Lean and Industry 4.0: A bibliometric analysis, opportunities for future research directions

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ABSTRACT

Lean is a philosophy that helps organizations develop a continuous improvement culture by eliminating waste and minimizing the use of resources. On the other hand, Industry 4.0 is a complex high-tech model that contributes to flexible organizations using different technologies such as IoT, cloud computing, blockchain, virtual reality, and Artificial Intelligence. The concept of integrating Lean Principles and Industry 4.0 is still very recent and limited, and the literature lacks a bibliometric perspective. The integration is challenging in terms of contentment-wise and is a broad multi-dimensional research area. This study aims to analyze Lean Industry 4.0 or Lean 4.0 and Lean digital transformation literature using bibliometrics, identifying its state of art, benefits, challenges, and scientific gaps. In this study, articles published between 2010 and 2022 from the Scopus database are analyzed to identify significant publications, journals, authors, institutions, and countries based on the number of publications and frequently used keywords and subject areas. This study contributes to developing the state of art of Lean Industry 4.0 and Lean digital transformation and helps researchers and practitioners direct their future studies. The literature performance is measured based on both the number of publications and the number of citations; this bibliometric analysis covers most of the published papers in both research domains.

1. Introduction

In recent decades, the market competition has become intense, increasing the need for organizations to minimize their resources, eliminate waste, and maximize profits (da Silva et al. 2018). This fact piqued the interest of researchers and practitioners in the study of continuous improvement methodologies and their development that enable companies to compete among others (Dave, Murugesh, and Devadasan 2015). Among the several continuous improvement methodologies, Lean is considered one of the tools that help build a culture of continuous improvement in firms and achieve operations perfections (Antony et al. 2019). Lean originated from the manufacturing industry, especially the Toyota Production System in the 1940s, and it has since gained popularity and become an essential in services (Gonzalez et al. 2019). The main focus of Lean methodology is to generate value by identifying and eliminating process waste, unevenness in operations, and overuse of resources (Antony et al. 2019; Sony, Naik, and Antony 2020).

Although Lean methods have proven beneficial and positively impacted organizations, many leaders lack a clear understanding of the principles, and focus only on its short-term benefits (Robinson and Schroeder 2009). Lean methodology is also limited by a lack of data-driven processes for improvement, which restricts its accuracy and precision (Hilton and Sohal 2012). The lack of data is because organizations do not use data extensively in their decision-making processes (Assarlind, Gremyr, and Bäckman 2013). Another limitation of Lean implementation is managerial, it is related to employee resistance to change as well as the presence of a broad set of tools which makes it difficult to determine the suitable one (Antony et al. 2019).

Despite the several publications, only a few have addressed the new functionalities or opportunities introduced by Industry 4.0, also known as smart manufacturing (Kang et al. 2016). The impact of Industry 4.0 on established management practices such as Lean manufacturing and the impact of Lean on Industry

4.0 has not been well researched (Buer, Strandhagen, and Chan 2018). Industry 4.0 is a high-tech project that the German government introduced to promote computerization. It is mainly a complex model structured to epitomize several digital technologies connected to provide real-time data to manufacturing and service systems for analytical purposes (Arcidiacono, Calabrese, and Yang 2012). Industry 4.0 comprises productivity-enhancing tools, including cyber–physical system (CPS) that is empowered by the Internet of Things (IoT), cloud computing, automation, big data, data sharing, artificial intelligence (AI), Blockchain, and analytics (Anvari et al. 2021). The benefit of Industry 4.0 is to contribute to a flexible organization that can respond to demand variations due to product customization, shortened product life cycle, and increased complexity in product design and production processes (Hirsch-Kreinsen and Weyer 2016). Due to the consideration of Industry 4.0 as a strategic model, its potential industrial advantage is improvements in different metrics, including cost, productivity, quality, customer satisfaction, and lead time. Organizations need to understand their current level of maturity in their particular context or supply network before adopting the Industry 4.0 strategic model. Firms can use this information to identify their areas of strength and weakness, prioritize improvement opportunities, and manage their development plans (Bibby and Dehe 2018).

After the development and adaptation of industrial processes, digital transformation or digitalization has been part of Industry 4.0, where its primary purpose is to achieve a digital and interconnected system (Müller, Kiel, and Voigt 2018). Digitalization enables or improves processes by leveraging digital technologies and digitized data. Digitalization increases productivity and efficiency while reducing costs as well as it improves an existing business process or processes but does not change or transform them. It takes an approach from a human-driven event or series of events to a software-driven. Digital Transformation is a business transformation enabled by digitalization. Industry 4.0 is a broader concept than digitalization, yet the relation between both terms Industry 4.0 and digital transformation helped in changing organizational workings to more networked ones; open, customer-oriented, and flat organizational structure that is determined and used to reflect trends in global markets (Bressanelli et al. 2018). The sequence and the set of Industry 4.0 technology implementation define the digital transformation of a firm (Culot et al. 2020).

Although the number of research contributions on Industry 4.0 subject is increasing (Frank, Dalenogare, and Ayala 2019; Rossini et al. 2019; Benitez, Ayala, and Frank 2020), companies still lack the understanding of how digital transformation can be implemented (Erol et al. 2016; Sanders, Elangeswaran, and Wulfsberg 2016). Companies are facing the risk of starting a potentially ineffective digital transformation that is not developed upon their characteristics and is only driven by the industry 4.0 hype (Rossini et al. 2021). Hence, it is noted that Lean principles and Industry 4.0 technology are interconnected (Buer, Strandhagen, and Chan 2018). The Integration of industry 4.0 techniques along with Lean principles could enhance the organization's sustainable performance (Kamble, Gunasekaran, and Dhone 2020). Also, the integration between Industry 4.0 and Lean production system received growing attention among practitioners and academicians (Buer, Strandhagen, and Chan 2018; Rossini et al. 2019), and most of the research focuses on either specific technologies or performance improvement achieved by a single digital technology implementation (Wagner, Herrmann, and Thiede 2017; Gillani et al. 2020). However, it is still unclear how the intrinsic characteristics of Lean production may influence a specific digital transformation and what impact it will lead to (Rossini et al. 2021). Therefore, the integration of Lean tools along with Industry 4.0 or digital transformation is observed to be a recent scholarly research interest that requires further investigation. For instance, the first case study on such an integration was conducted by Ramadan and Salah (2019) and it focused on the digitalization and smart monitoring of Lean tools in the manufacturing sector in order to achieve Lean goals. Hence, the combination of Industry 4.0 and Lean can also lead to new dimensions as well as the enhancement of Lean methodologies in terms of both efficiency and effectiveness (Peças et al. 2022).

Despite the several review studies that discuss the relationship between benefits Lean and Industry 4.0 or digital transformation, there are two main perspectives in the literature: either that Lean is the foundation of Industry 4.0 or that Industry 4.0 enhances Lean's effectiveness (Rosin et al. 2020). The few case studies presented in the literature suggest that testing the integrated methodologies and understanding the practical requirements of Lean and Industry 4.0 are necessary to ensure optimum results (Peças et al. 2022). However, a limited number of studies focus on the research trends and state of the art on the integration. This limitation calls for the need to analyze this field

of research as it is necessary to quantify the study literature, evaluate its performance, and identify the development direction. These can be obtained through the execution of a bibliometric study.

Bibliometric analysis is a methodology that provides a macroscopic overview of massive amounts of academic literature quantitatively through the analysis of publication history, the characteristics, and the scientific output within a specific field of research (Jia, Dai, and Guo 2014). The analysis has been widely applied to determine the significant authors, journals, institutions, countries, and articles to reflect the literature evolution in a certain period (Harande 2011). It is a powerful tool to investigate the research field of Lean Industry 4.0 and Lean digital transformation to show it has developed. The bibliometric analysis is applied to reply to some research questions that have directed this study: *What is the main macroscopic view of Lean Industry 4.0 and Lean digital transformation in literature? What research progress has been achieved in the domain of Lean Industry 4.0 and digital transformation? What are the scientific gaps? Where to direct the research on the determined research field?*

The main objective of this paper is to perform a bibliometric analysis of Lean Industry 4.0 and Lean digital transformation to identify the state of art, scientific gaps, benefits, challenges, and research trends. This study applies bibliometric analysis to determine the notable authors, journals, articles, countries, institutions, subject categories, and keywords in the literature of Lean Industry 4.0 and Lean digital transformation. The benefits, challenges, and scientific gaps identified from recent studies contribute to future research agenda.

The aspects of this paper make this research unique as it analyzes the literature published from the start of the subject activity till 2022. Thus, the bibliometric analysis covers approximately all publications' output. The literature performance is based on the number of publications and citations. This performance analysis measures the scholarly activity of studies in the field of research as well as its impact. The analysis conducted will also compare and contrast intercontinental findings.

Hence, this study contributes toward the characterization of the state of the art of Lean Industry 4.0 and Lean digital transformation holistically as it provides the research progress in a general perspective covering the service industry, manufacturing, government, higher education, among others, it helps researchers and practitioners direct their efforts toward the areas that are little explored, and identify the growth, fundamental influences from authors, journals, institutions, and countries related to those areas.

Section 2 covers the methodology of the research along with the data selection criteria, research parameters, and data analysis. In Section 3, the bibliometric results are illustrated and analyzed to provide scenarios on the subject. The study implications and discussions that describe the major research trends identified scientific gaps, benefits, challenges, and major findings are listed in Section 4. Section 5 states the conclusions and suggestions for future research.

2. Methodology

The methodology followed of this work is illustrated in Figure 1, and the main steps are discussed. The research criterion required to perform the bibliometric analysis are based on six parameters: scientific database, publication period, document type, source type, subject area, and language (da Silva et al. 2018). The Scopus database was used to search the articles, Scopus was chosen because it is known to be one of the largest abstracts and citation databases of peer-reviewed literature such as scientific journals, books, conferences, and proceedings (Aghaei Chadegani et al. 2013). It also encompasses articles from many sources including Emerald, Wiley Online Library, Springer Link, Science Direct and allows for data export (da Silva et al. 2018). In addition, the Scopus research database expands search area and provides selection and filtration options, making it more time efficient (Koemtzi et al. 2022).

