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How Industry 4.0 Can Enhance Lean Practices

The global industrial landscape has deeply changed over the last few years and the Industry 4.0 concept has emerged, being enabled by successive disruptive innovations and technological development that have transformed manufacturing processes. This concept is being pointed out as the fourth industrial revolution that embraces a set of new technologies that are shaping the future manufacturing vision. However, Lean Production is a widely used manufacturing approach that brings several benefits to organizations. Despite the integration between Industry 4.0 and Lean Production is being researched in the recent years, the impacts that result from the implementation of new technologies in established lean practices is not clear. The purpose of this study that consists in a systematic literature review is assessing how these emerging disruptive technologies can enhance lean practices and analyse their impacts and benefits for organizations that are moving towards this new industrial paradigm.

Keywords: *Industry 4.0; Fourth industrial revolution; Lean production; Lean practices; Technology*

1. INTRODUCTION

In the last few years, many new global concepts have emerged, due to disruptive advancements in manufacturing processes and technology. Industry 4.0 (I4.0), or the so-called fourth industrial revolution, is one of these concepts, being a new industrial paradigm that embraces a set of new technologies and holds an enormous potential for organizations. On the other hand, Lean Production is an approach widely used in manufacturing for decades, whose main aim is reducing wastes and improving productivity, while meeting customer's requirements.

The integration between I4.0 and lean production has been researched in the recent years by academics and companies, however, despite numerous studies approaching the integration between these two topics, the potential of each I4.0 technology in lean practices and tools is not clear. The purpose of this paper is the comprehensive understanding about how technologies enabled by I4.0 can enhance and potentiate lean practices, analysing the impacts and opportunities of the integration between these two domains. For this purpose, a systematic literature review has been carried out, in order to identify relevant studies that analyse the relationship between I4.0 technologies and lean practices, assessing which lean tools can be enhanced and improved by the implementation of each disruptive technology enabled by the fourth industrial revolution.

This paper is structured into six main sections. After this introduction, section 2 provides the background of this study, with a comprehensive definition about I4.0 and Lean Production, which are the two main topics that are approached in this study. In section 3, the research methodology is explained and section 4 presents the main findings about the impact of I4.0 on lean practices. The previous related studies are analysed in section 5 and, lastly, in section 6 a critical analysis is provided, while the main conclusions are drawn.

2. BACKGROUND

This section introduces briefly the background of the two main topics studied in this paper: I4.0 and Lean Production.

2.1 Industry 4.0

Over the last years, the global industrial landscape has deeply changed due to the emergence of several disruptive technologies that have resulted from successive developments and innovations. Consequently, with growing advancements in manufacturing processes, the I4.0 concept has emerged, becoming an increasingly relevant global topic in the last few years. This term was firstly presented in 2011, in an article published by German government regarding an initiative about high-tech strategy for 2020 [1].

I4.0 is the so-called fourth industrial revolution and can be compared with the last three industrial revolutions that have emerged over the last centuries, that have brought relevant changes in manufacturing due to disruptive technological advances [2]. The first industrial revolution, in the middle of the 18th century, was enabled by the use of steam and waterpower, while the second industrial revolution that emerged during the second half of 19th century was characterized by mass production and the replacement of steam power by electricity. In the last years of 20th century, the use of computers, electronics and Information Technology have triggered the third industrial revolution [3], [4].

The emerging fourth industrial revolution is being shaped by the integration of Cyber-Physical Systems

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(CPS) and Internet of Things (IoT) in industrial processes [5]. This new industrial paradigm will bring together the digital and physical worlds through the use of CPS technology, allowing the improvement of productivity and efficiency among the companies that are adopting this new manufacturing paradigm [1].

This concept is an umbrella term that embraces a set of future technological developments regarding CPS, IoT, Big Data, Cloud Manufacturing, Augmented Reality (AR) and Robotics [6]. The adoption of these technologies is crucial to the development of intelligent manufacturing processes, including smart devices, machines and product that are able to autonomously exchange information, trigger actions and control each other [7,8].

I4.0 is a complex technological system that has been widely discussed and researched by academics and companies in recent years, holding a huge potential to greatly influence the industrial sector and bringing several economic and social opportunities through the paradigm shift regarding to work organization, business models and production technology [5]. Furthermore, this emerging industrial revolution, besides the transformation in manufacturing, will have a great impact in many other areas, such as, products and services, new business models and markets, economy, work environment and skills development [6].

2.2 Lean Production

The oil crisis in 1973 had a huge impact on the global economy and even in Japan the economy broke down in 1974 resulting in zero growth. Amazingly the Toyota Motor Company had higher profits compared to other companies in Japan, Europe and USA. This increasing gap between Toyota and the other companies made managers and market expert curious of what Toyota was actually doing different from other companies [9]. This is probably the reason why the first time Toyota Production System (TPS) was referred in English in a scientific journal only in 1977 [10], although existing since the 50´s. In their article, the TPS was described as being focused in the following two main concepts: (1) the reduction of costs through the reduction of waste and (2) treat workers as human beings and with consideration. This second concept did not attract much attention by western companies. The TPS as referred by Ohno [11] and Monden [12] and many others, although being a completely new approach to production, only some of its dimension attract attention in the beginning. Waste reduction and in particular the Just-In-Time (JIT) concept (referred as one of the two pillars of TPS by Ohno [11]) and materialized in the Kanban technique, was the first TPS concept gaining considerable attention by academics and professionals in the western world. In the 80´s TPS was frequently referred to as "Just in Time" [13] and the term "Lean Production", so popular now, was coined by the first time by Krafcik [14]. The "Lean" was used as the analogy that can be made between the systematic reduction of waste that was recognized in the factories applying the TPS approach and the reduction of fat necessary for a person to become leaner. The book "The machine that changed the world" [15] is pointed out as being responsible for the popularization of the term "Lean" frequently used everywhere to classify any production approach that is inspired by TPS. Lean has been gaining reputation for making a positive impact in manufacturing systems, meeting costumer's requirements, while supporting the increasing efficiency and performance based on incremental continuous improvements [16]. However, nowadays the use of "Lean" approaches can be found not only in industry but in any activity sector such as services, construction, healthcare and education [17].

