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Industry 4.0: the future of manufacturing from the perspective of business and economics – a bibliometric literature review

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Abstract

Purpose – This paper aims to provide a comprehensive, systematic review of the literature on Industry 4.0 – and on the trends and implications of the digitalization of manufacturing – from the perspective of business and economics.

Design/methodology/approach – A bibliometric methodology was used, allowing to extract rigorously the relevant literature, leading to a purposefully constructed database of peer-reviewed publications depicting the state of the art in this area. A quantitative analysis of the key characteristics of – and trends emanating from – the literature was performed, and results were presented in a graphic way using the VOSViewer software as a mapping tool. Relevant thematic clusters were identified, and promising future research avenues were identified.

Findings – This literature is extremely recent – 90% of the publications are from 2019 and 2020, and the leading journal publishing in this area is the *Journal of Manufacturing Technology Management*. Key clusters identified relate digital transformation to value chains; a close link is observed between Industry 4.0 technologies and business models; a strong connection to sustainability is also clear; and the implications of Industry 4.0 for human resources management are, not surprisingly, extremely relevant.

Originality/value – This is, to the best of the authors' knowledge, the most comprehensive systematic review linking specifically Industry 4.0 to the business and economics literature, bridging with recent, state-of-the-art research in the economics/business and technological fields. This contribution may be very helpful to researchers interested in understanding the key trends and opportunities offered by this area.

Keywords Industry 4.0, Digitalization, Economics, Advanced manufacturing technology

Paper type Research paper

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1. Introduction

Productive systems are undergoing disruptive transformations, materializing the often called Fourth Industrial Revolution (Li, 2018; Horváth and Szabó, 2019; Bettiol *et al.*, 2021). 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 *et al.*, 2020). Former industrial revolutions brought as benefits the intensification of technological progress and significant increases in productivity (Morrar *et al.*, 2017). However, even though the Fourth Industrial Revolution may bring these benefits – even probably in a more pronounced way – it remains unclear which are the consequences, notably how it will affect the sociotechnical 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, *inter alia* (Chueke and Amatucci, 2015; Ozdagoglu *et al.*, 2020). Among the questions answered in this paper are:

Q1. What is the chronological evolution of the scientific output in this area?

Q2. Which are the main sources (Journals) with more titles published in this field?

Q3. What are the most cited and impactful publications?

Q4. Who are the authors publishing more, and who are the most cited?

Q5. What are the connections between these main authors?

Q6. Where are these authors based, institutionally and geographically?

Q7. What are the geographic connections between the authors?

Q8. 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. Section 2 includes a synthesis of the key literature based on the most impactful papers. 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 used: the Proknow-C *(Knowledge Development Process – Constructivist)* method, the bibliographic database (Web of Science [WoS]), the extraction criteria and identifies the steps involved in the construction of the publications' database specifically developed for this paper. Section 4 presents the results and discusses the detailed bibliometric analysis performed (including the answer to the i–viii questions above). 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 *et al.*, 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; Bettiol *et al.*, 2021) bringing considerable transformations to the business world (Haleem and 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.

The First Industrial Revolution (1760–1840) was mainly marked by the invention of the steam engine and the construction of railways. The Second Industrial Revolution (from 1870 well into the 20th century) had as trigger the discovery of electricity and the introduction of the assembly line in manufacturing production, enabling mass production. The Third Industrial Revolution (also called digital revolution) started in the 1960s with the use of semiconductors and mainframe computers, the use of personal computers (1970–1980) and the diffusion of the internet (1990). 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 (Schwab, 2016).

The Fourth Industrial Revolution is already underway globally (Slusarczyk, 2018). The internet and the use of information technology (IT) and robotics already existed; what is new is that Industry 4.0 integrates IT, 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 enables the introduction of a communication system among the equipments used in production and the products, via the hyperconnectivity based on 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 and 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 like Internet of Things (IoT), Big Data, CPS, Data Mining, Cloud Computing, Augmented Reality, Virtual Reality, Robotics and Additive Manufacturing (Kosacka-Olejnik and 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 and 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, the UK, Spain, among others (Kosacka-Olejnik and Pitakaso, 2019).

