The Synergic Relationship Between Industry 4.0 and Lean Management: Best Practices from the Literature

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Abstract
Industry 4.0 promises to make manufacturing processes more efficient using modern technologies like cyber-physical systems, internet of things, cloud computing and big data analytics. Lean Management (LM) is one of the most widely applied business strategies in recent decades. Thus, implementing Industry 4.0 mostly means integrating technologies in companies that already operate according to LM. However, due to the novelty of the topic, research on how LM and Industry 4.0 can be integrated is still under development. This paper explores the synergic relationship between these two domains by identifying six examples of real cases that address LM-Industry 4.0 integration in the extant literature. The goal is to make explicit the best practices that are being implemented by six distinct industrial sectors such as automotive, paper, furniture, healthcare, apparel, and machine manufacturing.

Introduction

Manufacturing companies face the continual challenge of improving their processes and systems in order to deliver the required production rates of high-quality products, while minimizing the use of resources (EFFRA, 2016). Thus manufacturing is constantly evolving from concept development to new practices for the production of goods for use or sale (Esmaeilian et al., 2016). In this regard, Lean Management (LM) is one of the major concepts in the creation of highly efficient processes since the early 1990s (Kolberg et al., 2017). It concerns the strict integration of humans in the manufacturing process, continuous improvement, and focus on adding value to activities by avoiding wastes (Mrugalska and Wyrwicka, 2017; Ohno, 1988). Nonetheless, in recent years, the rapid changes in technology and ever-changing cus-

tomer expectations are leading industries to undergo shifts in their operating and management systems. Even though LM is widespread and successful (Kolberg et al., 2017; Danese et al., 2018; Bortolotti et al, 2014), and supports a higher variety of products, its fixed sequence of production and fixed cycle times are not suitable for the mass production of highly customized products (Kolberg et al., 2017; Kolberg and Zühlke, 2015). In this context, the current trend in the industrial sector is towards Industry 4.0 implementation (Sony, 2018; Ciano et al., 2019; Culot et al., 2020). Considered by many authors and practitioners as the fourth industrial revolution (Bitkom, 2016; Piccarozzi et al., 2018), Industry 4.0 is one of the keywords used to describe a new paradigm shift that is based on the digitalization of factories (Chiarello, 2018). It is about the use of information and communication technology (ICT), cyber-physical systems (CPS), the Internet of things (IoT), cloud computing, big data analytics, and so on (Sendler, 2013), where all of which allow for decentralized decisions based on real-time data acquisition. As a result, Industry 4.0 is expected to improve existing manufacturing practices in terms of productivity, quality and flexibility, as well as driving changes in the nature and organization of work (Lu and Weng, 2018). In particular, three dimen-

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sions of change are expected from this phenomenon: technological change, social change, and changes in business models (Smit et al., 2016).

However, while on the one hand Industry 4.0 opens up new opportunities to the manufacturing companies, on the other hand it poses challenges not only from the technical point of view but also from the organizational and management ones (Piccarozzi et al., 2018; Wagner et al., 2017). In this regard, a subject that has been discussed in the literature is the integration of Industry 4.0 with management approaches such as LM (Moeuf et al., 2020; Buer et al., 2018). In light of the fact that LM is still considered the best practice in the automotive industry, as well as being even more present in other industry sectors, such as construction, services, and so on (Martinez et al., 2016), implementing Industry 4.0 mostly means integrating technologies in companies that already operate according to LM principles (Wagner et al., 2017). Reference (Kagermann et al., 2013) add that achieving Industry 4.0 vision will involve a gradual process within a long-term project and, therefore, it is very important to preserve the value of existing manufacturing systems. Furthermore, many authors have suggested the positive correlation that exists between these two approaches and its great impact on industrial performance (Tortorella et al., 2018; Rossini et al., 2019; Kamble et al., 2019).

These facts have led to an increase in studies exploring ways to integrate these two approaches (Kolberg et al., 2017; Sony, 2018; Buer et al., 2018; Kamble et a;., 2019; Bal and Satoglu, 2018; Tortorella and Fettermann, 2017; Sanders et al., 2016; Pagliosa and Tortorella, 2019). Nevertheless, the systematic literature review (SLR) conducted by reference (Pagliosa and Tortorella, 2019) indicates that research in this subject is still immature, so it still needs to be further developed. Particularly, a number of studies address the impacts of Industry 4.0 solutions on LM practices through a theoretical length (Sony, 2018; Buer et al., 2018; Sanders et al., 2016; Pagliosa and Tortorella, 2019), and highlight "potential" benefits regarding an LM-Industry 4.0 integration. Consequently, studies that explore the best practices that are being implemented by industries are still missing in the literature (Powell et al., 2018; Wagner et al., 2017; Pagliosa and Tortorella, 2019).

