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Industry 4.0: A Bibliometric Analysis in the Perspective of Operations Management

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ABSTRACT

This study aims to analyse the literature regarding the characteristics of Industry 4.0 in the context of operations management. The analysis covers the evolution of publications over time, the countries involved, the most prolific journals, the most cited authors, and the identification of the most frequent words that can generate insights for the research agenda. A total of 235 articles published between 2011 and 2017 were collected through an automated process from the Scopus and Web of Science databases and later analysed using data mining, bibliometric indicators analysis, clusters analysis, networks analysis, and word cloud. The bibliographic analysis explained the interaction between the various concepts and techniques associated with the central theme. These concepts and respective characteristics discussed allow an understanding and the development of agenda with theoretical possibilities to fill current research gaps.

Keywords: *advanced manufacturing, industry 4.0, manufacturing, operations management*

1. INTRODUCTION

The concept of industry 4.0 (i4.0) represents an evolutionary stage of production systems characterized by the fourth industrial revolution, with emphasis on the technological transformations that have emerged in the last decade. The term "Industry 4.0" was first presented in 2011 at the Hannover fair to discuss the relevance of technology as a factor of competitiveness for the German industry (Kagermann *et al*., 2013; Sanders *et al*., 2016; Schwab, 2017). During the last decade, industries in advanced economies have experienced significant changes in their manufacturing practices, processes, and technologies (Zonnenshain & Kenett, 2020). However, few companies have managed to reach high maturity levels regarding the implementation of i4.0 practices (Müller *et al*., 2018).

The logic presented by Porter & Heppelmann (2014) points out that information technology is turning products into complex systems that combine hardware, software, sensors, microprocessors, data storage, and connectivity, forcing companies to rethink how they do everything internally to reach competitive advantage. Thus, it is understood that the paradigm of the fourth industrial revolution has created new opportunities and challenges in manufacturing management, making possible the use of new technologies inherent to i4.0, i.e., the Industrial Internet of Things (IIoT), Cyber-physical Systems (CPS), Intelligent Factories, Additive Manufacturing, Big Data Analytics, among others (Rüßmann *et al*., 2015, Weinberg *et al*., 2015, Tamás *et al*., 2016).

The i4.0 concept is still in the developmental stage, both in the business environment and the scientific community. Some research organizations and institutions are directing their efforts towards creating Smart Factories based on automation and the internet (Kagermann *et al.*, 2013; Roblek *et al.*, 2016). With technological advances in digital automation, some companies that previously managed their information and processing technologies independently are now making significant investments to integrate modern manufacturing technologies (Agarwal & Brem, 2015). However, digital manufacturing is still limited to large corporations, so that small companies are still reluctant to invest in technologies of process automation and computer-aided manufacturing systems. These companies consider that implementing advanced manufacturing technologies is an unnecessary and irrelevant strategy for competitiveness (Thomas *et al.*, 2008). In addition, the multidisciplinary approach required for digital transformation initiatives in different economic segments makes the interpretation of i4.0 even more complex.

Given these considerations, the following research question emerges: How has international scientific production literature addressed the i4.0 issue in the operations management field? The present paper aims to present a bibliometric investigation regarding the i4.0 within the scope of operations management. The bibliometric analysis covers a sample of articles published in international journals between 2011 and 2017. Data mining and bibliometric techniques were used to achieve the proposed goal, including scientific publication indicators, network analysis, and word clouds. The results discuss the evolution of publications over time, the countries involved, the most prolific periodicals, the most cited authors, and the identification of the most frequent words in order to provide insights for future research.

This article is structured in five sections. The present section introduces the concept of i4.0 and highlights its importance in the scope of industrial engineering and operations management. The second section presents a brief theoretical foundation on the theme. The methods for collecting and analysing the data are presented in the third section. The fourth section presents the research results highlighting the evolution of the publications, the periodicals involved, the analysis of authorship of the publications, and analysis of the words and trends for future research. Lastly, the fifth section presents the conclusions and limitations of the study.

2. PREVIOUS LITERATURE REVIEW ON INDUSTRY 4.0

Since the beginning of the industrial age, significant events have been considered frontiers that represent "industrial revolutions" and characterize the mode of production in a society. The first industrial revolution occurred in the late eighteenth century through the systematic use of water and steam in mechanical systems and resulted in a significant increase in productivity. In the early twentieth century, electric-powered assembly lines, division of labour, and scientific management created a new industrial paradigm. In the early 1970s, many processes replaced mechanical and electrical production with programmable electronic devices, resulting in the third industrial revolution known as the "digital revolution." Finally, the concept of the fourth industrial revolution, which has been widespread in recent years, proposes advanced digitization inside the factories, combining internet and future-oriented technologies in the field of "intelligent" objects (Lasi *et al.*, 2014; Baygin, Yetis *et al.*, 2016).