In all, Industry 4.0 is a very rich and multidimensional concept, aiming at the transformation of manufacturing through digitalization and exploring the convergence of, and the interface and synergies among a host of technologies. This process establishes a new, smarter, industrial perspective, optimizing networks and value chains and enabling more efficient business models. In so doing, Industry 4.0 promotes sustainability in a truly "triple bottom line" way:

- environmentally, as the processes are more efficient, and customization and "made-to-order" are enabled, avoiding waste of resources and further negative impacts of imprecise planning;
- economically, as productivity and overall performance is enhanced, business processes and models are optimized, generating more profitable businesses – also by giving the customers what they want/need via flexible processes allowing to better meet their needs in terms of and individualized products/services; and
- socially, as Industry 4.0 is a human and social phenomenon, and it allows to focus the work of the human resources in the tasks that involve human attention, avoiding unpleasant, heavy, repetitive tasks and promoting the upskilling and reskilling of the labor force.

For the overall organization, Industry 4.0 is bound to improve resilience and to promote competitiveness.

2.2 Impact of industry 4.0 from the perspective of business and economics

This paper focuses on Industry 4.0 from the perspective of business and economics. Industry 4.0, as already explained, is a multidimensional concept and can be approached by different perspectives. In the literature, and as we understood when preparing the bibliometric analysis reported in subsequent sections, the perspective of Engineering/Technology is dominant and more frequent. Therefore, the aim of this article is to contribute specifically to understand the phenomenon from a business and economics standpoint, which is a relatively more scarce and less explored angle of analysis of Industry 4.0. Hence, the remainder of the paper adopts this perspective. We expect this literature to be different from the more Engineering/Technology-focused strand as the issues studied are also distinct: we are concerned with aspects such as business models, value chains, human resources' management, *inter alia*. This is particularly related with the content of Sections 4.2 and 4.3, where the clusters and key axes emerging from this research are explained.

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 noncorrespondence between industrial indices and gross domestic product, hence creating a disconnection with the real economy.

Other aspect enabled by Industry 4.0 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 *et al.*, 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 is 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 not satisfied with the available

solutions (Muller *et al.*, 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 small and medium-sized enterprises (SMEs) involved in the value chain have been neglected, both in theory and practice. Dutta *et al.* (2020) note that, as such, SMEs may be reactive to the implementation of Industry 4.0 technologies.

Regarding the implementation of Industry 4.0 technologies, 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 *et al.* (2020) argue, Industry 4.0 implementation may 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 technologies has international repercussions, impacting directly global value chains (Rodic, 2017). Industry 4.0 represents a way to digitalize the value chain relying on product and process innovation (Prause and 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 and Zhang, 2020).

3. Methodology

This section presents the methodology used in the paper, as well as the search tools and software used for data collection and analysis. This systematic literature review, as it aimed to be as rigorous and comprehensive as possible, used a bibliometric methodology.

"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). Bibliometrics allows assessing the state of the art of the literature on the topic under analysis (Broadus, 1987). 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 of bibliometric data offers quantitative insights about important aspects selected by the researcher, as well as about the relationships among several parameters, such as main themes of research, articles, authors, collaborations/networks among authors, geographical focus, chronological evolution of the literature, among others (Ozdagoglu *et al.*, 2020).

The analysis also relied on 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 (Tasca *et al.*, 2010; Lacerda *et al.*, 2012). Under the perspective of the approach to the research question, this method includes qualitative and quantitative dimensions. Tasca *et al.* (2010) note that the qualitative approach is revealed in the analysis of the alignment of the literature with the research context, while the quantitative dimension is related to the bibliometric analysis. This method will be explained in detail in Section 3.2.

3.1 Bibliographic database and criteria of extraction of relevant publications

The bibliographic database selected to extract the relevant publications was Clarivate Analytics's WoS, a prestigious and inclusive source for Applied and Social Sciences (Mugnaini and Strehl, 2008). This platform includes articles since 1900 until now, allowing access to over 1.9 billion references in total.

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 and 2 below. Table 1 provides a synthesis of the main criteria used for the collection of the database relevant for the present analysis.

Table 2 provides more details on the extraction of the database.

The first search only based on keywords (without further filters) yielded an extraction of 10,324 publications. A filter by document type was applied, including the following types: articles, review articles and book chapters. Articles and review articles published in international peer-reviewed journals are the most credible type, given their independent reviewing process. We also decided to include book chapters, as this is an emerging topic, and often, there are publications in books relevant to the analysis.

A second filter implemented reduced the results to 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.

