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Article

Towards 'Lean Industry 4.0' – Current trends and future perspectives

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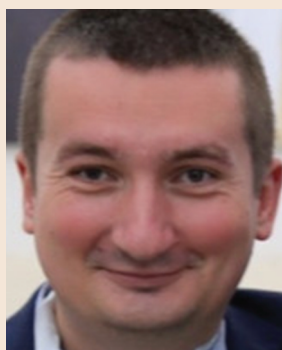
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OPERATIONS, INFORMATION & TECHNOLOGY | REVIEW ARTICLE

Towards 'Lean Industry 4.0' – Current trends and future perspectives

Krzysztof Ejsmont^{1*}, Bartłomiej Gladysz¹, Donatella Corti², Fernando Castaño³, Wael M. Mohammed⁴ and Jose L. Martinez Lastra^{4,5}

Abstract: The enterprises to be competitive are constantly looking for continuous increase of productivity, quality and level of services. With the development of Industry 4.0 concept, manufacturers are more confident about new advantages of automation and systems integration. Lean management is well developed and empirically proven effective managerial approach. Combining Lean and Industry 4.0 practices seems to be necessary evolutionary step for further raise the level of operational excellence (exploitation of finance, workload, materials, machines/devices). There is an increasing number of Industry 4.0 solutions used to reduce waste (as known from Lean Management). Therefore, the main objective of this article aims at presenting the results of a literature review on the concept of 'Lean Industry 4.0'. Dynamic methodology called "Systematic Literature Network Analysis (SLNA)" was used. It combines the Systematic Literature Review approach with the quantitative analysis of bibliographic networks to detect emerging topics and the dynamic evolution of the topics. The paper is a comprehensive systematization and rationalization of knowledge about the integration of LM and I4.0 concepts, identifies the most important research trends and defines directions for future research. The article contains a framework that presents the current state of knowledge in the area of Lean Industry 4.0.



Krzysztof Ejsmont

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Krzysztof Ejsmont PhD in Management, is an assistant professor in Faculty of Production Engineering at Warsaw University of Technology (WUT), Poland. His research is focused on smart manufacturing and Industry 4.0 from production/operations management perspective. He participated in few national and international R&D projects, including funded by EU (NanoForCE, e-Scop). Currently he is the administrator of global research project on "Industry 4.0 in Production and Aeronautical Engineering – IPAE" (10 partners from Europe, USA, Japan, Australia and South Korea).

The other co-authors are researchers who participate in the IPAE project. They are all scientifically related to Industry 4.0 issues and have extensive experience in scientific activity and in the implementation of R&D projects.

PUBLIC INTEREST STATEMENT

Industry 4.0 refers to a series of changes in the way products and services are delivered. Thanks to modern technologies, it enables quick collection and analysis of data between machines, faster and more flexible response to occurring problems, but also more efficient processes to produce high quality products at lower costs. The basis of lean management is the elimination of waste while taking into account the role of the employee in creating the value of manufactured products and services provided. Many companies are interested in implementing both concepts. The paper is a comprehensive review of the combination of these two concepts (called 'Lean Industry 4.0') and presents what has been done so far in this area. The article may be interesting to both theoreticians and practitioners, as it indicates the possibilities offered by the use of integrated Lean Industry 4.0 solutions to eliminate problems related to manufacturing and logistics.

Subjects: Operations Management; Lean Manufacturing; Production Systems & Automation; Engineering Management

Keywords: bibliometrics; Industry 4.0; lean management; lean manufacturing; systematic literature network analysis

1. Introduction

The ability to produce customized products has become the basis for being competitive in a dynamic, globalized and digitally connected world. Customers are used to receiving products and services specially tailored to their needs. The growing expectations of customers along with the progressing quality requirements have led to a growing number of products in portfolios and indirectly influenced the increase in the complexity of the production environment (Westkämper et al., 2013).

Therefore, companies are looking for concepts that can reduce complexity in the industrial area, as well as contribute to increasing value and reducing all types of wastes. Two of the most popular concepts used for this purpose are: Lean Management (LM) and Industry 4.0 (I4.0 or I4).

The cornerstone of the Lean Management philosophy is to reduce waste in the value chain to reduce total lead time including all operations (also those non-value adding). It is also important to focus on the client's value in the process of continuous improvement, as well as considering the role of the employee in creating the value of products and services provided (Schuh, 2013; Womack et al., 1990).

The basis of Industry 4.0 is the ability to quickly collect, process, analyze and exchange large data sets between machines. Thanks to modern technologies such as: Cyber-Physical Systems (CPS) or Internet of Things (IoT), it is possible to react faster and more flexibly to existing problems, but also to more efficient value creation processes, while reducing costs (Oztemel & Gursev, 2018).

Both concepts seem to be helpful in solving the problems facing modern production. Therefore, the research questions seems reasonable: (1) If and how can both concepts complement each other? and (2) Which Industry 4.0 technologies can support specific lean principles/tools. Therefore, the article aims to thoroughly examine what has already been described in the literature on this issue.

The motivation to take up this topic is relatively little research on the importance of the relationship between LM and Industry 4.0 (Buer, Strandhagen et al., 2018; Kolberg et al., 2017; Sanders et al., 2016, 2017; Tortorella & Fettermann, 2018). There is no comprehensive framework that connects LM and Industry 4.0 (Kolberg & Zuehlke, 2015; Leyh et al., 2017). The need to develop a framework for the integration of LM and Industry 4.0 is indicated in the literature (Sanders et al., 2016). In the paper (Buer, Strandhagen et al., 2018) it was found that the area of LM and Industry 4.0 is still immature, and therefore the framework of integration of LM and Industry 4.0 has not yet been published. The need to understand how these concepts interact is also suggested. Despite the existence of papers that combines these two approaches, there is no comprehensive systematization of existing knowledge in this area. Organizing available knowledge, presenting current research streams, as well as indicating which areas require further research will help in developing a holistic framework of integration of LM and Industry 4.0.

The scientific thesis of the article is as follows: systematizing knowledge on the combining the LM and I4.0 concepts will facilitate the development of a framework for their integration and will be a starting point for further research.

Hence, the aim of the paper is to present the landscape of scientific literature on the concept of Lean Industry 4.0 (LI4) using the method of dynamic literature review called "Systematic

Literature Network Analysis (SLNA)” (Ciano et al., 2019; Colicchia et al., 2012; Strozzi et al., 2017). This methodology combines a systematic literature review and bibliographic network analysis using modern bibliometric tools. Adopting such an approach seems to be adequate to the subject being studied, given its novelty and interdisciplinary nature. The proposed approach has been positively verified for other contexts, e.g., creating an academic landscape of sustainability science (Kajikawa et al., 2007), review on how this field of ethical sourcing research has grown and evolved over the decades, providing implications for future research (Kim et al., 2018). In these works, SLNA confirmed its potential value in identifying trends, evolutionary trajectories and key issues that affect the development of knowledge in a given field in a more scientific and objective way compared to traditional descriptive reviews. Traditional reviews are mainly based on content analyzes that do not cover the evolutionary aspect of the direction of publication and are based on subjective criteria for the selection of articles and the classification of research input into pre-defined coding schemes. Instead, SLNA relies on objective measurements and algorithms to quantify emerging topics based on available literature.

2. Theoretical background

2.1. *Lean management*

Toyota began optimizing operations by continuously eliminating all kinds of waste in 1949. Taiichi Ohno, the founder of the Toyota Production System (TPS) has developed a set of synchronized methods and principles for controlling production plants, which became the basis of the Lean philosophy. According to him, the essence of Lean is to reduce the time from the customer's order to the final receipt of the product, by eliminating all activities that are considered waste and do not add value to the customer (Ohno, 1988). The first books on the theory of Lean Management (LM) were published in English in 1978 and gained special recognition in the automotive sector. Over the past few decades, many articles and books have been published that focus on the description and characterization of LM content (Tortorella & Fettermann, 2018). A large number of authors consider LM to be the most well-known management paradigm of recent times (Holweg, 2007; Womack et al., 1990).

Currently, the Lean concept is seen as “a set of management principles and techniques aimed at eliminating waste in the production process and increasing the flow of activities that, from the point of view of customers, increase the value of the product” (Taj, 2008; Womack & Jones, 1996b).

In the literature, lean management is translated through various principles, guidelines or rules. Based on TPS values, five general principles can be distinguished (Womack & Jones, 1996a; Womack et al., 1990):

- (1) specify the value desired by the customer,
- (2) identify a value stream for each product/service providing value to the client; all waste in the value stream can be questioned,
- (3) ensure that the product flow is continuous,
- (4) introduce the pull principle—provide services on order,
- (5) strive for perfection through continuous improvement (kaizen).

The main idea of Lean is to eliminate all kinds of wastes (muda). Eight main types of waste have been identified in the literature (Liker, 2004; Ohno, 1988): (1) transport (2) inventory (3) motion (4) waiting (5) over-processing (6) overproduction (7) defects (8) skills.

The researchers (Sony, 2018) argue that the focus should be not only on the elimination of these 8 wastes, but also on the other two waste-generating elements: mura and muri. Mura refers to process variability and processes should be standardized to reduce it. Muri means excessive work

load that can be prevented by creating ergonomic and safe working conditions. The three main types of LM activities are (1) evaluation, (2) improvement, and (3) performance monitoring.

LM is supported by a set of well-known tools for the operationalization of its goals, both at the strategic and operational level, and the basic philosophy treats human as the most important issue in all activities (Varela et al., 2019). The most popular LM methods, tools and techniques include, among others (Chiarini, 2011): Value Stream Mapping (VSM), 5 S, Total Productive Maintenance (TPM), Single Minutes Exchange of Die (SMED), Kanban, Poka-Yoke, Just-in-time (JIT), Hoshin Kanri, Takt time, Jidoka, Heijunka.

2.2. Industry 4.0

The beginnings of the use of information and communication technologies (ICT) in the manufacturing industry took place in the 1970 s. However, the term 'Industry 4.0' was used for the first time in 2011 at the Hannover in Germany. The main ideas of Industry 4.0 were published in the same year (Kagermann et al., 2011), and also became a strategic initiative of the German government and was included in the "High-Tech Strategy 2020 Action Plan" (Kagermann et al., 2013). Similar strategies have also been implemented in other industrialized countries, e.g., USA ("Advanced Manufacturing Partnership"), China ('Made in China 2025'), United Kingdom ("Smart Factory") and others (Kumar et al., 2020).