As such, this work contributes to the existing body of knowledge in both, LM and Industry 4.0 fields by identifying six real cases of LM-Industry 4.0 integration that were implemented in distinct industrial sectors. In doing so, we intend to support industries and practitioners by providing insights on how they can successfully integrate these two approaches. In addi-

tion, companies that have already applied LM need guidelines to help them deal with the complexity of Industry 4.0 (Meudt et al., 2017).

This paper is structured as follows. Section 2 describes the methodology. Section 3 details the literature review in the LM and Industry 4.0 fields. Section 4 discusses the current research streams and provides six examples of best practices in LM-Industry 4.0 integration. Finally, section 5 presents the conclusions, contributions, suggestions for future research, and limitations of the study.

Methods

Traditionally, a literature review attempts to identify what has been written on a given subject (Savaget et al., 2019). According to reference (Paré et al., 2015), conducting an effective and methodologically sound literature review is essential to advance the knowledge of, and understand the breadth of the research on, a topic of interest, selection criteria, the empirical evidence, develop theories or provide a conceptual background for subsequent research, and identify the topics or research domains that require further study. As such, this paper uses an adapted version of the procedures proposed by (Savaget et al., 2019), which results in a two-stage process called the sampling stage, and the analytical stage. The search was conducted using two databases: ISI Web of Science and Scopus. These databases were chosen due to their consistency in the indexing content. To reach the purpose of this study, the Boolean expression "INDUSTRY 4.0" AND "Lean" was used in the title, abstract, and keyword search fields. Following reference (Crossan and Apaydin, 2010), the search was limited to papers written in English and published between 2015 and 2018. The decision to restrict the search to over these three years was made based on two factors: first, the research in Industry 4.0 and LM is relatively recent, since Industry 4.0 topic starts to be disseminated in 2011 by the German Government (Kagermann et al., 2013). Second, due to the growing number of papers published from 2015, with an identified peak of publications in 2016 (Pagliosa and Tortorella, 2019).

The initial phase resulted in a sample of 147 documents. Then, duplicate papers were eliminated. Next, the titles of all documents were reviewed in order to eliminate those that were unrelated to the goals of this study. Thereafter, the abstracts were reviewed before proceeding to a detailed reading of the papers, which resulted in an initial sample of 24 documents. This initial sample was subsequently complemented by semistructured snowballing to expand the literature, re-

sulting in a final sample of 88 documents. Finally, in the analytical stage, we employed the content analysis method. In addition, to ensure that all relevant publications were examined, our sample was complemented with emerging research in LM and Industry 4.0 fields. At this stage, the selection of publications was made based on suggestions from experts in the field and from scientific websites. Moreover, for each new publication read, the snowballing approach was used again. This adaptation on the review strategy was of great importance in ensuring that the appropriate literature was accurately covered (Snyder, 2019).

Literature review

State-of-the-art Lean Management

Lean Management (LM), arguably the most prominent manufacturing paradigm of recent times, originated at Toyota Production System (TPS) (Womack et al., 1990). The concept refers to a multidimensional approach that encompasses philosophical characteristics and a set of management tools and practices that must be implemented in an integrated way (Shah and Ward, 2003). The goal is to create a high quality system focused on adding value to the activities by reducing wastes (Kolberg et al., 2017; Shah and Ward, 2003; Danese et al., 2018). Since its initial developments, LM has evolved so that its original set of hard tools (i.e., technical and analytical tools) have been complemented with soft practices (i.e., lean practices related to people and relations such as small group problem solving, training, supplier partnerships, and customer involvement) (Bortolotti, et al. 2007; Martinez et al., 2016; Shah and Ward, 2007; Costa et al., 2019). These so-called soft practices are crucial for improving manufacturing performance and provide long-term benefits through LM implementation (Bortolotti et al., 2014; Hines et al., 2004). In fact, in the past, many organizations have failed on their Lean journey because they focused on the isolated use of hard tools and techniques and neglected the human elements (Costa et al, 2019; Akmal et al., 2020). Furthermore, this more human-centric approach allowed LM to be implemented to any process or context (Shah and Ward, 2007). Consequently, LM is able to meet market demands in many dimensions, such as product quality, faster delivery and lower costs, besides providing greater flexibility to meet customer requirements (Akmal et al., 2020; Ciano et al., 2019).

The benefits achieved through this approach contributed to intensifying the interest on LM, resulting in a steady rise in the number of articles published since 2007. At first, most studies focused on the manufacturing sector. In that context, LM research – which had hitherto focused on the automotive industry, mainly due to the influence of the success of TPS – began to expand into other sectors. The approach has now been adopted by a number of other industries, including textiles, construction, services, food, medical, electrical and electronic equipment, ceramics, furniture, services, and so forth. Moreover, its concepts and practices are being applied in all types of organizational systems, such as healthcare, human resources, and higher education (Martinez et al., 2016). According to the literature, organizations use a myriad of tools for a variety of purposes, such as Value Stream Mapping (VSM), Kaizen, Kanban, Pull Systems, Just-in-time (JIT), Total Productive Maintenance (TPM), Total Quality Management (TQM), Single Minute Exchange of Die (SMED), 5'S, Standard Work, Cellular Layout, Poka-Yoke, and Heijunka (Shah and Ward, 2003; Akmal et al., 2020; Jadhav, et al., 2014; Jasti and Kodali, 2015). However, most published articles focus on eliminating a specific type of waste, rather than reducing all types of waste. The wastes most commonly cited are stocks and defects since both directly influence product costs.