Each publication extracted included, in this order, the following fields: Author; Title; Year of publication; Number of citations; Document type; Digital Object Identifier (DOI); Language. All extractions were consolidated and thoroughly analyzed 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 has been used to support systematic literature reviews, as well as to facilitate bibliometric analysis (Tasca *et al.*, 2010; De Carvalho *et al.*, 2020). This method supports the methodology used in this paper, bibliometric analysis, which consists of a

Search criteria	Description
Database	WoS core collection
Collection period	13th–17th September 2020
Keywords	("industr* 4.0"OR"smart manufac*"OR"intelligent manufac*") AND "Fourth Industrial Revolution"/AND "Industrial Policy"/("Industrial Production"OR"manufac* production)/AND ("digitalization"OR"digitalization")
Type of search	By topics/WoS core collection
Publication period	Not delimited (inclusive of all years)
Document types	Filter: Articles, Reviews and Book Chapters
Categories/areas	WoS: Economics, Business and Management Research Area: Business and Economics
Languages	English, Portuguese and Spanish

Source: Own elaboration

Table 1.
Criteria for the search and collection of bibliographic data

Table 2.
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*”)	8,943	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“digitalization”)	545	53	34	12	14	49
Total	*10,324*	*561*	*365*	*158*	*127*	*529*

Source: Own elaboration

quantitative analysis of certain methodology parameters extracted from a database of scientific publications (Lacerda *et al.*, 2012). The Proknow-C method contributes to undertake a more systematic documents' selection process (Tasca *et al.*, 2010), avoiding that the choice of the scientific publications will be performed in a random and nonrigorous way. Hence, this methodology offers greater rigor in the construction of a database of publications about a certain research topic (Afonso *et al.*, 2012).

To have a deeper knowledge about a certain theme, it is crucial to gather a portfolio with representative publications on the topic. Proknow-C offers a path to constitute a publications database to allow a literature review and the application of bibliometric methods, later enabling a systematic analysis of the topic, as well as the identification of research opportunities (Dutra *et al.*, 2015; Vieira *et al.*, 2019).

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 and abstract. Then, a column with identifiers was added, and 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 cutoff 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 the 20% most cited publications, such 20% 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 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. This selection criterion consists of gathering an authors' database with the authors that are within the 20% of the most cited in the overall publications' portfolio and to try to identify whether they possess publications not among those already selected (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 – 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 to verify their relevance and alignment with the theme. It was found that 51 were not aligned, hence leading to a final database 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 Endnote, becoming the final database considered in this paper.

At 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, 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 of the bibliographic

metadata, as well as permitting the conversion into maps, networks and tables to be used to enrich the bibliometric analysis (Van Eck and Waltman, 2020).

Such path is explained in Figure 1 below, which adapts a scheme used by Frigo Souza *et al.*, 2016).

At this stage, we analyzed the chronology of the publications, the networks of authors, the main countries where the authors were based, the publications' sources and the occurrence of the main keywords – 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

This section is focused on the analysis of the bibliometric results. The following aspects will be analyzed: type of publication, year of publication (chronological analysis), sources of the publications, most cited publications, most cited authors, networks among authors, authors' main institutional affiliations, countries where authors work and the network of countries where the most cited authors in this topic are based.

4.1.1 Type of publication. Among the 207 documents composing the database underlying this analysis, 185 are articles (89% of total) and 22 are review articles (11%) – as reported in Figure 2 below.

4.1.2 Year of publication (chronological analysis). As expected, considering the recent genesis of the term, "Industry 4.0" only appears in publications 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 the reason why one of the publications reported in Table 4 below dates from 1995. Yoshikawa (1995) was focused on Intelligent Manufacturing Systems. Table 3 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% in 2019 and 2020.

4.1.3 Sources – journals. The 207 selected publications belong to 97 scientific journals. Table 4 identifies the 10 journals with more publications about Industry 4.0 in the areas of business and economics.