Over time, the concept of Industry 4.0 has become synonymous with the fourth industrial revolution (Buer, Strandhagen et al., 2018). Kolberg and Zuehlke (2015) present Industry 4.0 as a further development of Computer Integrated Manufacturing (CIM) and thus as a network approach that complements CIM through ICT. This approach is supported by the integration of automation technologies, e.g., cyber-physical systems (CPS), collaborative robots, cloud computing and big data sets, with the production environment via Internet of Things (IoT) (Xu et al., 2018). Chukwueke et al. (2016) suggest the existence of key Industry 4.0 technologies such as cloud computing, 3D printing, CPS, IoT, Internet of Services (IoS) and big data. Embedded systems, semantic machine-machine communication, CPS and IoT enable connection of the physical and virtual world which is the main goal of Industry 4.0 (Xu et al., 2018). This gives the opportunity to connect the entire factory into a network, creating an intelligent environment. Digitally developed smart machines, storage systems and production facilities enable comprehensive integration based on ICT systems throughout the entire supply chain, from inbound logistics to production, marketing, outbound logistics and services (Kagermann et al., 2013).

From the manufacturing point of view, Industry 4.0 is understood as the movement of intelligent objects that independently coordinate their paths in the factory. Machines are able to implement these paths and communicate in real time with the appropriate warehouse. Information is used primarily to evaluate and control current processes (Kaufmann, 2015). Industry 4.0 significantly affects the manufacturing environment, resulting in radical changes in the implementation of operations. Unlike conventional forecast-based production planning, Industry 4.0 enables real-time production planning, along with dynamic self-realization (Sanders et al., 2016).

Despite the fact that Industry 4.0 is one of the most discussed topics among practitioners and academic teachers in the past few years, no single, commonly accepted definition of this concept has been developed (Buer, Strandhagen et al., 2018; Mrugalska & Wyrwicka, 2017). Researchers and practitioners have divided opinions on which elements create Industry 4.0, how these elements are interrelated and where Industry 4.0 applies. Studies available in the literature show over 100 different definitions of Industry 4.0 (Moeuf et al., 2017). According to the authors, the definition that well reflects the idea of Industry 4.0 is that proposed by Leyh et al. (2017): "Industry 4.0 describes the transition from centralized production towards production that is very flexible and self-controlled. Within this production, the products, all affected systems, and all of the process steps of the

engineering, are digitized and interconnected to share and pass information and to distribute this information along the vertical and horizontal value chains and beyond in extensive value networks.”

It can therefore be assumed that Industry 4.0 is a strategy to compete in the future. In the paper (Mrugalska & Wyrwicka, 2017) can be found that Industry 4.0 focuses on optimizing value chains due to autonomously controlled and dynamic production, and enables the creation of flexible manufacturing and logistics systems.

2.3. Linking lean management and Industry 4.0

The relationship between LM and Industry 4.0 is increasingly emphasized in operations management research (Mourtzis et al., 2017; Sartal & Vázquez, 2017). Despite the significant differences between LM and I4.0, both concepts have the same goal—to increase added value (Prinz et al., 2018). On scientific and practical grounds, it is therefore reasonable to conduct research aimed at answering the question: can both approaches be combined, and if so, how?

Ohno (1988) described two pillars needed to support TPS: just-in-time (JIT) and autonomy (Jidoka). These pillars are also important for LM (Bicheno & Holweg, 2009). JIT can be supported by a digital supply chain (Zelbst et al., 2014), and autonomy can be increased by CPS (Thoben et al., 2014). Therefore, some researchers state that lean implementation is a prerequisite for successful transformation of Industry 4.0 (Kaspar & Schneider, 2015; Staufen, 2016).

Despite various indications in studies that examine the relationship between LM and I4.0, there is still a lack of empirical evidence to support their findings. Buer, Strandhagen et al. (2018) emphasized that the literature on LM and Industry 4.0 is not consistent as to their integration. In addition, they argue that it is necessary to examine the impact of the combination of LM and I4.0 on the results of organizations and the impact of external factors on the relationship between these two concepts. Over the past few years, scientists and practitioners have conducted research on how both approaches, when implemented together in companies, can raise operational and financial results to a higher level (Kolberg & Zuehlke, 2015; Mrugalska & Wyrwicka, 2017; Sanders et al., 2016; Tortorella & Fettermann, 2018).

The growth potential due to LI4.0 is quantified in some papers (Prinz et al., 2018), but it is very difficult to verify the validity of these estimates, as no long-term studies on the effects of I4.0 have been conducted. So despite the fact that the integration of LM and I4.0 was the subject of many theoretical works and practical experiments—it is reasonable to conduct further research to better understand this relationship (Leyh et al., 2017).

The most important publications on the integration of LM and I4.0 along with their characteristics are presented in Table 1.

Based on Table 1, it can be concluded that despite many papers on the subject of LM and I4.0 integration, many of them are theoretical studies regarding only selected aspects of combining both concepts. There is no publication that would be a comprehensive review of the literature, which thanks to the use of modern bibliometric tools will organize all previous research efforts in many areas related to LM and I4.0. There is also no full picture of the current state of literature that will show what has been done so far and what should be the subject of future research.

3. Materials and methods

Two databases were considered for the literature analysis: Web of Science Core Collection (WoSCC) and Scopus. The reason was that they are the most-used databases when it comes to citations for field delineation (Strozzi et al., 2017). WoSCC and Scopus are also the leading databases of scholarly

Table 1. Papers about the integration of LM and I4.0

Paper	Title	Type of paper	Description of the content
(Ejsmont & Gladysz, 2020)	Lean Industry 4.0—Wastes versus Technology Framework	Literature review	Explanation how I4.0 solutions can eliminate 8 LM wastes; indication of potential support for lean techniques through I4.0
(Kamble et al., 2019)	Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies	Survey	Determining the impact of I4.0 technologies on LM practices and sustainable organizational performance
(Rossini et al., 2019)	The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers	Survey	Examine the impact of the relationship between the adoption of I4.0 technologies and the implementation of lean production (LP) practices at the level of improving the operational performance of manufacturers
(Varela et al., 2019)	Evaluation of the Relation between Lean Manufacturing, Industry 4.0, and Sustainability	Literature review/survey	Establishing relations and measuring the effects of LM and I4.0 in terms of sustainability
(Buer, Strandhagen et al., 2018)	The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda	Literature review	Identification of main research streams regarding the relationship between LM and I4.0 and a future research program
(Mayr et al., 2018)	Lean 4.0—A conceptual conjunction of lean management and Industry 4.0	Conceptual/use case	Considerations on the complementarity of LM and I4.0; examples of how I4.0 technologies can support specific lean methods
(Sony, 2018)	Industry 4.0 and lean management: a proposed integration model and research propositions	Conceptual	Theoretical model of integration of I4.0 and LM
(Tortorella & Fettermann, 2018)	Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies	Survey	Examine the relationship between (LP) practices and the implementation of I4.0; the impact of LP and I4.0 on companies performance
(Leyh et al., 2017)	Industry 4.0 and Lean Production—A Matching Relationship? An analysis of selected Industry 4.0 models	Conceptual	Analysis of I4.0 models/framework in the context of LP
(Mrugalska & Wyrwicka, 2017)	Towards Lean Production in Industry 4.0	Conceptual/case study	Case studies of LP and I4.0 integration
(Sanders et al., 2016)	Industry 4.0 Implies Lean Manufacturing: Research Activities in Industry 4.0 Function as Enablers for Lean Manufacturing	Literature review	Indication of which I4.0 technologies are able to support particular dimensions of LM
(Kolberg & Zuehlke, 2015)	Lean Automation enabled by Industry 4.0 Technologies	Conceptual/use case	Theoretical and practical examples of combining I4.0 and lean production

impact and are characterized by high quality of reported journals (Powell & Peterson, 2017). Due to restrictive indexing procedures in databases, their content is considered to be of high quality.

Scopus is therefore very similar to WoSCC. It has some advantages and disadvantages. The main advantages are that in Scopus there are almost 60% more records than in WoSCC (Zhao & Strotmann, 2015) and the database also contains in-press articles. The main disadvantage is that the available data are not as clean as the WoSCC data. This means that some documents are not clearly identified and can be treated as different nodes in the resulting citation network. The study (Wang & Waltman, 2016) has stated that WoSCC classifies journals more accurately than Scopus.

WoSCC is better than Scopus when we want to find more accurate citation information (Crew et al., 2016) and identify “high-influence” publications (Tabacaru, 2019). For this reason, it was decided to choose the WoSCC database.

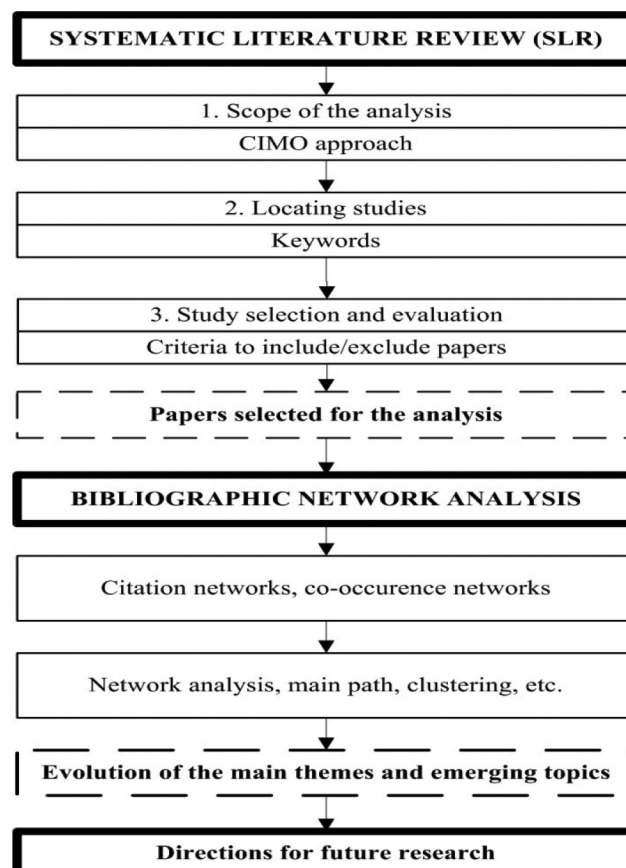
Systematic Literature Network Analysis (SLNA) is the procedure chosen for the selection and analysis of articles (Figure 1).

