08, 09, 10 e 11 de novembro de 2022
ISSN 2177-3866

Industry 4.0 and the Future of Manufacturing: A Bibliometric Review from the Perspective of Business and Economics

JOSÉLIA ELVIRA TEIXEIRA
UNIVERSIDADE ESTADUAL DO CENTRO OESTE (UNICENTRO)

ANA TERESA LEHMANN
UNIVERSIDADE DO PORTO

INDUSTRY 4.0 AND THE FUTURE OF MANUFACTURING FROM THE PERSPECTIVE OF BUSINESS AND ECONOMICS: A BIBLIOMETRIC STUDY

1. INTRODUCTION

Productive systems are undergoing disruptive transformations, materializing what is now often called a Fourth Industrial Revolution (Li, 2018; Horváth & Szabó, 2019). The digitalization of manufacturing (and other sectors) broke traditional barriers between industries, as new technologies allow combining products and services in a disruptive way, impacting on value chains (Schwab, 2016; Hoyer, Gunawan & Riaiche, 2020). Former industrial revolutions brought as benefits the intensification of technological progress and significant increases in productivity (Morrar, Arman, & Mousa, 2017). However, even though the Fourth Industrial Revolution that is underway may bring these benefits - even probably in a more pronounced way - it remains unclear which are the consequences, notably how it will affect the socio-technical system, new business models, and how the economy and the society will react to this new paradigm.

This paper develops a bibliometric study of the literature on Industry 4.0, from the perspective of Business and Economics. Bibliometric research aims to analyze the scientific production in a certain area, characterizing the literature, its trends, relevance and impact and, additionally, seeks to establish connections between themes, authors and academic communities, among other aspects (Chueke & Amatucci, 2015; Ozdagoglu et al., 2020). Among the questions answered in this paper are: i) What is the chronological evolution of the scientific output in this area?; ii) Which are the main sources (Journals) with more titles published in the field under research? iii) What are the most cited and impactful publications? iv) Who are the authors publishing more, and who are the most cited authors in the area?; v) What are the connections between these main authors?; vi) Where are these authors based, institutionally and geographically?; vii) What are the geographic connections between the authors?; viii) what key clusters and theme areas can be identified in the literature?

After this Introduction, the remainder of the paper is divided into the following sections. The second section includes a synthesis of the key literature, based on the most impactful papers identified by the Proknow-C *(Knowledge Development Process – Constructivist)* method used (described in Section 3.2). This literature review focused on the emergence of Industry 4.0 (or the Fourth Industrial Revolution) and the main associated technologies and the way in which these technologies affect production and other value-adding activities. Section 3 explains the methodology employed: the Proknow-C method, the bibliographic database (Web of Science), the extraction criteria and identifies the steps involved in the construction of the publications' database specifically developed for this paper and bibliometric analysis. Section 4 presents the results and discusses the detailed bibliometric analysis performed on the relevant literature. Finally, Section 5 synthesizes relevant final considerations.

2. LITERATURE REVIEW

2.1. Industry 4.0, related concepts and associated technologies

The term "Industry 4.0" was coined in 2011 in Germany, at the main world trade fair in industrial technologies (Hannover Messe) (Arnold, Kiel, & Voigt, 2016). The German government adopted the concept to initiate a high-technology based strategy to promote the digitalization of manufacturing (Sung, 2018). The process of digitalization of manufacturing has intensified worldwide, and the stage at which such developments are occurring is being questioned in many geographies (Nascimento et al., 2019). Industry 4.0 is often considered a "Fourth Industrial Revolution" (Reischauer, 2018) bringing considerable transformations to the

business world (Haleem & Javaid, 2019). According to Schwab (2016), the Fourth Industrial Revolution combines the digitalization of manufacturing with the integration of the digital, physical, and biological spheres. No matter how impactful were the former three Industrial Revolutions, what is truly distinctive about the Fourth is a blend of three reasons: velocity, scope and systemic impact.

The Fourth Industrial Revolution is already underway globally (Slusarczyk, 2018). The internet and the use of IT and robotics already existed; what is new is that Industry 4.0 integrates information technology, robotics and electronics, and the result of that integration are the so-called cyber-physical systems (CPS), which provide the integration of Information and Communication Technology with physical and computational components (Queiroz et al., 2019) and allow mass customization (Nascimento et al., 2019). Industry 4.0 is a production strategy that enables the introduction of a communication system among the equipments used in production and the products, via the hyperconnectivity based in the systems integrating manufacturing, known as the smart and connected factory (Nascimento et al., 2019). Many industrial projects include CPS as the key to new production systems. CPS define the Fourth Industrial Revolution (Lu, 2017), together with data processing and the use of that large amount of data in the management of intelligent systems (Strange & Zucchella, 2017).

The implementation of Industry 4.0 presupposes the adoption of disruptive technologies (Hannibal, 2020), notably digital technologies to manage processes that enable the creation of connections between machines, sourcing systems, production facilities, final products and clients (Ardito et al., 2019). Industry 4.0 is critically associated to digitally-based technologies such as: Internet of Things (IoT), Big Data, Cyber-Physical Systems, Data Mining, Cloud Computing, Augmented Reality, Virtual Reality, Robotics, and Additive Manufacturing (Kosacka-Olejnik & Pitakaso, 2019), as well as Artificial Intelligence, *Blockchain*, Nanotechnology, Quantum Computing and Biotechnology. Industry 4.0 is, thus, characterized by the use of several disruptive technologies (Hannibal, 2020). IoT allows integrating vertically and horizontally entire sectors, giving feedback in real time. Product customization in small scale, which before was not viable due to costs, becomes viable due to the technologies underlying Industry 4.0 (Lu & Weng, 2018).

The concepts of Industry 4.0 and smart factory are deeply interlinked (Shi et al., 2020), given the possibility of virtually reproducing the physical world (Morrar et al., 2017). As noted above, the term "Industry 4.0" (*Industrie 4.0*) was used initially in Germany (Federal Ministry for Economic Affairs and Energy, 2019). In other parts of the world, this concept was represented by other expressions such as "Smart Factory", "Smart Industry", "Smart Manufacturing" and also "Industrial Internet", the latter coined by General Electric (Slusarczyk, 2018). The Chinese version of Industry 4.0 is the "Made in China" government plan (Li, 2018). In the USA, the term used is "Advanced Manufacturing" (National Science and Technological Council, 2018). Other countries are following this trend, like Italy, UK, Spain, among others (Kosacka-Olejnik & Pitakaso, 2019).

2.2. Impact of Industry 4.0 from the perspective of Business and Economics

According to Maresova et al. (2018), the intensification of the digitalization of production and consumption relations and of digital innovation in relevant markets will have important consequences, notably contributing to the non-correspondence between industrial indices and GDP, in other words, creating a disconnection with the real economy.