In this context, i4.0 emerges at the turn of the 21st century, based on the advances of the digital revolution that have made information technology present in the daily life of modern society. The advances in the mobile internet, the miniaturization, and reduction of costs of sensors, even as the artificial intelligence and the creation of intelligent machines, allowed the integration between hardware, software, and networks, characterizing, thus, the end of the third industrial revolution (Kanderman *et al.*, 2013; Sanders *et al.*, 2016; Schwab, 2017).

Lasi *et al.* (2014) explain that "*the approaches and ideas that guide i4.0 encompass a multidisciplinary set of knowledge involving electrical engineering, computer science, management, information systems, and mechanical engineering, expanding the scope of applications of new technologies*". In addition, Shawab (2017) notes that "*many innovations in concepts and technologies are converging to the new industrial paradigm, including artificial intelligence, cloud computing, IIoT, cybersecurity, robotics, Smart Factories, 3D printing, and nanotechnology*".

According to a report titled "*Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries*", published by Boston Consulting Group, a set of nine technologies associated with i4.0 will transform the industrial environment in the coming years. These technologies are: (1) Big Data and Analytics; (2) autonomous robots; (3) simulation; (4) horizontal and vertical system integration; (5) IIoT; (6) cybersecurity; (7) cloud-based solutions; (8) additive manufacturing; and (10) augmented reality (Rüßmann *et al.*, 2015).

Aligned with the idea of i4.0, the term "advanced manufacturing" refers to the set of activities that depend on the coordinated application of information, automation, computing, sensing, and networks to process materials to explore new ways of manufacturing existing products and innovative. (Kagermann *et al.*, 2013). However, this term has been used mainly in English-speaking countries to express the context of Smart Factories and the application of emerging technologies in manufacturing (Kull, 2015).

Regardless of the term adopted, it is important to note that implementing solutions inherent to the i4.0 model requires certain conditions and requirements. Colombo *et al.* (2017) state that "*the performance of CPS depends primarily on the ability to collect, analyse, and use large-scale digitized data and information to sustainably and efficiently manage the operation in industrial environments*". In a study involving 300 industrial companies from different sectors in the United Kingdom, Thomas et al. (2008) points out that "*the perception of the entrepreneurs involved in the study regarding the conversion process for digital manufacturing is that the implementation phase of the technologies of advanced manufacturing represents the most challenging phase of the* *process*". These authors believe this process could be compromised due to the lack of planning and selection of these technologies before entering the implementation phase.

Beyond the technological developments, it is also important to note some criticism about the consequences of a new digital revolution in society. The main one considers reducing jobs in economic activities as a significant challenge imposed on the new industrial paradigm (Brynjolfsson & Mcafee, 2014; Hirsch, 2016). Although the i4.0 may decrease the number of manual operations, some authors advocate that the increase in the number of digital devices and technologies will also require more complex operations and new skills to operate in this new scenario (Baygin *et al*., 2016; Pfeiffer *et al*., 2016; Schuster *et al*., 2016).

The literature regarding the i4.0 also presents practical applications related to the technologies inherent to the fourth industrial paradigm in the scope of operations management. Zheng *et al*., (2016) developed an architecture to simulate and test the Smart Factory concept by integrating process technologies (manufacturing cells, robots, AGVs, and automated storage), information (wireless and virtual platform), and computational logic, in order to optimize the decision-making process in a Small Factory. In this project, each productive resource was considered an intelligent logical unit allowing agile responses to control disturbances in the manufacturing environment. The proposed architecture showed good performance in lead time, production volume, and loss reduction indicators.

Esengün & Ince (2018) have published an important work that reveals several practical applications on Augmented Reality that contribute directly to reducing costs with training and operational errors, mainly in the operations of manufacture, maintenance, assembly, and training operators. In the same direction, Pfeiffer et al. (2016) demonstrate the application of Egocentric attention-interaction documentation (EAID) technology with eye-tracking or "Mobile Eye Tracking." This technology uses small cameras capable of capturing the user's eye movements to measuring the distance and gaps between the focus of attention and the desired location, thus allowing corrections and improvements to be made, especially in environments that require greater operator attention.