Finally, the literature review revealed that LM is often associated with other approaches such as Agile, the Theory of Constraints (TOC), Six Sigma, and more recently, Industry 4.0 (Ciano et al., 2019; Sanders et al., 2016; Pagliosa and Tortorella, 2019; Hines et al., 2004). Indeed, from a strategic perspective, any practice that leverages the value provided to the end customer can be combined with LM.

Industry 4.0 – origins and concept

The first ideas on Industry 4.0 were published by the German government at the 2011 Hannover Fair as part of its "High-Tech Strategy 2020 Action Plan", and aimed to act as a politically established target for strengthening its international competitive position in manufacturing (Kagermann et al., 2013). Since then, the topic has been pointed out by academics, managers and policy makers (Bitkom, 2016; Schwab, 2018; Liao et al., 2017), as a critical means to face contemporary challenges such as high competition, increasing demands for customized products and shorter product life cycles and lead times (Hu, 2013).

The concept refers to the tight integration of physical objects (e.g. machinery, robots, conveyor, warehousing systems) and production facilities into valuable information networks (Cattaneo et al, 2017; Kagermann et al., 2013). Thereby, Industry 4.0 al-

lows flexible manufacturing and the analysis of a large amount of real-time data that will improve strategic and operational decision-making. In short, with data and connectivity as its main characteristics, Industry 4.0 is able to improve overall industrial performance by establishing intelligent and highly collaborative networks.

Industry 4.0 based technology

A range of advanced technologies, including cyber-physical systems (CPS), IoT and internet of services (IoS), cloud computing, advanced human-machine interfaces (HMI), simulation, 3D printing, and big data analytics are being applied to Industry 4.0 solutions (BCG, 2015). A breath of some relevant technologies is shown in Table 1.

As a result of the employment of CPSs and innovative ICTs in production systems, factories have become 'Smart Factories' (Iyer, 2018). These new-generation of factories operate with real-time data and continuous forecasting, which drive changes in the traditional decision-making process (Peres et al., 2018). To this end, smart objects (e.g. machines, products or devices) must be integrated with big data analytics (Zhong et al., 2017). Thus, the smart objects can dynamically reconfigure achieving great flexibility whereas big data analytics provide global feedback and coordination to achieve high levels of efficiency (Wang et al., 2016a). The consequence is the ability to respond almost automatically to any change at any time.

According to reference (Smit et al., 2016), to implement a smart factory, three key aspects must be addressed: (i) horizontal integration, (ii) vertical integration, and (iii) end-to-end digital integration.

Horizontal integration refers to the ability to collaborate with other entities such as partner compa-

Table 1
Industry 4.0 enabled technologies

Technology	Explanation
Cyber-Physical Systems	"It uses sensors, network technology, and computers to connect various devices, machines, and digital systems, enabling various machines to communicate and interact with each other, thereby realizing the seamless integration of the virtual and physical worlds" (Tsai and Lai, 2018).
Internet of Things (IoT)	"IoT devices are able to collect and share data directly with other devices through the cloud environment, providing a huge amount of information to be gathered, stored and analyzed for data-analytics processes" (Arcidiacono and Pieroni, 2018).
Internet of Services (IoS)	"Via the IoS, both internal and cross-organizational services are offered and utilized by participants of the value chain" (Hermann et al., 2016).
Cloud Computing	"Cloud technologies can be widely used in Industry 4.0 for increased data sharing across company boundaries, improved system performance, and reduced costs through bringing systems online" (Liu and Xu, 2016).
Human-Machine Interfaces (HMI)	"Human-machine interfaces will promote the interaction between both production elements and the required communication between smart machines, smart products and employees" (Pereira and Romero, 2017).
Simulation	"Simulation modelling is the method of using models of a real or imagined system or a process to better understand or predict the behavior of the modelled system or processes" (Rodič, 2017).
3D Printing	"3D printing is an additive manufacturing technology, facilitating convenient and rapid fabrication of physical objects of almost any shape. It has a wide range of practical applications, from fast product prototyping, product development, 3D visualization, to distributed manufacturing of larger-sized objects such as machine parts" (Song et al., 2015).
Data Mining	"Data mining involves discovering novel, interesting, and potentially useful patterns from large data sets and applying algorithms to the extraction of hidden information" (Chen et al., 2015).
Big Data Analytics	"Big Data is high-volume, high-velocity, and/or high variety information assets that require new forms of processing to enable enhanced decision making, insight discovery and process optimization" (Beyer and Douglas, 2012).

nies, suppliers and customers in order to create a true ecosystem of cooperation (Wang et al., 2016a). Hence may arise new value networks as well as new business models, such as servitization (Rymaszewska et al. 2017; Ardolino,et al., 2018). Following reference (Oh and Jeong, 2019), horizontal integration also increases customization. For example, supported by additive manufacturing (AM) technologies such as 3D printing, new solutions in the manufacture of small batches of complex products can be offered with a high degree of customization, which brings greater flexibility to the production environment, even in mass production contexts.

