

Industry 4.0 and Lean Manufacturing

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A systematic literature review and future research directions

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Received 19 December 2018
Revised 8 February 2019
7 May 2019
10 July 2019
29 July 2019
Accepted 15 September 2019

Abstract

Purpose – The purpose of this paper is to aim at identifying the relationships between Industry 4.0 (I4.0) technologies and Lean Manufacturing (LM) practices.

Design/methodology/approach – A systematic literature review was conducted, in which 93 studies were analyzed according to their content and contextualization level.

Findings – In total, 9 I4.0 technologies and 14 LM practices were identified and categorized according to different levels of both value stream application and synergy. From the 126 pairwise relationships, 24 were classified as being of high synergy (e.g. relationship between Cyber-Physical Systems and value stream mapping), revealing the existence of a positive interaction between LPs and I4.0 technologies toward the achievement of a higher operational performance. Further, three future research opportunities were suggested: to validate the proposed synergies among LPs and I4.0 technologies; to distinguish the effects of relationships on all levels of flow; and to examine the effect of such relationships on operational performance.

Originality/value – With the emergence of the Fourth Industrial Revolution, the specificities on the relationship between LM and I4.0 still need further investigation. This paper provides a better understanding of existing literature related to I4.0, LM, and their relationship, as well as pointing out research gaps to encourage future works.

Keywords Lean Manufacturing, Advanced manufacturing technology, Industry 4.0

Paper type Research paper

1. Introduction

Manufacturing companies are usually inserted within a highly competitive context, in which new challenges constantly emerge, such as the advent of disruptive concepts and technologies (Gligor and Holcomb, 2012; Schumacher *et al.*, 2016). In this context, manufacturers must operate with high levels of quality, productivity and low costs. Additionally, companies need to be capable of responding quickly to growing market demands (Lu and Xu, 2018). Thus, a number of approaches, such as Lean Manufacturing (LM) and, more recently, Industry 4.0 (I4.0), have been developed to support manufacturers to achieve these goals.

With the adoption of I4.0 technologies, a new management approach has been introduced (Nascimento *et al.*, 2019). According to Schumacher *et al.* (2016), I4.0 represents a new phase for industry, offering significant technological advances that allow real-time integration among all participants of the value chain, making them more productive, intelligent and agile. I4.0 is featured by an increased level of automation and data exchange, applying novel technologies such as Cyber-Physical Systems (CPS), Internet of Things (IoT) and Big Data (I-SCOOP, 2017). I4.0 technologies allow production systems to be modular and flexible, enabling them to mass-produce highly customized products (Kagermann *et al.*, 2013; Fettermann *et al.*, 2018). According to Landscheidt and Kans (2016), the use of automation improves product quality, entailing more stable and efficient manufacturing processes. I4.0 adopts the concept of smart manufacturing, so that new market requirements are met (Kolberg *et al.*, 2017).



LM has widely been used and disseminated among different industry sectors. LM aims at eliminating waste in the value stream, improving quality and productivity and producing according to customer's expectation (Womack *et al.*, 1991; Jasti and Kodali, 2015). Schonberger (2007) conceptualizes LM as a set of practices and principles that helps companies to organize and control production. Some of the reasons for the wide acceptance of LM are the ease of its application and its efficient results (Herlyn, 2011; Simpson and Power, 2005). LM enables the company to reduce the use of resources and to maximize revenue, generating positive impacts on stakeholders (Burch and Smith, 2019).

LM and I4.0 have similar goals, since both approaches seek improvements in productivity, quality, focus on the elimination of waste and are customer-oriented (Buer *et al.*, 2018). According to Tortorella and Fettermann (2018) and Rossini *et al.* (2019), LM practices (or Lean Practices – LPs) are positively associated with I4.0 technologies, allowing performance improvements. Sibatrova and Vishnevskiy (2016) argue that I4.0 can positively impact LM since some traditional barriers can be overcome, which increases the chances of a successful implementation.

However, LM is usually considered a low-tech approach that excels for simplicity (Dickmann, 2008), which might conflict with the technology-driven approach of I4.0. In addition, Gröbner (2007) emphasizes that LM is characterized by intense human integration focused on efficiency, which may be contrary to the higher levels of automation implied by I4.0. Moreover, the high level of capital expenditures required to implement I4.0 technologies and the lack of qualified professionals stand for obstacles that undermine I4.0 adoption (PWC, 2016). Additionally, there is a scarcity of works that examine the interaction between LM and I4.0 (Landscheidt and Kans, 2016; Gjeldum *et al.*, 2016; Kolberg *et al.*, 2017).

This paper aims at identifying the relationships between I4.0 technologies and LM practices in manufacturing companies based on a systematic literature review. Through a content analysis of the consolidated bibliographic portfolio (BP), different levels of synergy between technologies and practices are identified. A systematic literature review is an appropriate method when a proposed research problem is to be reinforced, avoiding duplication of studies on the same topic and identifying research gaps.

The remainder of this paper is divided as follows. Section 2 contains a brief description of I4.0 and the concepts inherent to it, while Section 3 presents the principles related to LM. Section 4 describes the applied method, whose bibliometric analysis and discussion of the results are presented in Sections 5 and 6, respectively. Section 7 concludes the paper presenting future research directions.

2. Industry 4.0

I4.0 may be defined as a group of technologies and concepts that establish real-time interconnection and communication among people, equipment and products (PWC, 2016; Hermann *et al.*, 2016; Tortorella *et al.*, 2018). The adoption of I4.0 technologies allows the integration of the benefits from customized and intermittent production with the high productivity and low costs of mass production systems (Lasi *et al.*, 2014; Posada *et al.*, 2015; Tamás *et al.*, 2016; CNI, 2016; Xu and Chen, 2016).

The First Industrial Revolution encompasses the use of the steam engine in manufacturing facilities, followed by the introduction of electrically-powered mass production (Second Industrial Revolution). The Third Industrial Revolution corresponds to the use of electronics and information technology (IT) to automate manufacturing (Kagermann *et al.*, 2013). I4.0, deemed as the Fourth Industrial Revolution, focuses on the digitalization of all physical assets and the massive integration of value chain participants (PWC, 2016).

I4.0 is the latest trend when it comes to automation and data exchange in production systems (I-SCOOP, 2017; CNI, 2016). The adoption of technologies, such as CPS, Big Data and

IoT provides relevant information and creates new possibilities for process improvement (Bohács *et al.*, 2013; Schuh *et al.*, 2017). In addition, one of I4.0 main advantages is the ability to adapt quickly to volatile demand scenarios and products with short life cycles (Sanders *et al.*, 2017). According to Tamás and Illés (2016), I4.0 has generated important changes in production systems and created demand for new jobs. Recent research on this subject indicates a lack of studies about the impact of I4.0 on manufacturing environments (Zuehlke, 2010; Landscheidt and Kans, 2016; Gjeldum *et al.*, 2016; Xu and Chen, 2016; Martinez *et al.*, 2016; Sanders *et al.*, 2016; Kolberg *et al.*, 2017; Santorella, 2017).

3. Lean Manufacturing

LM is an approach that encompasses a variety of manufacturing practices, aimed at reducing process variations (Shah and Ward, 2003), identifying and eliminating waste along the value stream (Ohno, 1988; Womack and Jones, 1997; Schonberger, 2007; Liker and Franz, 2011).

Several studies have shown that the implementation of LM principles and practices is positively associated with improved operational performance (Liker and Franz, 2011; Conger and Miller, 2013; Kanigolla *et al.*, 2014; Rezende *et al.*, 2016).