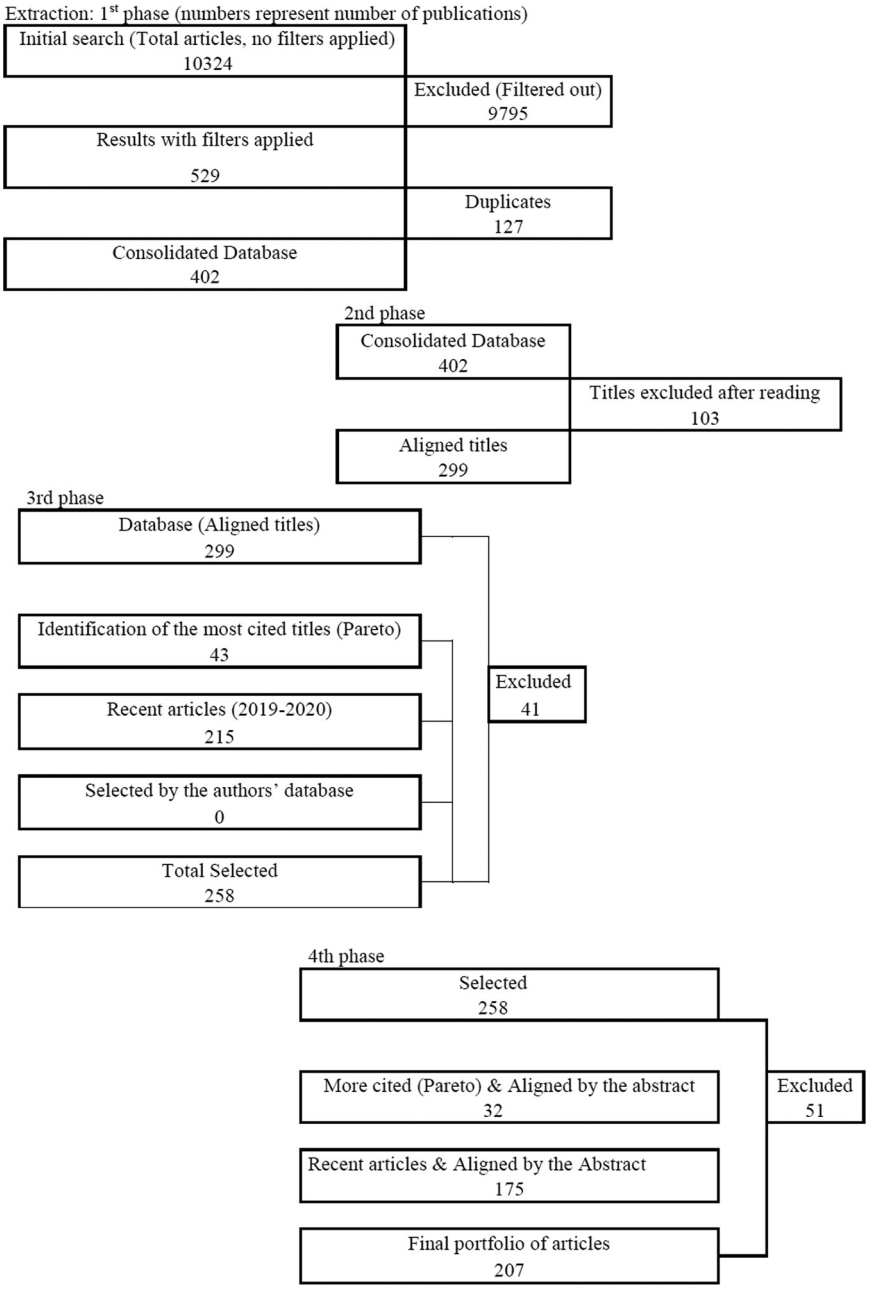
Table 4 can be read in two ways: number of articles or impact of the articles published (proxied by the number of citations of all articles published in each journal).

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).

4.1.4 Most cited publications. Table 5 below identifies the 10 most cited publications in our database. Despite the newness of these publications, two among these articles display over 100 citations: Li (2018) with 140 citations and Muller *et al.* (2018) with 105 citations.

4.1.5 Most cited authors. Table 6 below shows the 10 authors who published more works in our sample related to Industry 4.0 in business and economics. The information is organized by number of publications and by the joint number of citations of such articles.