While horizontal integration occurs through value networks that extend beyond factory boundaries, vertical integration takes place within the factory. It entails the connection of all levels of physical and informational subsystems in order to create a self-organized system of smart machines that can be dynamically reconfigured to adapt to different product types (Wang et al., 2016).

The first step in ensuring vertical integration is to digitalize the shop floor using sensors, actuators and Programmable Logic Controllers (PLCs) (Calderón Godoy and González Pérez, 2018). Thereafter, shop floor data is collected through Supervisory Control and Data Acquisition (SCADA) and then transferred to Manufacturing Execution Systems (MES), which represents the managerial layer of the system and will provide the production status to the ERP. Enabled by machine-to-machine communication (M2M), individual items of equipment are able to communicate with each other, facilitating their adaptation to any change in manufacturing lines and enabling a flexible and reconfigurable production system (Wang et al., 2016).

Finally, end-to-end digital integration takes into account all activities that aim to add value to the product from its development to after sales (Smit et al., 2016; Brettel et al., 2014). These activities can involve the expression of customer requirements, product design and development, production planning, production engineering, production, services, maintenance, and recycling.

LM and Industry 4.0 integration

Background

The ongoing trend towards the mass production of highly customized products and services is increasing the demand for production flexibility. Although the powerful effects of LM on production systems have already been established worldwide, the flexibility and adaptability required in the newest industrial environments is constrained in human-centered approaches such as LM (Kolberg, et al., 2017). It was in aid of overcoming these barriers that the early 1990s saw the rise of the first approaches proposing to integrate automation technology with LM systems, later known as Lean automation.

Curiously, over the years, companies that have made extensive use of automation were not considered to be Lean. In fact, LM tools and practices have their origins in the 1950s and therefore do not take into account the possibilities offered by modern technologies. However, according to the research on Lean automation, the issue is not whether LM ought to be automated, but rather concerns the appropriate type and level of automation (Harris and Harris, 2008). In this regard, reference (Kolberg, et al., 2017) argues that Lean automation attempts to combine LM and Industry 4.0 to take the best from both worlds. For instance, the human factors and other soft elements of the organization – the core of Lean principles – are considered critical elements for a successful implementation of Industry 4.0 (Piccarozzi et al., 2018). Once humans are involved in every technical or industrial system, whether it is operating the systems, developing new ideas, or as strategic decision-makers, taking into account the human element in a connected and complex system like Industry 4.0 is of crucial importance to ensure system reliability and, consequently, the expected performance of firms (Piccarozzi et al., 2018; Kinzel, 2017). The literature has acknowledged the human-being as the most flexible element of the factories and, therefore, the main responsible for improving business performance (Piccarozzi et al., 2018; Peruzzini et al., 2017; Dalenogare et al., 2018). In fact, when workers understand the role of new technologies in their day-to-day lives, weaknesses such as the reluctance to change can be overcome (Moeuf et al., 2020). Otherwise, individuals will not simply adapt to the new changes and the company will not be able to make profit from it. In addition, LM also means a philosophy of continuous improvement in which Industry 4.0 can give the technological support to achieve excellence in manufactured products, processes, and the organization in its entirety.

Research streams in LM-Industry 4.0 integration

Recent studies have seen authors approaching this subject from a number of perspectives. For instance, from a theoretical view, reference (Sanders et al., 2016) identified the main challenges to implement LM from an integrative perspective and then highlighted

suitable Industry 4.0 solutions to overcome these barriers. In doing so, the authors analyzed Industry 4.0 solutions for 10 dimensions of LM and grouped it into 4 LM factors (e.g. supplier, customer, processes, and control/human factors). Reference (Sony, 2018) proposed an integration framework that takes into account the 5 LM based principles (e.g. define value, identify de value stream for each product/service, create flow, establish pull, and pursuit perfection) and the 3 principles of integration proposed by Industry 4.0 (e.g. horizontal, vertical, and end-to-end digital integration). Empirical studies were addressed by reference (Tortorella and Fettermann, 2017), who carried out a survey in brazilian manufacturing companies to analyze the relationship between LM practices and Industry 4.0 implementation, and by reference (Kamble et al., 2019) that investigated the relationship between Industry 4.0 technologies, LM, and sustainable organizational performance (SOP) in Indian manufacturing companies. Both studies suggested that LM is positively associated with Industry 4.0 technologies and their integration can lead to greater performance.