In this study, we focus on Industry 4.0 and digital transformation terminologies integrated with Lean, any other individual technologies of Industry 4.0 were disregarded. Other terms like "Smart Lean" were also excluded as they are newly introduced to the research community and are currently limited to the manufacturing sector. Thus, they do not portray the broad concept of Industry 4.0 and digital transformation terminologies integrated with Lean. The keywords used in the Scopus database for the search in titles and/or keywords and the abstract of articles were "Lean" and "Industry 4.0," "Lean 4.0," and "Lean" and "Digital Transformation." The quotation marks were included to check the condition and ensure results accuracy (Liu et al. 2013). The published articles between 2010 and 2022 were included, and the publications' language is set to be only in English. The results obtained for keywords "Lean" and "Industry 4.0" or "Lean 4.0" where 661 publications were as for the keyword
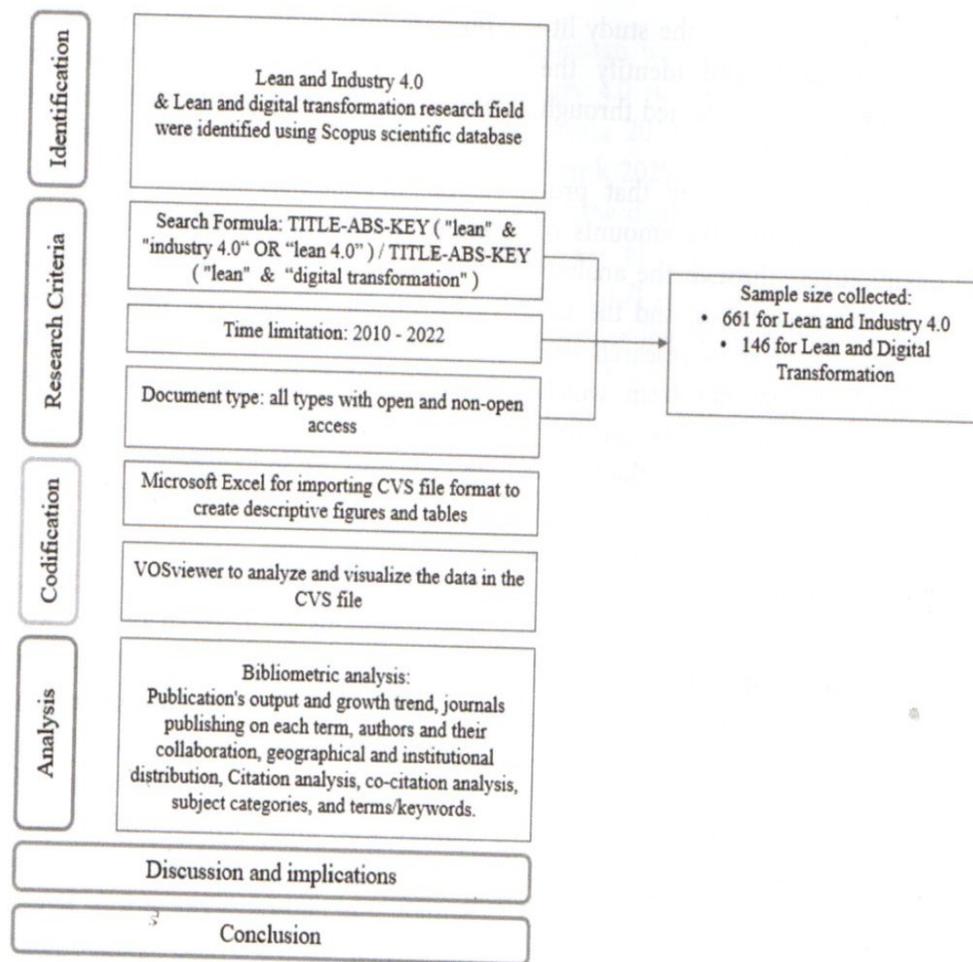
Figure 1. Methodological research flow chart.

Table 1. Publications research results.

Terms	Total publications	Journals	Conference proceedings	Others
Lean Industry 4.0 or Lean 4.0	661	251	298	112
Lean Digital Transformation	146	39	86	21

"Lean" and "Digital Transformation" resulted in a total of 146 publications. The publications were majorly journal papers and conference proceedings. Table 1 shows the total number of publications for the searched terms with the classification of numbers in published journals, conference proceedings, and others (such as books, book series, trade journals, or unidentified).

The bibliometric data for the resulting publications were exported in "CVS" file format. The data extracted contained the following information: publication year, authors, title, journal source, subject category, keywords, countries, institutions, authors' affiliation, references, document type, and the number of citations. Microsoft Excel was used to perform the bibliometric analysis. VOSviewer analyzes and visualizes the relationships between authors, countries, institutions, co-citations, subject categories, and terms. VOS (Visual Of Similarities) is a mapping method used to calculate and locate each subject or topic in a two-dimensional map that reflects the similarities or relatedness between two

items as accurately as possible. The clustering method of VOS is applied to cluster the topics into different groups, where each cluster is highlighted with a different color (Van Eck et al. 2010; Waltman, van Eck, and Noyons 2010). All visualizations are explained in the analysis and result section. However, the interpretations are as follows: the size of the circles and the font label represent the number of occurrences, the different colors resemble the different clusters, and the distance between two circles reveals the relatedness between them (Rizzi, van Eck, and Frey 2014; Khalil and Gotway Crawford 2015).

The bibliometric parameters used in this study were the number of publications, citations, and the average citation per year. These parameters illustrate the literature published up to September 20, 2022. The analyses highlighted the publications' output and growth trend, journals publishing on each term, authors and their collaborations, geographical and institutional distribution, citation, co-citation, subject categories, and terms/keywords.
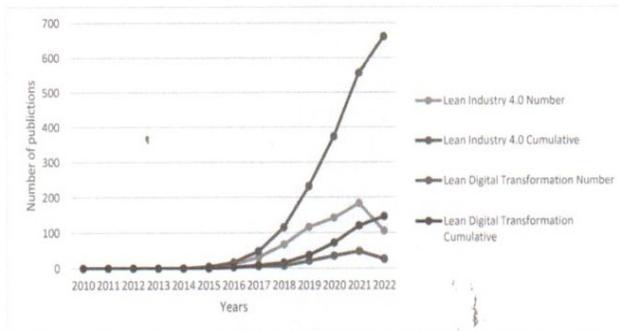
Figure 2. Number of publications and their corresponding cumulative.

3. Analysis and results

3.1. Publication output and growth trend

The number of reviewed publications under a specific topic is considered an important indicator that helps measure the scientific research discipline's development trend (van Nunen et al. 2018). A tendency of increasing interest of researchers to explore the Lean and Industry 4.0 domain from 2015 onwards has been growing since then. The first publication issued was a conference paper with the title "A concept of information system implementation (CRM and ERP) within industry 4.0" that presented the concepts of information system implementation (Enterprise Resource Planning (ERP) and Customer Relationship Management (CRM)) according to the Industry 4.0 recommendations (Stojkić, Veža, and Bošnjak 2015). On the other hand, Lean with digital transformation started in a Shaping the Digital Enterprise titled "Creating a market analytics tool that marketers LOVE to use: A case of digital transformation at Beiersdorf" in 2016 where it discussed how transformed digital technologies and Lean process work (Vom Brocke et al. 2016). Lean Industry 4.0 and Lean digital transformation are considered as a recent integration therefore no declination in the curve has been spotted. Based on the cumulative number of publications of both research fields in Figure 2 can be stated that Lean Industry 4.0 and Lean digital transformation research is becoming scholarly active. The significant increase in the number of publications for Lean Industry 4.0 occurred in 2019 as the number of publications increased by 49 compared to 2018 publications. Because the current study was conducted in September 2022, not all studies in 2022 were included in this study, therefore a downward trend can be observed between 2021 and 2022. Hence, the chart for both research topics shows a clear linear growth rate.

3.2. Journals publishing on each term

3.2.1. Lean and Industry 4.0

For the analysis and classification of journals publishing on Lean Industry 4.0, it was imposed that the journal has at least one publication as its recent activity. The accumulated number of publications as distributed among 120 different journals publishing about Lean and Industry 4.0 which resulted in 251 publications. The top 10 publishing journals are shown in Table 2 with their information about the corresponding number of publications, the journal impact factor, and the subject category. The journals presented correspond to more than one-third of the total published articles (37.5%; $n = 94/251$). *Sustainability* is the journal with 17 publications (highest number of publications). As part of the Multidisciplinary Digital Publishing Institute (MDPI) (Switzerland), the journal publishes scientific content in the subject areas of "Energy," "Environmental Sciences," and "Engineering." Hence, the publications will majorly discuss managing and operating systems and any engineering-related topics.

3.2.2. Lean and digital transformation

Among the total publications, 39 were journaled articles published in 33 different journals. The top journals where the articles have been published are listed in Table 3. The listed journals contribute more than two-fifth of all publications on Lean digital transformation (41.0%; $n = 16/39$). The highest number of publications (4 publications) is achieved by the *Journal of Manufacturing Technology Management and the International Journal of Lean Six Sigma*. As part of Emerald Group Publishing Ltd. (United Kingdom), the published scientific contents are in the areas of "Engineering" and "Business, Management, and Accounting," similar to the previous section. This gives an insight that Lean Industry 4.0 and Lean digital transformation have similar scientific applications in the subject area.