It is noteworthy that LM is a socio-technical approach that considers the human being as a fundamental factor to sustain continuous improvement (Schein, 2010; Leonard and Pakdil, 2016), influencing individuals and the quality of the performed work (Getty, 1999). Principles are the elements of the strategic level and represent the ideals and laws of the system. Womack *et al.* (1991) identify five basic principles for maximizing value and eliminating waste: specify value from customer's perspective; identify the flow of value; make the value flow; produce according to customer's demand; and pursuit of perfection.

LPs are the elements that operationalize the LM principles (Bhamu and Singh Sangwan, 2014) and seek to reduce waste and variability in manufacturing processes, resulting in company's performance improvements (Shah and Ward, 2003). Examples of such practices are: value stream mapping (VSM), 5S, visual management, kanban, rapid tool change, andon, among others (Melton, 2005; Vinodh *et al.*, 2011; Sanders *et al.*, 2017). The companies' contexts must be analyzed in order to select the appropriate LPs and verify their applicability, which are a key issue for industrial managers (Herron and Braiden, 2006).

4. Systematic literature review

The Systematic Search Flow (SSF) method was used due to its consistency and reliability (Ferenhof and Fernandes, 2016). The method was comprised by four phases divided into eight activities, as shown in Table I.

4.1 Research protocol – Phase 1

The first phase of the SSF methodology aimed at defining the research protocol, and was divided into five activities: search strategy; database query; document management; standardization and selection of documents; and organization of BP.

Phase	1 – Research protocol				2 – Analysis	3 – Synthesis	4 – Writing	
Activity	(1.1) Search strategy	(1.2) Database query	(1.3) Document management	(1.4) Standardization and selection of documents	(1.5) Organization of bibliographic portfolio	(2.1) Data consolidation	(3.1) Synthesizing information	(4.1) Writing

Source: Adapted from Ferenhof and Fernandes (2016)

Table I.
Phases and activities
of the SSF method

4.1.1 Search strategy. This activity aimed to establish the research topics, leading to the search command with the keywords. According to Ferenhof and Fernandes (2016), the search strategy covers a set of procedures that specifies the mechanisms of search and information retrieval. Due to the purpose of our study, two keywords were defined: “Industry 4.0” and “Lean.” For each keyword, a search command was defined by the combination between keywords and logical/relational operators.

A first search was performed in the Scopus database, due to its interdisciplinary nature and consistency in indexing content, resulting in a total of 1,332 documents. To verify the adequacy of the search command, an adherence test was carried out to validate the specified keywords. Five papers whose titles were aligned with the research topic and with the highest number of citations among the 1,332 papers were selected; they were: Lee *et al.* (2015) with 689 citations; Brettel *et al.* (2014) with 383 citations; Zuehlke (2010) with 343 citations; Kolberg and Zuehlke (2015) with 79 citations; and Sanders *et al.* (2016) with 33 citations. The keywords of these five papers were compared to the keywords used in the search command, in order to check whether there was still the need to improve the search command. The search command was considered adequate, since its keywords were already included in the papers, as shown in Table II.

4.1.2 Database query. Four databases were selected, namely: Scopus, Web of Science, ProQuest and Emerald. The search was carried out in 2018, and there was no time limit for publications. The total number of documents selected was 1,526. Through a Boolean search, keywords were combined and relationships identified between them. Filters were used for the language (English) and type of publication (journal article and conference paper), totaling 1,090 documents.

4.1.3 Document management. This activity targeted the organization of the retrieved documents, so that the processes of filtering and analysis could be performed. EndNote X7 software was used to facilitate this activity, enabling the establishment of folders for each database and importing relevant information about those papers.

4.1.4 Standardization and selection of documents. The standardization and selection of documents referred to the process of determining the filters for sorting papers. Initially, we verified the existence of duplicates among the 1,090 papers, which led to the exclusion of 68 documents. Thus, the alignment of the remaining 1,022 papers with the research topic was checked according to three aspects: (i) title, (ii) keywords and (iii) abstract. Regarding the (i), 333 papers out of 1,022 were disregarded due to titles that did not refer to the main

Keywords	Papers in the databases			
	Scopus	Web of Science	ProQuest	Emerald
“Industry 4.0” OR “Cyber Physical System” or “CPS” or “Smart Factory” or “Smart Manufacturing” or “Internet of Things” or “IOT” and “Lean”	1,332	58	76	60
<i>Criteria for papers analysis</i>				
Total		1,526		
Type of document and language		1,090 (–436)		
Papers not duplicated		1,022 (–68)		
Title, keywords and abstract		116 (–333 due to title)		
		(–197 due to keywords)		
		(–376 due to abstract)		
Search procedure used in the systematic literature review	Available	102 (–14)		
	Complete reading	93 (–9)		
	Final portfolio	93		

interest of this research. Second, keywords of the remaining 689 papers were analyzed, from which 197 were excluded as we did not identify a proper match with the investigated topic. Third, abstracts of 492 papers were verified, indicating that only 116 of them were actually aligned with the expectations of this research. Since 14 papers were not presented in their complete version, they were excluded and a full content analysis of the remaining 102 papers was performed.

4.1.5 Organization of bibliographic portfolio. In the last activity of the first phase, the organization of the BP was completed. All 102 papers were fully read to allow excluding the ones that were not aligned with the research topic. In total, 9 papers were disregarded, resulting in a final BP of 93 papers (see Table II).

4.2 Analysis – Phase 2

The second phase consolidated the data (Activity 2.1) through the analysis and interpretation of bibliometric data. This supported the identification of relevant aspects related to the research topic (Ferenhof and Fernandes, 2016). The analysis was divided into two categories: basic and advanced variables. The basic variables analyzed were: number of papers per journal; number of publications per year; countries where studies occurred; and type of study (conceptual or empirical). With regards to the analysis of the advanced variables, we went on to answer the following questions: what are the main I4.0 technologies used in manufacturing industry?; and which are the main LPs used in manufacturing industry?

4.3 Synthesis – Phase 3

At this stage (Activity 3.1), the information obtained from the previous phase was synthesized and presented through reports, tables and graphs. Such synthesis was performed from three conceptual perspectives: the levels of the value stream in which I4.0 technologies have been used; the synergy level between I4.0 technologies and LPs; and the disagreement of the I4.0 technologies with the LPs. A knowledge matrix was developed in MS-Excel to facilitate this synthesis, which is detailed in the following sections.

4.4 Writing – Phase 4

The last phase aimed at consolidating and recording the results. In this activity, we compared the results obtained from the previous phases with the initially established objectives. Such comparison allowed us to indicate the main findings of our research (Ferenhof and Fernandes, 2016).

5. Result of the bibliometric analysis: basic variables

From the 93 publications included in the final BP, 43 papers were published in 35 journals, while 50 papers were from 37 different conferences. Regarding the events, it is worth mentioning two conferences: “Changeable, Agile, Reconfigurable & Virtual Production Conference” and “International Federation of Automatic Control”, with four publications each. With respect to journals, *Advances in Manufacturing and International Journal of Production Research* stood out with four publications each, as displayed in Table III.

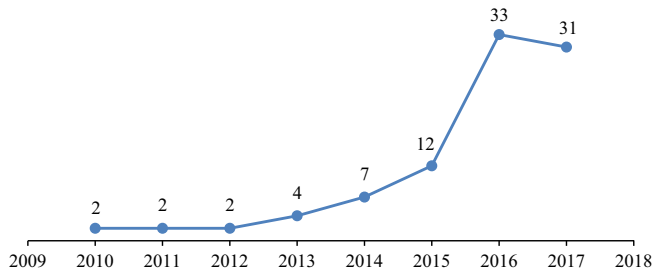
Regarding the number of publications per year, Figure 1 points that all papers were published between 2010 and 2017. This fact is justified because I4.0 is a relatively recent topic, and the search only contemplated works that have correlated LM and I4.0. Further, 68.8 percent of the BP were published over the last two years, with a peak of 33 papers in 2016 followed by 31 in 2017.