The first stage is a Systematic Literature Review (SLR). The scope of the study is identified by three steps:

- Scope of the analysis;

In order to formulate the research question and conduct a proper literature review, Denyer and Tranfield (2009) proposed to answer the questions related to Context, Intervention, Mechanism

Figure 1. Systematic Literature Network Analysis (SLNA) based on (Strozzi et al., 2017).



and Outcome (CIMO); The other possible approach is the systematic literature review strategy proposed by Levy and Ellis (2006) i.e. choose, know, understand, apply, examine, combine and evaluate;

- Identifying studies “keywords, time, type of documents, language”;
- Study selection and evaluation;

The result of this stage will be a set of selected documents.

The second stage of the SLNA methodology is the analysis and visualization of the bibliographic network. In the paper, the main attention will be devoted to the citation network and the keywords network, in accordance with the research methodology presented in Figure 1.

To conduct the analysis, it was decided to use 2 software applications, i.e. VOSviewer (<https://www.vosviewer.com>), CiteSpace (<http://cluster.cis.drexel.edu/~cchen/citespace/>).

The VOSviewer program (Van Eck & Waltman, 2010) is especially useful when working with a multi-element data set. The software is based on the approach to grouping and bibliometric mapping of the network, introduced by Waltman et al. (2010). It allows visualization of similarities (VOS) in several forms (network, overlay, density). The software, after selecting the type of analysis and counting method, as well as providing the minimum number of thresholds, e.g. keywords or citations, allows to create a coexistence network. The VOSviewer was used to create a citation network, to designate global and local citation and for creating co-occurrence network of author's keywords.

CiteSpace is an application for visualizing and analyzing trends and patterns in scientific literature. It was designed as a tool for progressive visualization of fields of knowledge (Chen, 2004). CiteSpace focuses on finding critical points in the development of a field or domain, especially intellectual turning points and key points. Detailed case studies are provided in (Chen, 2006) and other papers. The application supports structural and temporal analyzes of various networks from scientific studies (e.g., keywords). CiteSpace has a burst detection algorithm that makes it possible to detect series on keywords. The output of an algorithm is a list of popular keywords over time (topic bursts). The burst weight represents the size of the change in the keyword frequency. The CiteSpace was used to conduct a burst detection analysis. The primary source of input for application is Web of Science.

4. Systematic literature review

4.1. Scope of the analysis and identifying studies

This paper explores the concept of ‘Lean Industry 4.0’. This concept assumes the integration of Lean and Industry 4.0 mainly through modern technologies enabling the reduction of 8 major wastes.

The selection of keywords used in the construction of the searching query was carried out as follows: various terms and abbreviations related to the words “Lean” and ‘Industry 4.0’ have been identified in the literature.

Since the word “lean” was defined in literature in many ways, synonyms and abbreviations of that word had to be established. This was to correctly select all documents related to the Lean concept. Krafcik (1988) first used the word “lean”, which referred to “Toyota Production System”—TPS. It is worth noting that TPS is a major precursor of the more generic “Lean Manufacturing” (Womack et al., 1990). Taiichi Ohno (1988) and Eiji Toyoda, Japanese industrial engineers, developed the system between 1948 and 1975. Lean Production principles such as Just-In-Time (JIT)

and other quality management philosophies such as Total Quality Management (TQM) or Six Sigma, have become substitute terms among scientists and practitioners (Delbridge & Oliver, 1991). Given the large number of synonyms and abbreviations, four literature reviews (Ciano et al., 2019; Hasle et al., 2012; Jasti & Kodali, 2015; Martínez-Jurado & Moyano-Fuentes, 2014) suggest the following keywords: “Lean”, “LM”, “LP”, “Just-in-time”, “JIT”, “Toyota Production System”, “TPS”, “Total Quality Management”, “TQM”, “Six Sigma”. Looking at the approaches and tools in lean, two main key concepts are value and waste (Chroneer & Wallstrom, 2016). Since the main essence of lean philosophy is to eliminate all kinds of wastes (muda)—“waste” was also recognized as the keyword. As for ‘Industry 4.0’, there is no term in the literature that could be considered a synonym for it. As other names/abbreviations we can find: “4.0 Industry”, ‘Industrie 4.0’, ‘I4.0’, ‘I4’, “Fourth Industrial Revolution”, “4th Industrial Revolution”. Although the term ‘Industry 4.0’ appeared for the first time in 2011, a full description of this concept has been published in 2013 (Kagermann et al., 2013).

The query was formulated as follows:

< (“Lean” OR “LM” OR “LP” OR “Just-in-time” OR “JIT” OR “Toyota Production System” OR “TPS” OR “Total Quality Management” OR “TQM” OR “Six Sigma” OR “waste”) AND (‘Industry 4.0’ OR ‘Industrie 4.0’ OR “4.0 Industry” OR ‘I4.0’ OR ‘I4’ OR “Fourth Industrial Revolution” OR “4th Industrial Revolution”) >.

This step in the analysis is very important, because the results may change if other keywords are used. Considering the novelty of the examined issue, the selection of keywords refers to the combination of the Lean and Industry 4.0 concepts and finding their proper synonyms/abbreviations. The main purpose was therefore to extract from the literature the most used terms. To achieve the desired result, it is important to use various tools to extract information from a set of studies. Many terms closely related to Lean (e.g., types of losses) and Industry 4.0 (e.g., Cyber-Physical Systems, Internet of Things) were not included in the set of selected keywords, because this would significantly reduce the number of papers found. This selection was made in accordance with the purpose of this article, i.e. presenting the landscape of scientific literature on the concept of LI4. The selected set of keywords allows the appearance of specific concepts and related issues and trends using the adopted methodology and its bibliographic analysis tool.

4.2. Study selection and evaluation

The identified searching query was entered in the “Topic” field in WoSCC at the beginning of January 2020 (02.01.2020). 243 documents were identified. The aim was select papers about LI4, which was the main purpose of their analysis. Only documents published in English were considered. Papers dated 2011–2019 were investigated. Authors also considered reference lists of found articles from important references missed in the database search.

The rationale for selecting this time period is because the term ‘Industry 4.0’ was used for the first time in 2011, and the basic concept of the fourth industrial revolution was then described.

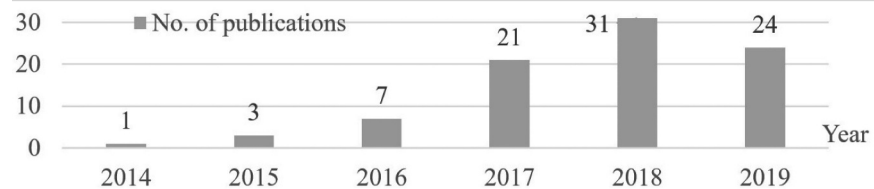
87 relevant studies were selected after screening abstracts and keywords of found papers. In case of doubt, after reading the abstract and familiarizing with the keywords, does the article concern the relationship between Lean and Industry 4.0—the full text has been read. Only publications with full versions in the WoSCC database were taken for further analysis.

4.3. Structure of the papers selected for the analysis

Interest in the topic LI4 over the years 2014–2019 (the oldest selected paper was published in 2014) is presented in Figure 2.

The largest part of selected papers was proceedings papers (51.72%) and articles (44.83%). Book chapters, reviews and early accesses constituted only 6.90% of the entire selected group (2.30%

Figure 2. Number of papers in the field of Lean Industry 4.0.



each). It is worth to mention that further research should approach also white papers as many technology providers tend to publish in that way. However, the quality of such papers is not peer-reviewed. Therefore, they were excluded as they are incomparable in their nature with scientific publications disseminated through channels of conferences and journals.

Figure 2 shows that in the period 2014–2016—the interest in the topic was not significant. In 2017, there was a clear increase in interest on the LI4 concept (21 papers). In 2018 another significant increase was recorded—close to 50% compared to 2017 (31).

Such a dynamic growth in interest in this subject emphasizes its importance and relevance. There were 24 papers identified in 2019, but the search was done in the beginning of January 2020 and probably not all publications from 2019 were indexed in the WoSCC database.

Research areas to which selected papers relate are presented in Figure 3.

The selected studies are dominated by one research area: engineering (64 papers). This proves that in most publications, the authors focus on aspects related to production, in which the combination of the concept of Lean and Industry 4.0 is based on engineering solutions for improving manufacturing. The next most numerous research areas related to the analyzed issue are computer science (13) and operations research, management science (12). This may indicate that in these studies the focus is on the development of IT tools/algorithms using the technologies of Industry 4.0, improving lean manufacturing. Other research areas are less numerous in terms of papers and cover many different fields, which may indicate the interdisciplinary nature of the LI4 issue.

As shown in Figure 4, most papers were created in Germany (29.89%), Italy (16.09%) and Poland (9.20%). Other studies constitute a small percentage of the total. Europe's dominance in this topic

Figure 3. Research areas of selected papers.

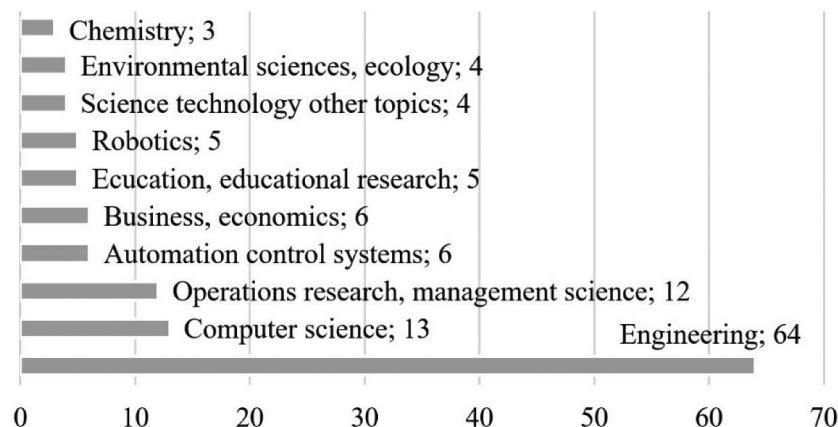


Figure 4. Countries/regions of selected papers.



can be clearly seen, which can be explained by the fact that Industry 4.0 was founded in Germany and this concept is very popular especially on the European continent.