Other aspect enabled by Industry 4.0, and noted in the literature, is the return of manufacturing production to traditionally industrialized countries like Germany and the USA. This process of reshoring has been supported by national governments (Ancarani, Di Mauro, & Mascali, 2019). The adoption of IoT in industrial management characterizes the digitalization,

automation and hyperconnection implied by the smart factory, requiring adaptations and innovations in business models (Arnold et al., 2016). A business model may be understood as all the mechanisms able to create, supply and capture value, among its connections and networks. Innovative business models not only bring adjustments in tasks, but also offer new solutions and are able to attract new consumers that were not satisfied with the available solutions (Muller, Buliga, & Voigt, 2018). To Muller et al. (2018), Industry 4.0 has been mainly directed to the business models of large firms, and the vast number of SMEs involved in the value chain have been neglected, both in theory and practice.

In the context of implementation of technologies associated to Industry 4.0, the digitalization of processes in organizations facilitates the integration of the functions in the firm and of the distinct agents in the supply chain, enabling an integrated and transparent ecosystem to all stakeholders involved, from raw materials suppliers to final consumers (Ardito et al., 2019). Industry 4.0 may be a powerful vehicle to improve efficiency and cost performance; however, as Demeter, Rácz & Losonci (2020) argue, Industry 4.0 implementation may even produce more pronounced effects on quality, delivery and flexibility. Citing these authors, "On a macroeconomic level, developing and supporting complex Industry 4.0 implementation projects might help countries to position themselves (and their companies) as potential locations for higher value-added manufacturing instead of pure cost-related offshore targets" (Demeter et al., 2020, p. 20). Furthermore, the implementation of Industry 4.0-related technologies has international repercussions, impacting directly the global value chain (Rodic, 2017). Industry 4.0 represents a way to digitalize the value chain relying on product and process innovation (Prause & Gunther, 2019). The concept of Industry 4.0 has been presented in different ways in the literature, and different maturity evaluation models have been proposed (Simetinger & Zhang, 2020).

3. METHODOLOGY

3.1. Bibliographic database and Criteria of Extraction of the Relevant Publications

"Bibliometrics", a term coined by Pritchard in the late 1960s, consists of the application of mathematical and statistical methods in the analysis of bibliographic references (Pritchard, 1969). It represents a methodology applicable to any area of knowledge, the task of the researcher consisting in adapting such methodology to the object of study and aim of the research (Oliveira et al., 2019). The analysis also relied on the application of a specific methodological instrument, the increasingly used method Proknow-C (Knowledge Development Process – Constructivist). According to the authors who developed it, this methodology facilitates the selection process of relevant articles that will integrate the portfolio of publications underlying the bibliometric analysis (Ensslin et al., 2010; Lacerda et al., 2012). Under the perspective of the approach to the research question, this method includes qualitative and quantitative dimensions. The bibliographic database selected to extract the relevant publications was Clarivate Analytics's Web of Science (WoS), a prestigious and inclusive source for Applied and Social Sciences (Mugnaini & Strehl, 2008). As the theme was Industry 4.0, the main keywords searched were "Industry 4.0" or substitute terms such as "Smart Factory" or "Intelligent Manufacturing". We combined such keywords with other relevant keywords like "Fourth Industrial Revolution", "Industrial Policy", "Industrial Production", "Manufacturing Production" and "Digitalisation", as detailed in Tables 1 below. Table 1 provides a synthesis of the main criteria used for the collection of the database relevant for the present analysis. Table 1 provides more details on the extraction of the database. A second filter implemented reduced the results to the areas of Business and Economics, resulting in 561 references extracted. Furthermore, another filter was applied, based on language. The following

languages were selected: English, Portuguese and Spanish, yielding 529 results. Such results were exported, accompanied by all relevant information fields, to an Excel data file.

Table 1. Results of WoS extractions

Keywords	Results (total)	Results by categories and document types	Categories			Results by categories, document types and languages
			Management	Business	Economics	
("industr* 4.0" OR "smart manufac*" OR "intelligent manufac*")	8943	424	286	120	86	405
("industr* 4.0" OR "smart manufac*" OR "intelligent manufac*") AND "Fourth Industrial Revolution"	642	76	42	23	23	69
("industr* 4.0" OR "smart manufact*" OR "intelligent manufact*") AND "Industrial Policy"	18	6	1	3	2	4
("industr* 4.0" OR "smart manufac*" OR "intelligent manufac*") AND ("Industrial Production"OR"manufac* production")	176	2	2	0	2	2
("industr*4.0" OR "smart manufac*" OR "intelligent manufact*") AND ("digitalization"OR"digitalisation")	545	53	34	12	14	49
TOTAL	**10324**	**561**	**365**	**158**	**127**	**529**

Source: Own elaboration (Collection Period: 13th-17th September 2020)

The data collection process was carefully managed using separate spreadsheets for the different WoS extractions. New spreadsheets were organized only with the dataset needed for the application of the Proknow-C method (explained in detail in the following section). All extractions were consolidated and thoroughly analyzed, in order to eliminate duplicated titles. After this stage, a database with 402 references remained.

3.2 Application of the Proknow-C method for document selection

The Proknow-C method contributes to undertake a more systematic documents' selection process (Tasca et al., 2010, Afonso et al., 2012). The method was implemented as follows. In the Excel spreadsheet containing the 402 documents, the following content was copied into specific columns: authors, title, year of publication, number of citations, abstract. Then, a column with identifiers was added, and all publications were numbered from 1 to 402; another column was added, designated "publications aligned by titles". All titles were read and selected according to the coherence of the title with the research topic, and among these resulted 299 aligned publications.

The next step consisted of selecting the relevant publications according to the number of citations, and establishing a cut-off point. For that, the Proknow-C method establishes as one of the criteria the Pareto Theorem (Pareto, 1896), which claims that a part of the sample will correspond to the majority of the results. That is, when selecting a minority (20%) of the most cited publications, such 20% will represent the most recognized publications in that portfolio (Lacerda et al., 2012). In this research, we followed that method, selecting the 20% most cited publications as the most representative of the database, totaling 43 scientific publications.

The method suggests that the most recent articles of the database should also be selected, i.e. the articles published in the two most recent years. The addition of this criterion to the

former resulted in 215 publications. Then, the next is to select certain publications that are neither among the 20% most cited, nor among the most recent. The selection criterion consists of gathering an authors' database with the authors that within the 20% of the most cited in the overall publications' portfolio, and to try to identify whether they possess publications that are not among the already selected ones (Dutra et al. 2015). As a result of this latter step, zero articles were found (19 articles by the same authors among the 20% Pareto-based sample were found, but they were included already in the array of most recent publications – i.e. from 2019 and 2020).

After these steps, the 43 most cited articles were added to the 215 most recent, corresponding to a portfolio of 258 publications. Finally, all the abstracts were read and screened in order to verify their relevance and alignment with the theme. It was found that 51 were not aligned, hence leading to a final database consisting of 207 publications. Among the most cited articles, initially 43, it was concluded that only 32 were aligned and relevant to the research (thus 11 not being relevant). This group of 207 publications with complete information in the relevant fields was exported to Excel and to Endnote, becoming the final database considered for the results presented in this paper.