As for countries, Germany stood out with 32 publications, corresponding to 31 percent of all the BP. USA and China presented seven and six publications, respectively, as shown

Conference	Journal	Description	Total number of publications
	X	<i>Advances in Manufacturing</i>	4
X		Changeable, Agile, Reconfigurable & Virtual Production Conference	4
X		International Federation of Automatic Control	4
	X	<i>International Journal of Production Research</i>	4
X		50th Conference on Manufacturing Systems	3
X		9th International Conference on Digital Enterprise Technology	2
X		6th Conference on Learning Factories	2
X		27th International Conference on Flexible Automation and Intelligent Manufacturing	2
X		49th Conference on Manufacturing Systems	2
	X	<i>International Federation for Information Processing</i>	2
	X	<i>International Journal of Innovation Management</i>	2
X		International Symposium on Intelligent Manufacturing and Automation	2
X		Other 29 events	29
	X	Other 31 journals	31

Table III. Number of publications in journals and conferences

Figure 1. Number of publications that correlate LM and I4.0



in Table IV. In total, 32 different countries were involved, with 84.4 percent of the research performed in developed countries (i.e. Europe and North America) and 15.6 percent in developing countries (i.e. Asia, Africa and South America). This outcome occurs due to the high level of industrialization in developed countries, which usually have more resources for developing research and technology. Since Germany is the place where I4.0 was first acknowledged (Lasi *et al.*, 2014), it is reasonable to expect that the majority of publications found in the portfolio was developed in this country.

With regards to the types of studies, we identified that the largest amount was mainly conceptual (86 percent of the publications); i.e., these studies simply envisioned or conceptually proposed certain relationships between I4.0 and LPs without any empirical validation. In opposition, only 14 percent of them had an empirical nature and actually verified how these relationships occurred, either through surveys with manufacturers, case studies, or action research in companies implementing both approaches.

6. Result of bibliometric analysis: advanced variables

6.1 Main technologies of I4.0

Table V presents the main I4.0 technologies identified in the literature according to their citation frequency. The citation frequency varied significantly among the nine technologies identified. This fact can be explained due to their different characteristics, applications and objectives. The most frequently cited technology was IoT (64 citations).

Socioeconomic context	Country	No. of publications
Europe and North America	Germany	32
	Austria	4
	Hungary	4
	England	4
	Norway	4
	Italy	3
	France	2
	Greece	2
	Poland	2
	Portugal	2
	Czech Republic	2
	Sweden	2
	Croatia	2
	USA	7
Other 13 countries	13	
South America	Brazil	4
Asia	China	6
	Malaysia	2
	Taiwan	3
Africa	South Africa	2

Table IV.
Number of
publications
per country

This high citation frequency can be associated with its great versatility, being able to be applied in many ways and in different environments (Shariatzadeh *et al.*, 2016; Islam *et al.*, 2015). The technological advances achieved, ease of access and reduction of cost of internet are some of the reasons that had positively contributed to IoT's dissemination. In addition, because it is a technology that often serves as a basis for other I4.0 technologies (e.g. CPS, cloud computing and simulation), IoT is seen as a gateway to I4.0 (CNI, 2016; Tamás *et al.*, 2016; Xu and Chen, 2016).

The technology with the second highest number of citations was CPS (56 citations). CPS can be defined as physical objects equipped with software that allows them to establish communication with other participants of the same system (Bagheri *et al.*, 2015). This technology is similar to IoT, since it uses the same architecture enabled by a network. However, CPS promotes greater exchange of data and information destined to the integration and coordination between physical elements and computational systems (Hermann *et al.*, 2016; Rad *et al.*, 2015). Through CPS, products are equipped with self-management capability and the factory can operate according to the smart factory concept (Chiang and Lee, 2017). Thus, production systems become Cyber Physical Production Systems, enabling a real-time operation in a remote and independent way (Almada-Lobo, 2016).

Simulation (20 citations) and Additive Manufacturing (AM) (15 citations) were the technologies with the lowest number of citations. According to Brettel *et al.* (2014), the level of process virtualization in which Simulation and AM are embedded depends on the company size, since small and medium-sized companies often have fewer resources intended for these technologies. Specifically with regards to Simulation, it contributes to company's information gathering and real-time data analysis (Machova, 2018; Wang *et al.*, 2016). The use of Simulation provides gains related to the reduction of time, mainly in the early stages of products and processes development. It enables building virtual prototypes, validating concepts, performing design tests and analysis and mitigating the occurrence of errors and failures (Qu *et al.*, 2011). The increasing use of information and communication systems allows more flexible digital engineering and rapid product innovation.

Table V.
Main I4.0 technologies identified in the literature

Code	technology	Definition/objectives	Papers	Conceptual study	Empirical study	Citation frequency
T1	I4.0 Internet of Things (IoT)	Enables interactivity between people and objects for the exchange of data and information between all objects connected to the internet	Zuehlke (2010), Tao <i>et al.</i> (2011), Strueker and Weppner (2012), Spath <i>et al.</i> (2013), Xu <i>et al.</i> (2013), Dugenske and Louchez (2014), Noonan <i>et al.</i> (2014), Radziwon <i>et al.</i> (2014), Schuh <i>et al.</i> (2014), Fleisch <i>et al.</i> (2015), Kirazli and Hormann (2015), Kolberg and Zuehlke (2015), Ren <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Weyer <i>et al.</i> (2015), Zhang <i>et al.</i> (2015), Almada-Lobo (2016), Ang <i>et al.</i> (2016), Arnold <i>et al.</i> (2016), Aydos and Ferreira (2016), Butzer <i>et al.</i> (2016), Dave <i>et al.</i> (2016), Doh <i>et al.</i> (2016), Edwards and Ramirez (2016), Erol <i>et al.</i> (2016), Giaino <i>et al.</i> (2016), Martínez <i>et al.</i> (2016), Miciceta <i>et al.</i> (2016), Rong <i>et al.</i> (2016), Sanders <i>et al.</i> (2016), Schumacher <i>et al.</i> (2016), Shariatzadeh <i>et al.</i> (2016), Shih <i>et al.</i> (2016), Stock and Seliger (2016), Stojkic <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Valmohammadi (2016), Wang <i>et al.</i> (2016), Xu and Chen (2016), Alias <i>et al.</i> (2017), Bassi (2017), Chen <i>et al.</i> (2017), Chiang and Lee (2017), Chromjaková <i>et al.</i> (2017), Dombrowski <i>et al.</i> (2017), Fera <i>et al.</i> (2017), Ferrara <i>et al.</i> (2017), Illés <i>et al.</i> (2017), Kiel <i>et al.</i> (2017), Kolberg <i>et al.</i> (2017), Lee, Zhang and Ng (2017), Lee, Lee and Chou (2017), Liao <i>et al.</i> (2017), Marjani <i>et al.</i> (2017), Mora <i>et al.</i> (2017), Mrugalska and Wyrwicka (2017), Sackey <i>et al.</i> (2017), Strandhagen <i>et al.</i> (2017), Tamás (2017), Trstenjak and Cosic (2017), Tortorella and Fettermann (2018)	54	8	62
T2	Cyber Physical System (CPS)	It allows high integration between people and physical systems in real time through the use of advanced technologies of computer systems, communication and control (cyberspace)	Broy <i>et al.</i> (2012), Spath <i>et al.</i> (2013), Dugenske and Louchez (2014), Schuh <i>et al.</i> (2014), Adeyeri <i>et al.</i> (2015), Bagheri <i>et al.</i> (2015), Kern <i>et al.</i> (2015), Kolberg and Zuehlke (2015), Lee <i>et al.</i> (2015), Ranz <i>et al.</i> (2015), Ren <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Weyer <i>et al.</i> (2015), Zhang <i>et al.</i> (2015), Almada-Lobo (2016), Ang <i>et al.</i> (2016), Brettel <i>et al.</i> (2016), Butzer <i>et al.</i> (2016), Doh <i>et al.</i> (2016), Eleftheriadis and Myklebust (2016), Erol <i>et al.</i> (2016), Giaino <i>et al.</i> (2016), Gronau (2016), Kolberg <i>et al.</i> (2016), Martínez <i>et al.</i> (2016), Prinz <i>et al.</i> (2016), Sanders <i>et al.</i> (2016), Schumacher <i>et al.</i> (2016), Shariatzadeh <i>et al.</i> (2016), Stock and Seliger (2016), Stojkic <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Wang <i>et al.</i> (2016), Xu and Chen (2016), Alias <i>et al.</i> (2017), Bassi (2017), Chen <i>et al.</i> (2017), Chiang and Lee (2017), Chromjaková <i>et al.</i> (2017), Dombrowski <i>et al.</i> (2017), Illés <i>et al.</i> (2017), Karaköse and Yetis (2017), Kiel <i>et al.</i> (2017), Kolberg <i>et al.</i> (2017), Lee, Zhang and Ng (2017),	49	7	56