Given the above, three major research streams can be highlighted. In the first research stream researchers argue that the Industry 4.0 technologies reinforce LM practices by enabling the collection and analysis of important plant floor and management data and then providing solutions to the main causes of failure and inefficiencies in operations management, such as lack of accurate information and time-sensitive data (Chongwatpol and Sharda, 2013). In this view, Industry 4.0 is applied to support LM (Buer et al., 2018). The second one claims that a manufacturing system that has implemented LM is more likely to be modelled and controlled, which may create an optimal foundation on which to build a smart factory (Wang et al., 2016b). As mentioned before, in most cases, Industry 4.0 will affect the shop floor practices that are typically related to LM (Buer et al., 2018). Thus, the initial company situation should be considered in order to ensure the system's ability to function safely (Kaspar and Schneider, 2015). In this sense, LM is an enabler for Industry 4.0. Lastly, the third research stream addresses the performance implications of an LM-Industry 4.0 integration (Kamble et al., 2019; Tortorella and Fettermann, 2017). These studies usually focus on which performance metrics are affected through this integration (Buer et al., 2018). The three research streams and their key characteristics are illustrated in Fig. 1.

This literature is however characterized by a significant limitation. Despite the interest in the relationship between LM and Industry 4.0 has increased in
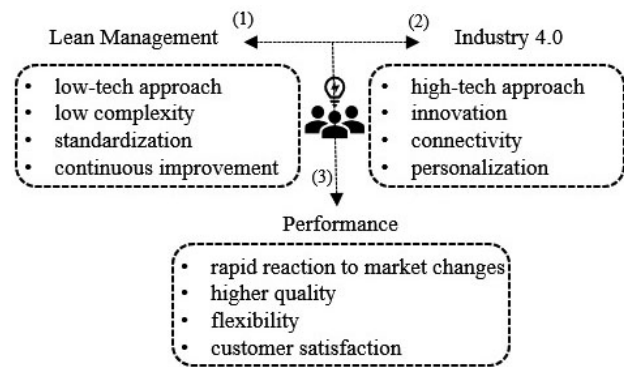

Fig. 1. LM-Industry 4.0 integration research streams

recent years, a number of studies address the impact of Industry 4.0 solutions on LM practices through a theoretical lens (Buer et al., 2018; Sony, 2018; Sanders et al., 2016; Pagliosa and Tortorella, 2019). In addition, the few existing empirical studies tend to focus on the effects of Industry 4.0 on LM and performance, emphasizing "potential" benefits that may arise from this integration (Kamble et al., 2019; Tortorella and Fettermann, 2017) rather than providing practical indications of how companies can take the first steps towards an effective LM-Industry 4.0 integration. Although we recognize the importance of these studies, companies that have already implemented LM need guidance on how to successfully integrate these two approaches. Indeed, regardless of the chosen point of view, it is undeniable that the synergy resulting from this combination brings new growth opportunities for industrial contexts, which make this research subject even more interesting (Buer et al., 2018; Tortorella and Fettermann, 2017; Pagliosa and Tortorella, 2019; Piccarozzi et al., 2018; Moeuf et al., 2020).

LM-Industry 4.0 integration: Best practices from the literature

In this section, six examples of real cases that address LM-Industry 4.0 integration are presented. The goal is to make explicit the best practices that are being implemented by six distinct industrial sectors such as automotive, paper, furniture, healthcare, apparel, and machine manufacturing. In addition, in order to provide a better understanding of the different types of synergy that may arise from an LM-Industry 4.0 integration and considering that both LM and Industry 4.0 approaches comprise a set of principles/practices (in the case of Lean) and technologies (in the case of Industry 4.0) that often re-

quire other tools or practices to fulfill their purposes, the cases were grouped into four key Industry 4.0 solutions, such as follows:

- cyber-physical systems (CPS),
- simulation,
- big data analytics and data mining,
- human-machine interfaces (HMI).

The choice of such structure was made based on the main integration objectives of each case.

Cyber-Physical Systems (CPS)

(1) Automotive industry

Reference (Wagner et al., 2017) presented a "cyber-physical Just-in-Time delivery" to balance the material stocks in a global automotive company with an advanced level of Lean maturity. As the first step, a decision support framework called Industry 4.0 impact matrix was developed in order to provide an estimation of the impact of Industry 4.0 technologies on the well-established LM practices. Thus, the next step was to carry out an assessment of all LM processes at the company. Afterwards, the authors found a potential application in the process stability of Just-in-Time (JIT) delivery for electrical assembly parts. Based on the proposed matrix, the Industry 4.0 solutions such as big data, data analytics, and vertical integration of machine to machine communication were identified as the solutions more likely to positively impact the JIT process. Thus, the next step focused on the implementation of these solutions. Since Kanban is the LM tool utilized to control JIT between workstations, the authors developed a cyber-physical application to replace the traditional Kanban cards by a vertically integrated solution based on M2M. It consisted in reducing the gap of information flow between manufacturing order, material delivery, material consumption, and material stock and the generation of an automatic purchase order to the supplier. At this point, a horizontally integrated solution was added by redesigning the database of the manufacturing execution system (MES). As such, it was also necessary to develop and integrate an additional JIT-service task on a middleware system. By using sensors, every material movement could be detected and posted in a big data architecture. Thus, when the material stock was reduced to a minimum stock level, an automatic purchase order for the supplier was generated. Moreover, the data related to the delivered material were automatically collected using an optical RFID system and considered in the forecast of material requirements. Finally, due to the increased level of traceability and process reliability, it was possible to reduce the warehouse space.