In a first stage, the data (from the 207 final publications) obtained via the Proknow-C method were duly subject to an initial treatment in Excel, and the data on the date of publication, most cited publications and authors in the topic, most relevant journals, among other variables, were extracted and scrutinized. At a second stage, in order to perform the application of bibliometric methods, the 207 publications extracted from WoS were exported to the VOSviewer (*Visualization of Similarities Viewer*) software, a tool allowing the manipulation the bibliographic metadata, as well as permitting the conversion into maps, networks and tables to be used to enrich the bibliometric analysis (Van Eck & Waltman, 2020). At this stage, we analysed the chronology of the publications, the networks of authors, the main countries where the authors of the publications were based, the publications' sources, and the occurrence of the main keywords – in order to understand the trends and the main areas of interest in Industry 4.0 from the perspective of Business and Economics.

4. RESULTS AND DISCUSSION

4.1. Bibliometric analysis about Industry 4.0 from the Perspective of Business and Economics

4.1.1. Type of publication and Year of Publication (Chronological Analysis)

Among the 207 documents composing the database underlying this analysis, 185 are articles (89% of total) and 22 are review articles (11%). As expected, considering the already explained genesis of the term, "Industry 4.0" only appears in publications available from 2012 onwards (Federal Ministry for Economic Affairs and Energy, 2019). However, this term is also associated and treated conceptually as similar to "Smart factory", "Smart industry" or "Smart manufacturing" (Slusarczyk, 2018). For this reason, it is possible to find publications related to these last three terms since 1992, according to the database extracted from WoS. This is a reason why one of the publications reported in Table 4 below dates from 1995. Yoshikawa (1995) was focused on Intelligent Manufacturing Systems. Table 2 below shows clearly a growing interest in the theme of Industry 4.0 in Business and Economics – among 207 selected publications, 50,2% were published in 2020, and about 90% only in 2019 and 2020.

Table 2. Year of Publication of the 207 Articles Selected

Year	N. of Articles	% of 207
2020	104	50.24
2019	81	39.13
2018	11	5.31

Year	N. of Articles	% of 207
2017	7	3.32
2016	3	1.44
1995	1	0.48

Source: Own elaboration.

4.1.2. Sources – journals

The 207 selected publications belong to 97 sources (scientific journals).

Table 3 below identifies the 10 scientific journals with more publications about Industry 4.0 in the areas of Business and Economics. Table 3 can be read in two ways: number of articles or impact of the articles published (proxied by the number of citations of all articles published in each journal). If we look at the first criterion (number of articles published), there are three leading journals in this theme, respectively: Journal of Manufacturing Technology Management (20 publications), Technological Forecasting and Social Change (16) and Systems Research and Behavioral Science (14). When the citations of the publications are taken into account, Technological Forecasting and Social Change leads the way, with 520 citations (taking the 16 publications together – representing 66,8% of the total of citations of the top 10 Business and Economics journals in this theme).

Table 3. Sources with more titles published in Industry 4.0 in Business and Economics

Ranking	Journals' name	No. of publications	Citations
1	Journal of Manufacturing Technology Management	20	77
2	Technological Forecasting and Social Change	16	520
3	Systems Research and Behavioral Science	14	21
4	Competitiveness Review	6	1
5	Entrepreneurship and Sustainability Issues	6	74
6	Journal of Intellectual Capital	5	11
7	Quality-Access to Success	5	2
8	Management Decision	4	17
9	Polish Journal of Management Studies	4	53
10	Problemy Zarzadzania-Management Issues	4	2

Source: Own elaboration.

Table 4 below identifies the 10 most cited publications in our database. Despite the newness of these publications, two among these articles display over 100 citations, notably Li (2018) with 140 citations, and Muller, Buliga and Voigt (2018) with 105 citations.

Table 4. Most Cited Publications

Ranking	Authors	Title	Year	Citations
1	Li, L	China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0"	2018	140
2	Muller, JM; Buliga, O; Voigt, KI	Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0	2018	105
3	Strange, R; Zucchella, A	Industry 4.0, global value chains and international business	2017	63
4	Sung, TK	Industry 4.0: A Korea perspective	2018	63

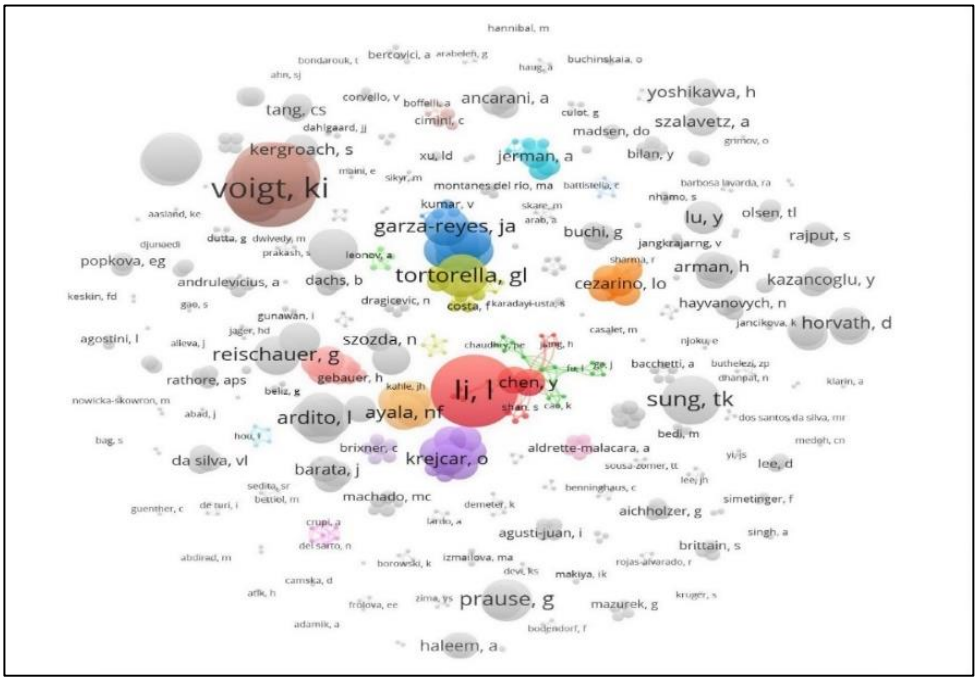
Ranking	Authors	Title	Year	Citations
5	Arnold, C; Kiel, D; Voigt, KI	How the Industrial Internet of Things changes Business Models in different manufacturig industries	2016	55
6	Slusarczyk, B	Industry 4.0 - Are we ready?	2018	48
7	Ardito, L; Petruzzelli, AM; Panniello, U; Garavelli, AC	Towards Industry 4.0 Mapping digital technologies for supply chain management-marketing integration	2019	41
8	Reischauer, G	Industry 4.0 as policy-driven discourse to institutionalize innovation systems in manufacturing	2018	39
9	Nascimento, DLM; Alencastro, V; Quelhas, OLG; Caiado, RGG; Garza-Reyes, JA; Lona, LR; Tortorella, G	Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context A business model proposal	2019	36
10	Prause, G; Atari, S	On sustainable production networks for Industry 4.0	2017	31

Source: Own elaboration.