(continued)

Code	technology	Definition/objectives	Papers	Conceptual study	Empirical study	Citation frequency
T3	Cloud Computing	CPS will generate large data volumes, and cloud computing will serve to store such data that can be accessed from anywhere	Liao <i>et al.</i> (2017), Mrugalska and Wyrwicka (2017), Nunes <i>et al.</i> (2017), Rodseth <i>et al.</i> (2017), Sackey <i>et al.</i> (2017), Strandhagen <i>et al.</i> (2017), Tamás (2017), Trstenjak and Cosic (2017), Wagner <i>et al.</i> (2017), Tortorella and Fettermann (2018), Zuehlke (2010), Tao <i>et al.</i> (2011), Broy <i>et al.</i> (2012), Strueker and Weppner (2012), Spath <i>et al.</i> (2013), Noonen <i>et al.</i> (2014), Ren <i>et al.</i> (2015), Zhang <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Almada-Lobo (2016), Ang <i>et al.</i> (2016), Arnold <i>et al.</i> (2016), Butzer <i>et al.</i> (2016), Doh <i>et al.</i> (2016), Erol <i>et al.</i> (2016), Esmailian <i>et al.</i> (2016), Sanders <i>et al.</i> (2016), Schumacher <i>et al.</i> (2016), Shariatzadeh <i>et al.</i> (2016), Stock and Seliger (2016), Stojkic <i>et al.</i> (2016), Wang <i>et al.</i> (2016), Xu and Chen (2016), Alias <i>et al.</i> (2017), Bassi (2017), Chen <i>et al.</i> (2017), Chromjaková <i>et al.</i> (2017), Dombrowski <i>et al.</i> (2017), Ferrera <i>et al.</i> (2017), Karaköse and Yetis (2017), Lee, Zhang and Ng (2017), Liao <i>et al.</i> (2017), Marjani <i>et al.</i> (2017), Mora <i>et al.</i> (2017), Mourtzis, Vlachou and Zogopoulos (2017), Mourtzis, Zogopoulos and Vlachou (2017), Mrugalska and Wyrwicka (2017), Sackey <i>et al.</i> (2017), Strandhagen <i>et al.</i> (2017), Mrugalska and Wyrwicka (2017), Tortorella and Fettermann (2018), Schuh <i>et al.</i> (2014), Bagheri <i>et al.</i> (2015), Fleisch <i>et al.</i> (2015), Kirazli and Hormann (2015), Lee <i>et al.</i> (2015), Ren <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Almada-Lobo (2016), Ang <i>et al.</i> (2016), Butzer <i>et al.</i> (2016), Doh <i>et al.</i> (2016), Edwards and Ramirez (2016), Esmailian <i>et al.</i> (2016), Sanders <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Wang <i>et al.</i> (2016), Stojkic <i>et al.</i> (2016), Chen <i>et al.</i> (2016), Wang <i>et al.</i> (2016), Alias <i>et al.</i> (2017), Bassi (2017), Chen <i>et al.</i> (2017), Chromjaková <i>et al.</i> (2017), Dombrowski <i>et al.</i> (2017), Illés <i>et al.</i> (2017), Lee, Zhang and Ng (2017), Liao <i>et al.</i> (2017), Marjani <i>et al.</i> (2017), Mora <i>et al.</i> (2017), Nunes <i>et al.</i> (2017), Rodseth <i>et al.</i> (2017), Sackey <i>et al.</i> (2017), Strandhagen <i>et al.</i> (2017), Trstenjak and Cosic (2017), Wagner <i>et al.</i> (2017), Tortorella and Fettermann (2018).	37	4	41
T4	Big Data	Vast use of sensors and control systems in industry results in the generation of a huge amount of data. Big data is the term that describes the huge volume of structured data and its management	Schuh <i>et al.</i> (2014), Bagheri <i>et al.</i> (2015), Fleisch <i>et al.</i> (2015), Kirazli and Hormann (2015), Lee <i>et al.</i> (2015), Ren <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Almada-Lobo (2016), Ang <i>et al.</i> (2016), Butzer <i>et al.</i> (2016), Doh <i>et al.</i> (2016), Edwards and Ramirez (2016), Esmailian <i>et al.</i> (2016), Sanders <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Wang <i>et al.</i> (2016), Stojkic <i>et al.</i> (2016), Chen <i>et al.</i> (2016), Wang <i>et al.</i> (2016), Alias <i>et al.</i> (2017), Bassi (2017), Chen <i>et al.</i> (2017), Chromjaková <i>et al.</i> (2017), Dombrowski <i>et al.</i> (2017), Illés <i>et al.</i> (2017), Lee, Zhang and Ng (2017), Liao <i>et al.</i> (2017), Marjani <i>et al.</i> (2017), Mora <i>et al.</i> (2017), Nunes <i>et al.</i> (2017), Rodseth <i>et al.</i> (2017), Sackey <i>et al.</i> (2017), Strandhagen <i>et al.</i> (2017), Trstenjak and Cosic (2017), Wagner <i>et al.</i> (2017), Tortorella and Fettermann (2018).	33	3	36
T5	Horizontal/Vertical Integration	Use of technology to integrate the information systems of the whole value chain	Tortorella and Fettermann (2018), Tao <i>et al.</i> (2011), Broy <i>et al.</i> (2012), Strueker and Weppner (2012), Yoon <i>et al.</i> (2012), Spath <i>et al.</i> (2013), Kibira <i>et al.</i> (2015), Kirazli and Hormann (2015), Ranz <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Weyer <i>et al.</i> (2015), Almada-Lobo (2016), Ang <i>et al.</i> (2016), Arnold <i>et al.</i> (2016), Butzer <i>et al.</i> (2016),	25	4	29

(continued)

Table V.