Source: Own elaboration

Figure 1.
Flowchart explaining the implementation of the Proknow-C method

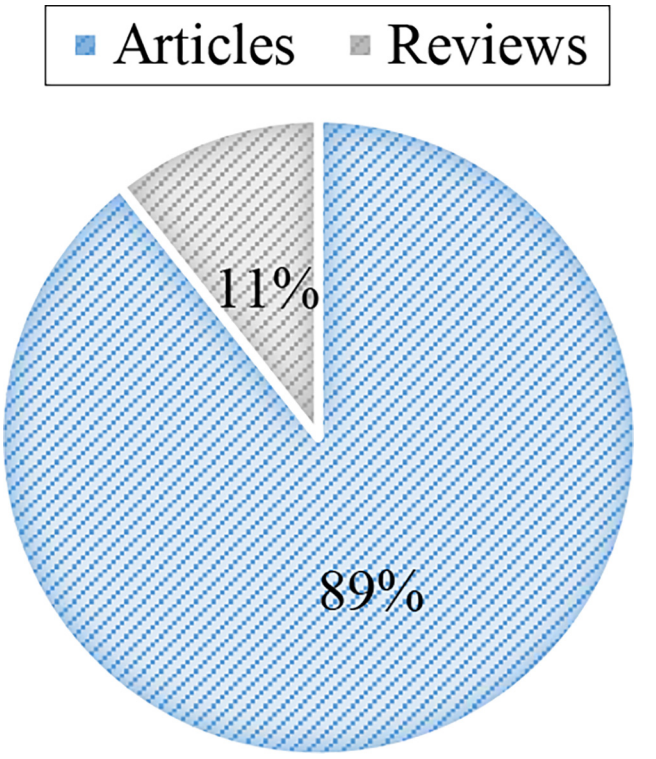


Figure 2.
Type of publications

Source: Own elaboration

Year	No. of articles	(%) of 207
2020	104	50.24
2019	81	39.13
2018	11	5.31
2017	7	3.32
2016	3	1.44
1995	1	0.48

Table 3.
Year of publication of the 207 articles selected

Source: Own elaboration

Those parameters allow an analysis of the strength of the connections between the authors. A total of 531 authors and coauthors were detected in the sample.

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).

Reinforcing the findings reported in Table 6, Figure 3 shows the clusters of authors, evidencing the (already identified) most cited authors and their links to other authors.

4.1.6 Most frequent institutions of affiliation of authors. When analyzing the main networks of authors and coauthors of the 207 publications under study, and the institutions to which they are affiliated, 337 institutions are included. Table 7 presents the 10 institutions with more occurrences and the respective number of citations by authors in the area. Four

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. Sources with more titles published in Industry 4.0 in business and economics

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
5	Arnold, C; Kiel, D; Voigt, KI	How the Industrial Internet of Things changes business models in different manufacturing 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

Table 5. Most cited publications

Author	No. of publications	No. of citations
Chen, Y.	6	21
Tortorella, G.L.	4	52
Voigt, K.L.	4	167
Gotz, M.	4	0
Garza-Reyes, J.A.	3	41
Jerman, A.	3	16
Li, L.I.	3	147
Mueller, J.M.	3	123
Krejcar, O.	2	27
Maresova, P.	2	27

Table 6.
Authors with more publications

Source: Own elaboration (based on references from WoS exported to the VOSviewer software)

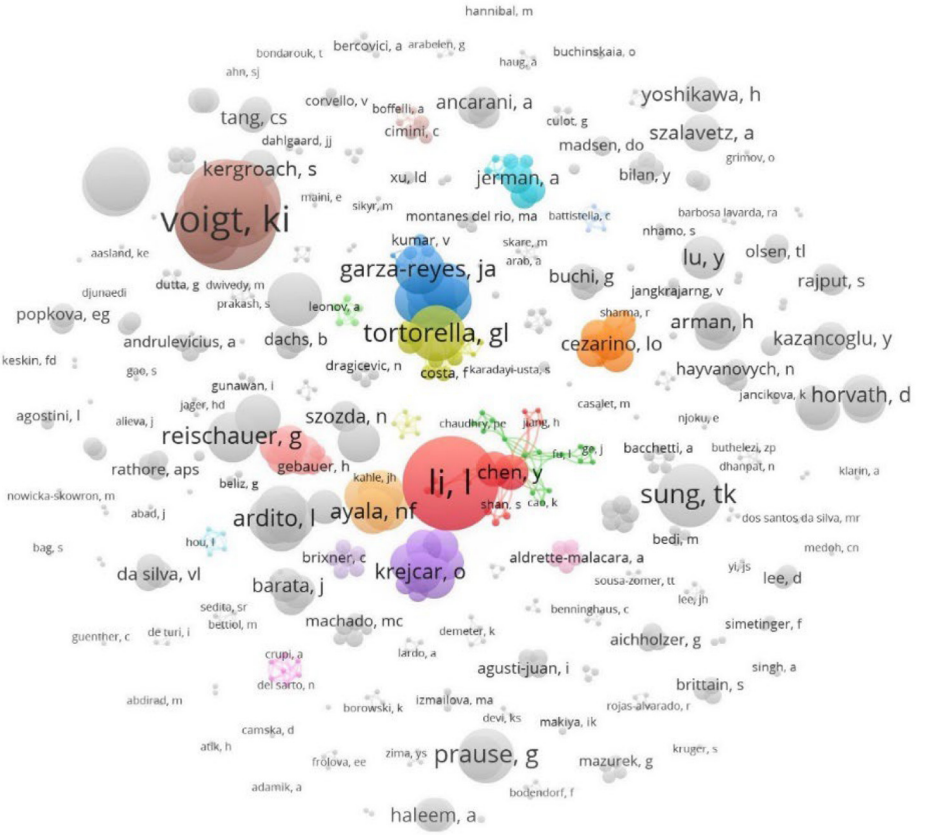


Figure 3.
Map of authors with more citations in Industry 4.0 in business and economics