4.1.3. Most Cited Authors

A total of 531 authors and co-authors were detected in the sample. , related to Industry 4.0 in Business and Economics. Chen is the author who has published a greater number of publications (6), followed by Tortorella, Voigt and Gotz (4 publications each). However, when one analyzes the number of citations these authors have (combining all articles in the theme), it becomes clear that the three most cited authors - and the only ones with a total of citations in this theme over 100 are: Voigt (167 citations), Li (147) and Mueller (123) (see Figure 1).

Figure 1. Map of Authors with More Citations in Industry 4.0 in Business and Economics

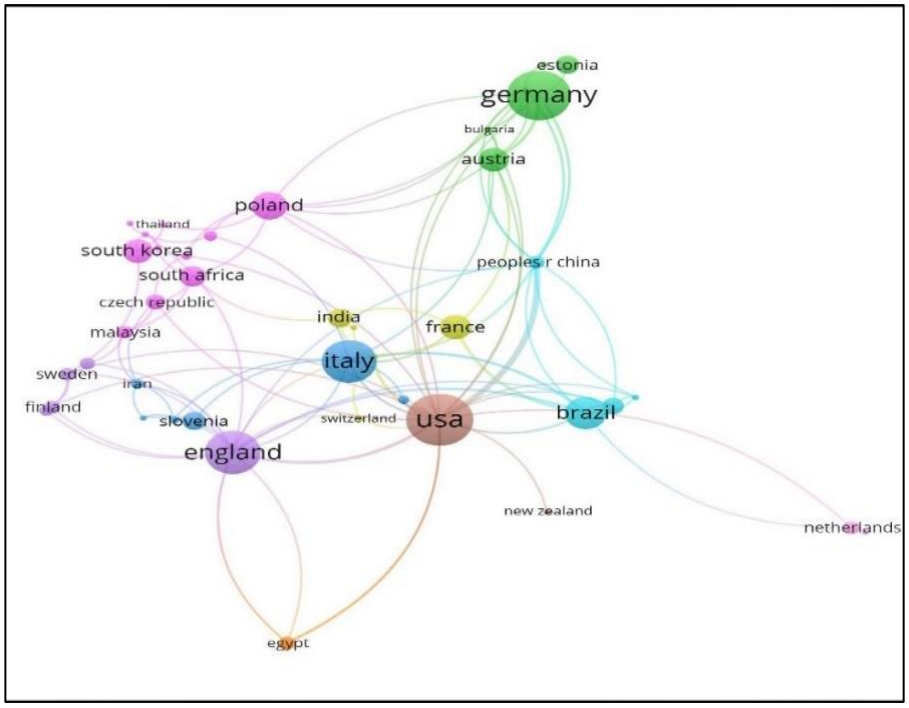


Source: Own elaboration with WoS references in the VOSviewer software.

When analyzing the main networks of authors and co-authors of the 207 publications under study, and the institutions to which they are affiliated, 337 institutions are included. The 10 institutions with more occurrences and the respective number of citations by authors in the

area. Four institutions have 5 publications by affiliated authors, notably: Old Dominion University (USA), Universidade Federal de Santa Catarina (Brazil), Texas A&M International University (USA) and University of Johannesburg (South Africa). When looking at the joint number of citations of the publications authored by researchers affiliated with such institutions, the institutions with more citations are Old Dominion University (USA, 150 citations) and Friedrich Alexander University Erlangen Nurnberg (Germany, 110 citations). The 207 publications under scrutiny include 54 countries of affiliation of authors / co-authors. The top 10 countries where more publications originate in the theme analyzed. Italy, the USA and Poland clearly lead in this criterion, all with more than 20 publications. By number of citations, the leading countries are: USA (284 citations), Germany (262), Brazil (205) and Italy (204). All the BRICS (Brazil, Russia, India, China and South Africa) countries are represented in the top 10. Figure 2 complements this analysis, evidencing the clusters of the most cited publications and the countries where the authors of such publications work. The clusters led by the USA, Germany, Italy, England, Brazil and France are the most salient.

Figure 2. Network of countries with more citations



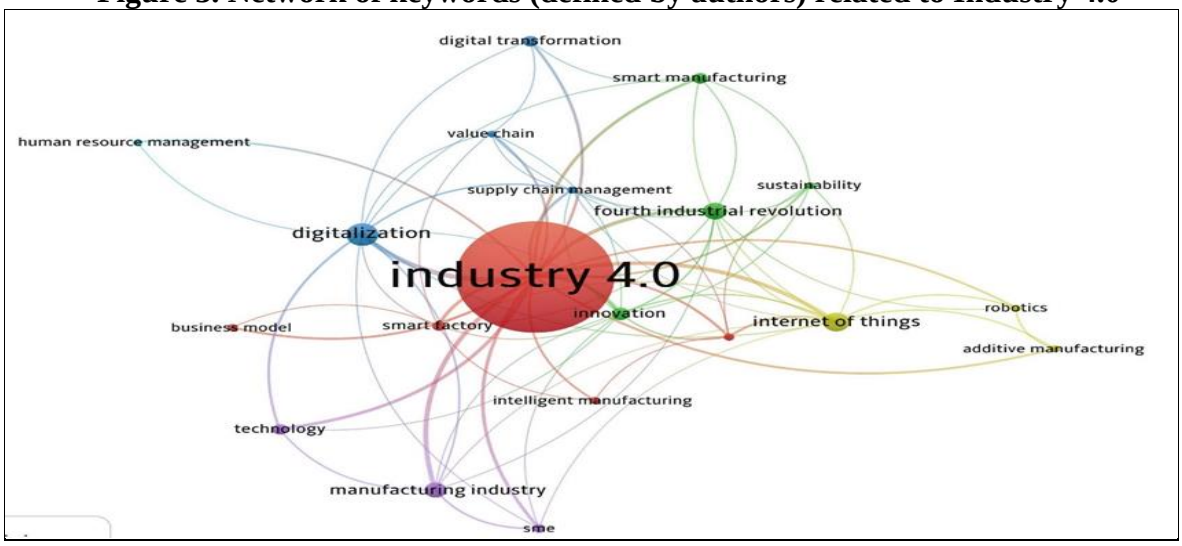
Source: Own elaboration with WoS references in the VOSviewer software.

4.2. Discussion of key clusters and main theme axis as pointers for future research

The groupings of keywords with more occurrences in the analyzed publications allow to identify the main themes about Industry 4.0 and the future of manufacturing from the perspective of Business and Economics, helping to understand the interplay of such themes at both the theoretical and empirical level, and providing indications for future research.