Due to the type of paper, conceptual studies pre-dominate (38). Then there are literature reviews (18) and case studies (11). The least numerous are empirical researches (11) and surveys (9). Therefore, theoretical papers dominantly outweigh the practical ones.

5. Bibliographic network analysis

5.1. Citation network analysis (CNA)

A citation network is a network where the nodes are papers and links mean that there are citations between them. Thanks to this, we can observe the flow of knowledge, as well as which works are linked with citations. This, in turn, makes it possible to isolate clusters (smaller networks), which include papers in which each must have at least one connection with another within the cluster. This enables, among others easier definition of the thematic scope of the cluster.

Figure 5 shows a citation network based on selected papers, using an overlay visualization form. As a result, it became possible to observe which publications were characterized by the largest number of links with others (weights) in the entire network (87 articles). At the same time, the total number of citations in the WoSCC database was presented using a color scale.

Because CNA is a citation-based method, publications that do not have a single link (40 papers) are excluded from the analysis because they are unrelated. In fact, citation analysis can only be

Figure 5. Citation network.

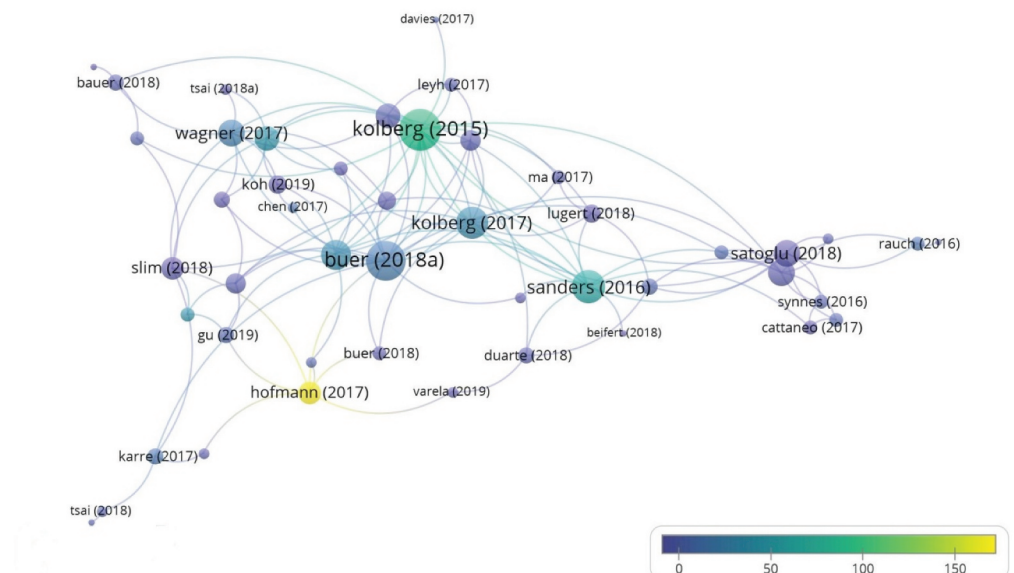


Table 2. Structure of the two largest clusters

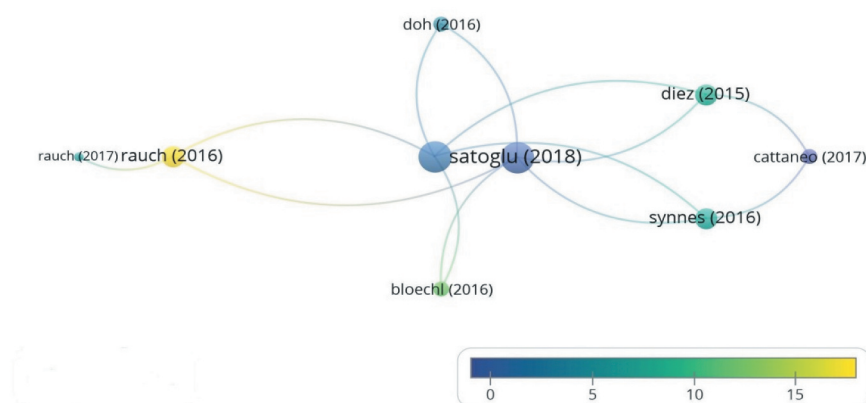
Cluster 1

Paper	Links within the cluster 1	Links within the citation network
(Satoglu et al., 2018a)	5	9
(Satoglu et al., 2018b)	5	9
(Rauch et al., 2016)	3	3
(Synnes & Welo, 2016)	3	3
(Diez et al., 2015)	3	3
(Cattaneo et al., 2017)	2	3
(Bloechl & Schneider, 2016)	2	3
(Doh et al., 2016)	2	2
(Rauch et al., 2017)	1	1
Paper	Links within the cluster 2	Links within the citation network
(Gu et al., 2019)	4	4
(Hofmann & Ruesch, 2017)	4	7
(Ciano et al., 2019)	3	6
(Tortorella & Fettermann, 2018)	3	10
(Yin et al., 2018)	3	3
(Slim et al., 2018)	2	7
(Fettermann et al., 2018)	2	2
(Buer, Fragapane et al., 2018)	1	3

applied to linked papers. A network constructed in this way consists of 47 nodes and 117 links (Figure 5). CNA gives the best results, when clusters consist of a large number of nodes because the amount of information that can be extracted is much larger than information from small clusters (Strozzi et al., 2014). Based on these assumptions, only two largest clusters were analyzed (Table 2).

It should be noted, that not all articles included in a given cluster must be closely related to a particular topic. This is due to the fact that sometimes the authors cite papers that practically do not relate to the topic discussed in the article or the main theme of the cluster (Rauch et al., 2016; Synnes & Welo, 2016). This may also be the case in literature review articles (Cattaneo et al., 2017; Ciano et al., 2019; Slim et al., 2018). Therefore, when using modern bibliometric tools, the traditional review of papers should not be overlooked.

Figure 6. Cluster 1—links and number of citations.



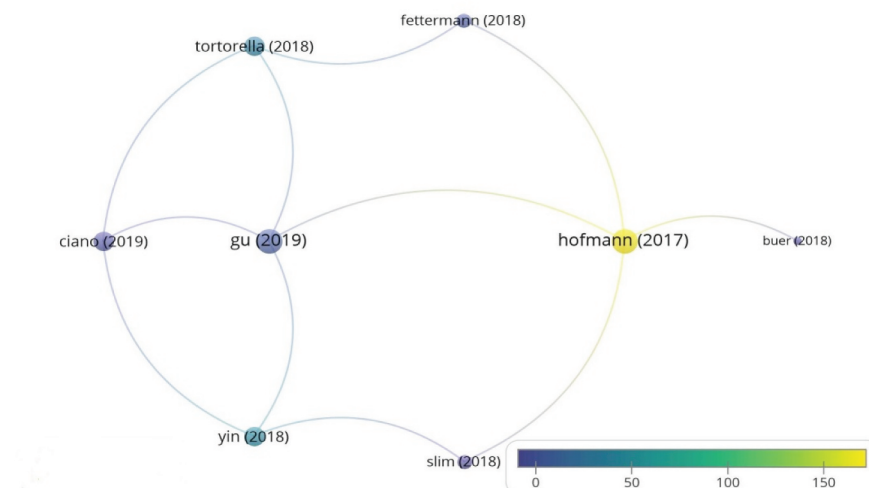
5.1.1. Cluster 1 CNA: Smart lean transformation using Industry 4.0 solutions

First cluster (Figure 6) is consisted of nine publications. Those publications may be labelled together as related to the smart lean transformation enabled through Industry 4.0 tools and technologies and vice versa. Two papers (Satoglu et al., 2018a, 2018b) address relation between particular (subjectively chosen by the authors) Industry 4.0 technologies and lean manufacturing tools or wastes. Authors discussed how specific technologies can support specific tools or lead to elimination of specific waste. However, those papers lack details and cover broad scope of technologies, but each only partially. Authors proved that lean and I4.0 are not mutually exclusive, by showing examples of their successful co-existence. Even though, this proof is very general as no real details and effects are discussed. The second sub-cluster within this cluster is related to product and process development issues (Rauch et al., 2016, 2017; Synnes & Welo, 2016). Authors discussed how the principles of lean product development could be achieved and supported by I4.0 technologies. Again, the choices seem to be subjective. Paper (Rauch et al., 2017) is more specific and it is focused on specifics of critical factors for lean product development in Italian small and medium enterprises. The third sub-cluster consists of papers which discuss some lean approaches and their support for coping with I4.0 challenges and implementation or I4.0 approaches to cope with lean challenges or the mix of both mentioned. It includes Hoshin Kanri (Diez et al., 2015), simulation game for lean and intelligent production logistics (learning factory) (Bloechl & Schneider, 2016), integration of information systems and technologies in the stages of the chain value manufacturing (Doh et al., 2016), lean thinking principles implementation in the context of smart factory (Cattaneo et al., 2017).

5.1.2. Cluster 2 CNA: The impact of Industry 4.0 on the improvement (main context: reduction of wastes) in production systems and logistics

The second cluster (Figure 7) consists of 8 papers. Those papers were related to Industry 4.0 technologies contribution to improvements of operations, production and logistics management. They did not directly indicate specific frameworks or methodologies of improvements (like lean management/manufacturing in case of cluster 1). It is worth to mention that this cluster is consisted of extensive journal papers (while cluster 1 included many conference papers). Four papers were from one journal (International Journal of Production Research) and may be therefore considered as a sub-cluster. One paper discussed how lean was addressed by the mentioned journal (bibliometric analysis) (Ciano et al., 2019). Second paper discussed a case of I4.0 and lean production implementation in the context of Brazilian companies (Tortorella & Fettermann, 2018), so it is somehow similar in approach to the paper (Rauch et al., 2017) (the context of Italian SMEs). Third paper proposed an integrated architecture for implementing extended

Figure 7. Cluster 2—links and number of citations.



producer responsibility in the context of Industry 4.0 (Gu et al., 2019). Fourth paper discussed the evolution from Industry 2.0 to the Industry 4.0 (Yin et al., 2018). Three of four papers (Buer, Fragapane et al., 2018; Fettermann et al., 2018; Hofmann & Ruesch, 2017) left in the cluster should be considered as related to general issues of the impact of the use of Industry 4.0 technologies on logistics, operations management and continuous improvement. The last paper discussed convergence and contradictions of lean and I4.0 for inventive design of smart production systems.