3.3. Authors and their collaboration

3.3.1. Lean Industry 4.0

There are 157 different authors wrote publications in the Lean Industry 4.0 field in total. Table 4 shows the top-5 most productive authors on the topic Lean and Industry 4.0, ranked based on the author's total number of publications. The table includes the author's country, citations, and the number of citations per publication. Author Daryl John Powell in the Norwegian University of Science and Technology

Table 2. Top 10 publishing journals on Lean and Industry 4.0.

No.	Journal title	No. of publications	Impact factor	Subject area
1	Sustainability (Switzerland)	17	3.251	• Energy • Environmental Science • Social Sciences • Computer Science • - Engineering
2	International Journal of Production Research	16	4.210	• Business, Management, and Accounting • Decision Sciences • - Engineering
3	Applied Sciences	10	2.679	• Chemical Engineering • Computer Science • Engineering • Material Science • - Physics and Astronomy
4	Production Planning and Control	10	3.605	• Business, Management, and Accounting • Decision Sciences • Computer Science • - Engineering
5	Journal of Manufacturing Technology Management	9	7.330	• Business, Management, and Accounting • Computer Science • Engineering
6	TQM Journal	8	2.47	• Business, Management, and Accounting • Decision Sciences
7	Procedia Manufacturing	7	1.790	• Computer Science • Engineering
8	International Journal of Production Economics	6	7.885	• Business, Management, and Accounting • Decision Sciences • Economics, Econometrics and Finance • Engineering
9	Sensors (Switzerland)	6	3.576	• Biochemistry, Genetics and Molecular Biology • Chemistry • Engineering • Physics and Astronomy
10	International Journal on Interactive Design and Manufacturing	5	2.681	• Engineering • Mathematics

Table 3. Top 10 publishing journals on Lean and digital transformation.

No.	Journal title	No. Of publications	Impact factor	Subject area
1	International Journal of Lean Six Sigma	4	4.204	• Business, Management, and Accounting • Decision Sciences • Engineering
2	Journal of Manufacturing Technology Management	3	7.330	• Business, Management, and Accounting • Computer Science • Engineering
3	International Journal of Production Research	2	8.568	• Business, Management, and Accounting • Decision Sciences • Engineering
4	Applied Sciences	1	2.679	• Chemical Engineering • Computer Science • Engineering • Material Science • Physics and Astronomy
5	Automation in Construction	1	7.700	• Engineering
6	BMC Health Services Research	1	2.512	• Medicine
7	Business Horizons	1	6.680	• Business, Management, and Accounting
8	CIRP Journal of Manufacturing Science and Technology	1	4.090	• Engineering
9	Competitiveness Review	1	2.357	• Business, Management, and Accounting
10	Designs	1	0.859	• Engineering

Table 4. Top-5 productive authors publishing on Lean and Industry 4.0.

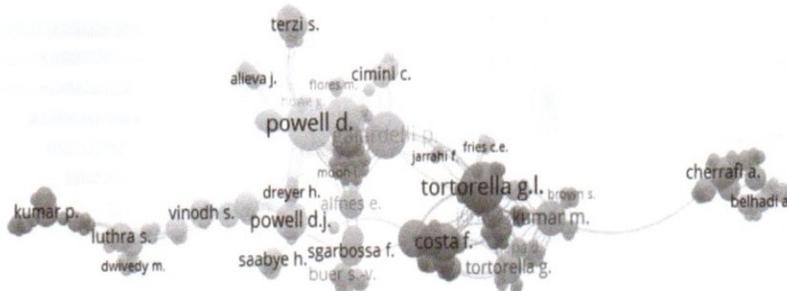| No.	Author name	Country of author	No. of publications	Total no. of citations	Citations per publication
1	Powell, D.	Norway	14	206	14.57
2	Tortorella, G.L.	Brazil	13	664	51.08
3	Gaiardelli, P.	Italy	11	176	16.00
4	Matt, D.T.	Italy	10	152	15.20
5	Alves, A.C.	Portugal	9	126	14.00

Figure 3. Author's collaborative network in Lean Industry 4.0.

Table 5. Top-5 productive authors publishing on Lean and digital transformation.

No.	Author name	Country of author	No. of publications	Total no. of citations	Citations per publication
1	Bildstein, A.	Germany	6	20	3.33
2	Baboli, A.	France	4	28	7.00
3	Bauernhansl, T.	Germany	4	20	5.00
4	Powell, D.J.	Norway	4	12	3.00
5	Rother, E.	France	4	28	7.00

(Norway) with the highest number of publications ($n = 14$) , while author Tortorella G. L. in the Universidade Federal de Santa Catarina (Brazil) ranked second ($n = 13$). The author with the highest number of citations is Tortorella, G.L. (664 citations). The top-5 authors, a wide range of citations per publication vary from 14.00 to 51.08.

The co-authorship pattern of the author's publishing was analyzed using VOSviewer. The pattern of the author's publishing is analyzed upon authors who are in-network, and who published at least one paper to ensure that all authors are included. Authors who are not connected with other authors in the network were not included in the pattern formation. The result of the author's co-authorship on the Lean Industry 4.0 network is shown below in Figure 3. The circle's size represents the number of publications, the line between the two authors represents the collaborative work between them in a publication, The line thickness demonstrates the collaboration strength, and the variety of colors portrays the different clusters. Based on the figure there are three major clusters with main researchers Powell, Tortorella, and Gaiardelli. All other research articles present in the scholarly field are linked to those three main authors.

Author Daryl Powell contributed primarily to the manufacturing sector by developing a comprehensive model that discusses the state of the art for implementing Lean thinking in smart factories. Powell also studied the integration of Lean and Industry 4.0 in practice along with its impact in an exploratory study.

Author Tortorella, G.L. contributed to the manufacturing sector through a case study on the relationship between Lean production practices and Industry 4.0. In addition, several studies have been conducted by author Tortorella to examine how Industry 4.0 technologies affect the relationship between Lean production and operational performance in Brazilian and European companies.

Regarding authorship, a bias possibility might be noted as authors with the same name could not be distinguished from each other. Also, authors using different names in their publications due to marital status changes could not be merged. In one of the reviewed papers, it was recommended by others that a mandatory allocation of a unique digital identity number when publishing the first paper as a researcher (such as ORCID), would be an excellent solution for such a problem (van Nunen et al. 2018).

3.3.2. Lean digital transformation

A minimum of one article published in Lean digital transformation was required for the authors' inclusion. Thus, from the categorized publications, 159 different authors have published in variety of disciplines. Table 5 presents the top-5 most productive authors, the country, number of citations, the number of publications, and the citations per paper. Author Andreas Bildstein, in Fraunhofer Institute for Manufacturing Engineering and Automation IPA (Germany) with the highest number of publications (6 publications), while other authors were equally productive (4 publications). Baboli and Rother were the authors with the highest number of citations (28 citations). The similarity justifies the collaborative work between both authors on this particular field. A narrow range can be noticed regarding the number of citations per publication (ranging from 3.00 to 7.00). The analysis of the co-authorship is demonstrated in Figure 4. Hence, there is no variety of different colors, and no major
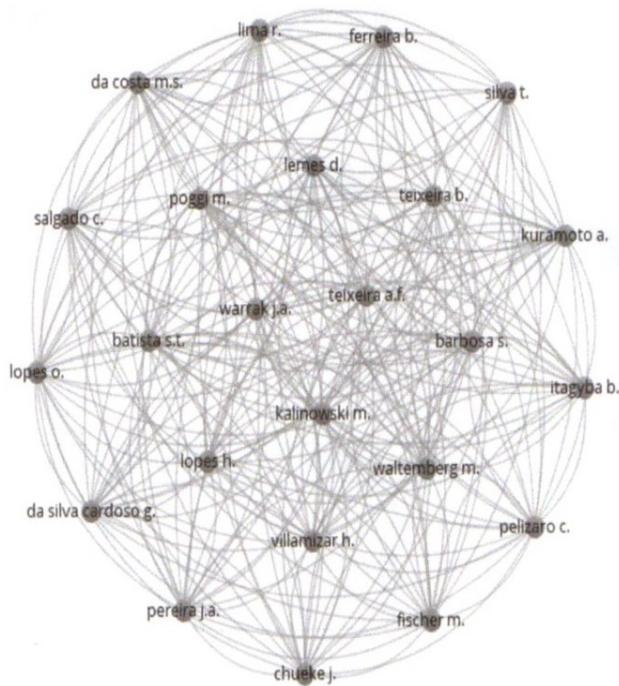
Figure 4. Author's collaborative network in Lean Digital transformation.

clusters, are identified in this subject. The authors in the figure are different from the distinguished ones in the table as there are no linked publications however, all authors presented are considered as main authors due to the equal number of publications.

Author Bildstein's primary contribution is a literature review on the main indicators that drive digital change within Lean production systems. Further research was conducted to examine the contributions of the main five levels of Lean production systems, considering digital transformation, which concluded that identified tools and processes were strongly influenced by digital transformation.

3.4. Geographical and institutional distribution

Every publication is assigned to a country or territory and to an institution based on the author's address(es) as available in Scopus retrieved data. Some publications had no information on the country or territory, as Lean Industry 4.0 had 49 publications and Lean Digital Transformation had 15; however, regarding institutions, no missing information were found. Articles with missing data were excluded from the analysis.

3.4.1. Countries

3.4.1.1. Lean Industry 4.0. To identify the ten countries with the highest number of publications based on the publication author affiliation, they were required to have at least one publication. Thus, the Lean and Industry 4.0 publications were derived from
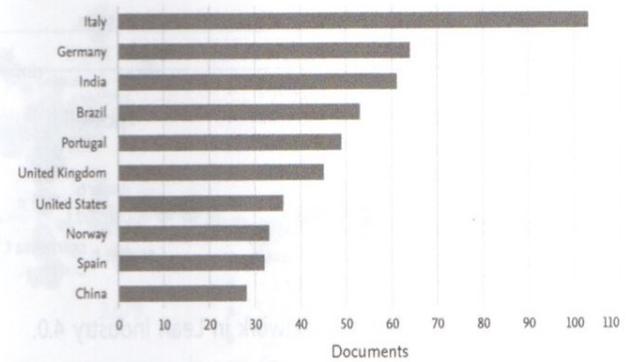

Figure 5. Top-10 publishing countries or territories on Lean Industry 4.0.