Code	technology	Definition/objectives	Papers	Conceptual study	Empirical study	Citation frequency
I4.0						
T6	Advanced Robots	Robots that use artificial intelligence and concepts like "machine learning" capable of performing tasks with a high level of complexity with minimal human interaction	Doh <i>et al.</i> (2016), Erol <i>et al.</i> (2016), Schumacher <i>et al.</i> (2016), Stojkic <i>et al.</i> (2016), Wang <i>et al.</i> (2016), Chen <i>et al.</i> (2017), Chiang and Lee (2017), Dombrowski <i>et al.</i> (2017), Ferrera <i>et al.</i> (2017), Kiel <i>et al.</i> (2017), Lee, Zhang and Ng (2017), Liao <i>et al.</i> (2017), Mora <i>et al.</i> (2017), Mrugaliska and Wyrwicka (2017), Strandhagen <i>et al.</i> (2017) Kirazli and Hormann (2015), Ranz <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Almada-Lobo (2016), Ang <i>et al.</i> (2016), Butzer <i>et al.</i> (2016), Doh <i>et al.</i> (2016), Edwards and Ramirez (2016), Erol <i>et al.</i> (2016), Esmaeilian <i>et al.</i> (2016), Micieta <i>et al.</i> (2016), Sanders <i>et al.</i> (2016), Schumacher <i>et al.</i> (2016), Stock and Seliger (2016), Alias <i>et al.</i> (2017), Chen <i>et al.</i> (2017), Chromjaková <i>et al.</i> (2017), Kolberg <i>et al.</i> (2017), Lee, Zhang and Ng (2017), Liao <i>et al.</i> (2017), Mora <i>et al.</i> (2017), Mourtzis, Zogopoulos and Vlachou (2017), Nunes <i>et al.</i> (2017), Sackey <i>et al.</i> (2017), Strandhagen <i>et al.</i> (2017). Yoon <i>et al.</i> (2012), Kolberg and Zuehlke (2015), Ranz <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Weyer <i>et al.</i> (2015), Ang <i>et al.</i> (2015), Ang <i>et al.</i> (2016), Arnold <i>et al.</i> (2016), Butzer <i>et al.</i> (2016), Doh <i>et al.</i> (2016), Edwards and Ramirez (2016), Alias <i>et al.</i> (2017), Chromjaková <i>et al.</i> (2017), Dombrowski <i>et al.</i> (2017), Lee, Zhang and Ng (2017), Liao <i>et al.</i> (2017), Mora <i>et al.</i> (2017), Mourtzis, Vlachou and Zogopoulos (2017), Mourtzis, Zogopoulos and Vlachou (2017), Mourtzis, Zogopoulos and Vlachou (2017), Nunes <i>et al.</i> (2017), Sackey <i>et al.</i> (2017) Tao <i>et al.</i> (2011), Yoon <i>et al.</i> (2012), Schuh <i>et al.</i> (2014), Adeveri <i>et al.</i> (2015), Kibira <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Ang <i>et al.</i> (2016), Doh <i>et al.</i> (2016), Gronau (2016), Prinz <i>et al.</i> (2016), Sanders <i>et al.</i> (2016), Tamas <i>et al.</i> (2016), Chromjaková <i>et al.</i> (2017), Kiel <i>et al.</i> (2017), Mora <i>et al.</i> (2017), Nunes <i>et al.</i> (2017), Sackey <i>et al.</i> (2017), Tamas (2017), Tortorella and Fettermann (2018) Dugenske and Louchez (2014), Ranz <i>et al.</i> (2015), Rüßmann <i>et al.</i> (2015), Almada-Lobo (2016), Ang <i>et al.</i> (2016), Brettel <i>et al.</i> (2016), Doh <i>et al.</i> (2016), Rong <i>et al.</i> (2016), Schumacher <i>et al.</i> (2016), Stock and Seliger (2016), Alias <i>et al.</i> (2017), Bassi (2017), Mora <i>et al.</i> (2017), Strandhagen <i>et al.</i> (2017), Tortorella and Fettermann (2018)	25	1	26
T7	Augmented Reality	It uses technology to make information interactive by adding an overlay of digital content and relevant information		17	3	20
T8	Simulation	Simulates in a virtual manner concepts, application and construction of prototypes and processes through computational resources		17	2	20
T9	Additive Manufacturing	It is an additive process of forming objects, layer upon layer from data and 3D models		14	1	15

AM comprises technologies such as 3D printing (Rüßmann *et al.*, 2015). AM refers to processes controlled by a computer system in which material is bonded and solidified at each layer forming objects based on digital models (Taufik and Jain, 2013). It can be applied for producing small batches of customized, complex and light products. AM is already utilized in industries such as aerospace (aircraft turbines), in which gains in reduction of raw materials, lighter components and shorter manufacturing time were observed (MIT Technology Review, 2018).

6.2 Main LPs

Table VI presents the 14 LPs identified in the BP according to their citation frequency and value stream level application. The one with the highest citation frequency was Kanban (14 citations). According to Kumar and Panneerselvam (2007), *Kanban* is basically a signal that contains the information needed to manufacture a product at all stages of its production. Such citation frequency is justified by its great importance within manufacturing systems. Further, it indicates a high association with the concept of smart factory (Sanders *et al.*, 2016, 2017; Kolberg and Zuehlke, 2015; Lage Junior and Godinho Filho, 2010; Kouri *et al.*, 2008; Kotani, 2007).

The second LP with the highest number of citations was VSM, which allows the identification of bottlenecks and waste in processes (Rother and Shook, 2003). This LP can be used to raise improvement opportunities in both material and information flows (Abdulmalek and Rajgopal, 2007).

Regarding to LPs with the lowest number of citations, Total Productive Maintenance (TPM) and Jidoka (or autonomation) had only three citations each, which was an unexpected result. I4.0 is able to provide a large amount of data and information that can be used to improve equipment performance, converging toward the desired objectives of the TPM implementation. The few works related to this topic, such as Yoon *et al.* (2012) and Geng *et al.* (2014) suggested the application of I4.0 technologies to improve predictive maintenance. Zhang *et al.* (2015) and Zhu *et al.* (2012) proposed the use of I4.0 technologies to assist maintenance, repair and operations of complex equipment such as those used in foundries in the steel industry.

With regards to Jidoka (or autonomation), this LP (together with JIT) represents one of the pillars of the Toyota Production System (Ohno, 1988). Its purpose is to ensure that anomalies are detected during processes and not sent to the next station (Ranky, 2007). On the other hand, I4.0 proposes the use of several technologies, such as Advanced Robotization, Artificial Intelligence, and machine learning and decision making, which can be used to support control of abnormalities identification (Bagheri *et al.*, 2015). As I4.0 seeks to provide means to detect the occurrence of anomalies allowing greater quality and productivity control (Sanders *et al.*, 2016), both Jidoka and I4.0 can be expected to be positively associated (Sanders *et al.*, 2017).

Although TPM and Autonomation practices present a potential association with I4.0 technologies according to the evidence provided, there is a reduced number of works relating them and their possible synergies. In this sense, it is worth mentioning that the low citation frequency may occur not because of the lack of association between them, but due to other factors. TPM, for example, is characterized by being a set of connected activities that seek to meet a common goal. However, I4.0 applications have focused on specific solutions in which technologies were applied without necessarily being related to the implementation of TPM. With respect to Jidoka, in the beginning, technologies that assisted the detection of problems have been applied to increase connectivity in manufacturing. Thus, some quality issues approached by Jidoka have not yet been fully explored.