In order to demonstrate the importance of predictive maintenance in i4.0, Lee *et al*., (2014) propose a framework for the "self-maintenance" of machines capable of integrating the Intelligent Plant with Big Data Analytics in the industrial environment to reduce the downtime machine and the costs with energy and workforce. Wang *et al*. (2017) present a cloud solution for the interaction between robots and Smart Factory through a multilayer structure, interconnected via networks, aiming to produce items controlled with the aid of RFID technology.

Another essential aspect inherent in advanced manufacturing systems is the project management approach applied to the digital transformation strategy. In this respect, Fulton & Hon (2010) present a roadmap that can be adopted in conversion projects for advanced manufacturing through seven stages that include: (i) initial mapping; (ii) detailed digital competency mapping and assessment; (iii) programme definition and roadmap; (iv) company engagement; (v) delivery of solutions; (vi) three-month review; and (vii) engagement complete or nine-month review.

The recent literature on i4.0 also reveals studies dealing with maturity models based on the use of the technologies, vertical, and horizontal integration levels. As an example, Leyh *et al*. (2017) developed a model called SIMMI, which was structured from four dimensions (vertical integration, horizontal integration, digital product development, and technology use extension) through five stages of maturity, which starts from the basic scanning stage to fully optimized scanning involving end-to-end solutions. Schumacher, Erol & Sihn (2016) propose another maturity model that includes sixty-two evaluation items distributed in nine organizational dimensions resulting in five evolutionary stages, where the first level describes the total lack of adherence to the i4.0 model and the fifth level represents the state of the art of the requirements inherent to the model.

3. METHODOLOGY

The research procedure for collecting and analysing data from this study combines data mining, bibliometrics, and network analysis techniques. Data referring to publications were extracted from Scopus and Web of Science (ISI) databases in December 2017, followed by filtering and technical data processing. Such databases were selected due to the relevance of indexed articles, published in journals with impact factor (Journal Citation Report and CIteScore), as well as the feasibility of stratification and access to the publications.

To retrieve the bibliographic records on the scientific production around the i4.0, we apply the first filter based on the keywords (search string) inserted in the databases. This procedure search was defined based on the terminology used regarding the research topic, as indicated in **Table 1**.

The search in the databases generated a total of 4,475 works published between 2011 and 2017. Using software VantagePoint v. 5.0 it was possible to apply the second filter by refining the search by deleting 42 duplicate papers. The third filter reduced the sample to 1,938 papers classified as "articles," excluding in this way, 2,495 publications in the form of books, conferences, and other types of publication. Following the structured method for selecting articles, a fourth filter was applied, considering the journal's relevance to the theme and alignment with the operations management. This action reduced the sample to 756 papers. Finally, the last filter was applied to analyse the records regarding the title and abstract. In this way, 235 papers were selected to compose the final sample of the study.

The data analysis was conducted in three steps. In the first step, the records were incorporated into a database in VantagePoint, composed of the fields: year of publication, research area, authors, institutions, title, keywords, abstract (when available), number of citations, etc. These records

Table 1. Search strategy of bibliographic references

1st filter (search string)	Bases	Data	Number of papers
("Industry 4.0" OR "Industrie 4.0" OR "manufacturing 4.0" OR "advanced manufacturing" OR "fourth industrial revolution")	Web of Science	05/12/2017	1,196
	Scopus	21/12/2017	3,279
		Total papers	4,475
		2nd filter (exclusion of duplicate papers)	4,433
		3rd filter (selection of papers classified as articles)	1,938
		4th filter (relevance of the journal and alignment with the theme)	756
		5th filter (reading titles and abstracts)	235

were then submitted to bibliometric analysis using occurrence lists and co-occurrence matrices. Lists and matrices were transferred into spreadsheets to proceed with the bibliometric indicators, presented in the form of tables and graphs.

To carry out a statistical analysis involving a sample of scientific publications on a given topic, researchers can apply the fundamental laws of bibliometrics (Lizarelli *et al.*, 2016; Ciftci *et al.*, 2016), including: (A) Bradford's Law, which analyses the productivity of journals highlighting the most prolific sources that explore a specific topic in an area of knowledge; (B) Lotka's Law, which analyses the number of publications and their frequency by authors with a specific theme and shows the contribution of the authors to the progress of science; and (C) Zipf's Law, which analyses the frequency and ranking of words that appear in a text.