72 countries. 29 were from Europe, 23 from Asia, 7 in Africa, 7 in South America, 4 in North America, and 2 in Oceania. Eleven countries and territories have published between 27 and 103 publications (15.3%), Eleven published between 10 and 20 (15.3%), and Fifty countries and territories published less than 10 (69.4%). Figure 5 shows that Italy is the country with the highest number of publications ($n = 103$), followed by Germany ($n = 64$), and India ($n = 61$) in Lean Industry 4.0 field. Extending information on countries and territories, geographical inequality can be determined by looking at the continents. In the case of one author being affiliated in more than one country, or several authors are writing the article with different affiliations, all countries were included. For this reason, the total count of countries belonging to the total number of publications is larger than expected (873). Europe was assigned to 54.9% of the publications ($n = 479/873$), Asia to 21.5% ($n = 188/873$), Africa to 5.27% ($n = 46/873$), South America to 8.25% ($n = 72/873$), North America to 8.36% ($n = 73/873$), and Oceania to 1.72% ($n = 15/873$), therefore, in the scientific research domain, the collaborative countries tend to be geographically correlated, and center around the most productive countries in terms of publication output (Zheng et al. 2016). Publication from Italy and Germany primarily discuss the integration of Lean with cyber–physical systems rather than other Industry 4.0 technologies. However, in India, the publications focused on integrating Lean with the Internet of Things (IoT) rather than the cyber–physical system, which is briefly addressed. The majority of papers discussed in Italy, Germany, and India were done in the manufacturing industry, whereas articles from other sectors such as the services industry, were lacking. This shows that Europe and Asia are examining the integration of Lean and Industry 4.0 in manufacturing. However, the research contribution from each continent is directed at different Industry 4.0 technologies integrated with Lean tools.
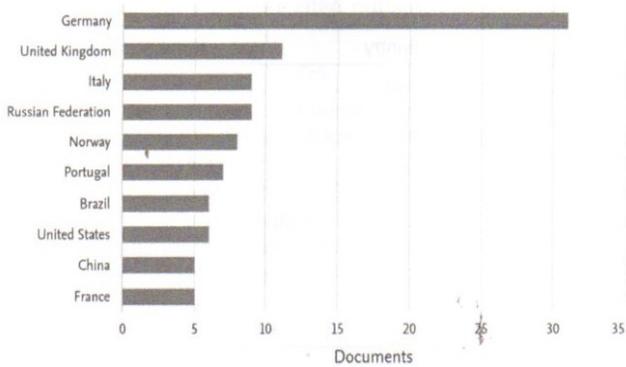
Figure 6. Top-10 publishing countries or territories on Lean digital transformation.

3.4.1.2. Lean digital transformation. Lean and digital transformation papers were from 45 different countries or territories. Of the 45 countries, 22 were from Europe, 14 were from Asia, 3 in Africa, 3 in South America, 2 in North America, and 1 from Oceania. A single country published 31 (2.22%) publications, thirteen published between 4 and 9 publications (28.9%), and 31 published less than publications (68.9%). Figure 6 presents Germany with the highest number of publications ($n = 31$), followed by the United Kingdom ($n = 11$). As mentioned in the previous section, the total count of countries belonging to the total number of publications is larger than expected; thus, for Lean digital transformation, it is 162. A geographical inequality can also be identified through the continents. As Europe accumulates 67.9% of the publications ($n = 110/162$), Asia accumulates 17.9% ($n = 29/162$), Africa accumulates 2.47% ($n = 4/162$), South America accumulates 4.94% ($n = 8/162$), North America accumulates 6.17% ($n = 10/162$), whereas Oceania accumulates 0.62% ($n = 1/162$). Several publications from Germany discuss Lean integration with different technologies such as cyber–physical systems, the Internet of Things (IoT), cloud computing, artificial intelligence, and Big Data. In contrast, the other countries did not discuss specific technologies but discussed the benefits of integrating Lean and digital transformation and the barriers faced. Most papers were for the manufacturing industry and were review studies, and very few have proposed frameworks that have not been tested. As a result, only Germany is integrating specific digital transformation technologies with Lean, while others are still reviewing the concept.

3.4.2. Institutions
3.4.2.1. Lean Industry 4.0. The top ten performing institutions in Lean Industry 4.0 are based on the author's affiliation (Table 6) with the highest number of publications. 160 different research institutions have 661 publications with institution information as one author can be affiliated to more than one institution, or several authors publish with multiple affiliations from different institutions. Of all institutions, 23.1% ($n = 37$) contributed to five publications or more, and 76.9% ($n = 123$) contributed to four publications or less. The major productive institutions are located in Europe. Regarding the number of publications, the Norwegian University of Science and Technology (Norway) stands out as the highest-performing institution (29 publications) because of author Powell's scholarly activity. Based on a scientific recommendation by (van Nunen et al. 2018) to subdivide all institutions participating in certain research as follows: academic (colleges and universities), private organization (e.g., industry, hospital), or governmental organization (policymakers). This classification would identify if the research were squarely suited to the world of academia an focus researchers on stakeholder involvement and policies (Gall, Nguyen, and Cutter 2015). However, the division is a hectic and time-consuming process as these classifications are not available on Scopus thus, they need to be searched and extracted manually.

3.4.2.2. Lean digital transformation. The top ten performing institutions in Lean digital transformation (Table 7) with the highest number of publications. The 146 publications have been published from 153 different institutions. The unexpectedly large number of institutions is due to the author's multiple affiliations. Out of the total institutions, 86.9% ($n = 133$) contributed to only one publication, and 6.54% ($n = 10$) contributed to two publications. Most active institutions in the Lean digital transformation field are located in Europe. The institutions with the highest number of publications in the Lean digital transformation field are Fraunhofer Institute for Manufacturing Engineering and Automation IPA (Germany), and Laboratoire d'Informatique en Image et Systèmes d'Information (LIRIS) (France) with eight publications. France's contribution is upon author Baboli and Rother top authors in the field.

3.5. Citation analysis

The cited analysis covers the knowledge output, which means other publications use this publication as a reference in the research (Li and Hale 2015). The citation analysis represents the number of times the publications have been cited by other publications listed in Scopus. In general, the number of citations portrays the publication's influence and notoriety,

Table 6. Top-10 publishing institutions on Lean Industry 4.0.

No.	Institution	Country	Number of publications
1.	Norwegian University of Science and Technology	Norway	29
2.	Polytechnic University of Milan	Italy	19
3.	Universidade Federal de Santa Catarina	Brazil	18
4.	University of Minho—Campus of Gualtar	Portugal	17
5.	Free University of Bozen-Bolzano	Italy	14
6.	University of Bergamo	Italy	12
7.	University of Aveiro	Portugal	11
8.	University of Johannesburg	South Africa	10
9.	Biblioteca Rostoni—LIUC Università Carlo CattaneoBottom of Form	Italy	10
10.	Politecnico di Torino	Italy	7

Table 7. Top-10 publishing institutions on Lean digital transformation.

No.	Institution	Country	Number of publications
1.	Fraunhofer Institute for Manufacturing Engineering and Automation IPA	Germany	8
2.	Norwegian University of Science and Technology	Norway	6
3.	Universität Stuttgart	Germany	4
4.	Istanbul Technical University	Turkey	4
5.	Polytechnic University of Milan	Italy	4
6.	Laboratoire d'Informatique en Image et Systèmes d'Information (LIRIS)	France	4
7.	Cranfield University	England	3
8.	Tecnologico de Monterrey	Mexico	3
9.	National Institute of Applied Sciences of Lyon	France	3
10.	Université de Lyon	France	3

thus, its quality (Smith 2007; Ugolini et al. 2015). In contrast, other authors (Walter et al. 2003; Chiu and Ho 2007) declared that the times a publication had been cited measures the publication visibility.

3.5.1. Lean Industry 4.0

The total number of times the publications on Lean Industry 4.0 have been used as a reference in other publications was 9900. However, the number of publications cited zero times contributed to 30.4% ($n = 201/661$), and publications cited 50 times or more contributed to 6.66% ($n = 44/661$). Literature presumed that open-access journal publications tend to be cited more than others (Whipple, Dixon, and McGowan 2013). Table 8 displays the ten most cited publications in the field. The paper with the highest number of citations is 'Industry 4.0 implies Lean manufacturing: Research activities in industry 4.0 function as enablers for Lean manufacturing' from Helmut-Schmidt-University, Institute of Production Engineering (Germany) in the *Journal of Industrial Engineering and Management* (Spain). The paper has been cited 439 times since its publication in 2016.

On the other hand, in terms of average citations per year the publication 'Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?' from Elsevier the *Technological Forecasting and Social Change (Netherlands) accumulated in 80 citations per* year. The time length of a publication is directly correlated to the number of times a publication has been cited (Qiu and Chen 2009). However, this does not

preclude recent publications from significantly impacting the scholarly field (Milfont and Page 2013). For example, based on the top cited papers determined a publication in 2018 and has been cited 363 times, compared to a published article in 2017 that has been cited 270 times. Most papers covered small-to-medium enterprises (SMEs); other industries, such as the service industry, were briefly discussed. Among the top 10 most cited papers, two papers investigated the impact of Lean and Industry 4.0 on manufacturing companies. Another study discussed and proposed a framework for assessing Lean and Industry 4.0 in Sustainable Supply Chain Management. The remaining publications reviewed literature and conducted exploratory studies on the enablers and barriers of integrating Lean with Industry 4.0. Thus, theoretical studies such as systematic literature reviews were more cited than other types of studies.