Considering the keywords defined by the authors of the publications under analysis, only 6 keywords exhibit 10 or more occurrences, and 20 of such keywords appear 5 times or more in the publications' database. Not surprisingly, our key theme (Industry 4.0) is the keyword with by far more occurrences (171) in the publications' database.Based on the authors' keywords, and on the strength of connection between such keywords, we were able to identify six clusters (networks of keywords), as per Figure 3 below.

Figure 3. Network of keywords (defined by authors) related to Industry 4.0



Source: Own elaboration with WoS references in the VOSviewer software.

These 6 clusters (networks of keywords with greater connection strength) are as follows:
-1st Cluster: Industry 4.0; Smart manufacturing; Smart factory; Big data; Business model.
-2nd Cluster: Fourth Industrial Revolution; Smart Manufacturing; Innovation; Sustainability.
-3rd Cluster: Digital transformation; Digitalization; Value chain; Value chain management.
-4th Cluster: Additive manufacturing; Internet of Things; Robotics.
-5th Cluster: Manufacturing industry; Technology; Small and Medium Enterprises.
-6th Cluster: Human resources management.

The 6 clusters identified provide important pointers about the key areas in the current and future research agenda.

The first cluster focuses on Industry 4.0 and on related topics like Smart manufacturing and Smart factory, linking those concepts to Big data, essential for the connectivity underlying Industry 4.0, and to enable new business models. This vindicates a part of our literature review above, when we highlight the impact of Industry 4.0 on new business models.

The second cluster departs from the general concept of the Fourth Industrial Revolution and Smart manufacturing to establish a clear link and strong connection with keywords such as Innovation and Sustainability. These are crucial factors of competitiveness for nowadays' economy, relying on the provision of goods, services and processes that are both innovative and sustainable. Sustainability is also a key trend that no manufacturer can ignore, and it is highly promoted by 4.0 production technologies.

The third cluster links clearly the phenomenon of Digital transformation / Digitalization to value chain, and value chain management, as identified earlier. The expansion of digital technologies allows to reconfigurate value chains in novel ways, including providing internationalization opportunities that are significantly less costly, and that may be particularly attractive for firms with relatively scarce resources, such as SMEs.

The fourth cluster is more technology-based, linking IoT to Robotics, to Additive Manufacturing. As reviewed in the literature above, the technologies associated to Industry 4.0 are one of the most critical conditions *sine qua non* for Industry 4.0 - without which it could not exist.

The fifth cluster relates manufacturing industry to technology then to SMEs. One of the most relevant areas of research refers to the extent that Industry 4.0 can be implemented in companies that lack scale and often resources, like often happens to SMEs. Thus, the deployment of technologies in the manufacturing industry according to firm size may be a promising area of research.

Finally, the last cluster is focused on the human resources area of management. Industry 4.0 is by no means a purely technological phenomenon; it is, crucially, a human and social reality. In this vein, managing human resources to enable the transition to Industry 4.0 is certainly one of the main challenges, both in the literature – theoretically – and in practice. There is a vast consensus about the fundamental needs for upskilling and reskilling of human resources implied by the implementation of Industry 4.0.

4.3. Main thematic axes of the publications associated to Industry 4.0 from the perspective of Business and Economics

Following the definition of these clusters, automatically performed by the software, using the keywords selected by the authors, it was decided to develop a deeper qualitative analysis. In order to accomplish this objective, not only the authors' keywords were considered, but also a careful analysis of the main themes emerging in each publication's title and abstract was conducted.

Table 5 synthesizes the main thematic axes identified in the 207 publications constituting the database. Some publications include more than one of such main theme areas.

Table 5. Main Thematic Axes of the 207 Publications Associated to Industry 4.0

N	Main thematic axes	Total
1	Technologies used in Industry 4.0	30
2	Programs/Plans/ Public policies for Industry 4.0	25
3	Management	24
4	Digitalization	23
5	Literature review about Industry 4.0	22
6	Smart factory/Smart manufacturing	17
7	Supply chain	16
8	Business models	16
9	Implications of Industry 4.0 for the workforce	15
10	SME/Startup	14
11	Strategy	12
12	Sustainability	7
13	Internet of Things	6
14	Finance/Financial services/Investments	6
15	Maturity models for Industry 4.0	5

Source: Own elaboration.

We now elaborate on these results, trying to interpret them and add value to the understanding of the phenomenon under scrutiny.

The technologies promoting Industry 4.0 and accelerating the Fourth Industrial Revolution is the most frequent theme arising in the analysis, representing the main interest in 30 publications. The main technologies studied in these publications are: Internet of Things (IoT) (Ardito et al., 2019; Matthyssens, 2019; Zhang & Chen, 2020; Nhamo, Nhemachena, & Nahamo, 2020); Cyber-Physical Systems (CPS) (Lu, 2017; Nascimento et al., 2019); Augmented Reality, Big Data (Poma, Al Shawwa, & Maini, 2020), Nuvem (Kosacka-Olejnik & Pitakaso, 2019) and Autonomous Robots (Klincewicz, 2019; Kolmykova & Merzlyakova, 2019). Cyber-Physical Systems, with the introduction of sensors allowing to recognize automatically objects and to evaluate performance associated to virtual businesses through IoT have an impact throughout all the value chain, being able to integrate the value chain *end-to-end*, improving products and processes throughout all the manufacturing value chain (Lu,

2017). The Internet of Things (IoT), a key topic in six documents in this portfolio, has a crucial role in the transition of manufacturing to Industry 4.0, permitting the digitalization of firms through the interconnection and integration not only of the human resources, but also of the objects or products (Rajput & Singh, 2019).

A significant number of the publications analyzed highlights the public policy realm, notably focusing on the creation of plans and programs by governments, and on Government as an enabler of the implementation of Industry 4.0 (Hoyer et al., 2020) – with a special prevalence of research mentioning the German government, who coined the term "Industry 4.0" (Reischauer, 2018; Slusarczyk, 2018). "Management" is the central topic in 24 documents, either focusing on managerial areas relevant to the Industry 4.0 concept, or how management is impacted by Industry 4.0. Aspects such as organizational learning for the adoption of Industry 4.0-related technologies (Lenart-Gansiniec, 2019), aspects concerning the skills of the human resources (Kruger & Steyn) skills required due to the adoption of new organizational paradigms (Marnewick & Marnewick, 2020) interaction between human resources and robots (Lobova et al., 2020). Related to this, the theme "Strategy" (present in 12 publications) appears vinculated both companies and to governments.

Digitalization of firms represents the focus of 23 publications. Sung (2018) observes that digitalization is a previous step to the implementation of Industry 4.0. The literature demonstrates that this topic is becoming essential in the literature (Szalavetz, 2019). A related theme that is still arising and consolidating in research is Digital Platforms (Schmidt et al. , 2019). Another finding is that Industry 4.0 commands a growing number of literature reviews (with 22 being identified in this research) – vindicating that this is a phenomenon of growing interest that needs to be properly understood (Kosacka-Olejnik & Pitakaso, 2019).