Therefore, the statistical analysis of the selected articles was based on the three laws presented above. The study also used other bibliometric techniques, such as the variation of the number of citations made by the authors during the analysed period, the number of citations and co-citations, and the productivity indexes of the authors (H-index). Cluster analysis was also performed between the prominent authors and network analysis, aiming to broaden the perception of relationships, the degree of centrality of the research, and the relevance of these authors. The analysis of the most frequent words located in the titles and keywords of the most recent articles allowed the elaboration of word clouds to identify trends and map the most relevant terms used in the areas of knowledge related to the concept of i4.0.

4. FINDINGS

4.1 Initial Analysis

Figure 1 shows the evolution of publication about the i4.0 in the scope of operations management, comparing the volume of papers published between 2011 and 2017, with other related approaches including "Computer Integrated Manufacturing" (CIM), "Flexible Manufacturing System" (FMS), Big Data Analytics, and "The Internet of Things - IoT." It is possible to observe that, unlike the contemporary themes (Industry 4.0, Big Data Analytics, and IoT), the traditional topics related to processing technology (CIM and FMS) did not show any increase in the research but instead showed stagnation and decline in the number of publications.

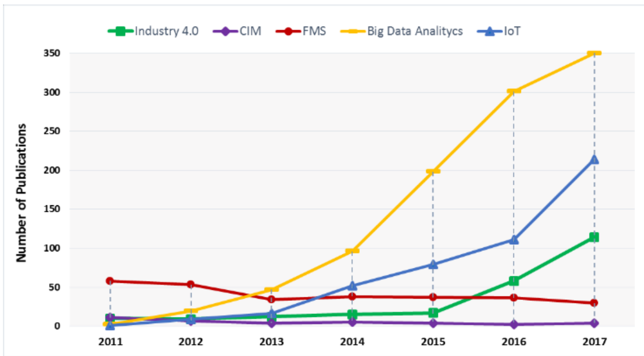

Figure 1. The evolution of the volume of publications by research theme

In this scenario, although Big Data Analytics appears as the most representative in terms of the volume of publications, slower growth can be seen from 2016, while IoT and i4.0 themes show evident growth in the same period. However, work on the fourth industrial revolution in production engineering intensifies only after 2015, four years after the event in Hannover, which gave rise to the i4.0 theme.

Figure 2 shows the distribution of the number of publications between 2011 and 2017 stratified by countries and the number of citations received per article (CRPA) in each country. The CRPA indicator was obtained by dividing the total number of citations received and the number of papers published in each country. Among the countries with the most significant volume of publication, we highlight here, in descending order, those with more than ten published. These countries include Germany (33 articles), United States (27 articles), China (23 articles), United Kingdom (17 articles), India and Italy (both with 11 articles published).

The observation of CRPA indicators reveals that countries with a lower volume of publications, such as Hungary, Austria, and Japan, are responsible for many cited articles. This information reveals that the isolated analysis of the volume of publications is not enough to highlight the relevance of published scientific papers since a country can present a large number of publications without necessarily contributing to the dissemination of knowledge. In addition, it is possible to observe the relevant contribution of the United States, which has the highest CRPA (21.2) among the countries with the highest volume of publications on the i4.0.

Figure 3 presents a map with the geographical distribution of the 25 countries that contributed more than