3.5.2. Lean digital transformation

The total number of publications was referenced 793 times in other publications. The number of publications cited zero times accumulated 45.2% ($n = 66/146$), and publications that were cited ten times or more accumulated 15.8% ($n = 23/146$). Table 9 represents the ten most cited publications in the Lean digital transformation field. The with the highest number of citations and the highest average of citations per year since its publication is 'Corporate survival in Industry 4.0 era: the enabling role of Lean-digitized manufacturing' from Emerald Group Publishing Ltd. *The Journal of Manufacturing*

Table 8. Top-10 frequently cited publications on Lean Industry 4.0.

No.	Title	Author(s)	Published year	Times cited	Average citation per year
1	Industry 4.0 implies Lean manufacturing: Research activities in industry 4.0 function as enablers for Lean manufacturing	Sanders A., Elangeswaran C., Wulfsberg J.	2016	439	62.7
2	The link between industry 4.0 and Lean manufacturing: Mapping current research and establishing a research agenda	Buer S.-V., Strandhagen J.O., Chan F.T.S.	2018	363	72.6
3	Lean automation enabled by Industry 4.0 Technologies	Kolberg D., Zühlke D.	2015	353	44.1
4	Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?	Horváth D., Szabó R.Z.	2019	323	80.8
5	Implementation of industry 4.0 and Lean production in Brazilian manufacturing companies	Tortorella G.L., Fettermann D.	2018	314	62.8
6	The evolution of production systems from Industry 2.0 through Industry 4.0	Yin Y., Stecke K.E., Li D.	2018	297	59.4
7	Toward Lean production in Industry 4.0	Mrugalska B., Wyrwicka M.K.	2017	270	45.0
8	Industry 4.0 Impacts on Lean production systems	Wagner T., Herrmann C., Thiede S.	2017	223	37.2
9	A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case	Yadav G., Luthra S., Jakhar S.K., Mangla S.K., Rai D.P.	2020	187	62.3
10	Industry 4.0 and Lean manufacturing practices for sustainable organizational performance in Indian manufacturing companies	Kamble, S., Gunasekaran, A., Dhone, N.C.	2020	183	61.0

Table 9. Top-10 frequently cited publications on Lean digital transformation.

No.	Title	Author(s)	Published year	Times cited	Average citation per year
1	Corporate survival in Industry 4.0 era: the enabling role of Lean-digitized manufacturing	Ghobakhloo M., Fathi M.	2020	122	40.7
2	Internet of Things (IoT) for integrating environmental and localization data in Building Information Modeling (BIM)	Teizer J., Wolf M., Golovina O., Perschewski M., Propach M., Neges M., König M.	2017	54	9.00
3	Textile Learning Factory 4.0 – Preparing Germany's Textile Industry for the Digital Future	Küsters D., Praß N.b, Gloy Y.-S.a	2017	52	8.67
4	Digital transformation priorities of India's discrete manufacturing SMEs—a conceptual study in perspective of Industry 4.0	Dutta G., Kumar R., Sindhwani R., Singh R.K.	2020	45	15.0
5	Rethinking Jidoka systems under automation and learning perspectives in the digital Lean manufacturing world	Romero D., Gaiardelli P., Powell D., Wuest T., Thürer M.	2019	35	8.75
6	Digitalization of learning resources in a HEI—a Lean management perspective	Tay H.L., Low S.W.K.	2017	32	5.33
7	Deriving essential components of Lean and Industry 4.0 assessment model for manufacturing SMEs	Kolla, S., Minufekr, M., Plapper, P.	2019	29	7.25
8	Mobile BIM implementation and Lean interaction on construction site: A case study of a complex airport project	Koseoglu O., Nurtan-Gunes E.T.	2018	28	5.60
9	COVID-19: Outcomes for Global Supply Chains	Fonseca, L.M., Azevedo, A.L.	2020	24	8.00
10	A conceptual framework to support digital transformation in manufacturing using an integrated business process management approach	Butt, J.	2020	24	8.00

Technology Management (United Kingdom). Similar to the previous section, the most frequently cited studies focus on SMEs' manufacturing sector. One study conducted an exploratory study in Higher Education Institutions to explore the integration of Lean with digital transformation to identify key factors that would facilitate this integration. Additionally, two other studies conducted conceptual studies based on a case study for firms to assist in framing their digital strategies and motivate them to adopt Lean tools and digital transformation technologies. As for the remaining publications, they are review studies that focus on the enablers and benefits of combining Lean and digital transformation.
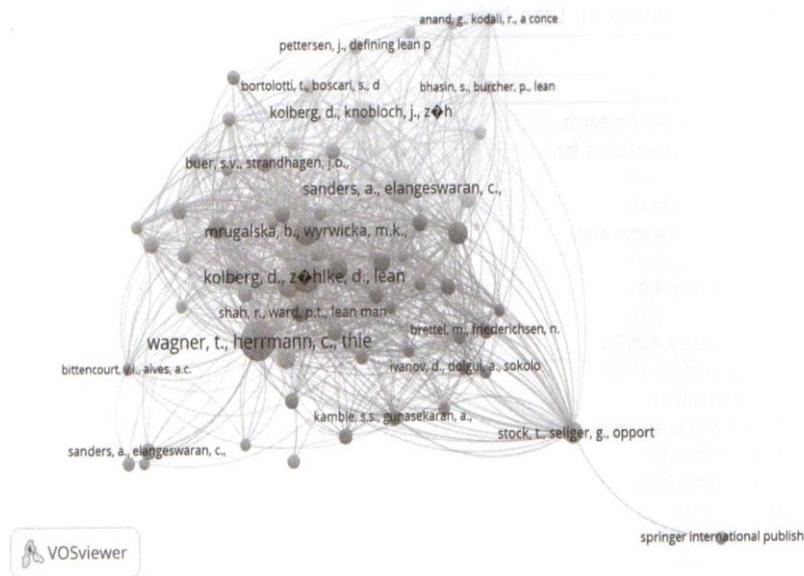
Figure 7. Co-citation analysis of publications on Lean Industry 4.0.

3.6. Co-citation analysis

Another citation process is the one that covers the knowledge input, i.e., the citing behavior in a publication or the references that are used in the publication (Li and Hale 2015). The citation analysis gives the number of references used by the publications on a topic. Co-citation analysis focuses on the relationship or interaction between two publications and provides an overview of publications that have been cited together in other publications (van Nunen et al. 2018). The more two publications are cited together, the more similarities between them are distinguished (Li and Hale 2015).

3.6.1. Lean Industry 4.0

For the analysis of co-citations used in Lean Industry 4.0 publications, it was required that the paper bibliography contain at least 8 references. Of the 26727 unique references included, only 65 met this condition. The Analysis and visualization of co-citations are executed using VOSviewer. The resulting co-citation map analysis is presented in Figure 7. The size of the circles represents the number of citations, the larger a circle, the more a publication has been cited in the Lean Industry 4.0 publications. The small distance between the two publications indicates a strong relation and a higher similarity between them. Circles with the same color imply a similar shared topic among these publications. The map shows how the references of the Lean Industry 4.0 publications cluster together, it illustrated five distinct clusters, where each cluster represents a field of Lean Industry 4.0 research: a yellow cluster (top), a blue cluster (bottom left), a green cluster (top left), a purple cluster (bottom right), and a red cluster (center). All clusters are

combined with each other creating 1282 links between them. The main cluster is the blue cluster as it has the biggest circle size. The blue cluster blong to Wagner, T,. Hermann, C., Thie.

3.6.2. Lean digital transformation

The minimum number of references used in a publication bibliography must be at least three. Out of the 5101 unique references, only 18 met the threshold. The co-citation map on Lean Digital transformation is shown in Figure 8. The map represents 3 distinct clusters where each cluster represents a field of Lean digital transformation research: a green cluster (left), a blue cluster (center), and a red cluster (right). The map has 55 links, the main cluster is the green belonging to Wagner and Mruglaska.

3.7. Subject categories

3.7.1. Lean Industry 4.0

The Scopus database assigns at least one subject area to each journal. The subject area can be defined as a particular field of research that assists in defining the publication's scope. The total count of the assigned subject areas to Lean Industry 4.0 publications is 20. Diverse subject areas are not observed. However, there are a variety of research themes. Out of the 20 subject areas, 3 subject areas (62.1%) contained at least 200 publications, and another 2 subject areas (16.3%) contained at least 50 publications. Figure 9 shows the top-5 assigned subject areas to Lean Industry 4.0 publications and the division over the years. The legend portrays the top-5 subject areas and the total number of Lean Industry 4.0 publications. The subject area with the most publications is 'Engineering' with 442. The distribution of the subject area over the years
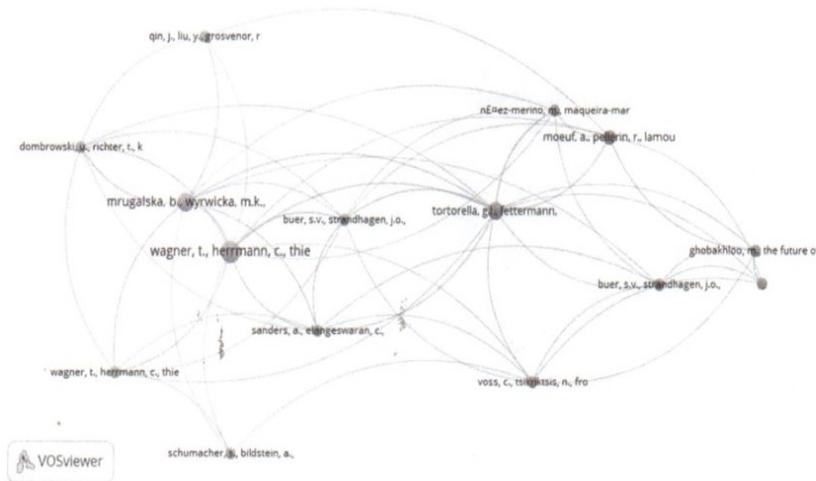
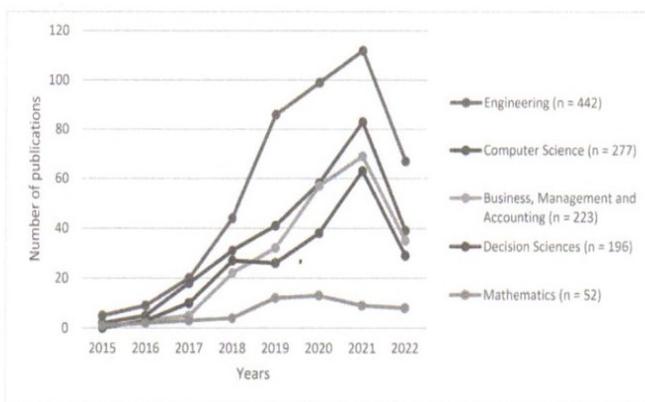**Figure 8.** Co-citation analysis of publications on Lean digital transformation.