3. RESEARCH METHODOLOGY

In order to understand the influence of I4.0 technologies in Lean practices, a systematic literature review has been carried following the set of phases identified by Moher et al. [18]. The papers have been identified and selected following the defined inclusion and exclusion criteria. These phases are described in the following sections.

3.1 Identification of Papers

In order to cover a wider range of journals and scientific documents, the literature review was conducted considering the following electronic databases: Scopus and Web of Science.

This review has been orientated towards the application of technologies that are enabled by I4.0 can enhance Lean practices. Furthermore, the purpose of this study can be categorized into two main objectives: (1) understanding the relationship between the so-called fourth industrial revolution – often referred as Industry 4.0 or Industrie 4.0 – and lean and (2) assessing how the application of these technologies can improve Lean practices and tools.

Table 1. Search strings

Search Strings	Results
#1: (("industry 4.0" OR "industrie 4.0") AND ("lean manufacturing" OR "lean production" OR "lean thinking" OR "lean management"))	102
#2: (("industry 4.0" OR "industrie 4.0") AND (vsm OR "value stream mapping" OR "standard work" OR "standardized work" OR "continuous improvement" OR kaizen OR smed OR "single minute exchange of die" OR andon OR (levelling AND lean) OR heijunka OR "visual management" OR (5s AND lean) OR poka-yoke OR "pull production" OR "cellular manufacturing" OR autonomation OR jidoka OR kanban OR e-kanban OR ekanban OR jit OR just-in-time OR "just in time" OR "production supermarket" OR mizusumashi OR milkrun OR milk-run OR "production flow" OR "problem solving" OR problem-solving OR kpi OR "key performance indicators" OR kobetsu OR kamishibai OR kaikaku OR "hoshin kanri" OR hoshin-kanri OR "daily management" OR "daily meeting" OR (lean AND people) OR "team work" OR tpm OR "total productive maintenance"))	128
Total	230

The selected keywords and search terms have resulted from the above-mentioned objective, in order to relate I4.0 with Lean. Moreover, based on two main objectives of this work, two different search strings based on Boolean Logic have been constructed and are summarized in Table 1.

The number of collected studies from each database and search string is presented in Table 2.

Table 2. Search results

Databases	#1	#2	Total
Scopus	81	105	186
Web of Science	21	23	44
Total	102	128	230

3.2 Selection of Relevant Papers

The selection process has included several screening procedures, following three phases: (1) Duplicates removal, (2) inclusion and exclusion criteria and, finally, (3) relevance screening.

The research has resulted in a total of 230 records identified through database searching. The first phase consisted in duplicates removal, which resulted in 186 records.

In the second phase, exclusion and inclusion criteria have been defined. Firstly, the title, abstracts and keywords of these records have been scanned in order to assess the relationship with the topic and 14 records have been excluded due to this reason. Furthermore, only studies available in English have been included, which led to the exclusion of 27 records that were not available in this language, resulting in 145 records. The last exclusion criterion was the non-availability of the full-text, which means that only 124 full-text articles have been included in the third phase.

The third and last screening phase consisted in the assessment of articles' eligibility, based on their relevance to this work. Firstly, only articles that show the relationship between I4.0 and lean have been considered. Furthermore, the articles that do not study a specific I4.0 technology and its impacts on lean practices have been excluded. Figure 1 shows a diagram that describes the inclusion and exclusion criteria, as well as, the screening phases, which have resulted in a total of 54 relevant studies that have been included in systematic literature review.

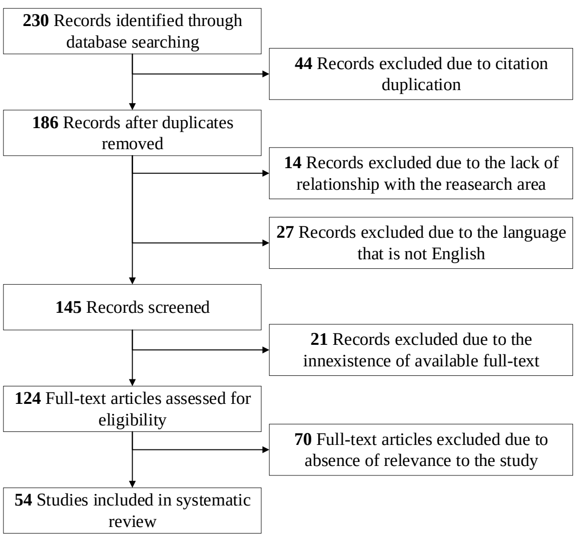

Figure 1. Definition of the final sample by applying the exclusion criteria

The relevant studies that have been included in this work consist in 25 journal articles and 29 papers in conference proceedings that have been collected from two databases: Scopus and Web of Science (Table 3).