(2) Paper industry

Another example related to a CPS solution is given by reference (Tsai and Lai, 2018) who described a study case relating the benefits gained from the implementation of Industry 4.0 technologies in the paper industry. In their work, CPSs combined with other popular Industry 4.0 technologies such as IoT and sensors were used to monitor and control quality. In terms of the Industry 4.0 objective, given that in LM systems the reliability of production equipment has an important impact on production efficiency and product quality, sensors were installed on the machines in order to track their status and detect abnormalities. This allowed to collect more accurate and reliable data to monitor equipment's performance. The result was an increase of 15% in the machine operation rate and a decrease of 20% in non-performance. To control product quality, the company took advantage of technologies such as IoT, PLC and MES to gather, analyze and share real-time production data. In general, the authors conclude that the Industry 4.0 technologies were able to integrate software and hardware with production control to improve the overall system.

Simulation

(3) Furniture industry

Reference (Rosienkiewicz et al., 2018) presented a study performed in the furniture industry in Poland. The company in question produced kitchen and bathroom furniture and primarily used an online marketing channel. The main goal of the study was to develop a Lean hybrid production system that incorporate Industry 4.0 technologies to provide a more precise production planning capable of maximizing the usage of workstations in unpredictable environments. The approach proposed by the authors, was based on LM principles, Glenday Sieve, Artificial Neural Networks (ANNs), simulation modelling and was composed of a multi-stage process. As the first stage, the company was analyzed in-depth to gather historical data related to production volumes and customer orders. Thereafter, the Glenday Sieve method was used in order to classify the products into four groups, while the production forecast was estimated using ANNs. As a result, three different ways of manufacturing the products have been identified: (1) products could be manufactured using the sequential pull system, (2) the replenishment pull system, or (3) a separated production line could be built to satisfy individual and customized orders. Using the forecast results, an appropriate number of machines were set up and the simulation model was used to optimize the use of workstations and workers, identify abnormalities, and as-

sess the reaction of the control system in relation to these factors. The results of the study confirmed that the proposed hybrid approach increased productivity while decreasing stock levels by reducing the number of incorrect forecasts. This was possible due to the introduction of an additional production line that was dedicated exclusively to unpredictable and customized orders. Finally, the authors point out that, especially for small and medium enterprises (SMEs), it is important to invest in new knowledge and technologies in order to remain competitive.

Big data analytics and data mining

(4) HealthCare industry

Reference (Arcidiacono and Pieroni, 2018) demonstrates the advantages of applying LM and Six Sigma methods in light of the Industry 4.0 paradigm in the healthcare context. The integration of LM and Six Sigma has created Lean Six Sigma (LSS) (Arcidiacono et al., 2016). The Lean Six Sigma combines Six Sigma methodology with Lean thinking and has already proven to be highly successful in a variety of sectors, including in hospitals. In fact, the growing demand for patient-oriented and more efficient health services has increased the application of LSS in the healthcare service. In this context, since most of the tools in this methodology are based on data for the purpose of investigating the root causes of problems in-depth, the authors argued that the integration of LSS and Industry 4.0 is an important area of research to be explored. Thus, they proposed a new methodology called "Lean Six Sigma 4.0" (LSS 4.0). The LSS 4.0 methodology aimed to optimize the supply services process and to reduce waste of human and/or material resources, while improving the Quality of Experience (QoE) of patients. Next, the processes involved in the admission of patients were evaluated using the LSS 4.0, which proved to be a valuable tool to provide more effective performance measures. More specifically, thanks to the technologies of Industry 4.0 it was possible to gather real-time data, enabling the continuous improvement of processes. For example, the registration of the specialist consulting activities in the hospital information system and the knowledge about the available beds in the ward were improved. Moreover, as IoT makes continuous feedback easier (e.g. through social networks), customer involvement has become even more important. Thus, customers inputs could be collected and used to adjust processes in real time. In this sense, big data was a valuable tool providing information about the entire "customer experience". In conclusion, this case study shows that the integration of Industry 4.0 with LM and its re-

lated methodologies, such as Six Sigma, is not limited to the manufacturing industries, but also extends to other sectors, such as services and public administration.