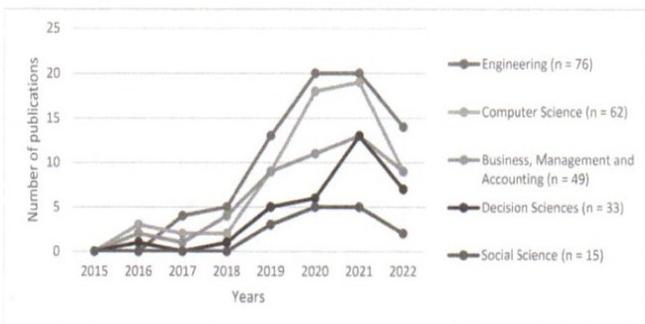**Figure 9.** Top-5 subject areas to the publications on Lean Industry 4.0.

Figure 10. Top-5 subject areas to the publications on Lean digital transformation.

gives an insight on the level of research each year spent on a specific area, and it can uncover subjects that gained more attention over time. A dropdown trend can be spotted, and again this is due the fact that the current study includes publications up to September 2022.

3.7.2. Lean digital transformation
The total count of the assigned subject areas to Lean digital transformation publications is 18. Of the 18 subject areas, 10 contained less than 8 publications (12.6%), and 4 contained at least 30 publications (71.3%). The top-5 assigned subject areas on Lean

digital transformation are presented in Figure 10. The subject area with the highest number of publications on Lean digital transformation is also 'Engineering' with 76 publications. It is expected to have Engineering as the active subject area since Industry 4.0 and digital transformation technologies are majorly applied in the manufacturing sector hence, the integration of Lean along with these technologies enables organizations to reduce waste and have efficient operating systems. Therefore, major publications published today and, in the future, will be Engineering related.

3.8. Terms analysis

3.8.1. Lean Industry 4.0
The analysis of terms used in the titles and abstracts of a publication can provide insight into the main topics and research trends. VOSviewer is used to analyze and visualize the terms or keywords. In the analysis, all noun terms are extracted; however, terms such as 'article' and 'introduction' were excluded. A minimum of keyword co-occurrence in a publication must be 4 at least. Thus, only 301 keywords met the threshold. The analysis is presented in Figure 11. The circle size represents the occurrence of a term, so the bigger the circle, the higher the term occurred in the abstract or title of the Lean Industry 4.0 or Lean 4.0 publications. The distance between the terms provides the overall information on their relatedness. The relatedness was determined by counting the number of times the terms occurred together in the titles and abstracts (Rodrigues et al. 2014). The different colors differentiate the formed clusters. The term analysis map portrays how the terms of Lean Industry 4.0 cluster together, the clusters with the major keywords used were the green (middle) and the yellow (middle). The most common keywords in the green cluster are
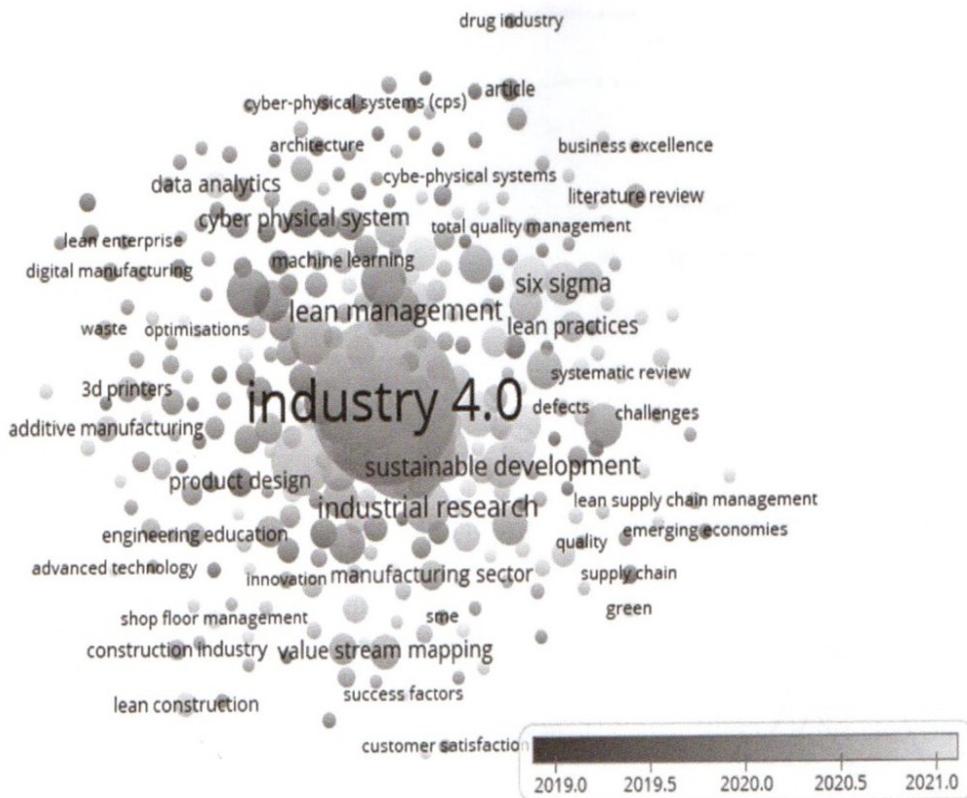
Figure 11. Terms analysis of Lean Industry 4.0 publications.

industry 4.0, Lean production, and smart manufacturing. The most common keywords in the yellow cluster are data analytics, production control, and Six Sigma. The time information in the figure represents the paradigm change of terms. Terms that are used more toward 2019 are in blue, while terms that are used more toward 2020 are in green. Looking at the periods and change happening, in 2018 the keywords focus was on cyber–physical systems; moving forward to 2019 Industry 4.0, and Lean manufacturing was the focus. In 2020, researchers started to include data analytics and Lean Six Sigma keywords.

3.8.2. Lean digital transformation

The co-occurrence of keyword inclusion criteria in this section must be in 2 publications at least. The reason for having a low number of occurrences is due to the recent activity of the Lean digital transformation field. Thus, 226 met this condition. The analysis is illustrated in Figure 12. The map represents how the terms of Lean Digital Transformation cluster together, the clusters with the major keywords used were the green (middle) and the light blue (middle-bottom). The most common keywords in the green-blue cluster are agile methods, Lean production, and digitalization. Now, based on the paradigm change of terms, in 2019 the major terms were design and system-focused. In 2019 and 2020, the main terms used were Industry 4.0 and digital transformation. In 2021

the terms like Lean principles, customer experience, and sales were used.

4. Discussion and implications

4.1. Benefits

Typically, improvement programs are most interested in how they affect performance. Hence, the obtained publications outlined several benefits for integrating Lean and Industry 4.0 as identified in the literature.

According to Doh, Deschamps, and Pinheiro De Lima (2016), a framework was designed to integrate the value chain into the system for better communication between users and processes. Saldivar et al. (2016) developed computational intelligence to manage customers' needs and wants to achieve mass customization of products. Tamas and Illés (2016) integrated several techniques with the following effects: enhanced equipment flexibility, real-time decision-making instead of complex decision-making, and modularizing the production system. Also, Tamás, Illés, and Dobos (2016) integrated value stream mapping and simulation tools to identify the most suitable future state map. As a result, the developed logistics intelligent solution eliminated the need for complex decision-making by implementing real-time decision-making. Tonelli et al. (2016) developed a model to help firms identify their core competencies for adding value at both a strategic and operational level.
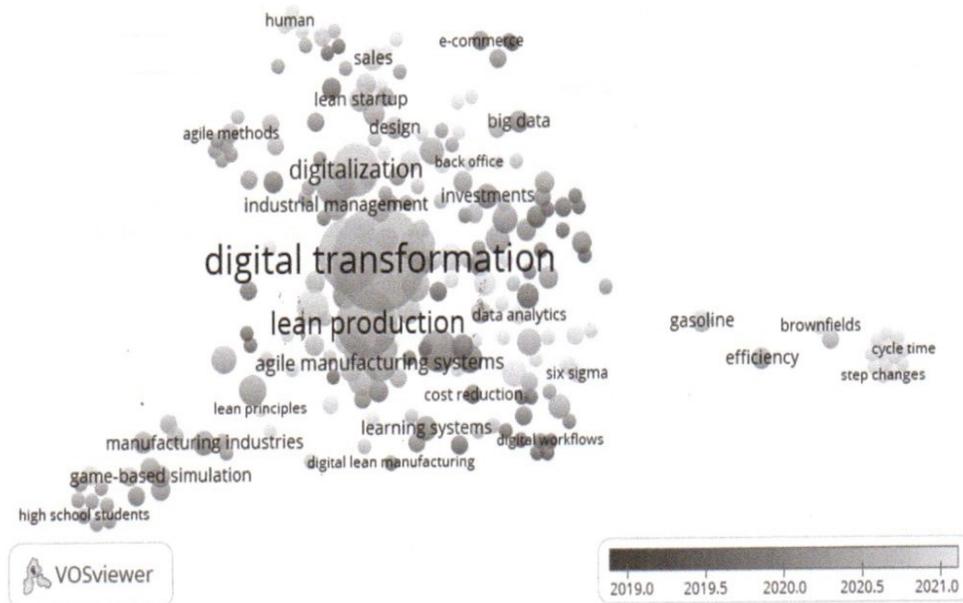
Figure 12. Terms analysis of Lean digital transformation.