Table 3. Databases and type of publications

Databases	Journal	Proceedings	Total
Scopus	25	24	49
Web of Science	0	5	5
Total	25	29	54

The selected records were published between 2015 and 2018 and the country that holds the biggest number of relevant publications is Germany, with a total of 21 records. Five of the relevant records have been published in Italy, while Brazil, Portugal and Austria have three records each.

4. MAIN FINDINGS

This chapter presents relevant findings about the relationship between the implementation of disruptive technologies enabled by I4.0 and lean. The purpose of this work is to assess, through the analysis of selected relevant studies, how these technologies can enhance Lean practices in the I4.0 environment.

According to Pereira and Romero [6], the main technologies enabled by the so-called fourth industrial revolution are CPS, IoT, Big Data, Cloud Manufacturing, AR and Robotics. This study relies on these technologies and their potential to enable Lean tools and practices. However, there are other technologies that have been often related with I4.0 by several authors in the studies included in the systematic review that are analyzed in the last section of this chapter.

4.1 Lean Production Enhanced by Cyber-Physical Systems

Davies et al. [19] argue that Lean and Six Sigma capabilities can be potentially enhanced by I4.0 technologies, in particular, through CPS networks that enable access to real-time operational data. The CPS-supported real-time data allows the improvement of several Lean practices, such as automatic orders processing and inventory level control through e-kanbans. Furthermore, production surveillance can be ensured through the use of smart devices that automatically capture Key Performance Indicators (KPI) and collect relevant data and information about equipment to anticipate production problems. Regarding to Total Productive Maintenance (TPM), CPS are able to collect data about maintenance needs and automatically send signals to maintenance staff. The real-time collected data can be stored and further used for continuous improvement implementation.

Müller et al. [20] propose a computerized production solution that aims to install CPS along the value chain in order to digitalize the information sharing between shop floor and business departments, achieving more responsive, optimized and leaner processes. This solution supports employees with recording and communication of changes about components and technical drawing, which allows the reduction of projects overall cycle time, decreasing the number of errors and increasing of departments' capacity, which allows the achievement of better customer satisfaction

Regarding the creation of more transparent processes and more responsive and leaner production systems through the improvement of information sharing, the previous authors [21] have proposed another solution that consisted in upgrading existing material shuttles through CPS technology. These smart material shuttles that combine CPS with Radio-Frequency Identification (RFID) technology are able to collect relevant information about inventory, location, identification, networking, man-machine interface and information processing, providing this information to production management through a Manufacturing-Executive System (MES).

Kolberg and Zühlke [22] support that I4.0 can be integrated in Lean Production and the last one can be improved by the emerging technologies. In this context, the authors have introduced the term Lean Automation, a new concept to describe the application of I4.0 technologies with Lean Production in order to combine benefits from both domains. Several examples of possible combination between these two domains have been provided and, regarding the use of CPS, one of the possibilities is the use of CPS-based smart devices that allow operators to receive error messages in real time. This approach consists in an Andon method that notifies the operator as soon as possible in case of failure, triggering repair actions and reducing delay times due to failure occurrences. A flexible kanban production scheduling is another possibility enabled by Lean Automation, which consists in the digitalization of the Kanban system within a smart factory, where smart products contain information about kanbans and production process in order to realize an order-oriented production, while machines interact with them, establishing an interface for receiving and sending kanbans. Furthermore, smart machines send failure information to operators and trigger repair actions. The smart planner optimizes processes, reconfiguring production lines and updating kanbans in real-time, based on changes, while CPS-based devices provide information about cycle times to operators via AR technology, in order to perform JIT tasks.

Hofmann et al. [23] present a work with the purpose of identifying the implications of I4.0 in logistics management area, concerning to JIT systems and Kanbans. The use of CPS based solutions can bring opportunities regarding to decentralization, self-regulation and efficiency. With respect to JIT systems, a reduced bullwhip effect, improved production planning and a more transparent and integrated supply chain can be expected with the integration of I4.0. Regarding kanbans, CPS solutions can reduce cycle times. Generally, I4.0 integration provides real-time information flow, flexibility and optimized value-creation.

The Lean Intelligent Production System concept is proposed by Wang et al. [24], whose aim is improving production efficiency and reducing wastes. In a pull production environment, supermarkets and kanbans are key lean practices and CPS technology is used to enable the transmission of the information contained in kanbans through sensors that send signal to Enterprise Resource Planning (ERP) system, which allows the achievement of JIT production, meeting the customer's' requirements. A use case of a cyber-physical JIT delivery application is presented by Wagner et al. [25], showing the improvement of lean processes through the use of I4.0 technologies that have been selected using an impact matrix that depicts the impacts of I4.0 on Lean Production Systems. Regarding JIT processes, beyond the use of CPS, according to the matrix, the highest impact is supported by Big Data technology and data analytics. The use case consisted in the replacement of Kanban cards by an integrated solution that provides information flow within the whole supply chain and the standardization of ID labels. With this solution, every material is detected by sensors and relevant real-time data is transferred to system, providing a continuous data flow that generates KPI, and an active decision support, increasing the level of traceability and process reliability, eliminating stock and minimizing warehouse space.