(5) Apparel industry

Reference (Phuong and Guidat, 2018) presented a study case of an apparel company where "Sustainable Value Stream Mapping" (SVSM) was used to explore potential sustainability issues in production processes. In addition, the authors also discussed the impact of employing Industry 4.0 technologies on process sustainability. They argued that despite the considerable body of research about extending VSM implementations and their proved benefits, its visual presentation does not share sufficient data about the processes. However, the authors point out that even though Industry 4.0 technologies are able to bring advantages related to real-time data tracking, a comprehensive Industry 4.0 system implementation could demand substantial investment. In this sense, they claim that a more feasible solution would be to employ a single technology instead of implementing automation in wholesale. As such, they proposed the use of RFID tags. The implementation of RFIDs enabled the company to identify and eliminate significant sources of waste by improving the traceability of items. Thereon, the data gathered through the RFID system was stored in the ERP as a primary database, facilitating data mining. Thus, a real-time SVSM could be properly tracked and displayed via a dashboard screen. At the end, an Excel file connected to the main database of the ERP system was used as a secondary database to provide a simple method to support data mining. Finally, aside from the presented advantages at the production and management levels, the SVSM supported by RFID tags has proved to be a great tool to support decision making, allowing managers and engineers to detect potential issues related to the company.

Human-Machine Interfaces (HMI)

(6) Machine manufacturing industry

In the Industry 4.0 era, human-machine interfaces are a determining factor mediating the interaction between workers and machines. From this point of view, reference (Müller et al., 2017) presented a study based on the use of smart devices, such as Smart Pens, Tablet PCs and the development of a CPS production-APP called "shop floor-information-application" (SIA) to support employees in SMEs. The goal is to integrate the shop floor and top floor departments of a special machine manufacturer by us-

ing LM methods for the digitization of information. At the factory in question, customized machines are designed in the company's design and development department. All subsequent processes are fulfilled on the shop floor. The main problem faced by the company was when drawing and construction mistakes occurred, so it was necessary to correct them, not only on the product but also on the technical drawings. In fact, as in SMEs the transmission of information between business departments is often carried out in a paper-based way, any changes in components or changes in the technical drawings had to be rewritten by hand, which is labor-intensive, in addition to causing delays. Thus, the authors proposed a solution for SMEs to gather real-time information on the shop floor and distribute it to the organizational departments by combining LM tools with Industry 4.0 technologies. In this sense, by specifying requirements and elaborating a functional model, the authors developed six functionalities for the production-APP SIA. More in detail, after the employee logs into the APP, a QR-Scan is executed. In this phase, the employee moves the tablet over the QR-Code on the technical drawing, which allows its data to be downloaded, thereby, allowing the previously corresponding drawing to be viewed on the shop floor on the screen of the Tablet-PC. In the next step, the user chooses between four different functionalities, "Tablet Pen", "Take Picture", "Smart Pen", and "3D Model". Once the information related to the selected function has been transferred, the changes made to the technical drawing are sent to the design and development department using the "Send Email" function. The result of this implementation was a closed loop between the company's physical objects and its information system, enabling vertical integration.

Summary

The aforementioned cases show strong evidence that LM-Industry 4.0 integrating solutions are being successfully implemented in a wide range of industries, such as automotive, paper, machine manufacturing, furniture, healthcare and apparel and in different levels within the value chain (e.g. shop floor, organizational and management process, and cross-organizational).

As expected, the cases indicate that the LM-Industry 4.0 integrating solution chosen will vary according to the context in which the company operates. In this sense, the initial situation of the company must be taken into account before any LM-Industry 4.0 project starts to be implemented. In doing so, it
must balance the available resources (e.g. physical, human, and financial), the specific requirements of the company, and its business strategy. The results are summarized in Table 2.

More in detail, in the automotive industry (case 1), a CPS framework was developed to support LM practices by integrating physical materials, digital/virtual components and employees. The main idea was to develop an IT system based on real-time data, capable of supporting Just-in-Time material flow process. In this sense, the first contribution was given by the "Industry 4.0 impact matrix" which allowed to identify potential LM-Industry 4.0 integrating solutions. After choosing the right solution, material flow measurement and data acquisition points were implemented (e.g. through the employment of sensors on every machine) to ensure that all necessary information were available in real-time, increasing the traceability and the reliability of the processes. Finally, the virtual representation of all operations contributed to increase the visibility and transparency for employees, allowing processes to be better controlled. In the paper industry (case 2), CPS was used in production processes control to provide machines with self-awareness and self-predictive capabilities to enhance the equipment's performance. In LM, the reliability of production equipment is a critical factor, as production efficiency and product quality are strongly related to equipment maintenance. So, along with the Statistical Process Control method (SPC), sensors were implemented to collect real-time data, and technologies such as PLC, MES and IoT were applied for data statistics, analysis, transmission, and monitoring. Thus, when the monitoring system identified any abnormality, the information was automatically transmitted to the manager, who was able to adjust the production parameters, avoiding the production of defective products. Regarding simulation technologies, the furniture industry (case 3), combined a simulation model with LM principles, such as pull production to scheduling and planning production processes. By using ANNs, more reliable forecasts could be provided, due to the optimized use of the workstations and workers. It led the decrease of stock levels and the increase of productivity. Moreover, this combination increased the system's resilience, which is crucial for systems operating under rapidly changing environments. Lastly, the improved production planning has reduced delivery times to 48 hours for online sales. This was an important achievement for the company since this type of business model in Poland is still in development. Regarding the healthcare sector (case 4), it took advantage of technologies such as big data analytics to increase data visibility and investigate the root causes