The terms "Smart factory" and "Smart manufacturing" are also being used in many publications – in 17 of them, they arose clearly as the focus. Another key theme is how management in the Industry 4.0 era impacts domestic and global supply and value chains (Chauhan & Singh). In this topic, the simulation made by (Ghadge et al., 2020) confirmed that Industry 4.0-related Technologies may strongly affect the supply and value chain. The supply chain represents the focus of 16 documents (Krykavskyy, Pokhylchenko, & Hayvanovych, 2019). As already mentioned in the Introduction and synthesis of the literature above, business models have been altered with the advent of digitalization and the path towards Industry 4.0 (Zhang & Chen, 2020), and 16 publications specifically analyze that.

The implementation of such technologies and of digitalization lead to substantial changes in the businesses' networks. All that impacts on operations, networks, organizational culture, managerial strategy and business models (Arnold, Kiel, & Voigt, 2016). Business model implications of Industry 4.0 is a major theme in the literature, although further research is needed. The implications for the workforce of Industry 4.0 is also a crucial topic, the focus of 15 of the publications surveyed. The new business models related to Industry 4.0 affect directly the workforce and its interactions and relations with the technologies, with the organizations, and with a diversity of stakeholders. The digitalization of manufacturing provides a new meaning to the interactions between the workforce, the company and the clients (Kazancoglu & Ozkan-Ozen, 2018).

Other relevant themes, albeit with a smaller number of specific documents, that have emerged in the present dataset are: Sustainability (7 publications), Finance/Financial Services/Investments (6), and Maturity models for Industry 4.0 (5). These themes tend to be present in the discussions, and by no means have less relevance; probably this indicates the need for further research about these topics or the lack of data or concrete empirical cases to develop these topics in a deeper manner. According to Simentinger & Zhang (2020), there are several models to assess the maturity of the implementation of Industry 4.0 that help mapping possible horizons for such implementation, and the willingness of the firms to assimilate this

concept. However, the Industry 4.0 concept (and what it exactly entails) is not yet consensual; hence, different maturity models have been proposed, generating gaps and debates in the literature. Industry 4.0 also brings new solutions in terms of sustainability, which is at the core of a future perspective for a new era of manufacturing (Prause & Atari, 2017). Industry 4.0 technologies tend to be consistent with sustainability, and better and more efficient use of resources throughout the value chain. In this context, maturity models should also take this aspect into consideration.

5. FINAL REMARKS

The implementation of Industry 4.0, or in other words of the "Fourth Industrial Revolution" is underway. This paper, after reviewing the relevant concepts and the key literature on Industry 4.0 from the perspective of Business and Economics, performed a systematic analysis of the literature based on a rigorous bibliometric methodology. The Web of Science was used as the source of the publications surveyed. 10.334 publications were identified in the realm of Industry 4.0 in this bibliographic database. We applied filters to select the relevant literature, notably according to type of publication (articles, reviews & book chapters), by categories of WoS (Business/Management and Economics), and by language (English, Spanish and Portuguese). The increasingly popular, Proknow-C method was used to perform the bibliometric analysis. As explained in Section 3.2, more specifically on Figure 1, a purposefully constructed database (portfolio) included, finally, 207 publications.

Using this portfolio, a detailed bibliometric methodology was followed to extract a clear characterization of the current state of the art of the literature on Industry 4.0 from the perspective of Business and Economics. The predominant type of publication (89%) were articles, and 11% were literature reviews – none addressing specifically our topic. One of the key conclusions emanating from a chronological analysis of the literature was the newness of this literature: about 90% of the publications were from 2019 and 2020, and 50,2% were from 2020. Regarding the sources of these publications, the top 10 journals (both by number of publications and by number of citations of the respective articles) were identified. Clearly, if one looks at a measure of relevance, the leading journal is Technological Forecasting and Social Change, whose 16 publications jointly represent 520 citations (exactly two thirds of the total of citations included in the database). This number of citations is remarkable, considering how recent is the literature, as just stated.

The most cited publications were also scrutinized, and only two articles (both from 2018) had over 100 citations. The same analysis was conducted in terms of the most cited authors – from a total of 531 authors and co-authors detected in the publications' portfolio, we extracted the top 10 authors (with 2 or more publications). Clearly, Voigt and Mueller are the more influential – and more cited authors – in this field of research. By number of papers, Chen leads with 6 articles published in this area. We also reported then network of authors around these main academics, and the most frequent affiliations of authors (institutions to which they are affiliated), as well as the countries where such authors work, and the network of such countries. By number of citations, USA, Germany, Brazil and Italy lead. The 5 BRICS countries (Brazil, Russia, India, China and South Africa) are represented in the top 10 countries where the represented authors work. After this comprehensive and systematic bibliometric study, we discussed the key clusters and the main thematic axes as pointers for future research. The main trends and the state of the art in this literature were analyzed – including themes such as the link between digital transformation and value chains; the technologies underlying Industry 4.0 and the impact of their use in the business models; the link between Industry 4.0, innovation and sustainability; the relationship between manufacturing industry, technology and SMEs; and

last but by no means the least, the implications for human resources' management arising from Industry 4.0.

Hence, the main trends of Industry 4.0 are associated to the integrated and connected use of technologies. Such technologies are provoking important change in business models; moreover, the process of digitalization of the firms impacts on the management and organization of the value chain, as well as impacting on key current trends such as sustainability, and the need to minimize waste and inefficiencies by implementing a better approach to the circular economy.

The challenges brought by Industry 4.0 are important and ever present. Governments all over the world are launching public policies, programs and strategies to accompany and stimulate this process, and to create competitive advantage via the deployment of technologies and managerial practices associated to Industry 4.0. Our research concluded, beyond any doubt, that this is a flourishing area of interest in the literature on Business and Economics. In terms of future research, there are multiple avenues worth following. One of such research opportunities would be to deepen research on the evaluation of the impact of Industry 4.0 on value chains. Another area would be to investigate, in theoretical and in empirical terms, the implications of Industry 4.0 in terms of new and/or improved business models. A further research avenue could be to analyze additive manufacturing as a paradigm leading to reshoring and re-industrialization (as stimulated by numerous governments in different continents, from Europe to the Americas, not forgetting Asian countries like Japan, among others). Finally, a survey and a comparative/benchmarking study of relevant Industry 4.0-focused public policies would be a much-needed and useful strand of research.