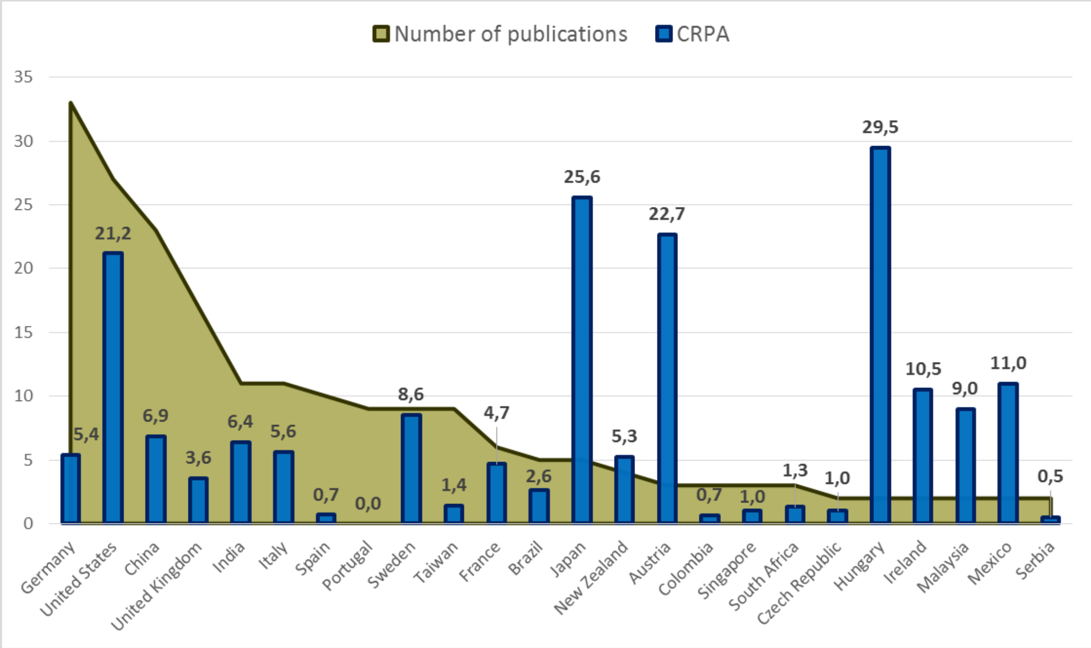

Figure 2. Evolution of the volume of publications by research theme (2011 to 2017)

two articles published and offers another perspective to understand the origins of the scientific research regarding the i4.0 in the scope of operations management. The colour scale within the circles that identify the countries reflects the volume of publications in the country. The closer to the red colour, the greater the volume of publications. The map was built using the Power-map tool.

The analysis of the contribution among the research institutions (including universities and research centers) dedicated to the i4.0 topic shows that among the 106 institutions identified in the sample, only eight universities have published more than two papers from 2011 to 2017. They are Cranfield University and University of Southampton (United Kingdom); Technical University of Darmstadt and Technical University of Berlin (Germany); Beihang University, Chinese Academy of Sciences and Shanghai Jiao Tong University (China); and Tallinn University of Technology (Estonia). The other 98 institutions have only 1 article published in the databases investigated.