7. Analysis of conceptual perspectives

7.1 Relationship between I4.0 technologies and value stream levels

The nine technologies identified for I4.0 were classified according to different levels of the value stream applications evidenced in the BP. Value stream is the set of activities

Table VI.
Main LPs identified
in the literature

Code	LP	Publications	Intracellular level	Macro-processes level	Supply chain level	Conceptual study	Empirical study	Citation frequency
P1	<i>Kamban</i>	Kouri <i>et al.</i> (2008), Bhamu and Singh Sangwan (2014), Fleisch <i>et al.</i> (2015), Kolberg and Zuehlke (2015), Dave <i>et al.</i> (2016), Esmaelian <i>et al.</i> (2016), Martinez <i>et al.</i> (2016), Micieta <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Kolberg <i>et al.</i> (2017), Küsters <i>et al.</i> (2017), Mrugalska and Wyrwicka (2017), Tortorella and Fettermann (2018)		X	X	14		14
P2	Value Stream Mapping (VSM)	Kouri <i>et al.</i> (2008), Bhamu and Singh Sangwan (2014), Ranz <i>et al.</i> (2015), Villalba-Diez <i>et al.</i> (2015), Aydos and Ferreira (2016), Micieta <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Ferrera <i>et al.</i> (2017), Mrugalska and Wyrwicka (2017), Küsters <i>et al.</i> (2017), Sanders <i>et al.</i> (2017)	X	X	X	11	1	12
P3	<i>Poka Yoke</i>	Bhamu and Singh Sangwan (2014), Kolberg and Zuehlke (2015), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Illés <i>et al.</i> (2017), Küsters <i>et al.</i> (2017), Mrugalska and Wyrwicka (2017), Sanders <i>et al.</i> (2017), Wiech <i>et al.</i> (2017)	X			8	1	9
P4	<i>Kaizen</i>	Bhamu and Singh Sangwan (2014), Martinez <i>et al.</i> (2016), Sanders <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Dombrowski <i>et al.</i> (2017), Illés <i>et al.</i> (2017), Mrugalska and Wyrwicka (2017), Sanders <i>et al.</i> (2017)	X	X		9		9
P5	Pull Production	Esmaelian <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Dombrowski <i>et al.</i> (2017), Ferrera <i>et al.</i> (2017), Kolberg <i>et al.</i> (2017), Küsters <i>et al.</i> (2017), Sanders <i>et al.</i> (2017), Tortorella and Fettermann (2018)	X	X	X	9		9
P6	Andon	Bhamu and Singh Sangwan (2014), Kolberg and Zuehlke (2015), Dave <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Illés <i>et al.</i> (2017), Mrugalska and Wyrwicka (2017), Sanders <i>et al.</i> (2017)	X			8		8
P7	Single Minute Exchange of Dies (SMED)	Bhamu and Singh Sangwan (2014), Martinez <i>et al.</i> (2016), Sanders <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Küsters <i>et al.</i> (2017), Sanders <i>et al.</i> (2017)	X			7		7
P8	Standardization	Kouri <i>et al.</i> (2008), Bhamu and Singh Sangwan (2014), Dombrowski <i>et al.</i> (2017), Illés <i>et al.</i> (2017), Kolberg <i>et al.</i> (2017), Sanders <i>et al.</i> (2017)	X	X		6		6

(continued)

Code	LP	Publications	Intracellular level	Macro-processes level	Supply chain level	Conceptual study	Empirical study	Citation frequency
P9	Total Quality Management (TQM)	Bhamu and Singh Sangwan (2014), Kibira <i>et al.</i> (2015), Eleftheriadis and Myklebust (2016), Dombrowski <i>et al.</i> (2017), Illés <i>et al.</i> (2017), Mrugalska and Wyrwicka (2017)		X	X	6		6
P10	<i>Takt</i> Time	Kouri <i>et al.</i> (2008), Bhamu and Singh Sangwan (2014), Salmi <i>et al.</i> (2015), Aydos and Ferreira (2016), Sanders <i>et al.</i> (2017)		X		4	1	5
P11	Heijunka	Kouri <i>et al.</i> (2008), Bhamu and Singh Sangwan (2014), Tamás <i>et al.</i> (2016), Kolberg <i>et al.</i> (2017), Sanders <i>et al.</i> (2017)		X	X	5		5
P12	5S	Bhamu and Singh Sangwan (2014), Tamás <i>et al.</i> (2016), Tamás and Illés (2016), Illés <i>et al.</i> (2017), Sanders <i>et al.</i> (2017)	X	X		5		5
P13	Jidoka	Bhamu and Singh Sangwan (2014), Sanders <i>et al.</i> (2016), Tamás <i>et al.</i> (2016), Sanders <i>et al.</i> (2017)	X			3		3
P14	Total Productive Maintenance (TPM)	Bhamu and Singh Sangwan (2014), Sanders <i>et al.</i> (2016), Sanders <i>et al.</i> (2017)	X	X		3		3

encompassed in the manufacture of a product, from the receiving of raw materials to delivery of finished product to the customer. Value stream levels can be categorized in various ways (Womack and Jones, 1997) and according to application levels (Duggan, 2012): intracellular, which addresses the operational activities performed within production cells; macro-processes (intercellular or interdepartmental), which corresponds to the management of interdepartmental processes and the interfaces between information and materials flows (e.g. production planning and control, finance, material logistics, among others); and (supply chain (extended value stream), which involves all processes and flows that go beyond the boundaries of the company, involving suppliers and customers. It is noteworthy that both material and information flows are contemplated at all levels of value stream (Kozlenkova *et al.*, 2015).

Table VII shows the levels of value stream in which I4.0 technologies have been used, describing examples of their applications. Regarding the main I4.0 technologies, five of them have been applied at all levels of the value stream, such as “T1 – IoT,” “T2 – CPS,” “T4 - Big Data,” “T5 – Horizontal and Vertical Integration” and “T8 – Simulation.” This result indicated that such technologies are more versatile since they can be applied at different levels. In addition, they are related to the transmission and exchange of data among the three different levels. Moreover, IoT and CPS technologies, usually deemed as high-level systems, presented high citation frequencies reinforcing the potential of applying them in the manufacturing environment. Conversely, technologies “T3 – Cloud Computing,” “T7 – Augmented Reality” and “T9 – Additive Manufacturing” were mentioned at two levels of the value stream. These are indeed technologies with a narrower focus of application. Cloud Computing is often used to support data capturing and processing. Augmented Reality can be applied in training operators and maintenance engineers, for example. AM is a specific manufacturing process that bonds materials to make items from 3D model data. Overall, these technologies have the flexibility to be applied in different contexts, but to a lesser extent when compared with the previous ones.

Finally, technology “T6 – Advanced Robotization” was mentioned in only one level of the value stream (i.e. intracellular), indicating that this technology has more specific applications and it is often used to replace human labor (Frey and Osborne, 2017). Besides, robots can operate with machines and systems equipped with Artificial Intelligence in a semi-structured environment (Pfeiffer, 2016). According to Rübmann *et al.* (2015), Robotization has been used in operational activities with a high level of complexity, remaining restricted to the intracellular level.

7.2 Levels of synergy between I4.0 technologies and LPs

We now identify the relationship intensity between I4.0 technologies and LPs. Evidence was retrieved from the BP in order to establish relationships and to analyze their synergy. The level of synergy was used to represent the interaction or cooperation level between a determined pair of I4.0 technology and LP, whose combined effect could be greater than their individual ones.

Table VIII displays the interaction matrix for the nine technologies of I4.0 and 14 LPs, indicating the level of synergy for each of the 126 associations. Three criteria were considered to assign the level of synergy: (i) citation frequency of I4.0 technologies and LPs (Tables V and VI); (ii) application of I4.0 technologies and LPs at different levels of value stream (Tables VI and VII); and (iii) relevance of the evidence found in the literature. For the first criterion, both I4.0 technologies and LPs were categorized into three citation frequency ranges within their respective groups. The groups referred to as “high citation” represented 33.33 percent (approximately) of the corresponding most cited practices (i.e. P1, P2, P3, P4 and P5) and technologies (i.e. T1, T2 and T3). In opposition, the respective groups with 33.3 percent of the practices (i.e. P10, P11, P12, P13 and P14) and technologies (i.e. T7, T8 and T9)