Sanders, Elangeswaran, and Wulfsberg (2016) discuss how integrating Lean manufacturing and Industry 4.0 can enhance productivity, decrease waste, and reduce costs accordingly. Kolberg and Zühlke (2015) demonstrate how autonomic Kanban bins that can detect their inventory levels and automatically order parts from suppliers can help reduce inventory levels for modular workstations and flexible manufacturing lines. Using CPS-based smart Jidoka, Ma, Wang, and Zhao (2017) demonstrate that CPS can improve production flexibility and efficiency, improve reliability, and cut costs significantly. Tortorella, Giglio, and van Dun (2019) determined that the relationship between continuous flow and operational performance improvement is positively moderated by technology-related products or services. In contrast, process-related technologies are negatively moderated by low setup times. Mayr et al. (2018) performed a case study on the electric drives of a sheet metal stamping machine and found that Industry 4.0 tools enable them to achieve Lean targets more effectively. Ramadan and Salah (2019) showed how VSM, 5S, and POKA-YOKE, ICT, and RFID techniques, can be integrated with Lean practices to digitalize and smartly control and monitor Lean systems.

Other studies have also shown that processes and systems can be improved. Table 10 summarizes the performance benefits identified in the articles reviewed. It is expected that the corresponding benefits will motivate practitioners and senior managers to begin integrating and embed Lean and Industry 4.0 into their organizations. Furthermore, individuals will be able to enhance their skills through Lean Industry 4.0 benefits since the existing ones are inadequate.

4.2. Challenges

The integration of Lean and Industry 4.0 is a challenging process for organizations. Hence, based on the literature reviewed the authors have encountered several barriers.

Kolberg and Zühlke (2015) argued that a framework is needed to integrate Lean principles and Industry 4.0. Doh, Deschamps, and Pinheiro De Lima (2016) pointed out, that the implementation of Industry 4.0 can face challenges such as cloud storage, speed, security, and confidentiality. According to Dombrowski, Richter, and Krenkel (2017), the classification of Industry 4.0 characteristics, technologies, and systems must be verified and validated. Zuniga, Moris, and Syberfeldt (2017) suggest that a detailed methodology is needed to coordinate SBO (simulation-based optimization) and Lean practices with Industry 4.0 to improve firm performance efficiency. Mayr et al. (2018) suggested that to prevent failure, firms should integrate Industry 4.0 techniques holistically across their workforces to prevent failure. Gallo et al. (2021) argue that the human factor must be considered when integrating I4.0 tools with Lean production techniques. Yilmaz et al. (2022) stated that technological readiness and cost measures are critical to achieve a high degree of integration. Table 11 summarizes the challenges discussed while integrating Lean and Industry 4.0 that must be considered and mitigated to ensure the appropriate application.

4.3. Most integrated tools

The literature analyses had several scattered theoretical ideas about the integration of various Lean tools along

Table 10. Lean and Industry 4.0 integration benefits.

Benefits	References
Efficient communication	Doh, Deschamps, and Pinheiro De Lima (2016)
Managing customer needs	Saldivar et al. (2016)
Real-time decision making	Tamás, Illés, and Dobos (2016), Tamás and Illés (2016)
Identify core competencies	Tonelli et al. (2016)
Cost	Ma, Wang, and Zhao (2017), Sanders, Elangeswaran, and Wulfsberg (2016)
Flexibility	Gallo et al. (2021), Kolberg, Knobloch, and Zühlke (2017), Kolberg and Zühlke (2015), Ma, Wang, and Zhao (2017), Sanders et al. (2016), Tamás and Illés (2016), Wang et al. (2016)
Productivity	Dombrowski, Richter, and Krenkel (2017), Gallo et al. (2021), Sanders et al. (2016), Tortorella and Fettermann (2018), Wang et al. (2016), Zarte et al. (2016)
Quality	Ghi and Rossetti (2016), Jayaram (2016), Rossini et al. (2019)
Reduced inventory	Kolberg, Knobloch, and Zühlke (2017), Kolberg and Zühlke (2015), Tortorella and Fettermann (2018), Wagner, Herrmann, and Thiede (2017)
Reliability	Ma, Wang, and Zhao (2017), Wagner, Herrmann, and Thiede (2017)
Safety	Tortorella, Giglio, and van Dun (2019)
Delivery service level	Tortorella, Giglio, and van Dun (2019)
Performance improvement	Buer, Strandhagen, and Chan (2018), Gallo et al. (2021), Rauch, Dallasega, and Matt (2016), Tortorella and Fettermann (2018), Zuniga, Moris, and Syberfeldt (2017)
Achieve Lean targets	Mayr et al. (2018), Ramadan and Salah (2019)

Table 11. Lean and Industry 4.0 integration challenges.

Challenges	References
Framework required	Kolberg and Zühlke (2015)
Internet facility	Doh, Deschamps, and Pinheiro De Lima (2016)
Validation and verification	Dombrowski, Richter, and Krenkel (2017), Saldivar et al. (2016)
Detailed methodology	Zuniga, Moris, and Syberfeldt (2017)
Failure	Mayr et al. (2018)
Human factor	Gallo et al. (2021)
Technological readiness	Yilmaz et al. (2022)
Cost	Yilmaz et al. (2022)

with Industry 4.0. Limited papers (Buer, Strandhagen, and Chan 2018; Shahin et al. 2020; Gallo et al. 2021) have discussed and categorized the integration of Lean tools and Industry 4.0. This limitation shows that the integration is newly introduced to the scholarly field, and there are still studies measuring the several benefits, opportunities, and implications that could be gained. Table 12 briefly presents several studies that have mentioned the merge of different Lean tools and Industry 4.0 to give an insight into which tools and technologies are mainly getting integrated. The analysis has shown that Kanban is the most frequently integrated Lean tool with Industry 4.0 technologies. Various technologies have been combined with Kanban, such as Big Data, RFID, Cloud Computing, Real-Time Data, and Wireless Networks. In a future study, researchers can test and see the impact of integrating Kanban with HMI, SMED with cloud computing, or Poka-yoke with cloud computing.

4.4. Key gaps in literature

The literature reviewed in this study presented significant scientific gaps in the Lean Industry 4.0 and Lean digital transformation research domain. To motivate organizations for successfully integrating Lean and Industry 4.0, it is necessary to explore the potential performance implications through empirical studies. Although the current studies provide some indications on the potential performance impact, clearly, the studies are inadequate.

Moreover, although several of Lean tools have been integrated with Industry 4.0, there is no disciplined, systematic, organized, strategical, and practical framework that can integrate e Lean and Industry 4.0 in the literature. A framework for Lean Automation (LA) implementation, which incorporates I4.0 technologies into Lean Production (LP) in particular, has only been proposed by Tortorella et al. (2020). Their study showed that Lean Production and Industry 4.0 are directly related, and the proposed framework can overcome barriers and challenges to LP implementation. However, there is a lack of articles that propose a generic framework that could assess professionals in adapting Lean and Industry 4.0 in any sector.

Also, studies that present evaluations on the organizational performance based on the initiated framework are not available.

One of the most significant scientific gaps is the absence of real case studies. Although the literature has featured two case studies that discussed the benefits of integrating Lean and Industry 4.0 or digital transformation and proposed ways of integrating the tools and methodologies together. Currently, there is

Table 12. Frequent integrated Lean tools and Industry 4.0 technologies.

	Big data	RFID	Cloud computing	Real-time data	Wireless networks	HMI
Kanban (Pull)	(Chen and Lin 2017)	(Mrugalska and Wyrwicka 2017; Satoglu et al. 2018)	(Krishnaiyer and Chen 2017; Shahin et al. 2020)	(Mrugalska and Wyrwicka 2017)	(Dave et al. 2016; Kolberg, Knobloch, and Zühlke 2017)	
Poka yoke	(Mrugalska and Wyrwicka 2017)	(Satoglu et al. 2018)	(Mrugalska and Wyrwicka 2017)			(Satoglu et al. 2018)
Andon				(Ma, Wang, and Zhao 2017)		
SMED	(Sanders, Elangeswaran, and Wulfsberg 2016)	(Karre et al. 2017)				
Jidoka		(Ma, Wang, and Zhao 2017)		(Ma, Wang, and Zhao 2017)	(Ma, Wang, and Zhao 2017)	(Ma, Wang, and Zhao 2017)
VSM				(Meudt, Metternich, and Abele 2017; Mrugalska and Wyrwicka 2017)	(Meudt, Metternich, and Abele 2017)	
Kaizen						(Sanders, Elangeswaran, and Wulfsberg 2016)
TPM	(Wagner, Herrmann, and Thiede 2017)		(Hambach, Kümmel, and Metternich 2017; Mrugalska and Wyrwicka 2017)			(Sanders, Elangeswaran, and Wulfsberg 2016)
Heijunka						(Kolberg, Knobloch, and Zühlke 2017)
5S						(Karre et al. 2017)

no qualitative case study with data that presents a firm's overall performance enhancement as a result of the integration. Several organizations still do not understand the importance of embedding Industry 4.0 in their processes and operations. This gap impacts professionals and practitioners as they are demotivated to integrate due to the insufficiency of studies that portrays a successful Lean and Industry 4.0 integration entails, as well as comparing performance impacts to prove the efficiency of such integration.