Source: Own elaboration (based on references from WoS exported to the VOSviewer software)

Ranking	Organization	N. of publications	Citations
1	Old Dominion University	5	150
2	Universidade Federal de Santa Catarina	5	52
3	Texas A&M Int. University	5	21
4	University of Johannesburg	5	3
5	Friedrich Alexander University Erlangen Nurnberg	3	110
6	University of Derby	3	41
7	Politecnico di Milano	3	38
8	Corvinus University Budapest	3	30
9	University Primorska	3	16
10	Salzburg University of Applied Sciences	3	15

Source: Own elaboration (based on references from WoS exported to the VOSviewer software)

Table 7. Institutions with more (and most cited) publications

institutions have five publications by affiliated authors: 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).

4.1.7 Countries where authors work. The 207 publications under scrutiny include 54 countries of affiliation of authors/coauthors. Table 8 highlights the top 10 countries where more publications originate. Italy, the USA and Poland clearly lead in this criterion, all with more than 20 publications.

By number of citations, the leading countries are the USA (284 citations), Germany (262), Brazil (205) and Italy (204). All the BRICS countries (Brazil, Russia, India, China and South Africa) are represented in the top 10.

Figure 4 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.

Ranking	Country	No. of documents	Citations
1	Italy	25	204
2	USA	24	284
3	Poland	21	98
4	England	16	126
5	Brazil	16	205
6	Peoples Republic of China	15	27
7	Germany	14	262
8	India	12	51
9	Russia	11	14
10	South Africa	10	59

Source: Own elaboration (based on references from WoS exported to the VOSviewer software)

Table 8. Countries with authors with more publications

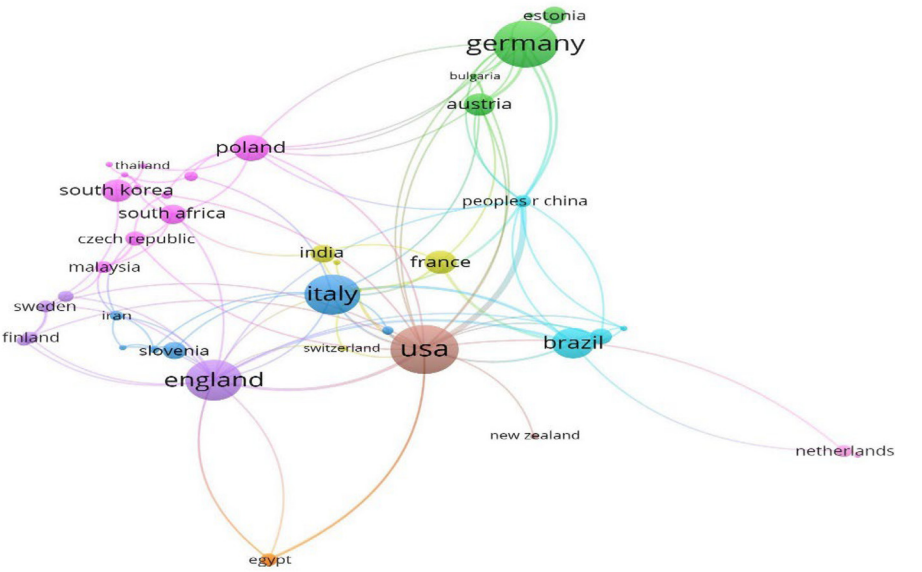


Figure 4.
Network of countries with more citations

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, helping to understand the interplay of such themes at both theoretical and empirical levels, and providing indications for future research.

Considering the keywords defined by the authors of the analyzed publications, only six keywords exhibit 10 or more occurrences, and 20 of such keywords appear five times or more in the publications' database – as Table 9 shows. Not surprisingly, our key theme (Industry 4.0) is the keyword with by far more occurrences (171) in the 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 5 below.