Analyzing topical areas and the scope of papers included in both discussed clusters, it is worth to mention that papers within cluster 2 are rather loosely topically connected, and therefore CNA does not provide in their case solid base for clustering. However, cluster 1 is mainly focused of relations between lean features like techniques, methods, set of wastes and their possible support by the applications of I4.0 technologies. Some of the papers also tackle the problems of vice versa relation, i.e. how lean approach may be used when implementing I4.0 technologies.

5.2. Global and local citation score analysis

Global citation score (GCS) analysis can be used to detect groundbreaking publications. GCS shows the total number of citations in the WoSCC database. Studies with high GCS are considered seminal or have a significant impact on the area of knowledge to which they relate (Knoke & Yang, 2008). In other words, GCS allows the identification of papers that form the basis of a given field, which are often used by other authors to develop their publications. Citations are counted from the entire WoSCC database, even if they are from articles that have not been identified or selected.

Table 3 presents the 10 most frequently cited papers ranked by their GCS. Their local citation score (LCS) is also given, which shows the number of citations the publication obtained in the citation network of selected studies. By comparing GCS and LCS, groundbreaking papers can be identified that has received a small number of citations within the citation network, but has a significant number of citations in the entire WoSCC database.

According to Table 3, among the 10 most frequently cited papers, six studies do not belong to any of the two largest clusters analyzed. Table 3 confirms that some papers belonging to the two largest clusters are groundbreaking, and not just a lot of citations. In addition, 6 publications not belonging to any of the largest clusters confirm the main topics that are currently the objects of research of scientists (e.g., Industry 4.0 supporting lean automation, the impact of Industry 4.0 on production systems).

Table 3. GCS and LCS of the 10 most cited papers

Rank	Paper	GCS	LCS	Part of one of the two largest clusters
1	(Hofmann & Ruesch, 2017)	163	7	Yes
2	(Kolberg & Zuehlke, 2015)	89	19	No
3	(Sanders et al., 2016)	61	13	No
4	(Mrugalska & Wyrwicka, 2017)	44	8	No
5	(Yin et al., 2018)	43	3	Yes
6	(Tortorella & Fettermann, 2018)	37	11	Yes
7	(Kolberg et al., 2017)	34	12	No
8	(Wagner et al., 2017)	27	9	No
9	(Buer, Strandhagen et al., 2018)	24	17	Yes
10	(Bonilla et al., 2018)	21	0	No

Table 4. Ranking of the 10 most cited papers in 2019

Rank	Paper	GCS	No. of citations in 2019	Citations per year since publication
1	(Hofmann & Ruesch, 2017)	163	100	33.33
2	(Yin et al., 2018)	43	34	17
3	(Tortorella & Fettermann, 2018)	37	30	15
4	(Buer, Strandhagen et al., 2018)	24	20	10
5	(Gu et al., 2019)	10	10	10
6	(Bonilla et al., 2018)	21	19	9.5
7	(Mrugalska & Wyrwicka, 2017)	44	26	8.66
8	(Sanders et al., 2016)	61	32	8
9	(Wagner et al., 2017)	27	20	6.66
10	(Kolberg et al., 2017)	34	17	5.66

In order to identify recent groundbreaking studies that could have a potentially large impact and promising scientific input on LI4, papers were ranked according to the number of citations received in the entire WoSCC database in 2019, divided by the number of years since the year of publication. This allowed the identification of those studies that have (potentially) low GCS, but have recently gained considerable interest from the scientific community. In fact, this process “weighed” citations received in 2019 based on the “lifespan” of papers. The ranking of papers elaborated in this way is shown in Table 4. Thanks to this, it became possible to identify one article (Gu et al., 2019) that was not included in the previous ranking (see Table 3). It is also important to notice that the high GCS value does not always mean that the study have a large impact and promising scientific input on LI4.

The papers presented in Table 4 suggest that the latest breakthrough literature is heading towards topics related to the integration of Industry 4.0 with lean automation and lean production (Kolberg et al., 2017; Mrugalska & Wyrwicka, 2017; Tortorella & Fettermann, 2018; Wagner et al., 2017), the use of modern technologies (CPS, IoT, sensors) in production processes and logistics (Gu et al., 2019; Hofmann & Ruesch, 2017), integration of Lean and Industry 4.0 in the context of improving manufacturing systems (Buer, Strandhagen et al., 2018; Sanders et al., 2016; Yin et al., 2018). There is also a study presenting the impact of Industry 4.0 on sustainable development in the context of reducing wastes (Bonilla et al., 2018).

It is worth noting that paper (Gu et al., 2019), which, despite being published in 2019, already has 10 citations and belongs to the second biggest cluster. Usually, papers get more citations in the years following publication. In this case, it may indicate that it could be a breakthrough study, setting further directions of research. The paper proposes an integrated architecture to achieve effective and efficient extended producer responsibility (EPR) using Industry 4.0 technologies. The authors promote the sharing of information, sustainability and reduction of wastes.

5.3. Co-occurrence network of author's keywords

The minimum number of author's keywords in the set of selected documents was 3. After setting a higher value, the number of searched keywords and clusters will decrease, which may lead to the omission of an important issue that has not yet been sufficiently investigated and described or is simply not properly exposed in the paper. For example, for the value of 4 for a minimum number of author's keywords in a set of selected documents, there will be 15 keywords and 4 clusters, and for the value of 5 there will be 10 keywords and 2 clusters. Setting a lower than 3 value means that too many words will be treated as keywords. Three as the number of keywords was also proposed as a reference in the publication (Ciano et al., 2019). Using the VOSviewer program, a network (Figure 8) consisting of 16 nodes corresponding to 5 clusters was obtained. Occurrences were used

Figure 8. Co-occurrence network of author's keywords.

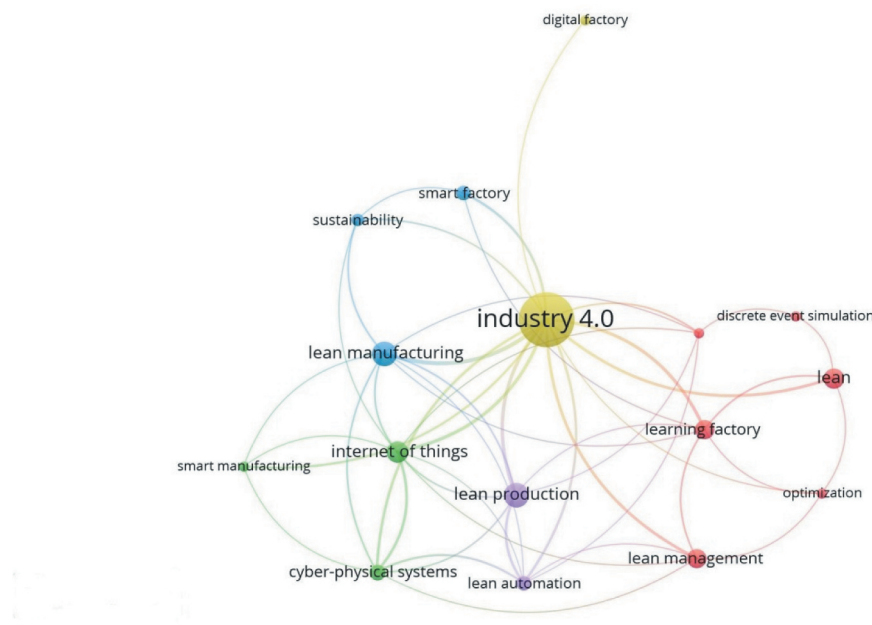


Table 5. Information about author's keywords

Author's keywords	Total link strength	Occurrences	Links
Industry 4.0	59	48	14
Lean manufacturing	21	12	9
Lean production	19	12	7
Internet of things	19	10	9
Cyber-physical systems	17	6	7
Lean automation	15	5	7
Learning factory	14	8	7
Lean management	11	8	6
Lean	9	9	4
Production management	7	3	6
Smart factory	6	5	3
Sustainability	6	4	4
Smart manufacturing	6	3	4
Optimization	4	3	4
Discrete event simulation	2	3	2
Digital factory	1	3	1

as weights. The size and clarity of the node suggests the frequency of its occurrence in the analyzed set. In turn, the proximity of the location of the elements indicates more frequent than in the case of distant ones, co-occurrence in specific sets.

There were 47 links in the developed co-occurrence network and total link strength was 108. Total link strength attribute indicates the total strength of the co-occurrence of a given keyword with other keywords. The higher its value, the more frequently a given keyword coexists with others and is more relevant to the network. Detailed information on selected author's keywords is

provided in Table 5. In order to understand the research trajectories, keywords are listed according to their total link strength, i.e. their importance in the cluster (Waltman et al., 2010).

The obtained clusters were described referring to the papers in which the searched keywords appeared. This allowed to present the results of research in given areas related to LI4.

5.3.1. Cluster 1 author's keywords: Learning factory, lean management, lean, production management, optimization, discrete event simulation

Based on the definition given in (Veza et al., 2015): "A Learning Factory is an environment to support a practice-based engineering curriculum with the possibility of learning the necessary tools and methods, using real life and didactical equipment". Learning factories can successfully provide an appropriate environment for the education of students as well as industry employees (Chrysosouris et al., 2016). There are several modern learning techniques, such as project-based learning or problem-based learning that are widely used and integrated into the practical environment provided by learning factories (Ahmad et al., 2018). The literature describes several examples of learning factories that allow to practice the application of Lean and Industry 4.0 tools. In the learning factory wbk Institute of Production Science, the impact of implementing Lean and Industry 4.0 tools on key performance indicators (KPI) for participating production planners was described (Hofmann et al., 2019). The Institute of Innovation and Industrial Management has been running a learning factory (LeanLab) since 2014. Its goal is to improve the level of academic education, industrial training and practical research in the field of industrial engineering and logistics (Karre et al., 2017). Study (Küsters et al., 2017) describes the functioning of The Textile Learning Factory 4.0 at the Institut für Textiltechnik der RWTH Aachen University in Aachen, Germany. In the literature, we can also find contributions related to the development of design guidelines for I4.0 learning factories and examples of their use in the Smart Mini Factory (Rauch et al., 2019), description of the transition process from Lean learning factory to a learning factory for intelligent production logistics (Bloechl & Schneider, 2016), the theoretical study presenting the framework for connecting Lean and Industry 4.0 in a learning factory (Prinz et al., 2018).