An interface for digitalizing Lean Production methods using CPS has been presented by Kolberg and Zühlke [26], which consists in a unified communication interface that allows a higher level of changeableness in Lean Production for workstations. This means that the interface increases the flexibility of workstations, supporting a fast and easy installation and enabling their integration into workflows and with other new third-party applications. Moreover, Ma et al. [27] proposed an integrated and standardized approach to design and implement a CPS-based smart Jidoka system, which has been considered a cost-efficient and effective solution regarding flexibility improvement, ensuring system standardization, changeability and modularization. This system is mainly based on CPS technology, however the use of Cloud and IoT technologies allows the data collection of resources, ensuring the flexible configuration, deployment and performance of Jidoka system.

Regarding the autonomous generation of KPI on CPS technology environment, several methodologies have been proposed. Shafiq et al. [28] presented a model that gathers raw data at machine level and converts it into relevant information using CPS. The collected information is analysed by the system that provides KPI visualization. Moreover, based on collected information, this system enables dynamic changes and triggers actions, which facilitates the decision-making process. On the other hand, Samir et al. [29] describes a case study that consists in data acquisition through CPS technology for the purpose of extracting KPI. The advantage of a CPS environment relies on the use of sensors and actuators to collect data.

Pisching et al. [30] had proposed an architecture based on Reference Architecture Model 4.0 that is used to find and select the most suitable equipment to process operations according to the requirements of each product during manufacturing process. This architecture is supported by CPS and IoT technologies and contributes for smart production and the development of digital manufacturing systems, where each product is processed individually, meeting one of the main I4.0 features: Mass customization and on-demand production abased on customer requirements.

Blunck et al. [31] presented a framework supported by CPS, where intelligent agents in a manufacturing system make autonomous decisions about their routes with the objective of reducing their own throughput time on capacity design process. These decisions are based on capacity allocation and decisions of all other agents, creating a feedback between flow and capacity, proving a higher flexibility and an optimal allocation of production capacity.

A management portfolio matrix for assessing the optimal collaboration between human and Cyber-Physical production Systems (CPPS) is proposed by Ansari and Seidenberg [32]. These authors discussed the complementarity between these two elements, providing five criteria for the comparison between them in I4.0 context, namely, cost, flexibility, capacity and quality. It was concluded that the interaction of human and CPPS in smart factories during problem-solving procedures allows the knowledge sharing and reciprocal learning, which characterizes the optimal collaboration between them.

4.2 Internet of Things and Industrial Internet of Things in Lean Environments

Jayaram [33] proposed a global logistics model for transportation that follows Lean Six Sigma approach. The combination of this approach with Industrial Internet of Things (IIoT) technology and I4.0 allows a fully autonomous global supply chain, with an optimized process flow, increased overall efficiency and free from defects. The proposed model allows the IIoT-supported network communication between production and supply chain, providing real-time data regarding operations and machines. Using the available data, it is possible to optimize processes, increase gains and reduce costs and resource consumption, while the model monitors the enterprise, predicting changes and taking autonomous actions itself. Furthermore, the introduction of IoT technology holds a huge potential in the field of providing real-time data to be analysed, eliminating the need for human intervention [34].

A management system called MAESTRI was proposed by Ferrera et al. [35]. This system is supported by an IoT infrastructure to support easy integration and data exchange among shop-floor, business systems and tools, which target is based on continuous improvement, efficiency assessment and optimization to decision support, gaining value from waste. Using IoT technology, this system is able to interchange data between machines, systems, and sensors to end user software tools and applications at the industrial sites.

Xu and Chen [36] proposed a framework to support dynamic production planning and scheduling in a JIT production system. This framework is able to react to dynamic changes regarding orders, production and available resources, allowing the users to adjust schedules during production in order to maximize productivity.

4.3 Big Data and Data Analytics Role for Lean Tools Enhancement

Meudt et al. [37] proposed a new approach that consists in an upgraded Value Stream Mapping (VSM) that allows companies to understand the opportunities that are emerging with digitalization and I4.0. These authors have introduced the concept of VSM 4.0, a method that is focused on data collection, handling, storage and utilization of information and KPI generation. This project focused on waste reduction, as well as, a comprehensive understanding about every information and material flow within logistic processes, while the analysis of calculated KPI have allowed the process improvement and production digitalization.

Similar to the previous authors, Lugert et al. [38] and Wagner et al. [39] supported the potential of using Big Data technology for improving VSM procedures. A dynamic VSM is an innovative approach that has been proposed, which the main focus is optimizing the value stream through the use of data analytics, simulation and a user interface that allows the real-time visualization of results using RFID technology, which enables process improvements and increases employees involvement [38]. One of the previous authors, Lugert et al. [40], carried out an empirical survey that relates Lean Management, VSM and I4.0 topics. The main aim was understanding the integration of these approaches in different industrial branches, evaluating the current status of VSM from the user's point of view. This paper emphasizes the implementation of VSM supported by I4.0 technologies, combining this lean tool with automated data analytics supported by the use of real-time data and simulation. Furthermore, the majority of the participants considers that the static VSM has to be further developed to a dynamic VSM through digitalization technologies that include an integrated data model and optimization tools, which allow quicker and more flexible reaction to unexpected changes. Based on the proposed Lean Intelligent Production System, Wang et al. [24] implemented a value stream analysis and design, implementing a FIFO logic that is able to determine the safety inventory, based on Big Data model that collects information from the products and their attributes of process.