Table 2
Summary of Industry 4.0 solutions that match LM tools/practices

		Industry 4.0 solutions	LM practices	Contributions
CPS	(1)	– CPS – Sensors/RFID – Big Data Analytics – Vertical/Horizontal integration	– Heijunka – JIT – Kanban	– Deliver traceability – Processes' reliability – Increased efficiency – Reduction of warehouse space
	(2)	– CPS – IoT – Sensors – PLC – MES	– Performance's equipment – Statistical Process Control	– Improved equipment's performance – Predictive maintenance – Increased production efficiency – Enhanced quality – Reduced defect waste
Simulation	(3)	– Artificial Neural Networks (ANN)/AI	– Production scheduling and planning – Pull production	– Maximized usage of workstations – Decreased stock levels – Increased productivity – Reduced delivery time
Big Data Analytics/ Data Mining	(4)	– Big Data Analytics – IoT	– Six Sigma – Standardization – Customer involvement – Continuous improvement	– Reduced wastes of waiting – Enhanced customer experience
	(5)	– Data mining – RFID – ERP – Vertical Integration	– VSM – Waste reduction	– Traceability – Greater connectivity – Improved decision-making process
HMI	(6)	– HMI – CPS – QR code – Vertical integration	– 5S – JIT – VSM	– Traceability – Improved flow of information – Decreased waste of defects and extra processing – Reduced cycle time

of common problems in the healthcare service. By integrating Industry 4.0 technologies with Six Sigma methodology and LM approach, the flow of information and resources could be optimized, which reduced the waste of waiting. In addition, the possibility to access and analyze real-time data allowed the continuous improvement of the whole process as well as enhanced customer experience. The apparel company (case 5) used data mining, RFID and ERP to allow vertical integration and reduce the gap of information. These solutions were implemented along with a VSM tool, in order to identify wastes and support the decision-making process. Finally, the machine manufacturing industry (case 6), developed an ergonomic human-machine interface to support employees in receiving, transmitting, and documenting the correct information. Once employees play an important role in the acceptance and the implementation of any technological change, user-friendly technologies are critical to empowering employees, enabling them to perform their roles more efficiently.

The result was a significant reduction in important sources of waste, such as defects and extra processing and the overall cycle time. In addition, the best practice procedure can be used by other SMEs to develop their own production application, in order to connect production and business departments and share relevant information.

Conclusions

This study carried out a comprehensive literature review regarding the synergic relationship between Lean Management and Industry 4.0. The analyzed documents revealed that, despite this research topic has grown over the last few years, studies that show best practices of LM-Industry 4.0 integration are still missing in the literature. In this context, as the implementation of Industry 4.0 will affect traditional manufacturing practices that are typically related to LM,

it seems important to investigate how the new technologies can be integrated into existing production systems.

The results have shown that Industry 4.0 solutions are enabled to match the well-established LM practices in a variety of ways. Particularly regarding the LM-Industry 4.0 solutions presented, most of them favor technologies that improve traceability (e.g. sensors and RFID) in order to identify and eliminate critical sources of waste, such as waiting, extra-processing, defects, and stocks. In addition, the increase in real-time data exploration through the use of data mining, big data analytics and IoT has allowed equipment, products, and processes to be better monitored and controlled, reducing the risk of failure. Therefore, in all cases – no matter whether large corporations or SMEs – data and connectivity were decisive competitive advantages.

This study contributes to theory by intensifying the debate on LM-Industry 4.0 integration. Hereby, an attractive direction for future research could be to investigate the role of soft Lean practices in facilitating Industry 4.0 implementation, for example in terms of their contribution to creating openness orientation, and to promoting autonomy and team working. There is also a need for additional empirical studies that take into account the particular situation of SMEs. SMEs often lack expertise and have less resources to invest in new technologies than large corporations (Moeuf et al., 2020; Mittal et al., 2018), therefore, this group of industries certainly deserves more attention. Thus, with more studies exploring best practices in SMEs, they could be more willing to take the first steps to transform its operations through Industry 4.0.

This study also contributes to practice, as it provides insights for practitioners on how to improve the effectiveness of their systems. Furthermore, it can also be useful for companies seeking to redesign their business strategy and adopt new business models in order to target new markets prospects and gain competitive advantage.

This paper has however two main limitations. The first limitation concerns the exploratory character of the research design. Despite exploratory studies being extremely important to deepen the knowledge in new research areas, empirical studies are critical to the improvement and assessment of existing theories, adding credibility. The second limitation is that the initial search of the study was limited to papers published between 2015 and 2018. However, in order to reduce this constraint, more recent and relevant documents suggested by experts in the field and scientific websites were used for further analysis.

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