Changes and requirements regarding production management principles, in particular changes in customer requirements in the era of Industry 4.0, are not clear (Yin et al., 2018). Many authors have confirmed in their papers that Lean Manufacturing and Industry 4.0 are not mutually exclusive. They can be integrated with each other for effective production management (Duarte & Cruz-Machado, 2018; Sanders et al., 2016; Satoglu et al., 2018a). Industry 4.0 can provide support through continuous resource management due to the availability of detailed information in real time at every stage of the production process (Gabriel & Pessl, 2016). Therefore, data monitoring provides information on resource consumption and enables flexible production management (Bonilla et al., 2018). Emerging Industry 4.0 technologies enabling the collection of production management data offer the opportunity to receive accurate information and feedback for reliable production planning and control (Dallasega et al., 2017; Reuter et al., 2016). Paper (Araújo et al., 2018) presents the development of an intelligent and automated system for lean industrial production, ensuring maximum productivity and efficiency of the production process. The study (Hrušecká et al., 2018) presents the discrete-event simulation model for increasing the efficiency of warehouse management, which had a direct positive impact on production management.

A review of existing in the literature frameworks, methods and methodology of lean connection and discrete event simulations, along with their characteristics is presented in (Goienetxea Uriarte et al., 2019). Discrete event simulation (DES) is according to many authors (Jahangirian et al., 2010; Negahban & Smith, 2014) the most popular method of simulation. According to the authors (Stadnicka & Antonelli, 2019), discrete event simulations or experiments should be carried out on similar work cells already operating in the factory to determine the correct allocation of tasks. Siemens Tecnomatix Plan Simulation software is recognized as the basic discrete event simulation software that helps create digital models of logistics systems, such as production, to test

performance and optimize the system. It also helps in developing what-if scenarios. The usefulness of this tool for conducting virtual experiments on production and logistics systems has been documented by various researchers (Kikolski, 2017; Siderska, 2016; Zupan & Herakovic, 2015). However, there are many other software applications for discrete event simulation and the choice of the most appropriate should be case sensitive. Discrete event simulation is a powerful tool for modeling complex dynamical systems. An example of using the 3D software environment to build a discrete simulation model can be found in the literature (Grube et al., 2019). The use of discrete event simulation to develop Value Stream Mapping (VSM) and the simulation of many production-related parameters such as lead time, added value, stock, utilization were also identified (Trebuna et al., 2019). An example of using discrete event simulation related to physical objects placed on the Digital Twin Module (DTM) is found in (Grube et al., 2019).

5.3.2. Cluster 2 author's keywords: Internet of things, cyber-physical systems, smart manufacturing

Thanks to the intelligent production system, production processes are more flexible, intelligent and agile and are well adapted to meet the challenges of a dynamic and global market (Zhong et al., 2017). Smart manufacturing (sometimes synonymous with Industry 4.0 [Kang et al., 2016]), directs existing production systems towards the development of an open, digital, automated and intelligent production platform for information applications in the industrial network (Kamble, Gunasekaran, Sharma et al., 2018; Vaidya et al., 2018). The concept of smart manufacturing is based on the integration of the IoT and CPS to create Cyber-physical Production Systems (CPPS), which results in the continuous generation of large amounts of data known as Big Data (Basios & Loucopoulos, 2017). CPS is responsible for technology integration, and IoT enables smart data collection, storage, analysis, and sharing technologies (Kamble et al., 2019). The use of machine learning based on embedded sensors in the CPS is presented in (Castaño et al., 2017). In response to the German concept of Industry 4.0, the United States proposed a Smart Manufacturing Plan (Smart Manufacturing Leadership Coalition, 2011) and suggested connecting everything using the IoT (Porter & Heppelmann, 2014, 2015). The Internet of Things and smart manufacturing are the core of Industry 4.0 (Tsai & Lai, 2018). Publication (Duarte & Cruz-Machado, 2018) presents the following definition of smart manufacturing: production equipped with sensors and autonomous systems that will allow to optimize operations with minimal employee intervention (Roblek et al., 2016; Shrouf et al., 2014). The use of sensing systems and signal analysis to monitor tool wear during the production process is shown in (Beruvides et al., 2013). Automatic selection of optimal parameters based on simple soft-computing methods in the micromilling process is presented in (La Fe-Perdomo et al., 2019). There are also technical studies in the literature that show how available optimization methods can contribute to improving industrial efficiency (Beruvides et al., 2016). It will be possible to produce smaller lots of different types more efficiently (Wang et al., 2016). Smart manufacturing is also defined as the ability to solve current and upcoming problems using an open infrastructure, which allows faster implementation of solutions, building advantage and additional value in the process (Odważny et al., 2018). Some studies suggest that smart manufacturing in Industry 4.0 may be the key to implementing mass customization (MC) strategies. The authors in (Zawadzki & Żywicki, 2016) suggested smart product design and production control for efficient operations in the smart factory to implement the MC strategy. Paper (Cattaneo et al., 2017) contains results of the literature review on smart manufacturing and lean. Paper (Yin et al., 2018) presents an example of a smart manufacturing system for Industry 4.0, and study (Zhang et al., 2017) describes a cloud-based smart manufacturing paradigm based on CPS.

5.3.3. Cluster 3 author's keywords: Lean manufacturing, smart factory, sustainability

A smart factory is the foundation of Industry 4.0 (Germany Trade & Invest (GTAI), 2014). A smart factory will be more flexible, dynamic and intelligent (Roblek et al., 2016). People, systems and objects found in it are connected with each other (Germany Trade & Invest (GTAI), 2014). The IoT is the main technology enabling a smart factory (Germany Trade & Invest (GTAI), 2014; Shrouf et al., 2014). A smart factory is usually associated with lean practices (Tortorella & Fettermann, 2018) and sustainable development (Kusiak, 2018). The smart factory has been designed in accordance

with sustainable and business practices, emphasizing flexibility, adaptability and self-adaptability, learning ability, fault tolerance and risk management (Duarte & Cruz-Machado, 2018; Germany Trade & Invest (GTAI), 2014). Sarkis and Zhu (2018) highlighted waste as a link between lean practices and sustainable development. Kusiak (2018) added a new element to this perspective, namely the role of sustainable development in smart production. In particular, the ubiquitous ICT infrastructure of Industry 4.0 can be a factor conducive to the implementation of sustainable production (Gu et al., 2019). Therefore, the relationship between lean, sustainable development, and Industry 4.0, converging on a circular economy, can be a promising future prospect (Ciano et al., 2019). The main research trends identified are increased interest in combining Lean and simulation in the context of Industry 4.0 and their combination with optimization, Six Sigma, as well as sustainable development (Goienetxea Uriarte et al., 2019). Many authors share the opinion that Industry 4.0 technologies will contribute to the organization's sustainable development goals (Carvalho et al., 2018; Lin et al., 2018; Luthra & Mangla, 2018; Kamble, Gunasekaran, Gawankar et al., 2018; Tortorella & Fettermann, 2018; Zhong et al., 2017). An assessment of the relationship between Lean Manufacturing, Industry 4.0 and sustainability is available in the paper (Varela et al., 2019). Study (Slim et al., 2018) presents an analysis of convergence and contradictions occurring between Lean and Industry 4.0 for the innovative design of smart manufacturing within the smart factory. It is also worth paying attention to two very extensive reviews of the literature on: the concept of smart factory (Strozzi et al., 2017) and smart factory in combination with sustainable development and green growth concepts (Odważny et al., 2018).

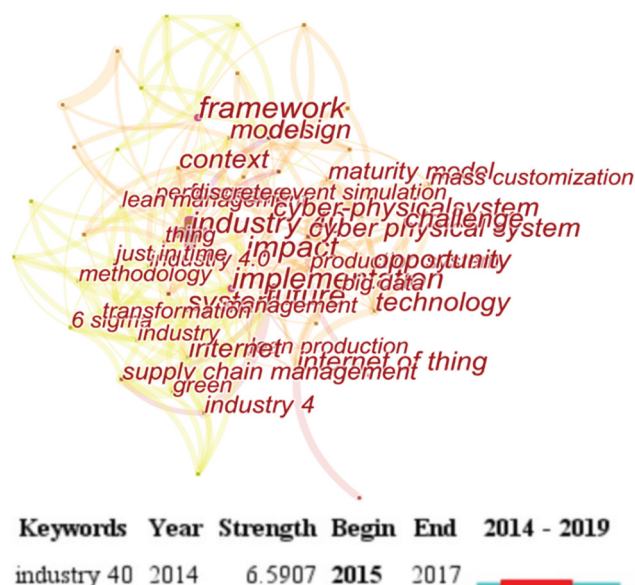
5.3.4. Cluster 4 author's keywords: Industry 4.0, digital factory

The term digital factory, which is one of the key concepts in Industry 4.0, is used interchangeably with a virtual factory or a digital twin (Mrugalska & Wyrwicka, 2017). An example of the digital twin application is presented in work (Guerra et al., 2019). The digital factory is defined as an integrated simulation model providing advanced decision support capabilities (Jain, Lechevalier et al., 2016; Jain, Shao et al., 2016). Simulation is therefore an important tool in the context of Industry 4.0 (Goienetxea Uriarte et al., 2019). The publication (Dombrowski et al., 2019) presents the concept of Digital Factory 4.0, which is a teaching-learning environment in which participants along with a partner cooperating with the industry can independently solve complex tasks having a practical context. Analysis and explanation of the problem is possible based on a visit to a real object. In publication (Tsai, 2018), the author state that Industry 4.0 of the textile industry requires a digital factory. CPS and IoT were recognized as the basic technologies. Publication (Dallasega et al., 2017) presents state-of-the-art planning and real-time production control in the digital factory of the future. An important requirement of the Digital Factory is to provide stakeholders with information and knowledge support during the decision-making process. Just-in-time information retrieval (JITIR) in a digital factory environment is designed to provide stakeholder support through proactive but non-invasive delivery of required information at the right time based on user context. Decision-making activities are taken throughout the entire life cycle of the factory and include location and network planning, material handling and equipment design, process planning or factory operation (Constantinescu et al., 2014; Westkämper, 2006).