On the other hand, a used case in automotive electronics production has demonstrated that I4.0 technologies have high potential into industrial value streams, using elements of design thinking. The identified problem has been the missing traceability for shop floor KPI reporting process and data analytics has been crucial for live data acquisition from all lines in the production network supported by a cloud solution [39]. Regarding KPI generation, Rauch et al. [41] supported that the combination of data analytics and cloud technologies during product development processes provides real-time KPI and improves data processing, reducing waiting and operation times during product development. Furthermore, the standardized data formats can decrease inefficiencies due to excessive and obsolete information, allowing real-time data exchange and promoting the involvement of the whole development team. Arcidiacono and Pieroni [34] focused their study on Six Sigma and presented a methodology called Six Sigma 4.0. This methodology relies on real-time data collection applied to HealthCare context, in order to optimize services processes, reducing the wastes regarding human and material resources, while improving the Quality of

Experience perceived by the patients and reducing costs. Using Big Data to collect and analyse data in real-time, it is possible to improve process efficiency and provide more effective performance measurement, in order to enhance Six Sigma tools.

A tailor-made management system that has been designed to deal with the high volume of data a company deliver to their customers is the focus of the work developed by Astola et al. [42]. The system is supported by Big Data technology and shares real-time information directly in customer's information system, reducing communication times and costs and increasing efficiency and value added for costumer.

Neuböck and Schrefl [43] emphasized the importance of business intelligence methods and data analytics in I4.0 context in order to improve processes and enhance problem-solving techniques in critical situations. Moreover, Karlovits [44] suggested that problem-solving methods hold a huge potential for production efficiency and companies should implement network solutions based on Big Data, data mining and analytics techniques for process improvement.

Kassner et al. [45] presented an IT architecture for data driven manufacturing that intends to address the weaknesses of traditional manufacturing IT and implement the data-driven factory in I4.0 context. The developed solution has a strong focus on data collection, storage and analytics, as well as, on the empowerment of human workers through mobile information provisioning that actively integrates them in smart manufacturing environment, promoting quality, process management and continuous improvement through the whole product life cycle.

4.4 Cloud Manufacturing to Reduce Wastes

A cloud computing-based application able to process inputs for electronic work instructions creation and standard work generation has been developed by Silva et al. [46]. The application relies on I4.0 principles and allows real-time access of information and integration with other computational systems within the company, being able to automatically create work instructions and generate an optimal standard work based on operation description, sequences, production times, assembly lines and assigned products. This kind of project was also reported by Pereira et al. [47] and Abreu et al. [48].

Ogu et al. [49] presented a study that relies on the potential of integrating cognizant computing and Lean practices in order to ensure business success. Cognisant computing provides real-time databases that are mainly supported by cloud computing and powered by IoT technologies. The authors argue that cognizant computing can enhance lean practices through the elimination of wastes, providing several benefits in lean manufacturing context. The identified benefits are related with increased financial savings and returns, reduction in lead-times, inventory volumes, process wastes and less rework. Furthermore, this technology can provide a better understanding about production processes, tasks and needs of customers. The available real-time information provided by cognizant computing will allow managers and executives to make better decisions, reducing wastage, minimizing business risks and ensuring a better customer satisfaction.

Concerning to product development processes, the implementation of cloud manufacturing can be very useful, reducing the wastes that result from wrong sent information or disconnected users [41].

Mayr et al. [50] introduced the concept of Lean 4.0 as the combination of Lean Management and I4.0, presenting a use case that exemplifies how cloud computing and machine learning-based condition monitoring can enhance TPM. According to the authors, these technologies have enabled the improvement of production, reducing machines downtime, scrap and rework, increasing quality, while proving maintenance data to workers and dynamically scheduling maintenance activities.

4.5 Virtual and Augmented Reality to Virtualize Lean Tools

Virtual Reality (VR) technology can be combined with CPS networks that provide real-time data in order to create virtual VSM, which is one of the core lean practices. The virtual VSM allows every stakeholder to be immersed in a virtual model, observing and mapping current and future state of processes, without the need of understanding the conventional VSM symbols [19].

Kolberg and Zühlke [22], the authors that have firstly introduced the Lean Automation concept, presented an approach that consisted in the use of AR and CPS-based wearable devices that provide information to operators about cycle time and tasks to perform via AR, in order to support JIT production. Furthermore, the wearable devices are able to receive failure information and display it in real-time to operators.

Pfeffer et al. [51] argued that plant control will deeply change due to the emergence of disruptive technologies. Regarding to problem-solving processes, VR and AR technologies can enhance efficiency and performance, providing additional real-time information. Moreover, these technologies have the ability to represent a product true to scale, improving development activities and making processes more intuitive. Rauch et al. [41] also supported that visualization technologies hold a huge potential regarding the decreasing of failures and mitigating its impacts during product development procedures. Furthermore, these visualization technologies allow the examination of hazardous situations, maintenance and training scenarios, holding a huge potential to completely change and revolutionize the way humans work and communicate [51].

4.6 Autonomous and Collaborative Robotics for Cooperative and Flexibility Manufacturing Systems

Müller et al. [52] presented a project that addresses the cooperative relationship between humans and technology that is being enhanced by I4.0 framework. The coexistence of machines like robots and humans consists in hybrid workplaces which bring new challenges regarding to work analysis. These authors give an overview about several standardized work analysis methods that can be used in production. However, most of these approaches do not consider the interaction and communication between human and robots, and authors argue that and adaptation of conventional methods in order to be suitable for analyzing hybrid production workplaces is required in I4.0 context, considering every aspect, such as communication interface, robotic system control, social structures and individual consequences.