REFERENCES

Afonso, M. H. F., Souza, J. V. D., Ensslin, S. R., & Ensslin, L. (2012). Como construir conhecimento sobre o tema de Pesquisa? Aplicação do processo Proknow-C na busca de literatura sobre Avaliação do desenvolvimento sustentável 10.5773/rgsa.v5i2.424. *Revista de Gestão Social e Ambiental.* doi:10.24857/rgsa.v5i2.424

Ancarani, A., Di Mauro, C., & Mascali, F. (2019). Backshoring strategy and the adoption of Industry 4.0: Evidence from Europe. *Journal of World Business, 54*(4), 360-371. doi:10.1016/j.jwb.2019.04.003

Ardito, L., Petruzzelli, A. M., Panniello, U., & Garavelli, A. C. (2019). Towards Industry 4.0 Mapping digital technologies for supply chain management-marketing integration. *Business Process Management Journal, 25*(2), 323-346. doi:10.1108/bpmj-04-2017-0088

Arnold, C., Kiel, D., & Voigt, K. I. (2016). How the industrial internet of things changes business models in different manufacturing industries. *International Journal of Innovation Management, 20*(8), 25. doi:10.1142/s1363919616400156

Chauhan, C., & Singh, A. A review of Industry 4.0 in supply chain management studies. *Journal of Manufacturing Technology Management*, 24. doi:10.1108/jmtm-04-2018-0105

Chueke, G. V., & Amatucci, M. (2015). O que é bibliometria? Uma introdução ao Fórum . *InternexT - Revista Eletrônica de Negócios Internacionais da ESPM*, 10(2), 1-5. e-ISSN: 1980-4865

Demeter, K., Losonci, D., & Nagy, J. (2020). Road to digital manufacturing - a longitudinal case-based analysis. *Journal of Manufacturing Technology Management*, 20. doi:10.1108/jmtm-06-2019-0226

Dutra, A., Ripoll-Feliu, V. M., Fillol, A. G., Ensslin, S. R., & Ensslin, L. (2015). The construction of knowledge from the scientific literature about the theme seaport performance evaluation. International Journal of Productivity and Performance Management, 64(2), 243-269. doi: 10.1108/ijppm-01-2014-0015

Federal Ministry for Economic Affairs and Energy (2019). Industrie 4.0. Germany. Retrieved: 17 jun. 2019. from: < https://www.bmwi.de/Redaktion/EN/Dossier/industrie-40.html>
Ghadge, A., Kara, M. E., Moradlou, H., & Goswami, M. (2020). The impact of Industry 4.0 implementation on supply chains. *Journal of Manufacturing Technology Management, 31*(4), 669-686. doi:10.1108/jmtm-10-2019-0368
Haleem, A., & Javaid, M. (2019). Additive Manufacturing Applications in Industry 4.0: A Review. *Journal of Industrial Integration and Management-Innovation and Entrepreneurship, 4*(4), 23. doi:10.1142/s2424862219300011
Hannibal, M. (2020). The influence of additive manufacturing on early internationalization: considerations into potential avenues of IE research. *Journal of International Entrepreneurship*, 19. doi:10.1007/s10843-019-00267-y
Hoyer, C., Gunawan, I., & Reaiche, C. H. (2020). The Implementation of Industry 4.0 - A Systematic Literature Review of the Key Factors. Systems Research and Behavioral Science, 37(4), 557-578. doi:10.1002/sres.2701
Horváth, D., & Szabó, R. Z. (2019). Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? Technological Forecasting and Social Change, 146, 119-132. doi:10.1016/j.techfore.2019.05.021
Kazancoglu, Y., & Ozkan-Ozen, Y. D. (2018). Analyzing Workforce 4.0 in the Fourth Industrial Revolution and proposing a road map from operations management perspective with fuzzy DEMATEL. *Journal of Enterprise Information Management, 31*(6), 891-907. doi:10.1108/jeim-01-2017-0015
Klincewicz, K. (2019). Robotics in the Context of Industry 4.0: Patenting Activities in Poland and Their Comparison with Global Developments. *Problemy Zarzadzania-Management Issues, 17*(2), 53-95. doi:10.7172/1644-9584.82.3
Kolmykova, T., & Merzlyakova, E. (2019). Human role in the modern robotic reproduction development. *Economic Annals-Xxi, 180*(11-12), 183-190. doi:10.21003/ea.V180-20
Kosacka-Olejnik, M., & Pitakaso, R. (2019). Industry 4.0: state of the art and research implications. *Logforum, 15*(4), 475-485. doi:10.17270/j.Log.2019.363
Kruger, S., & Steyn, A. A. A conceptual model of entrepreneurial competencies needed to utilise technologies of Industry 4.0. *International Journal of Entrepreneurship and Innovation*, 12. doi:10.1177/1465750320927359
Krykavskyy, Y., Pokhylchenko, O., & Hayvanovych, N. (2019). Supply chain development drivers in industry 4.0 in Ukrainian enterprises. *Oeconomia Copernicana, 10*(2), 273-290. doi:10.24136/oc.2019.014
Lacerda, R. T. d. O., Ensslin, L., & Ensslin, S. R. (2012). A bibliometric analysis of strategy and performance measurement. *Gestão & Produção, 19*(1), 59-78. doi:10.1590/s0104-530x2012000100005
Lenart-Gansiniec, R. (2019). Organizational Learning in Industry 4.0. *Problemy Zarzadzania-Management Issues, 17*(2), 96-108. doi:10.7172/1644-9584.82.4
Li, L. (2018). China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0". *Technological Forecasting and Social Change, 135*, 66-74. doi:10.1016/j.techfore.2017.05.028
Lobova, S. V., Alekseev, A. N., Litvinova, T. N., & Sadovnikova, N. A. (2020). Labor division and advantages and limits of participation in creation of intangible assets in industry 4.0: humans versus machines. *Journal of Intellectual Capital, 21*(4), 623-638. doi:10.1108/jic-11-2019-0277
Lu, H. P., & Weng, C. I. (2018). Smart manufacturing technology, market maturity analysis and technology roadmap in the computer and electronic product manufacturing industry. *Technological Forecasting and Social Change, 133*, 85-94. doi:10.1016/j.techfore.2018.03.005