5.3.5. Cluster 5 author's keywords: Lean production, lean automation

The integration of Lean Production (LP) practices with Industry 4.0 technologies has been defined as Lean Automation (LA). Its assumption is greater flexibility, changeability and shorter information flow to meet future customer requirements (Kolberg & Zuehlke, 2015). Due to the potential benefits of implementing Industry 4.0 technology, several authors (Gjeldum et al., 2016; Sanders et al., 2016) argued for the existence of new available application areas for LA. An example here is the implementation of flexible, efficient and affordable CPS (Kolberg & Zuehlke, 2015). Currently, LA (Jidoka) using CPS is considered a profitable and effective approach to improving the flexibility of production systems. The publication (Ma et al., 2017) proposed the concept of Smart Lean Automation Engine Enabled by Cyber-Physical Systems Technologies (SLAE-CPS). Another example of LA is the use of modern ICT technologies for the Kanban method (electronic Kanban) (Kolberg

Figure 9. Burst detection algorithm applied to author's keywords.



et al., 2017; Lugert et al., 2018). The next stage will be the integration of a larger number of available LP methods with the developed interface and the creation of other LA solutions using this interface (Kolberg et al., 2017). LA levels are presented in (Satoglu et al., 2018a, 2018b).

5.4. Burst detection analysis

Available literature from a research field can be treated as a series of topics that appear, gain popularity and intensity during a certain period, and then disappear. The appearance of a given topic in the document stream is signaled by a “burst of activity”. Some features increase rapidly as a topic appears (e.g., citations). Kleinberg (2003) developed a formal approach to modeling “bursts” in such a way that they can be reliably and effectively identified.

The Kleinberg approach is based on stream modeling using an infinite state automaton in which bursts occur naturally as state changes. In some ways this is an analogy to queuing theory models for burst network traffic.

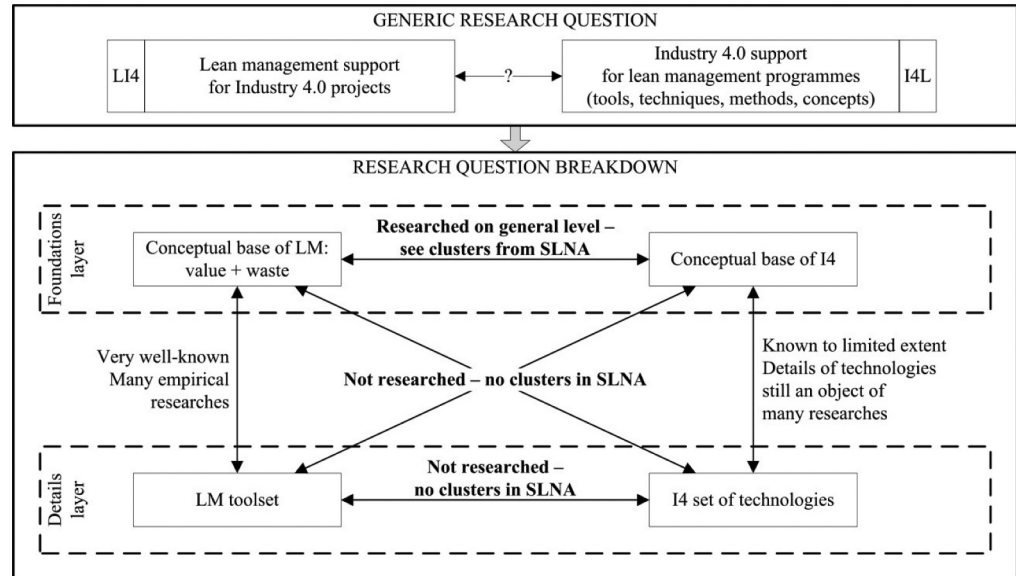
In the paper the Kleinberg’s algorithm was applied for author’s keywords. The results of applying the burst detection algorithm using the CiteSpace application are shown in Figure 9.

Authors’ keywords generated (Figure 9) mostly coincide with those obtained by the VOSviewer program. Just one keyword (Industry 4.0) with the strongest citation was obtained. This is mainly because the analysis period is too short to indicate emerging keywords (bursts). Burst was found only for Industry 4.0 keyword. Therefore, it is obvious that all the papers relate to Industry 4.0 keyword as it effects directly from the designed query. Burst detection has not indicated any emerging and ending topics as the Industry 4.0 is relatively new itself. Considering citations, the only paper with burst was (Kagermann et al., 2013), which is the first one giving comprehensive description of I4.0. Therefore, this analysis also has not indicated any trends.

6. Discussion and further research

According to Dombrowski et al. (2017) two main perspectives are available in the literature: LM is considered a prerequisite for the introduction of I4.0 tools or I4.0 is the LM promoter. The third perspective may be the thesis that the combination of both concepts gives positive synergy effects. This is confirmed by the literature review made by Ejsmont and Gladysz (2020). However, it should be emphasized that the implementation of LM and I4.0 can influence iteratively. Therefore, progress does not have to be sequential (Nyhuis et al., 2017). Mrugalska and Wyrwicka (2017)

Figure 10. Comprehensive framework of Lean Industry 4.0.



support the statement that lean and I4.0 can coexist and support each other. Vogel-Heuser et al. (2017) rejected the contradiction between LM and I4.0. What's more, I4.0 can be helpful in implementing lean and overcome existing obstacles in this process (Sanders et al., 2016).

Combining the results of several analyzes, the paper gave a general picture of the state of scientific work and research trajectories regarding the concept of LI4. Thanks to this, it became possible to set out some ideas for future research directions.

Analyzing the available literature on LI4, interest in this topic has been increasing in recent years. Despite the growing interest of scientists, there is a research gap regarding the assessment of the combination of I4.0 and LM (Slim et al., 2018). The current state of knowledge in the area of Lean Industry 4.0 is presented in the Figure 10.

Based on the created framework (Figure 10), it can be concluded that:

- Lean concept has been verified empirically and there is available extensive literature on empirical and field studies,
- Industry 4.0 is a relatively new concept with few examples of industrial applications described and researched by scientists,
- the impact of I4 on lean and lean on I4 has not been empirically verified and no qualitative, nor quantitative data is widely available in scientific papers,
- LI4 is presented mainly as a concept in which theoretical models are built and verified only by analogy and logical construction.

It would also be interesting to include in the research the precursors of the I4 concept, i.e. CIM (Computer Integrated Manufacturing) or FMS (Flexible Manufacturing Systems) and verify literature on their synergy/contradiction with lean.

It should be noted that the most detailed information about I4, which appears in keywords is discrete-event simulation and big data. Most papers do not present practical examples and empirical evidence, but only describe some general concepts and frameworks. There are no specific lean methods and tools and no specific technologies/solutions I4 listed in keywords.

Therefore, it is highly desirable to conduct further mixed and multi-method research—quantitative and qualitative. It could be organized in the following form:

- Quantitatively—diagnosis, diagnostic surveys, surveys, interviews—initially necessary to narrow down to a selected region/industry and conduct pilot studies,
- Qualitatively—case studies of organizations implementing lean programs and using I4 technologies/tools.

The authors were also tempted to formulate a preliminary hypothesis, which should be verified in further studies: some LM tools and some I4 technologies are used together frequently, while others are less common, which is the signpost of stronger synergies between some pair of Lean/I4 and I4/Lean tools/technologies, and possible contradictions between some other pairs.

Applying citation network analysis, global and local citation scores, co-occurrence network of author's keywords, and using the Kleinberg series detection algorithm, it became possible to identify the main research trajectories for LI4 and indicate its main advantages. Scientists are working on topics related to the use of Industry 4.0 technologies to improve the performance, productivity, efficiency, efficacy and effectiveness of manufacturing systems (Iarovyi et al., 2015). This is indirectly related to the elimination of wastes, which in turn is the basic assumption of LM. It is worth emphasizing that Industry 4.0 is the concept that forms the basis of all clusters, and this concept focuses on the support for other available concepts, including those related to LM (e.g., just-in-time, kanban). In the future, research efforts are needed to investigate the reasons why some Industry 4.0 technologies (e.g., 3D printing, augmented/virtual reality) currently appear to be less popular in the scientific community in the context of LI4.

Based on the literature review carried out in the article, many advantages of combining the LM and I4.0 concepts were identified. The vast majority of advantages are associated with the use of Industry 4.0 technology to support Lean principles/tools (Mayr et al., 2018; Mrugalska & Wyrwicka, 2017; Sanders et al., 2016). For example, the paper (Pereira et al., 2019) presents the matrix “Lean tools supported by Industry 4.0 technologies”, (Ejsmont & Gladysz, 2020) presents complex review of Industry 4.0 solutions that may support lean techniques, tools and methods, and (Mayr et al., 2018) presents combinations of I4.0 tools and lean methods. Shah and Ward (2007) conducted a comprehensive, multi-step study to identify a multidimensional lean structure. They quantified the conceptual definition and proposed measuring LM in ten factors, which in turn were divided into 4 categories:

- Supplier factors: supplier feedback, JIT delivery by suppliers, supplier development;
- Customer factor: customer involvement;
- Process factors: pull production, continuous flow, setup time reduction;
- Control and human factors: TPM, statistical process control, employee involvement.

The advantages of combining LM and I4.0 can be demonstrated grounding on the presented above categories of factors (Pereira et al., 2019; Sanders et al., 2016):

a. Supplier factors

- RFID, cloud computing and IoT allow better adaptation to production needs,
- CPS, RFID, IoT support the exchange of information between customers, manufacturers and suppliers (shortening lead times and response to customer complaints),
- digital performance tables to speed up response times.

b. Customer factor

- Customer involvement at the product development stage due to IoT, cloud computing or platforms cooperating with I4.0 technologies.