Several authors argue that the implementation of autonomous robots increases the flexibility of manufacturing systems. A distributed approach for a fleet of autonomous robots to perform transportation tasks is proposed by Lutz et al. [53]. The system is able to work with flexible production flows and fast changing environments, responding to unpredictable changes and providing an efficient, reliable and predictable path-based navigation. However, robots are flexible enough to fast react to obstacles and persons, avoiding them and blocking their way, meeting the safety challenges of service robot fleets.

A measurement-aided welding cell is described by Tuominen [54] with the aim of satisfying the increasing demand of flexible and reconfigurable manufacturing systems in welding process. The proposed system is supported by collaborative robots and its main operating principle is the reconfigurable real-time measurement, which allows the users to change instantly between manufactured products, increasing production capacity, decreasing set-up times and investment costs and allowing the capacity adjustment and the production of small batches in a single manufacturing system. Also about intelligent metrology, Durakbasa [55] pointed out sensor technology and robotics as the two main elements for the implementation of autonomation concepts in I4.0 framework. The author supports that Multifunction Intelligent Measurement Robots allow the flexible implementation of autonomation in process control and quality assurance.

4.7 Other Referred Technologies and Their Impact on Lean

In this section, a set of technologies that are pointed out in the studies included in this systematic review as disruptive tools enabled by I4.0 are analyzed, as well as their impact on Lean practices.

4.7.1 3D Printing

Chen and Lin [56] presented a discussion about 3D printing technology, focusing on the technical challenges that must be addressed before its implementation and the main managerial concerns that can influence the cost effectiveness of manufacturing systems. The authors have concluded that 3D printing technology facilitates the achievement of lean manufacturing principles, pointing as main benefit the small batches production, since this technology allows a print-on-demand production systems, which eliminates inventory and promotes pull systems. Furthermore, this technology allows JIT manufacturing, decreasing the lead times and enhancing logistics efficiency, since 3D printers can be installed near customer's location, in order to reduce distance and delivery costs. Regarding human factors, with 3D printing implementation, more tasks are performed by machines, which reduces wastes related with overburden or unevenness workload, improving employees' well-being and releasing them to focus on continuous improvement processes.

Rauch et al. [41] supported that the use of additive manufacturing technologies, such as 3D Printing, potentiates smart product development processes, improving their efficiency, while Wang et al. [24] argue that this technology is useful to produce complex parts, which cuts down setup times, enabling the one-piece flow production.

4.7.1.1 Simulation and Digital Twin

The use of simulation technologies can be very useful for analyzing and reconfiguring production systems. However, these practices can be enhanced by 3D laser scanning in order to capture and digitalize spatial data, proving information to simulation models. Nåfors et al. [57] propose a simulation model supported by 3D scanning and VSM, which facilitates the understanding about an existing production system and increases the flexibility regarding when designing a new production system. Furthermore, Mayr et al. [50] argued that digital twin concept supported by simulation technologies enables dynamic VSM, through the real-time replication of the whole manufacturing system, allowing the access to updated information as well as a more predictable and reliable planning.

Krenczyk et al. [58] presented an approach based on simulation models and heuristic for balancing of mixed and multi model assembly lines. The authors argue that this solution is an efficient and effective tool for planning, control, as well as for ensuring a correct reconfiguration of manufacturing resources and production flow.

On the other hand, Kukushkin et al. [59] described a new concept for scheduling analysis of production lines that consists in a simulation model. The developed model allows the automatic generation of KPI and the establishment of optimal production strategies. Furthermore, a simulation-based real-time solution for production planning has been described by Dallasega et al. [60] that resulted in a drastic reduction of the inventory levels on manufacturing environment through the achievement of production on-demand and JIT delivery of components.

Ferro et al. [61] carried out a survey with the aim of analyzing the integration of Discrete Event Simulation in operations management tools, such as, MES, ERP, RFID, core manufacturing simulation data and e-Kanban. The authors argue that these tools should be simultaneously used in order to solve problems related with operations and manufacturing systems. A simulation based tool that allows the assessment of the impact of new logistics solutions and identifying the best transportation scheduling has been developed by Campos et al. [62]. This solution has increased vehicle utilization, productivity and efficiency, providing flexibility to rapidly reconfigure logistic system and optimizing the material flows.

4.7.1.2 Video-based Models and 3D Models

Bauters et al.[63] focused their work on a video-based system for automatically analyze manual assembly work tasks through a 3D-model. This system captures information about the way tasks are performed by the operator, being able to detect anomalous events that are linked with video data for further analysis. Based on this, the system is able to detect best practices and generate event list enriched with video data and KPI to analyze the operator's performance. The collected information is useful for continuous improvement processes and the identified best practices are used for standard work instructions and information sharing within the company.

4.7.1.3 Optimization Algorithms

Regarding the use of I4.0 technologies to enhance standard work, Gomes et al. [64] presented an Ambient Intelligent decision support system development that intends to improve the creation and planning of Standard Work procedures, as well as to support the elaboration of Work Instructions. This tool aims to address Lean thing principles in the context of I4.0 framework, using ambient intelligence, optimization heuristics and machine learning. The main purposes of this decision support system consisted in process automation, real-time data updates, implementation of electronic Work Instructions, provide analytical support in the decision-making process and apply ambient intelligence approaches that allows complex analysis and learning, in order to respond to dynamic environments.