Lu, Y. (2017). Cyber Physical System (CPS)-Based Industry 4.0: A Survey. *Journal of Industrial Integration and Management-Innovation and Entrepreneurship, 2*(3), 57. doi:10.1142/s2424862217500142
Maresova, P., Soukal, I., Svobodova, L., Hedvicakova, M., Javanmardi, E., Selamat, A., & Krejcar, O. (2018). Consequences of Industry 4.0 in Business and Economics. *Economies, 6*(3), 14. doi:10.3390/economies6030046
Marnewick, C., & Marnewick, A. L. (2020). The Demands of Industry 4.0 on Project Teams. *Ieee Transactions on Engineering Management, 67*(3), 941-949. doi:10.1109/Tem.2019.2899350
Matthyssens, P. (2019). Reconceptualizing value innovation for Industry 4.0 and the Industrial Internet of Things. *Journal of Business & Industrial Marketing, 34*(6), 1203-1209. doi:10.1108/jbim-11-2018-0348
Morrar, R., Arman, H., & Mousa, S. (2017). The Fourth Industrial Revolution (Industry 4.0): A Social Innovation Perspective. *Technology Innovation Management Review, 7*(11), 12-20. doi:10.22215/timreview/1117
Mugnaini, R., & Strehl, L. (2008). Recuperação e impacto da produção científica na era Google: uma análise comparativa entre o Google Acadêmico e a Web of Science. Encontros Bibli: *Revista eletrônica de biblioteconomia e ciência da informação*, (Esp), 92-105. doi: 10.5007/1518-2924.2008v13nesp1p92
Muller, J. M., Buliga, O., & Voigt, K. I. (2018). Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. *Technological Forecasting and Social Change, 132*, 2-17. doi:10.1016/j.techfore.2017.12.019
National Science and Technological Council (2018). Strategy for American leadership in Advanced Manufacturing. A report by the Subcommitee on Technology of the National Science and Technological Council. [Retrieved 25 sept. 2020]. from: https://www.whitehouse.gov/wp-content/uploads/2018/10/Advanced-Manufacturing-Strategic-Plan-2018.pdf
Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Lona, L. R., & Tortorella, G. (2019). Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context A business model proposal. *Journal of Manufacturing Technology Management, 30*(3), 607-627. doi:10.1108/jmtm-03-2018-0071
Nhamo, G., Nhemachena, C., & Nhamo, S. (2020). Using ICT indicators to measure readiness of countries to implement Industry 4.0 and the SDGs. *Environmental Economics and Policy Studies, 22*(2), 315-337. doi:10.1007/s10018-019-00259-1
Oliveira, O. J., Silva, F. F., Juliani, F., Barbosa, L., & Nunhes, T. (2019). Bibliometric method for mapping the state-of-the-art and identifying research gaps and trends in literature: An essential instrument to support the development of scientific projetcs. *Scientometrics*, 1-20. doi: 10.5772/intechopen.85856
Ozdagoglu, A., Ozdagoglu, G., Topoyan, M., & Damar, M. (2020). A predictive filtering approach for clarifying bibliometric datasets: an example on the research articles related to industry 4.0. *Technology Analysis & Strategic Management, 32*(2), 158-174. doi:10.1080/09537325.2019.1645826
Pareto, V. (1896), Cours D'Économie Politique, Switzerland.
Poma, L., Al Shawwa, H., & Maini, E. (2020). Industry 4.0 and big data: role of government in the advancement of enterprises in Italy and UAE. *International Journal of Business Performance Management, 21*(3), 261-289. doi:10.1504/IJBPM.2020.108317
Prause, G., & Atari, S. (2017). On sustainable production network for Industry 4.0. *Entrepreneurship and Sustainability Issues, 4*(4), 421-431. doi:10.9770/jesi.2017.4.4(2)
Prause, M., & Gunther, C. (2019). Technology diffusion of Industry 4.0: an agent-based approach. *International Journal of Computational Economics and Econometrics, 9*(1-2), 29-48. doi:10.1504/IJCEE.2019.09779

Pritchard, A. (1969) Statistical Bibliography or Bibliometrics. *Journal of Documentation*, 25, 348-349.
Queiroz, M. M., Wamba, S. F., Machado, M. C., & Telles, R. (2019). Smart production systems drivers for business process management improvement An integrative framework. *Business Process Management Journal*, 18. doi:10.1108/bpmj-03-2019-0134
Rajput, S., & Singh, S. P. (2019). Identifying Industry 4.0 IoT enablers by integrated PCA-ISM-DEMATEL approach. *Management Decision, 57*(8), 1784-1817. doi:10.1108/md-04-2018-0378
Reischauer, G. (2018). Industry 4.0 as policy-driven discourse to institutionalize innovation systems in manufacturing. *Technological Forecasting and Social Change, 132*, 26-33. doi:10.1016/j.techfore.2018.02.012
Rodic, B. (2017). Industry 4.0 and the New Simulation Modelling Paradigm. *Organizacija, 50*(3), 193-207. doi:10.1515/orga-2017-0017
Schmidt, M. C., Veile, J. W., Muller, J. M., & Voigt, K. I. (2019). Kick-Start for Connectivity - How to Implement Digital Platforms Successfully in Industry 4.0. *Technology Innovation Management Review, 9*(10), 5-15. doi:10.22215/timreview/1271
Schwab, Klaus (2016). The Fourth Industrial Revolution. 1º ed., Geneva: World Economic Forum.
Shi, Z., Xie, Y. P., Xue, W., Chen, Y., Fu, L. L., & Xu, X. B. (2020). Smart factory in Industry 4.0. *Systems Research and Behavioral Science, 37*(4), 607-617. doi:10.1002/sres.2704
Simetinger, F., & Zhang, Z. P. (2020). Deriving secondary traits of industry 4.0: A comparative analysis of significant maturity models. *Systems Research and Behavioral Science, 37*(4), 663-678. doi:10.1002/sres.2708
Slusarczyk, B. (2018). Industry 4.0 - Are we ready? *Polish Journal of Management Studies, 17*(1), 232-248. doi:10.17512/pjms.2018.17.1.19
Strange, R., & Zucchella, A. (2017). Industry 4.0, global value chains and international business. *Multinational Business Review, 25*(3), 174-184. doi:10.1108/mbr-05-2017-0028
Sung, T. K. (2018). Industry 4.0: A Korea perspective. *Technological Forecasting and Social Change, 132*, 40-45. doi:10.1016/j.techfore.2017.11.005
Szalavetz, A. (2019). Digitalisation, automation and upgrading in global value chains-factory economy actors versus lead companies. *Post-Communist Economies, 31*(5), 646-670. doi:10.1080/14631377.2019.1578584
Tasca, E. J., Ensslin, L., Ensslin, S. R., & Alves, M. B. M. (2010). An approach for selecting a theoretical framework for the evaluation of training programs. *Journal of European Industrial Training*, 34(7), 631-655. doi: 10.1108/03090591011070761
Van Eck, J. N & Waltman, L. (2020). *Vosviewer Manual*. Leiden University. [Retrieved: 25 sept. 2020]. from: <https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.8.pdf>
Vieira, E. L., Da Costa, S. E. G., De Lima, E. P., & Ferreira, C. C. (2019). Application of the Proknow-C Methodology in the Search of Literature on Performance Indicators for Energy Management in Manufacturing and Industry 4.0. *Procedia Manufacturing, 39*, 1259-1269. doi:10.1016/j.promfg.2020.01.343
Yoshikawa, H. (1995). Manufacturing and the 21st- Century – Intelligent Manufacturing Systems and the renaissance of the manufacturing-industry. Technological Forecasting and Social Change, 49(2), 195-213. doi:10.1016/0040-1625(95)00008-x
Zhang, C. M., & Chen, Y. (2020). A Review of Research Relevant to the Emerging Industry Trends: Industry 4.0, IoT, Blockchain, and Business Analytics. Journal of Industrial Integration and Management-Innovation and Entrepreneurship, 5(1), 165-180. doi:10.1142/s2424862219500192