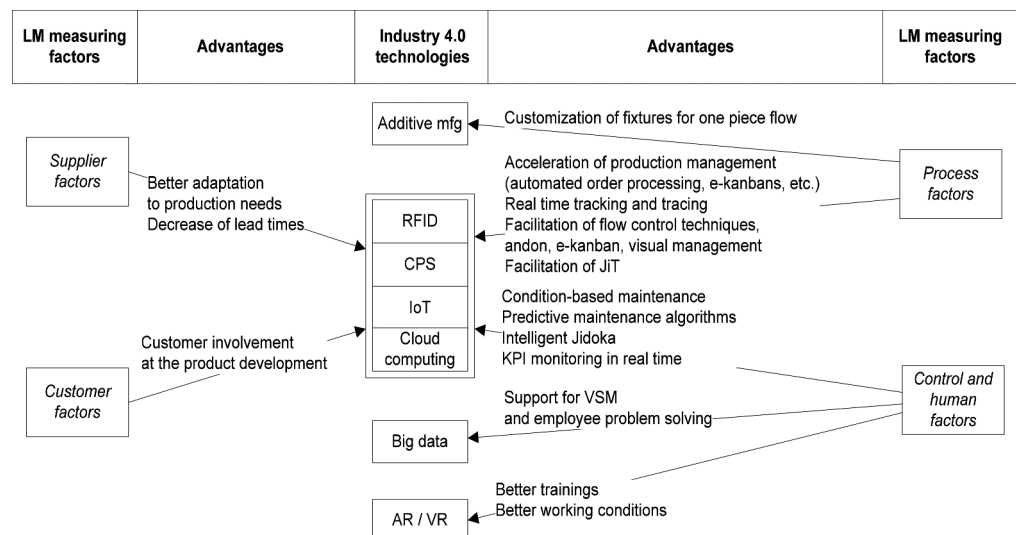
c. Process factors

- access to operational data in real time due to the use of CPS and RFID speeds up and facilitates production management (e.g., automatic order processing, level control using e-kanban or kanban 4.0),
- CPS and RFID makes it possible to monitor the status of details (finished products or work in progress) and to track the quantity and location in real time, as well as communication with machines,
- CPS provide simplified use of andon and e-kanban systems as well as other production flow control techniques,
- additive manufacturing technology for the production of customized spare parts and ensuring one-piece flow,
- sensors, embedded devices and software facilitate more efficient changes,
- IoT and IIoT facilitate JIT implementation.

d. Control and human factors

- CPS are able to collect real-time data on maintenance needs and automatically send signals to the service (e.g., automatic notifications from machines when errors or failures are detected),
- predictive algorithms streamline automatic maintenance,
- quality control based on real data supports self-control (e.g., intelligent Jidoka),
- the use of smart devices, CPS, Big Data, Data Analytics for registration and monitoring of KPI in real time,
- a combination of digital standard operating procedures with cloud technology and augmented reality (AR) to improve operator performance,
- sensors and training in virtual reality (VR) to improve working conditions,
- AR and VR enable testing of dangerous situations,

Figure 11. Lean Industry 4.0 advantages.



- hybrid jobs with collaborative robots,
- Big Data and Data Analytics streamline VSM procedures and facilitate employee problem solving.

Figure 11 depicts summary of advantages that could be achieved through applications of I4.0 technologies as a support for lean management principles. It is clear that the vast majority of synergies is seen in the categories of process factors and control & human factors. However, categories are interrelated and advantages classified as process or control and human factors affect supplier and customer factors as well. E.g. customization of fixtures for one-piece flow, could be also employed for suppliers and customers relations, flow control techniques could be used in-house shop-floor wise, but also in external supply chains.

The conducted research shows that relatively little attention has been devoted to organizational aspects related to the implementation of LI4. The results obtained show that the papers focus mainly on management aspects and responding to changing production requirements, but only in a conceptual way (Sony, 2018). A lot is said on conceptual level of frameworks, but detailed models and extensive case studies are still missing. LI4 models are also missing details considering waste elimination or the combination of I4.0 specific technologies with specific LM tools and techniques (Ejsmont & Gladysz, 2020). Hence, an interesting research agenda can be in-depth research on organizational impact, change management and integration of human resources in the development of LI4, as well as the development of applied models (including reference models and best practices) in these contexts.

The analyzed literature emphasized the fact that LI4 is a concept that goes beyond the enterprise and covers the extended supply chain (Gu et al., 2019). However, LI4 in the extended supply chain is still not discussed in the literature. Another important research direction is the integration of horizontal and vertical systems of Industry 4.0 and LM. This may lead to the need for a holistic approach to LI4 in the supply chain through further research that could also provide empirical evidence (of synergies and contradictions) to complement few theoretical studies.

Most of the publications are of a conceptual, philosophical or review nature and concern only preliminary considerations regarding the possibilities of synergy I4.0 and LM. The descriptive approach dominates, and the presented possibilities of integration of Industry 4.0 and LM for waste reduction or methodological foundations for their cooperation are at a very general level. Studies have shown that despite the existence of models, frames and architectures related to the functioning of LI4 (Arica & Powell, 2014; Kamble, Gunasekaran, Gawankar et al., 2018; Sony, 2018; Xu & Chen, 2017), these are mainly conceptual works. It should be noted that they are rarely supported by empirical researches or case studies confirming the statements presented in the analyzed articles. There are also no conclusions based on practice. Therefore, it would be advisable to examine the functioning of LI4 in an industrial environment in order to supplement the results of the literature study. For example, surveys or case studies of companies located on different continents (not just in Europe) would be beneficial to give a slightly broader view of how LI4 is and can be implemented in the industrial community.

It would be also interesting to examine the barriers and contradictions that influence the synergy of Industry 4.0 and LM. Empirical research and case studies would be desirable as they represent a minority of the available work.

Further research should cover more available papers. In this purpose, studies on LI4 can also be identified in other databases such as: Scopus, IEEE, etc. For more complete results, it should be also consider extending the query of Anglo-Saxon terminology, i.e. “smart manufacturing” and “smart factory”, which appear in some clusters. Analysis can also include German-language papers due to the source of I4. It is also worth considering the inclusion of “white papers”, but this would

require establishing a rational method of their selection. It will be also very important to carry out additional analyzes, e.g., co-authorship, co-citation, bibliographic coupling. This will allow obtaining information such as: how many scientists deal with a given topic, what countries/organizations are represented by the authors, what are the relations between authors etc.

Future actions should also focus on issues that have not yet been thoroughly researched and described on scientific grounds. As an example, practical verification of the possibilities of Lean and Industry 4.0 integration to reduce 8 major types of LM wastes can be given. The literature lacks both theoretical models combining Lean and Industry 4.0, as well as case studies or empirical research results in a quantitative (measurable) form. This is important because only then it will be possible to interpret them objectively and to clearly state whether Lean and Industry 4.0 are complementary or not.

7. Conclusions

Even though the literature can identify the works of linking Lean and Industry 4.0, these studies have some limitations. Kolberg and Zuehlke (2015) conclude that a common framework is lacking because the concepts are discussed in an example without a structured approach. This is also confirmed by research carried out by Ejsmont and Gladysz (2020). They show that the majority of Lean and Industry 4.0 combinations are presented at a very general level and there is a lack of quantitative data verifying the benefits of the combination of Lean and Industry 4.0. Descriptive approach dominates, and the presented possibilities of integration of LM and Industry 4.0 in the field of e.g., waste reduction are at a very basic level. There is definitely a lack of empirical research and case studies confirming the synergy of both concepts. Only Wagner et al. (2017) presented the matrix to illustrate the impact of eight I4.0 tools on several lean principles that include specific methods. However, only the effect of CPS on JIT is described in detail. Ejsmont and Gladysz (2020) presented '8 Wastes—Industry 4.0' framework. Despite this, Lean Industry 4.0 concept still should be thoroughly investigated, delivering frameworks to eliminate contradictions and strengthen synergies.

From the best of authors' knowledge, this work is the first attempt to comprehensively systematize existing scientific knowledge about the concept of LI4. By conducting quantitative bibliometric analyzes using algorithms and software tools, it is possible to obtain a full landscape of knowledge about the conducted study. It is also possible to identify some research trends, as well as to determine the directions of future research, which will cover the dynamic evolution of LI4.

The main theoretical implication of this study is to broaden knowledge of LI4 by analyzing the on-going developments, new trends and emerging topics which have not been sufficiently addressed and require further research. An additional contribution is the use of SLNA methodology to examine a relatively new contributions reflected in literature. This may facilitate the application of the adopted procedure in other areas. The obtained research results enabled the use of citation networks and keyword networks in their main clusters. This can be helpful for scientists to further develop the topic by identifying key issues, emerging trends and evolutionary trajectories.

In relation to the performed analysis, based on the author's keywords, there some benefits of the presented study. The selected author's keywords enable identification of detailed information on the latest topics and issues discussed (five described clusters). Analysis of co-occurrence network of author's keywords has also given the opportunity to isolate topics that have not yet been thoroughly studied (e.g., the role of simulation or Big Data in the concept of LI4, the use of LI4 in supply chains). The results obtained were confirmed and enriched by the use of a burst detection algorithm, which was the last step in the adopted methodology.

The paper also has practical implications: it is the first comprehensive study on the issue of LI4, and also presents information on the current state of knowledge and sets further development directions. Thanks to bibliometric analyzes, critical areas of development of the LI4 concept have

been identified, and information has been provided on what the scientific and industrial environment should focus on to enable effective connection of LM and I4.0.

The main disadvantage of the used methodology is the inclusion of keywords that may not always fully correspond to the content of the reports or may contribute to an erroneous determination of the real meaning of the article for a given area of knowledge. Related keywords can sometimes overlook important details of the study being considered. Some keywords may also be omitted when building the network, as they may not meet the coexistence requirements. Another disadvantage is that the data for bibliometric analyzes were taken from one database—WoSCC, which, although quite comprehensive and prestigious, contains only a small part of all scientific publications. One drawback may also be that researchers very often cite works that already have a large number of citations. This is mainly due to the fact that such articles are considered as reliable sources of information, and also have a certain reputation and popularity.

Despite the limitations presented, the results obtained should be considered interesting. The usability of the SLNA method was proven, which thanks to, among others using tools to visualize the citation network and co-occurrence network of author's keywords, enables the support of dynamic analyzes for the presentation of knowledge, or allows the identification of activities to promote and develop further research of a given issue.

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No potential conflict of interest was reported by the authors.

Supplementary material

The supplemental data for this article can be accessed [here](#).

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