Moreover, several authors present optimization approaches that intend to enhance problem-solving and decision-making procedures. Legat and Vogel-Heuser [65] proposed an approach for order planning, based on artificial intelligence and supported by linear programming and optimization techniques, concluding that the proposed approach facilitates efficient problem-solving regarding planning procedures. On the other hand, Teschemacher and Reinhart [66] described an ant colony optimization that has been applied to solve milk-run logistic problems regarding routes planning in manufacturing systems where high flexibility is required. This approach has proven its potentials in vehicle routing problems, being able to operate in real-time, reducing the number of vehicles and increasing the systems flexibility to respond to unexpected changes.

5. OTHER RELATED STUDIES

In the past few years, several authors have studied the relationship between I4.0 technologies and lean practices, as well as the potential of integrating these domains and the synergies related with this relationship. The recent integration between lean practices and technologies enabled by I4.0 has been firstly referred as Lean Automation by Kolberg and Zühlke [22].

Buer et al. [67] presented a literature review that identifies the relationship between I4.0 and lean, categorizing these relationship into four different frameworks: (1) I4.0 technologies supports lean manufacturing practices, (2) lean manufacturing supports I4.0, (3) the integration of I4.0 and lean manufacturing affects the systems' performance and (4) environmental factors influence the potential to integrate I4.0 and lean manufacturing. However, the authors have identified several research gaps, proposing further research regarding the impact of I4.0 on lean practices, the facilitating effect of lean manufacturing on I4.0 implementation and the implication of these both domains integration. Furthermore, gaps have been identified in the field of environmental factors effects on the above-mentioned integration, as well as regarding implementation frameworks for moving toward that.

Regarding the relationship between I4.0 and lean production, Dombrowski et al. [68] carried out a literature review that sorts their interdependencies into four domains: (1) Lean as basis of I4.0, (2) I4.0 completes lean, (3) I4.0 increases lean efficiency and (4) lean principles are changing. Moreover, these authors consider that synergies between I4.0 and lean found in the existing literature can be structured into two perspectives: (1) Lean as enabler towards I4.0 and (2) I4.0 advances lean systems. On the other hand, Mayr et al. [50] went further than the previous authors and, after introducing the concept of Lean 4.0 and studied how I4.0 can support specific lean tools, have outlined three different perspectives regarding the integration between I4.0 technologies and lean based on existing literature: (1) Lean management enables I4.0, (2) I4.0 advances lean management and (3) positive correlation between lean management and I4.0.

The correlation between lean manufacturing and I4.0 is also studied by Sanders et al. [69], that summarize ten dimensions of lean manufacturing, grouped into four domains: (1) Supplier, (2) customer, (3) process and control and (4) human factors. The authors discuss how the technologies and concepts enabled by I4.0 can enhance these dimensions, overcoming the challenges in lean implementation and it has been concluded that the integration of I4.0 can solve the issues associated with lean implementation within the four domains. Furthermore, companies that integrate digitalized processes with a lean based structure have the potential to expand itself, becoming leaner, cost-effective and waste-free. The findings of Tortorella and Fettermann [70] are similar, since they argue that lean practices are positively associated with technologies enabled by I4.0, leading to a performance increasing. These authors have studied the relationship between lean practices and I4.0 implementation through a survey which has been carried out with 110 Brazilian companies.

Sanders et al. [71] argued that the concept of lean management will become more important for a successful implementation of I4.0. Furthermore, an interdependence matrix that explains the co-existence of lean practices and I4.0 design principles is presented, proving numerous synergies between them. These authors have concluded that the introduction of I4.0 principles like real-time capability, decentralization and interoperability holds a high potential to lean tools. On the other hand, the use of several lean practices, such as TPM, Kanban, autonomation, heijunka and waste elimination can be highly enhanced by the implementation of I4.0 technologies, while concepts like takt time will no longer be used in smart factories. Mrugalska and Wyrwicka [72] also supported that I4.0 and lean approaches can complement each other, proving several case studies found in existing literature that addresses the integration between them. This is supported by the systematic literature review developed by Bittencourt et al. [73].

A theoretical model has been developed by Mora et al. [74] in order to integrate lean and smart manufacturing dimensions. These authors argue that the combination of I4.0 technologies enables a smart manufacturing system that consists in five main components: smart product, smart operator, smart machine, smart workstation and smart planner. Regarding Lean Production, four Lean bundles have been identified: JIT, Total Quality Management (TQM), TPM and Human Resources Management (HRM). The proposed model has proven that the implementation of I4.0 solutions can lead the enhancement of lean benefits and synergies between these two paradigms can be applied to achieve a better performance.

On the other hand, while the relationship between I4.0 and lean has been identified by the previous authors, Martinez et al. [75] after reviewing the abstracts of publication about I4.0 and measuring its relation with the lean topic, concluded that there is a low level of correlation between these two topics.

6. CRITICAL ANALYSIS AND MAIN CONCLUSIONS

The systematic literature review reported in this article is focused on how technologies enabled by I4.0 can enhance Lean practices. The objective is to understand the relationship between I4.0 and Lean, as well as assessing how the implementation of these technologies can improve Lean practices. From the 128 articles published between 2015 and 2018 initially identified, only 54 have been considered as relevant to this study. From those 54 published studies, 55% of the articles propose methodologies regarding the use of I4.0 technologies in Lean environments, 32% are basically literature reviews and surveys, while the remaining 13% rely to case studies. It can be argued that the vast majority of the published works is based on proposals, surveys or literature reviews. A few studies are actually based on results obtained in industrial applications. This paper's contribution relies on the study about how I4.0 technologies can benefit lean practices. **Error! Reference source not found.** presents a summary of which I4.0 technologies impact and support which lean practices.