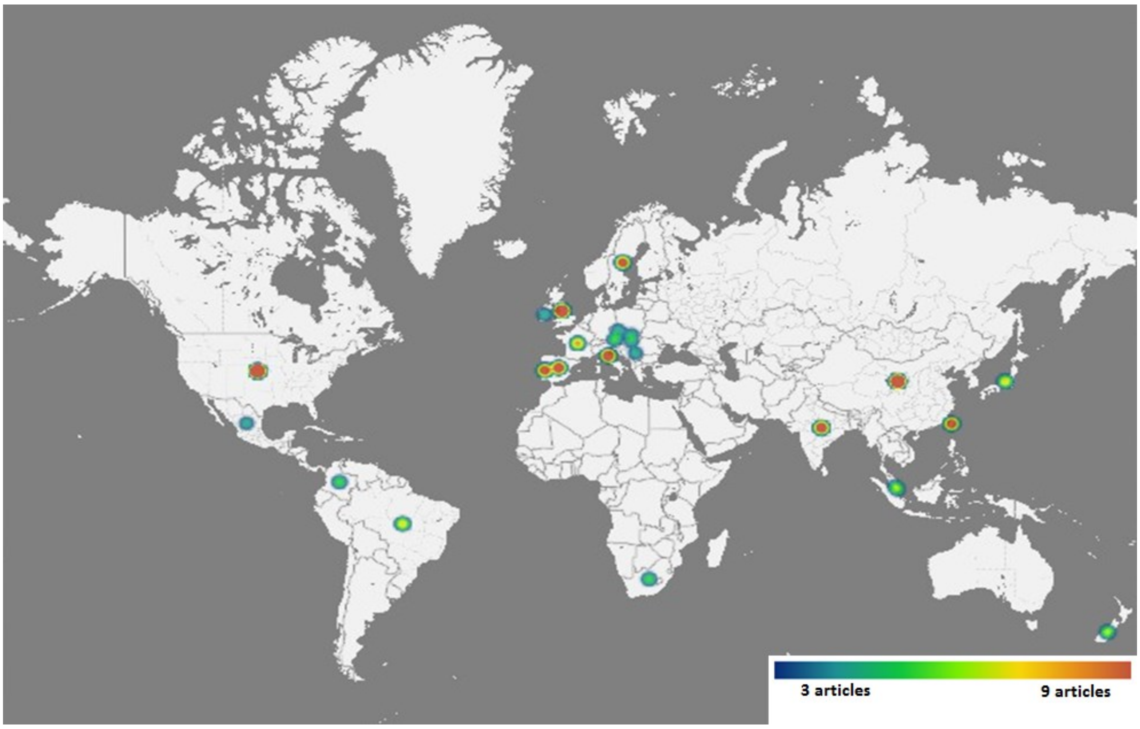

Figure 3. Map of the countries with the largest number of publications

The Boxplot chart shown in Figure 4 shows the number of references cited per year. Although the mean number of references cited in the period is 53.35, the median for each year is between 24 and 50 references. It is possible to observe outliers in the last two periods (2016 and 2017), which represent extreme values above 100 cited references. These values may reflect papers aimed at analysing the literature on the topic, such as bibliometric studies or selective literature examination, which require more references.

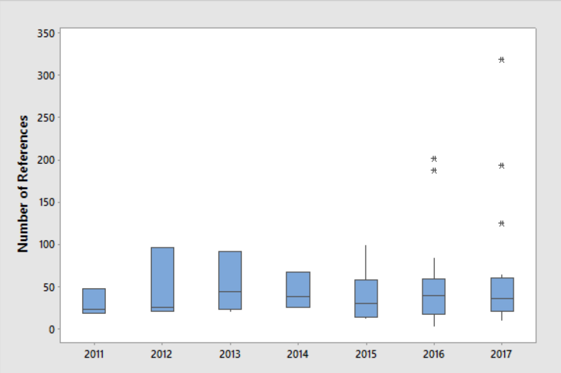

Figure 4. The number of references cited in the articles

4.2 *Analysis of the Journals*

The distribution of the 235 articles published in the 92 journals was conducted according to Bradford's Law. This Law proposes a model for the distribution of journals, emphasizing that most articles on a particular subject are published in a group of few periodicals, from a proportion n, n^2, n^3, ..., where n is the number of journals in the first group called "nucleus" (Rostaing, 1995).

Table 2 shows that the sample distribution is close to the Bradford Law since the core consists of 69 articles (29.36% of the sample) published in 4 journals. Zone 1 consists of 19 periodicals responsible for 73 articles (31.06% of the sample), close to the Bradford proportion (4^2). The analysis of zone 2 corroborates Bradford's conception that many journals produce few articles since 75% of the journals in the sample published less than three articles, 24 journals with two publications, and 45 journals with only one publication. Zone 2 also approaches the Bradford ratio (4^3), with 69 journals.

Table 2. Distribution of journals according to Bradford's Law

Areas	*Journals*		*Articles*	
	Number	%	Number	%
Core	4	4,35	69	29,36
Zone 1	19	20,65	73	31,06
Zone 2	69	75,00	93	39,57
Total	92	100.00	235	100.00

The ten most prolific journals with their respective impact indicators in 2016 are presented in **Table 3**, with the first four journals representing the core of the sample, as shown in **Table 2**. The CIRP Annals - Manufacturing Technology has the most significant impact factor. The Procedia Manufacturing presents the highest proportion of articles published on i4.0, compared to the total of articles published in the analysed period.

Table 3. The most prolific journals

Journal Ranking	Number of articles	% Of articles on the sample	Total articles published in the period	% Of articles published on the subject	Impact Indicator
(1) *Procedia Manufacturing*	40	17.02	2.044	1.96	0.09**
(2) *Int. Journal of Advanced Manufacturing Technology*	14	5.96	7.817	0.18	2.209*
(3) *Int. Journal of Computer Integrated Manufacturing*	8	3.40	588	1.36	1.949*
(4) *CIRP Annals – Manufacturing Technology*	7	2.98	1.074	0.65	2.893*
(5) *Int Journal of Production Research*	6	2.55	3.015	0.20	2.325*
(6) *Journal of Manufacturing Systems*	6	2.55	500	1.20	2.770*
(7) *Journal of Chinese Institute of Engineers*	5	2.13	696	0.72	0.395*
(8) *Int. Journal of Productivity and Perf. Management*	5	2.13	462	1.08	1.85**
(9) *Computers and Industrial Engineering*	5	2.13	2.140	0.23	2.623*
(10) *Journal of Manufacturing Technology Management*	4	1.70	354	1.13	1.71**

* *Journal Citation Reports - JCR 2016 (Base Web of Science)*
** *CIteScore – 2016 (Base Scopus)*

Bibliometric impact indicators measure the importance of journals based on the number of cited references and published articles. The research considered the Journal Citation Report - JCR (Web of Science) and CiteStore (Scopus) indicators for 2016. Our analysis highlights the Journal of Operations Management, which holds the sample's highest impact factor (JCR of 5,207).