These six clusters (networks of keywords with greater connection strength) are as follows:

(1) 1st Cluster: Industry 4.0; Smart manufacturing; Smart factory; Big data; Business model.

(2) 2nd Cluster: Fourth Industrial Revolution; Smart Manufacturing; Innovation; Sustainability.

(3) 3rd Cluster: Digital transformation; Digitalization; Value chain; Value chain management.

(4) 4th Cluster: Additive manufacturing; IoT; Robotics.

(5) 5th Cluster: Manufacturing industry; Technology; Small and Medium Enterprises.

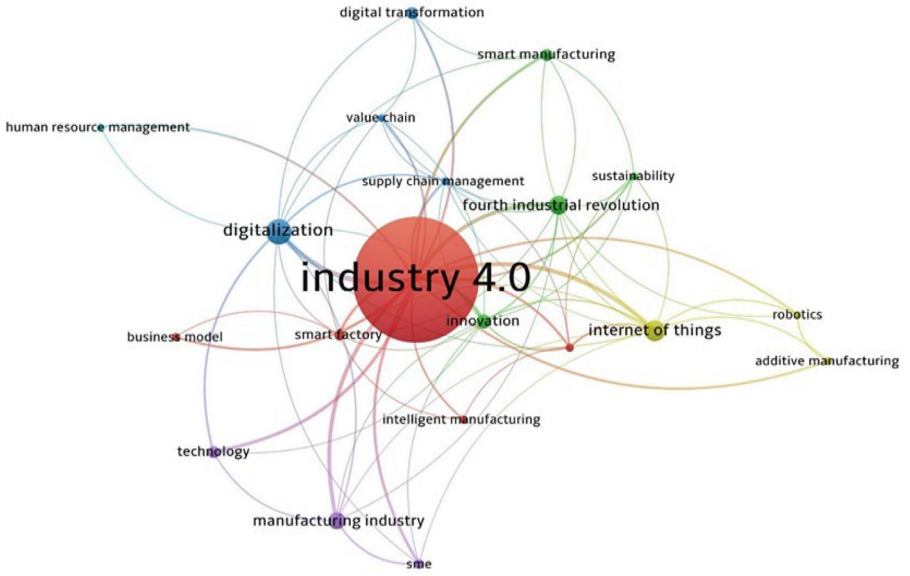
(6) 6th Cluster: Human resources management.

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

Ranking	Keywords	Occurrences
1	Industry 4.0	171
2	Digitalization	23
3	Internet of Things	18
4	Fourth Industrial Revolution	16
5	Manufacturing Industry	14
6	Innovation	11
7	Digital Transformation	9
8	Smart Manufacturing	9
9	Technology	9
10	Smart Factory	8
11	SME	7
12	Additive Manufacturing	6
13	Big Data	6
14	Business Model	6
15	Smart Industry	6
16	Supply Chain Management	6
17	Human Resources Management	5
18	Robots	5
19	Sustainability	5
20	Value Chain	5

Source: Own elaboration (based on references from WoS exported to the VOSViewer software)

Table 9.
Main keywords (identified by the authors) about Industry 4.0



Source: Own elaboration with WoS references in the VOSviewer software

Figure 5.
Network of keywords (defined by authors) related to Industry 4.0

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. The expansion of digital technologies allows to reconfigurate value chains in novel ways, including providing internationalization opportunities significantly less costly, and eventually particularly attractive for firms with relatively scarce resources, such as SMEs.

The fourth cluster is technology-based, linking IoT to Robotics, to Additive Manufacturing. As explained 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 and 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 resources like often happens to SMEs. Thus, the deployment of technologies in manufacturing 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 need 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. 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 10 synthesizes the main thematic axes identified in the 207 publications constituting the database. Some publications include more than one of such main theme areas.

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 IoT (Ardito *et al.*, 2019; Matthyssens, 2019; Zhang and Chen, 2020; Nhamo *et al.*, 2020); CPS (Lu, 2017; Nascimento *et al.*, 2019); Augmented Reality, Big Data (Poma *et al.*, 2020), Cloud-computing (Kosacka-Olejnik and Pitakaso, 2019) and Autonomous Robots (Klincewicz, 2019; Kolmykova and Merzlyakova, 2019).

No.	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 with WoS references

Table 10. Main thematic axes of the 207 publications associated to Industry 4.0

CPS, 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 manufacturing value chain (Lu, 2017).

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 human resources but also of objects or products (Rajput and Singh, 2019).