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Code	I4.0 technology	Intracellular level	Macro-processes level	Supply chain level	Examples of application
T1	Internet of Things (IoT)	X	X	X	Support in the execution of adjustments and setup of the workstation Monitor quality through recording of information Manage the movement of robots for gathering and transporting materials Control inventory and traceability of materials Share data with network to optimize preventive maintenance Use automation to optimize key indicators Provide information in real time to support decision making by management Remotely manage the plant in real time Share data within global logistics chain
T2	Cyber Physical Systems (CPS)	X	X	X	Change the production schedule Correct faults through interconnected systems Employ self-optimization manufacturing systems targeting zero defects Provide information in real time to optimize decision making by management Share data with network to optimize preventive maintenance Ensure process safety Improve equipment efficiency Increase speed in decision making
T3	Cloud Computing		X	X	Integrate and share information with different sectors of the plant Perform remote maintenance management of complex equipment Reduce space for data storage Store and share data between different companies (data warehouse) Share company data and information with internal and external audiences Establish communication between ERP systems of different companies Increase productivity due to ease of storing and sharing documents Increase security for storing and retrieving information Optimize customer relationship management (CRM) systems
T4	Big data	X	X	X	Manage data to optimize the maintenance of complex equipment Reduce time to make decisions based on history Reduce costs with data storage Assist in creating new products based on customer relationship management (CRM) and their preferences Perform market analysis Monitor company's degree of satisfaction with customers

(continued)

Table VII.
Application of I4.0 technologies in different levels of the value stream

Code	I4.0 technology	Intracellular level	Macro-processes level	Supply chain level	Examples of application
T5	Horizontal/ Vertical Integration	X	X	X	Integrate different sectors of the company such as engineering and production Integrate information technology systems horizontally and vertically to achieve productivity, cost and quality gains Share data within the entire value stream
T6	Advanced Robotics	X			Perform complex tasks with high accuracy Eliminate errors in the release of products Eliminate inventory errors Test and inspect finished products Perform high precision assemblies (e.g. mount microdevices on microchips) Perform tasks in collaboration with humans (collaborative robots)
T7	Augmented Reality	X	X		Troubleshooting the workstation through the use of devices such as tablets, smart glasses or smartphones Support in performing maintenance remotely through knowledge sharing and technical guidance
T8	Simulation	X	X	X	Assist operators in performing complex tasks Perform operational training Simulate projects and processes Simulate different production and programming scenarios Analyze bottlenecks in production
T9	Additive Manufacturing	X	X		Minimize the impact of design changes Optimize manufacturing processes such as machining and welding Facilitate the construction of prototypes and samples Repair damaged components

Table VII.

LP	Industry 4.0 technology																																											
	T1				T2				T3				T4				T5				T6				T7				T8				T9											
	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)				
P1	3	2	3	8	3	2	3	8	3	2	3	8	3	2	3	8	3	2	3	8	3	2	3	8	2	1	1	4	2	2	1	5	2	2	1	5	2	2	1	5	2	2	2	6
P2	3	3	3	9	3	3	3	9	3	2	3	8	3	3	3	9	3	3	3	9	3	3	2	8	3	2	1	6	2	2	2	6	2	2	2	6	2	2	2	6	2	2	1	5
P3	3	2	3	8	3	2	3	8	3	2	3	8	3	2	2	7	3	2	1	6	3	1	2	6	2	2	2	6	2	2	2	6	2	2	2	6	2	2	1	5				
P4	3	3	3	9	3	3	3	9	3	2	3	8	3	3	3	9	3	3	2	8	3	2	2	7	2	2	2	6	2	2	2	6	2	2	2	6	2	2	1	5				
P5	3	2	3	8	3	2	3	8	3	2	2	7	3	2	1	6	3	2	2	7	2	1	1	4	2	2	1	5	2	2	1	5	2	2	1	5								
P6	3	2	2	7	3	2	2	7	3	2	3	8	2	2	1	5	2	2	1	5	2	1	1	4	1	2	1	4	1	2	1	4	1	2	1	4								
P7	3	2	1	6	3	2	1	6	3	1	2	6	2	2	2	6	2	2	1	5	2	2	2	6	2	2	2	6	2	2	2	6	1	2	1	4	2	2	2	6				
P8	3	3	1	7	3	3	1	7	3	2	1	6	2	3	1	6	2	3	1	6	2	2	1	5	1	2	1	4	2	3	1	6	1	2	1	4								
P9	3	3	2	8	3	3	2	8	3	2	2	7	2	3	1	6	2	3	1	6	2	2	1	5	1	2	1	4	2	3	2	7	2	2	2	6								
P10	2	2	1	5	2	2	1	5	2	2	1	5	1	2	1	4	1	2	1	4	1	1	1	3	1	2	1	4	1	2	1	4	1	2	1	4								
P11	2	2	3	7	2	2	1	5	2	2	1	5	1	2	1	4	1	2	1	4	1	1	1	3	1	2	1	4	1	2	1	4	1	2	1	4								
P12	2	3	1	6	2	3	1	6	2	2	1	5	2	3	1	6	2	3	1	6	1	2	1	4	1	2	1	4	1	3	1	5	1	2	1	4								
P13	2	2	2	6	2	2	3	7	2	1	2	5	2	2	2	6	1	2	1	4	2	2	3	7	1	2	3	6	1	2	1	4	1	2	1	4								
P14	2	2	3	7	2	2	3	7	2	2	3	7	2	2	3	7	2	2	2	6	1	2	1	4	1	2	1	4	1	2	1	4	1	2	1	4								

Table VIII.

Matrix of interaction between the main technologies of I4.0 and LPs

Notes: (a) Citation frequency of I4.0 technologies and LPs; (b) application of I4.0 technologies and LPs at different levels of value stream; (c) relevance of the evidence found in the literature; (d) total score based on the sum of criteria (a)–(c)

with lowest citation frequencies were denoted as “low citation.” The remaining practices (i.e. P6, P7, P8 and P9) and technologies (i.e. T4, T5 and T6) were categorized as “medium citation.” Scores of 3, 2 and 1 were associated with “high citation,” “medium citation” and “low citation,” respectively.

For criterion (ii), relationships in which LPs and I4.0 technologies approached the same value stream levels were considered as “highly” related. In contrast, those in which applications did not match the same value stream level were assigned as “unrelated.” For associations in which I4.0 technologies and LPs were concomitantly applied in at least one of the levels, their relationship was considered at an “intermediate” level. Analogously, each category received the following scores: 3 (high), 2 (medium) and 1 (low).

Finally, the third criterion covered a qualitative analysis of the evidence found in the BP. This evidence was analyzed regarding the relevance and robustness of the inferences made throughout the papers. Relationships between LPs and I4.0 technologies that have been suggested based upon more consistent methodological procedures were defined as “high” level. Consequently, “low-” and “middle-level” relationships were attributed to evidence based on studies whose approach presented a medium or low methodological consistency. Scores 3, 2 and 1 were assigned to “high,” “medium” and “low” level relationships, respectively.

Therefore, the classification of the synergy level for the 126 pairwise relationships was based on the sum of the scores for each criterion, being defined in three different levels: low (relationships whose sum of the scores was equal to 3 or 4); moderate (associations whose scores added up to 5, 6 or 7); and high (relationships whose sum totaled a score of 8 or 9). Hence, we identified that 24 (19 percent) relationships were classified as being of high synergy, 72 (57 percent) being of medium and 30 (24 percent) as low synergy. The interactions classified as highly synergistic revealed the existence of a favorable relationship and collaboration between LPs and I4.0 technology toward the achievement of a higher operational performance. In this type of interaction, there was a large probability that the I4.0 technology and the LPs work in a constructive way to improve results, as it is the case of the interaction between CPS and VSM. Both CPS and VSM have a high pervasiveness across the value stream, being used as a supportive technology/practice on which others can build or expand upon. As an adequate application of VSM requires a large amount of information (Bhamu and Singh Sangwan, 2014) that is almost always outdated or does not consider stochasticity (Tamás and Illés, 2016), the incorporation of CPS could provide more accurate data so that managerial decisions would prioritize continuous improvement initiatives based upon more realistic scenarios.