Another gap present in the literature is the lack of empirical studies. The only empirical study conducted in the context of integrating Lean and Industry 4.0 was this year in 2022 by Najwa et al. (2022). Based on a survey and data obtained from different companies, the paper study concluded that Industry 4.0 technologies strongly correlate with Lean management tools. Organizations can improve their performance by understanding the relationship between these technologies and Lean management tools. It also explained the benefits of integrating Lean and Insurance 4.0 tools and technologies into firms. However, the main limitation of the study is the limited number of countries included and the use of only five organizational dimensions to evaluate firm maturity. The need for a practical application-based empirical study still exists despite this research. Practitioners, academicians, and researchers must direct their efforts on gathering and analyze data based on practical application. The empirical study will help us understand the organization's overall performance from an expert's perspective.

In addition, most of the most frequently cited papers discussed in the literature focus on the manufacturing industry and SMEs. However, other sectors, such as the service industry, are briefly discussed. Therefore, there is a need for reviews regarding integrating Lean and Industry 4.0 in other sectors to determine its impact on overall performance. Review studies in other industries will help practitioners and professionals understand the benefits, challenges, and how Industry 4.0 could be integrated with Lean.

In addition, it is found in the literature that Big Data is the most frequently used Industry 4.0 technology. However, there is no evidence that it is the ultimate technology that all organizations use to analyze their data most efficiently and effectively.

Furthermore, the majority of the articles published regarding the integration of Lean and Industry 4.0 are related to the manufacturing sector. Thus, limited studies have discussed the integration of Lean and Industry 4.0 and its impact on other sectors such as healthcare, higher education, and service.

This research contributes to developing the state of the art of Lean Industry 4.0 as well as Lean digital transformation to help professionals, researchers, and senior managers understand the challenges and benefits of integrating Lean along with Industry 4.0 and its

Table 13. Bibliometric analysis key findings.

Authors analysis	• Powell and Bildstein are the most productive authors. The cooperation network of authors in Lean Industry 4.0 reveals that Powell is linked (directly or indirectly) to other authors. Authors are mainly from Europe and publish in the field of engineering.
	• Majority of Lean Industry 4.0 authors (64.3%) are attributed to two or three publications only, and a small proportion (4.46%) has published at least 9 articles.
	• Most authors of Lean digital transformation (62.2%) are credited with only one publication. A small number of highly productive authors (4.40%) published at least four articles.
Journal analysis	• The Sustainability journal (Switzerland) is the key journal publishing on Lean Industry 4.0 research.
	• The International Journal of Lean Six Sigma is the key journal publishing on Lean digital transformation.
	• Of all Lean Industry 4.0 journals, 66.7% only published one publication. A small proportion of the journals (1.67%) accumulated one fifth of the publications.
	• From all Lean digital transformation journals, 90.9% published only one article.
Country/territory analysis	• Italy in Lean Industry 4.0 and Germany in Lean digital transformation are the countries and territories dominating the publication production. Publications are produced primarily on the European continent.
	• Of the countries and territories publishing on Lean Industry 4.0, 30.6% produced at least ten publications.
	• From all the countries and territories publishing on Lean digital transformation, 24.4% published five or more studies.
Institutional analysis	• The leading institution in Lean Industry 4.0 is the Norwegian University of Science and Technology (Norway).
	• Fraunhofer Institute for Manufacturing Engineering and Automation IPA (Germany) is the leading institution in Lean digital transformation publications.
	• 18.8% of the institutions contributed to at least six publications on Lean Industry 4.0.
	• 14.4% of the institutions contributed to two or more publications on Lean digital transformation.
	• Universities contributed to both research areas more than private or government organizations.
Citation analysis	• In Lean Industry 4.0 the most cited paper is from Sanders, Elangeswaran, and Wulfsberg (2016), and the paper with the highest average citations per year is from Horváth and Szabó (2019). Major number of publications (30.4%) were not yet cited, and minority (6.66%) was cited at least fifty times.
	• In Lean digital transformation the most cited paper with the highest average citations per year is from Ghobakhloo and Fathi (2019). Large proportion of publications (45.2%) was not yet cited, and a small proportion (7.53%) was cited at least twenty times.

impact on organizational performance. Also, it highlights new studies and methodologies by integrating different Lean tools and Industry 4.0 technologies that could impact organizational performance.

4.5. Key findings

Bibliometric analysis provided significant insights used in future studies and recommendations. The Power-law distribution, observed in other bibliometric studies in other areas, applies to many aspects of Lean and Industry 4.0 or digital transformation integration (Li and Hale 2015). Also, the analysis provides information on who is standing on the frontier of this research. All findings and knowledge are shown in Table 13.

It can be stated that Lean Industry 4.0/Lean 4.0 and Lean digital transformation attract academics and practitioners. Practitioners require enhanced knowledge to improve their results and overall performance, which is why they should integrate Lean and Industry 4.0 into their ongoing processes. Conversely, academics need to shed some light on areas where there are gaps or that are of global significance.

5. Conclusion, limitations, and future work

This paper analyzed Lean Industry 4.0/Lean 4.0 and Lean digital transformation using bibliometrics to characterize this research field and identify its benefits, challenges, and trends. The parameters that have been used in the bibliometric analysis presented in this study are the number of publications, number of citations, citation per publication, and average citation per year. The analysis in the study characterizes the evolution of Lean Industry 4.0 and Lean digital transformation in terms of publication output, journals, authors, countries, institutions, subject categories, and keywords. Articles published during 2010 and 2022 were examined to determine the benefits, challenges, gaps in the literature, and the major findings. The research objectives were achieved with the appropriate application of bibliometric analysis in the determined scope.

The results show that Lean Industry 4.0 and Lean digital transformation tend to be a field of active and extensive research, especially in the last five years; the publication's output follows exponential growth. As organizations continuously strive to improve productivity and sustain growth, Lean and Industry 4.0 provide valuable tools leading to impactful transformations; therefore, in the next few years the publications will keep rising, and the trend in publications is expected to increase.

In Lean Industry 4.0 the article "Industry 4.0 implies Lean manufacturing: Research activities in industry 4.0 function as enablers for Lean manufacturing" (Sanders, Elangeswaran, and Wulfsberg 2016) is the most cited article, and Daryl John Powell is the most published author in Lean Industry 4.0.

The *Sustainability Journal* (Switzerland) is the journal with the most significant number of publications on Lean Industry 4.0. The Norwegian University of Science and Technology (Norway) is the institution with the highest number of publications. Concerning all countries, Italy has the most significant number of publications in the literature. The subject category analysis highlighted that Engineering has the highest number of publications.

On the other hand, in Lean digital transformation, the article "Corporate survival in Industry 4.0 era: the enabling role of Lean-digitized manufacturing" (Ghobakhloo and Fathi 2019) is the most cited article Andreas Bildstein is the most productive author in Lean digital transformation. The *International Journal of Lean Six Sigma* has the highest publications on Lean digital transformation. Fraunhofer Institute for Manufacturing Engineering and Automation IPA (Germany) is the most important institution regarding the number of publications. Germany seems to have the highest number of publications related to Lean digital transformation. Hence, most publications for both research fields were issued in the European region. The subject category analysis also illustrated Engineering with the highest number of publications.

Significant positive aspects can be derived from the conducted study. Firstly, it concludes that the discussed research topics are newly introduced to the scholarly domain and most of the research is collaborative. Secondly, many different journals are published on topics with a variety of subject areas assigned however, they are not wide which indicates that they have a specific scope, and it is still a recent activity. Also, it pinpoints a geographical inequality that can be seen in research topics.

According to the results, Lean Industry 4.0 and Lean digital transformation have several benefits and challenges that should be considered while integrating. Also, new research studies should direct their effort in conducting empirical studies and case studies with before and after evaluations on organizational performance.

This paper contributed by highlighting the benefits and challenges while integrating Lean and Industry 4.0 or Lean and digital transformation and focusing on the scientific gaps in the literature, as no bibliometric studies have been found. In addition to the practical contribution, this article provides researchers and practitioners a guide to understanding the main topics being researched, and the literature trends, and encourages them to explore emerging issues. Furthermore, the traditionally investigated business segments like the manufacturing industry, however, less profoundly studied segments such as higher education, service sector, and healthcare can benefit from the integration of Lean and Industry 4.0 or Lean and digital transformation. Lastly, the study analyses, compares, and contrast the intercontinental findings to see countries or territories' research activity on the topic.

The limitations faced in this study are finding the academic material to support the merge of Lean and Industry 4.0 or digital transformation as it is newly introduced in the scholarly domain and it is not yet widely discussed. Also, the period set for the analysis had an interval of 8 years only as it is recent activity. In addition, it is depending on one scientific research database to obtain scholarly data. In addition, there is no mapping between specific Lean tools integrated with different Industry 4.0 technologies.

Future work should also focus on bibliometric studies or literature reviews on the integration of Lean Six Sigma and Industry 4.0 to visualize the scholarly activity, and trends, and to highlight the importance and impact of integrating both principles together on the organizations. It is suggested to initiate a tested and validated conceptual framework for the integration of Lean and Industry 4.0 to mitigate the organization's transitional journey toward the implementation of Industry 4.0 and the use of Lean principles will help in limiting the risk of failure factors (e.g., cultural, structural, and strategic), as firms are known for their resistance to change this will lessen the resistance. Also, empirical studies are highly recommended in order to investigate the researcher's and practitioner's perceptions on the integration and to motivate the application of the proposed integration. Recently, the integration issue is one of the most active topics and should be investigated carefully with real case studies and guidance.

Disclosure statement

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