CPS is referred by several authors as a technology that can be effectively used to enhance Lean practices. CPS provides real-time data that can be used to give instant visual feedback regarding performance (KPI) and provide transparency and better communication between production stakeholders.

This technology can be helpful in simplifying the use of Andon and e-Kanban systems, as well as, other production pull flow control techniques. The Pull Flow is a key Lean principle. Regarding Maintenance, CPS are able to collect data about maintenance needs and automatically send signals to maintenance staff. Smart Jidoka system to reduce process variability and errors is also referred as examples of CPS enhancing Lean solutions.

Table 4. Lean tools supported by Industry 4.0 technologies

Lean Practices	Industry 4.0 Technologies									
	CPS	IoT and IIoT	Big Data and Data Analytics	Cloud	VR and AR	Robotics	Other Referred Technologies			
							3D Printing	Simulation	Video-based and 3D Models	Optimization Algorithms
VSM			x		x			x		
Standard work	x		x	x		x			x	x
Continuous improvement and wastes elimination	x	x	x	x	x	x	x	x	x	x
Andon	x									
Heijunka and production planning	x	x						x		x
Pull production	x						x			
Jidoka / Autonomation	x					x				
Kanban	x							x		
JIT	x	x					x	x		
Supermarket	x									
Milk run										x
Problem-solving and decision support	x	x	x	x	x					x
KPI	x		x					x	x	
Empowerment and involvement of workers			x							
Improved human factors					x		x			
Six Sigma	x	x	x							
TPM	x			x						
Communication and Information sharing	x	x	x	x	x	x		x	x	
Decreased operation and waiting times	x		x	x		x	x			
Decreased stocks and inventory management	x		x	x			x	x		
Increased flexibility	x		x			x		x		x

Big Data and Data Analytics are referred by many authors in their major role in improving VSM construction and maintenance, allowing what some authors call dynamic VSM. Other authors refer similar advantages as CPS in real time data collection, allowing effective KPI monitoring. Big Data and Data Analytics are also mentioned in some publications as facilitator to problem-solving, as well as, promoting the empowerment of human workers through mobile information provisioning that actively integrates them in smart manufacturing environment. The human factors are very seldom referred in literature dedicated to I4.0 in lean environments.

IoT and IIoT are referred as being effective in improving the supply chain management as a whole, bringing autonomous optimized decisions in terms of flow, facilitating the JIT pillar of TPS. Cloud computing is mentioned in its real time access to information and integration with other computational systems from other companies. Its capacity is associated to the idea of creating automatically standard work instructions in an optimized way. The information sharing possibly available through this technology is the main advantage that can be taken to enhance lean practices.

Although mentioned its role in VSM virtual mode, one of the most obvious uses of VR and AR technologies regards the creation of safe examination of hazardous situations, providing low cost scenarios for training in operation and maintenance, which holds a huge potential to completely change and revolutionize the way humans work and communicate.

Autonomous and Collaborative Robotics appear having great potential in creating hybrid workplaces where humans and robots work in a collaborative way. Such hybrid workplaces although having great potential in improving production flexibility and productivity still facing severe challenges mainly in safety terms. 3D printing is mentioned as being very lean friendly because it perfectly fits one-piece-flow concept with all its benefits to lean thinking.

Other technologies referred in this review may not be consensual in terms of being enabled by I4.0, although their use can benefit lean practices. Examples are Simulation and Digital Twin, Video-based models and 3D models, as well as, Optimization Algorithms.

The most common benefits taken to lean from the technologies enabled by the fourth industrial revolution referred in this literature are related to data collection, ease of communication between different productive actors, information processing capabilities, and data display. These technologies, if aligned with lean principles and concepts can, indeed, reduce non-value adding activities in organizations, as well as, improving workers satisfaction. The other technologies such as 3D printing and collaborative robots can also bring even more benefits to lean movement.

In general terms, every emerging technology can provide potential benefits in the existing reality, however it is important to evaluate carefully how effective that technology is in each real case and context. Many mistakes have been made over the years with different technologies, creating many problems in many companies. Lean principles and concepts must be very well grasped in order to take effective advantage of these new technologies. Lean principles and concepts such as pull flow, visual management, team work, empowerment and continuous improvement are just few examples that cannot be underestimated when new technologies will be introduced in the existing organizations.

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КАКО ИНДУСТРИЈА 4.0 МОЖЕ ДА УНАПРЕДИ „ЛИН“ ПРАКСУ

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Глобални индустријски пејзаж се дубоко променио током последњих неколико година и појавио се концепт Индустрије 4.0, који је омогућен узастопним иновативним и технолошким развојем који су трансформисали производне процесе. Овај концепт се истиче као четврта индустријска револуција која обухвата низ нових технологија које обликују будућу визију производње. Међутим, „Лин Производња“ је широко коришћен производни приступ који доноси неколико користи организацијама. Упркос истраживањима интеграцији Индустрије 4.0 и „Лин“ производње у последњих неколико година, утицаји који произлазе из примене нових технологија у успостављеним „лин“ праксама није јасно.

Сврха ове студије, која се састоји у систематском прегледу литературе, процјењује како ове настајуће дисруптивне технологије могу побољшати „лин“праксу и анализирати њене учинке и користи за организације које се крећу према овој новој индустријској парадигми.