Strandhagen, and Chan 2018; Pagliosa, Tortorella, and Ferreira 2019; Rossini et al. 2019), but it adds that the two paths have a different nature. More in detail, while LP enables I4.0 (creating opportunities for its development), I4.0 empowers LP (leading to the achievement of self-efficacy and of best version). This classification of enablement and empowerment (Dunst, Trivette, and Deal 1988) allows an easier and more direct understanding of the links between the two paradigms.

Third, we highlight a set of potential relationships between I4.0 and LP, that were not highlighted by previous research (see the underlined items in Figure 1). Some examples of these relationships are the empowering effects of Autonomous Robots and IIoT on SMED and Standardised Work, of Big Data and Analytics on Employees Commitment, and of AR on Lean Layout, as well as the enabling effects of Statistical Process Control on Descriptive Analytics, of Lean Layout on Autonomous AGV, and of One Piece Flow and JIT on Vertical Integration (see Section 5.7 for further details). While these identified relationships deserve certainly to be tested on a wider and more heterogeneous sample, their identification might in our view guide future research in this field.

Finally, our study highlights the impact of I4.0 on the so-called 'soft' LP techniques, which according to a recent review (i.e. Buer, Strandhagen, and Chan 2018) represents a significant research gap. The analysis (Table 5) found specific effects of I4.0 technologies or characteristics on Kaizen and Teamwork, and in general, insights from companies support the idea that the gaming atmosphere led by I4.0 can empower and make the adoption of all the LP techniques and practices more pleasant.

6.2. Contribution to practice

The findings of our study have also significant managerial implications.

First, we identify the key concepts in the I4.0 and LP fields (i.e. I4.0 technologies and LP principles/techniques, respectively) (see Tables 1 and 2). These concepts might be used by managers to assess the implementation level of I4.0 and/or LP in their companies.

Second, the proposed framework that summarises the one-to-one relationships between I4.0 technologies and lean practices and vice-versa (see Figure 1) shows to managers all the possible synergies among the two manufacturing paradigms. It can be used as an assessment tool by both, companies that have already adopted one of the two paradigms, to exploit the possible links and synergies among I4.0 technologies and LP practices/techniques (or vice versa), and by companies that have adopted none of them and in this case to identify possible *lacunae* (or gaps) that should be addressed before implementing I4.0 (or LP). As an example, companies should re-design their plant layout (lean layout) before adopting autonomous AGV. Automating a (logistics) process that is not (yet) optimised/efficient would indeed lead only to limited performance improvement.

Third, the eight analysed cases allow us to present some insights and tangible experiences of the interdependence of LP and I4.0 in specific contexts, that can inspire managers in similar situations. For instance, managers can understand the right tools of both paradigms to deal with layout problems, with customisation's requirements, with material handling issues, etc.

6.3. Limitations and future research

This study presents some limitations. First, while the multiple case study (and the qualitative data analyses) are widely recognised as a valid research method for theory building purposes (Eisenhardt 1989; Voss, Tsikriktsis, and Frohlich 2002) and we performed several actions to enhance the validity and the reliability (see section 3), caution is needed to statistically generalise the results of our study to a wider population. Furthermore, some results were reported by a single case and perhaps they can be due to subjective situations dictated by the context. Nevertheless, the insights given by these companies, detailed in section 4, can provide interesting points of view that future research could verify.

The framework with the one-to-one relationships between Industry 4.0 technologies and Lean Production techniques (Figure 1) should, therefore, be further validated with additional case studies in other contexts as well as empirically tested, for instance with a survey on a wider and statistically significant sample.

Moreover, once the relationships will be validated, there is the need to understand the implication they have in terms of performance, a pivotal aspect that can help companies to understand the importance and the measurable advantages of specific practices or technologies. Other studies can also deepen the understanding of the LP practices or the I4.0 technologies for which the sample here considered did not recognise any direct effect on specific items of the other paradigm. In addition, future studies could focus on a temporal perspective, adding, in the light of the one-to-one relationships depicted in this paper, the stages a company should follow in the LP-I4.0 transformation journey.

Second, case studies based on a retrospective longitudinal approach, like ours, are characterised by two potential problems: lack of memory and post-rationalization (Voss, Johnson, and Godsell 2016). We however adopted various strategies to minimise these issues (e.g. proper selection of interviewees and assessment of their knowledge about the topic and triangulation of evidence among different sources and multiple interviewees). Future research might employ 'real' longitudinal case studies or action researches to analyse the relationships between the two paradigms during the implementation of either Industry 4.0 or Lean production.

Third, the sample consisted of eight Italian manufacturing companies. While Italy is one of the most important manufacturing countries in Europe (together with Germany, France and UK) and has significantly invested in I4.0 in the last few years (e.g. in 'Piano Nazionale Industria 4.0'), future research – both based on qualitative (e.g. case studies) and quantitative (e.g. survey) methods – should include a wider sample of companies in different countries and sectors in order to confirm/validate our results. Contextual factors (e.g. country, industry, level of I4.0 or LP adoption) that might potentially moderate the one-to-one relationships between Industry 4.0 technologies and Lean Production techniques could also be investigated in future research.

Note

1. According to the definition of the European Union Commission (recommendation 2003/361/EC).

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