For relationships with a moderate level of synergy, it was assumed that technologies and practices were compatible in certain aspects. Occasionally, some adaptations need to be made for the association to succeed. The use of such associations requires a more detailed analysis of the characteristics of each pair of I4.0 technology and LP. For example, the relationship between Simulation and the *Poka Yoke* (error proof system) significantly depends on the application context. Although the utilization of Simulation can anticipate potential difficulties and mitigate failures in the productive process (Adeyeri *et al.*, 2015), it does not avoid errors, which is the essence of *Poka Yoke* (Kolberg and Zuehlke, 2015). A certain complementarity between Simulation and *Poka Yoke* is clearly identified, even though studies that reported their concomitant application are still scarce.

Low-synergy relationships indicated that some characteristics from the practice/technology may undergo significant modifications to make the association feasible. This kind of association requires a deeper analysis to be justified and to support the achievement of desired results. For instance, the relationship between Advanced Robotization and SMED can generate conflicting efforts for operational improvement of manufacturing companies if not well planned (Pfeiffer, 2016). On one hand, the utilization of Advanced Robotization can bear complex activities (Mourtzis, Zogopoulos and Vlachou, 2017), which are usually found in a

machine changeover. On the other hand, high levels of Robotization and Automation can lead to less flexible production lines (Sanders *et al.*, 2017), limiting the range of product families processed in this line and undermining changeover time. This was a relevant remark since there may be relationships that still need to be developed to allow overcoming technology/practice functionalities that entail different outcomes.

Regarding the technologies that presented the largest number of high-synergy interactions (corresponding scores of 8 or 9), IoT and CPS (both with six interactions) stood out. IoT and CPS play a key role in the exchange and transmission of data needed to connect the factory (Hermann *et al.*, 2016; Bagheri *et al.*, 2015; Rad *et al.*, 2015), which is aligned with certain LM principles proposed by Liker and Franz (2011), such as “foster a culture that stops to fix problems” and “continuous flow establishment to raise and identify issues.” These principles are extensively operationalized by LPs such as *Kaizen*, *Poka Yoke* and *Kanban*, which were all indicated as highly synergistic with both technologies (see Table VIII). In addition, both technologies have high flexibility and can be applied in different ways and for various purposes (Tamás *et al.*, 2016; Xu and Chen, 2016), enabling the achievement of enhanced quality and productivity levels by facilitating interconnectivity among productive processes.

On the other hand, with respect to technologies with the largest number of low-synergy relationships (corresponding scores of 3 or 4), Advanced Robotization (seven interactions) stood out. Such result reflects the restrictions regarding the applicability of this technology outside the operational context. It is worth mentioning that these low-synergy levels could be derived from the fact that this technology is more likely to be utilized on shop floor processes (intracellular level). Therefore, when compared to technologies whose application can be extended across different levels of the value stream, Advanced Robotization would provide little support to LPs that aim at macro-processes and/or supply chain levels, such as *Kanban* and *Heijunka*.

With regards to LPs, VSM was the one that presented the largest number of high-synergy interactions with I4.0 technologies (six interactions). This result can be justified by the fact that VSM covers all levels of the value stream, being efficient in reducing waste and it is well-known either in manufacturing (Rother and Shook, 2003) or in service (Shih *et al.*, 2016) organizations. Thus, this practice is considered potentially beneficial for the adoption of I4.0 (Kolberg and Zuehlke, 2015), since it provides a structured approach to identify improvement opportunities and to guide organizations toward a leaner operation. As aforementioned, a digitally-integrated VSM input with real-time data allows a more in-depth understanding of companies' *status quo* and assertive design of lean value streams.

Finally, the LP that had the largest amount of low-synergy interactions was *Takt* Time. One of its major objectives is to precisely adjust the rhythm of the productive system according to market demand (Rother and Shook, 2003). Further, *Takt* Time is based on predictable demand and presents difficulties in absorbing demand fluctuations (Ali and Deif, 2014). I4.0, in turn, allows the production system to be modular and flexible, enabling it to mass produce highly customized products (Kagermann *et al.*, 2013). Thus, it can be pointed out that *Takt* Time is somewhat contradictory to the principles of decentralization and autonomy implied by the adoption of I4.0 technologies (Sanders *et al.*, 2017).

8. Conclusions and future research directions

This work aimed at identifying the relationships between I4.0 technologies and LPs in manufacturing companies. A systematic literature review, which is an appropriate method to reinforce a research problem and gaps, was carried out to consolidate a BP with 93 papers so that a panorama on the topic is presented. It is noteworthy that the search only included works that approached I4.0 technologies and LM, indicating a lack of

research related to both topics. This study contributes to strengthening the body of knowledge on I4.0 technologies and LPs by pointing out their characteristics and applications in different levels of the value stream, and identifying the synergies between them (theoretical contribution).

Although our findings were limited to conceptual/theoretical propositions, they can be used as initial guidelines to integrate the novel digital technologies from I4.0 into LPs, suggesting an expectation with regards to the synergy level between them, and allowing the prioritization of their implementation. Regarding practical implications, our findings indicate that manufacturers undergoing an LM implementation and wishing to benefit from I4.0 should preferably invest efforts in adopting IoT and CPS. These I4.0 technologies are the ones with the largest number of high-synergy relationships with LPs and, hence, are the most likely to provide shorter-term results. In contrast, from a LM perspective, Advanced Robotization should not be prioritized due to its limited level of synergy with LPs. Other technologies whose conceptualization and application occurred before the formal acknowledgment of I4.0, such as Simulation, may have lost their novelty, reducing their research interest. Conversely, this fact does not mean that Simulation is not extensively applied in manufacturers, since there may be different forms for utilizing it in production systems and manufacturing processes that can converge to the objectives of LPs.

Based on these outcomes, a few opportunities were identified for future research on this topic, as follows:

- (1) Empirical validation of the proposed synergies between LPs and I4.0 technologies: as our study proposed synergy levels based on a systematic literature review, an empirical validation of those relationships still needs to be addressed. Such analysis could truly verify the existence of those synergies and better quantify their intensity levels. Thus, studies that conduct a cross-sector survey-based research could support our propositions and provide more robust arguments on such relationships.
- (2) Categorization of I4.0 technologies and LPs in different levels of value stream: unlike the literature on LM, the body of knowledge on I4.0 is significantly more recent and incipient. This fact indicates that much still needs to be investigated in order to have a clearer understanding of I4.0's potential benefits. Therefore, the categorization of these technologies and LPs according to the level of the value stream can be enhanced as companies and researchers increase their understanding. Future studies on LM and I4.0 could better clarify and indicate how this relationship can impact the entire organization, distinguishing its effects on all levels of value stream (i.e. intracellular, macro-processes and supply chain levels).
- (3) Examine the effects of the relationship between I4.0 and LM on operational performance: few studies examined the impact of the association between I4.0 and LM on the operational performance of manufacturers. The application of I4.0 technologies may create new possibilities for problem solving as well as improvement of current production processes (Gubán and Kovács, 2017). Hence, we suggest that further studies related to operational performance could be conducted in different industry sectors. Such expansion could contribute to the confirmation and generalization of the actual benefits of this relationship on operational performance.

Since this study was solely based on papers that examined both I4.0 and LM, there may be technologies or practices that were approached only in specific studies on either LM or I4.0. Hence, we acknowledge that the set of LPs and I4.0 technologies included in this research does not necessarily cover all the existing ones. In fact, our study is restricted to this evidence and additional pairwise relationships could be identified if other practices and technologies were considered. Another limitation is related to the identification of the

synergy levels between I4.0 technologies and LPs, for which three criteria were adopted to determine whether the pairwise relationship was synergistic or not. These criteria do not consider any companies' contextual factors that may influence such relationships. In this sense, further research could investigate how contextual factors influence these relationships, indicating complementary criteria that allow the assessment of synergy between both approaches.

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