4.3 *Leading Authors in the Research Field*

In order to identify the most prolific authors in the context of this study, Table 4 was initially elaborated, ordering articles according to the number of citations received up to the research data. The table also shows the period of publication and the title and classification of the subject in which the article was registered. Altogether, these ten papers have 622 citations. The author Jay Lee is the most cited on the topic i4.0 (301 citations). His article entitled "The Cyber-Physical Systems Architecture for Industry 4.0-based manufacturing systems" represents 48% of all citations referring to the ten most cited articles.

According to Lotka's Law, a limited number of authors can produce much in a given area of knowledge, while a large number of authors will produce little (Rostaing, 1995). According to this Law, the number of authors who publish n articles in a given scientific area is equal to $1/n^2$ of authors who only publish one article. Thus, the number of authors with two publications should equal ¼ of the number of authors with only one published paper. In this scenario, we highlight the authors Cheng, Y. and Tao, F., for presenting 8 published papers on i4.0. In total, 635 authors were identified, of which 541 contributed with the publication of only 1 article, 85 published 2 articles, and only 9 authors published 3 or more articles. However, Lotka's Law is not evident here since the proportion of authors with two publications is approximately 1/6 of the number of authors with only one publication.

Figure 5 shows the co-citation network involving 82 authors present in the 20 most cited articles. This network was elaborated from the Ucinet / Netdraw software. The nodes (authors) are represented in the graph, linked by edges, which indicate the citations made by each author, both unidirectional and bidirectional. The size of the nodes is proportional to the total number of citations received between the authors, and the proximity between them indicates the ability of a node to connect to the other nodes of the network through geodetic distance.

Table 4. Top 10 articles based on citations

(Rank) Name of the first author	Year of publication	Title of the article	Subject category	Number of Citations
(1) Jay Lee.	2015	A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems.	Engineering	301
(2) Qingyun Dai.	2012	Radiofrequency identification-enabled real-time manufacturing execution system: a case study in an automotive part manufacturer.	Engineering, Computer Science	60
(3) Monostori, L.	2016	Cyber-physical systems in manufacturing.	Manufacturing Engineering	55
(4) Gao, R.	2015	Cloud-enabled prognosis for manufacturing.	Manufacturing Engineering	52
(5) Kang, H.	2016	Smart manufacturing: Past research, present findings, and future directions.	Manufacturing Engineering	41
(6) Cheng, Y.	2013	Energy-aware resource service scheduling based on utility evaluation in cloud manufacturing system.	Manufacturing Engineering	37
(7) Ivanov, D.	2016	A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0.	Operations Research Management	24
(8) Schlechtendahl, J.	2015	Making existing production systems Industry 4.0-ready.	Manufacturing Engineering	20
(9) Roy, R.	2016	Continuous maintenance and the future: Foundations and technological challenges.	Manufacturing Engineering	17
(10) Zawadzki, P.	2016	Smart product design and production control for effective mass customization in the industry 4.0 concept.	Industrial Engineering	15

When analysing the indicators of centrality of degree and intermediation of the network, it is observed that Tao, F. has the highest centrality index input (2,778). This index represents the sum of the interactions between the nodes connected to the author. In this sense, we also highlight the authors: Monostori, L. (2,370); Zhang, L. (2,148); Wang, L (1926); Lee, J. (1,802); and Dornfeld, D. (1,321). On the other hand, four authors stand out with the centrality index of output, representing the sum of the interactions an author has with the other authors when citing them. These authors are Kumara, S. (1975); Mori, M. (1,321); and Kondoh, S. and Ueda, K, who together share the same index (1,173).

4.4 Word Analysis

The keywords defined by the authors and words present in the titles of the 235 articles were analysed in this section. For a better understanding of terminology, stop words such as articles, adjectives, verbs, pronouns, etc., have been removed. In addition, words with the same meaning, including acronyms, plural and singular terms, synonyms, and abbreviations, such as "Industry 4.0" and "Industry 4.0", "Cyber-Physical Systems", and "Cyber-Physical Production Systems", etc. The data mining technique made it possible to identify 572 occurrences of keywords present in the 235 articles. With the removal of stop words and grouping of words, the sample was then reduced to 322 keywords.