A significant number of the publications analyzed highlight 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; Hervas-Oliver *et al.*, 2021) – with a special prevalence of research mentioning the German Government, who coined the term "Industry 4.0" (Reischauer, 2018; Slusarczyk, 2018) and the implementation of pilot studies (Götz, 2021).

"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 technologies (Lenart-Gansiniec, 2019; Grashof, 2021), aspects concerning the skills of human resources (Kruger and Steyn) skills required due to the adoption of new organizational paradigms (Marnewick and Marnewick, 2020) interaction between human resources and robots (Lobova *et al.*, 2020). Related to this, the theme "Strategy" (present in 12 publications) appears vinculated to 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 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 and 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 main focus.

Another key theme is how management in the Industry 4.0 era impacts domestic and global supply and value chains (Chauhan and Singh, 2019). In this topic, the simulation made by Ghadge *et al.* (2020) confirmed that Industry 4.0 technologies may strongly affect the supply and value chain. The supply chain represents the focus of 16 documents (Krykavskyy *et al.*, 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 toward Industry 4.0 (Zhang and Chen, 2020), and 16 publications specifically analyze that.

The implementation of such technologies and of digitalization lead to substantial changes in businesses' networks (Dutta *et al.*, 2020). All that impacts on operations, networks, organizational culture, managerial strategy and business models (Arnold *et al.*, 2016). Business model implications of Industry 4.0 is a major theme in the literature, although further research is needed.

The implications of Industry 4.0 for the workforce 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 with the technologies, the organizations and with a diversity of stakeholders (Ruel *et al.*, 2021). The digitalization of manufacturing provides a new meaning to the interactions between the workforce, the company and the clients (Kergroach, 2017; Kazancoglu and Ozkan-Ozen, 2018).

Other relevant themes, albeit with a smaller number of specific documents that have emerged in the data set 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 Simetinger and 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 and 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 WoS was used as the source of the publications surveyed. In all, 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 the type of publication (articles, reviews and 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 in Figure 1, a purposefully constructed database (portfolio) included, finally, 207 publications.

Using this portfolio, a detailed bibliometric methodology was implemented to extract a clear characterization of the current state of the art of Industry 4.0 literature 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. A key conclusion emanating from a chronological analysis of the literature was its newness: about 90% of the publications were from 2019 and 2020, and 50.2% 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.

The most cited publications were scrutinized, and only two articles (both from 2018) had over 100 citations. The same analysis was conducted for the most cited authors – from a total of 531 authors and coauthors in the publications' portfolio, we extracted the top 10 authors (with two or more publications). Clearly, Voigt and Mueller are the most influential – and most cited authors in this field. By number of papers, Chen leads with six articles published in this area. We also reported the network of authors around these main academics, and the most frequent institutional affiliations of authors, as well as the countries where authors work and the network of such countries. By number of citations, the USA, Germany, Brazil and Italy lead. The five countries BRICS are represented in the top 10 countries where the included 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 business models; the link between Industry 4.0, innovation and sustainability; the relationship between manufacturing industry, technology and SMEs; and last but not least, the implications of Industry 4.0 for human resources' management.

Hence, the main trends of Industry 4.0 are associated to the integrated and connected use of technologies. Such technologies are provoking important changes 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. This deployment of adequate public policies is very important as, notably, Industry 4.0 may have significant social impacts (especially in the short-term) given that it represents significant disruption and a significant part of the workforce needs to be upskilled/reskilled or even it may happen that some tasks/jobs will be rendered obsolete. Hence, governments need to pay attention to this challenge and work with companies, sectors, business associations to minimize the negative impacts and embrace the opportunities brought by Industry 4.0 in a socially sustainable manner.

Our research concluded, beyond any doubt, that this is a flourishing area of interest in the business and economics literature. Even if we provided a rigorous and comprehensive account of the state-of-the-art of this increasing literature, this paper presents some limitations, particularly as it needed to use a methodology, albeit prestigious, but that implied selecting a subset of papers and not the whole of the literature. The application of the Pareto rule and the Proknow-C method, although considered adequate and essential to perform the analysis and treat the data, involve a significant filter imposed to the vast initial database (over 10,000 papers).

In terms of future research, there are multiple avenues worth following. One of such research opportunities would be to deepen the evaluation of the impact of Industry 4.0 on value chains. Another area would be to investigate, theoretically and empirically, the implications of Industry 4.0 for new and/or improved business models. A further avenue could be to analyze additive manufacturing as a paradigm leading to reshoring and reindustrialization (as stimulated by numerous governments, 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.

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