Zipf's Law is often used in bibliometric studies to prioritize the most frequently occurring terms in an academic text. This Law establishes that the number of times a word is identified in a text (f) multiplied by its position in the frequency ranking (r) is a constant (Rostaing, 1995). However, the identification of the most representative terms in a bibliometric analysis can also be performed by applying the Goffman Transition Point index, known as "T-Point," which represents an unfolding of Zipf's Law (Pao, 1989).

Figure 6 shows a Pareto chart with the distribution of the 22 most frequently keywords presented in the articles, according to Goffman's T-Point index. It should be noted that the first keywords represent trivial terms associated with the i4.0 concept since the "Cyber-physical Systems" through the integration of computer science, information, and communication technologies (including IoT and cloud), and manufacturing technology may lead to the i4.0 concept (Monostori et al., 2016). Furthermore, CPS is a key technology for realizing Smart Factories with close relationships with the cloud, IoT, and Big Data (Kang *et al*., 2016). On the other hand, terms such as "RFID" and "Manufacturing systems" can be associated with the integration of RFID devices and MES to collect data in real-time to improve shop-floor management (Dai *et al*., 2012). The most significant keywords in the sample (with more than 10 observations) include: "Industry 4.0", "Cyber-Physical Systems", "Internet of Things", "Smart factory", "Advanced Manufacturing", "Cloud manufacturing", "Big Data", and "Additive manufacturing". Furthermore, it is possible to observe the presence of words directly related to manufacturing practices, including "Supply Chain", "Maintenance", "Lean Manufacturing", and "Quality control".

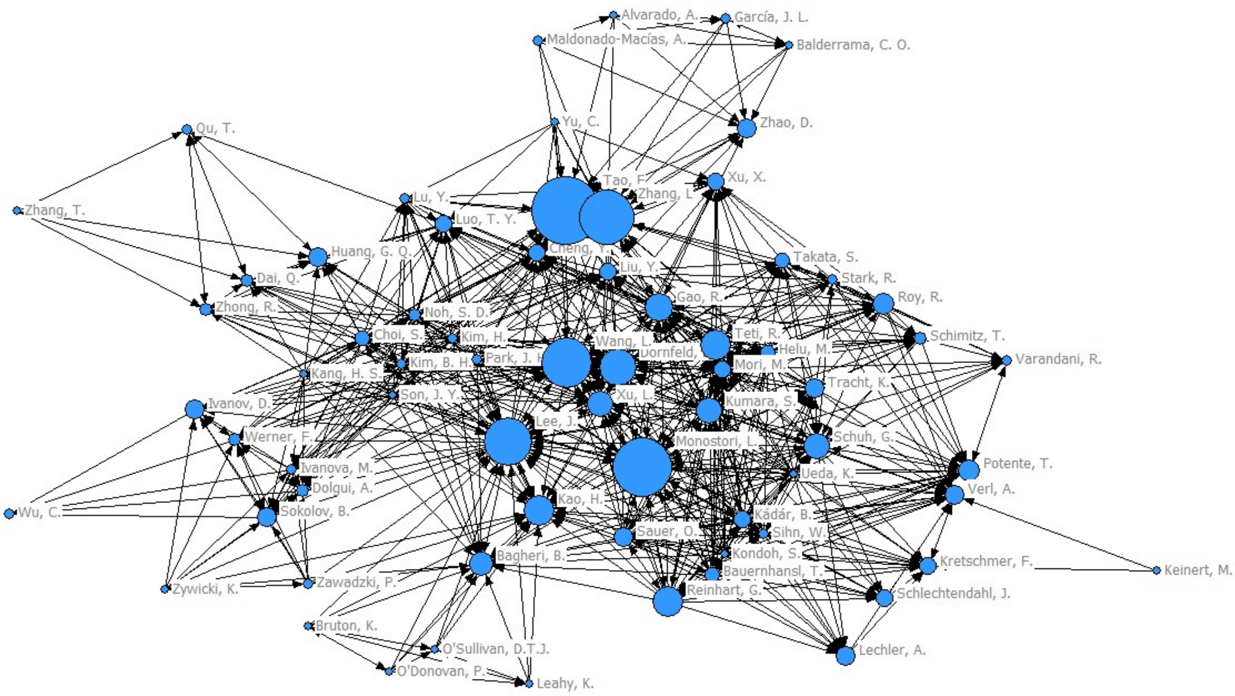

Figure 5. Co-citation network

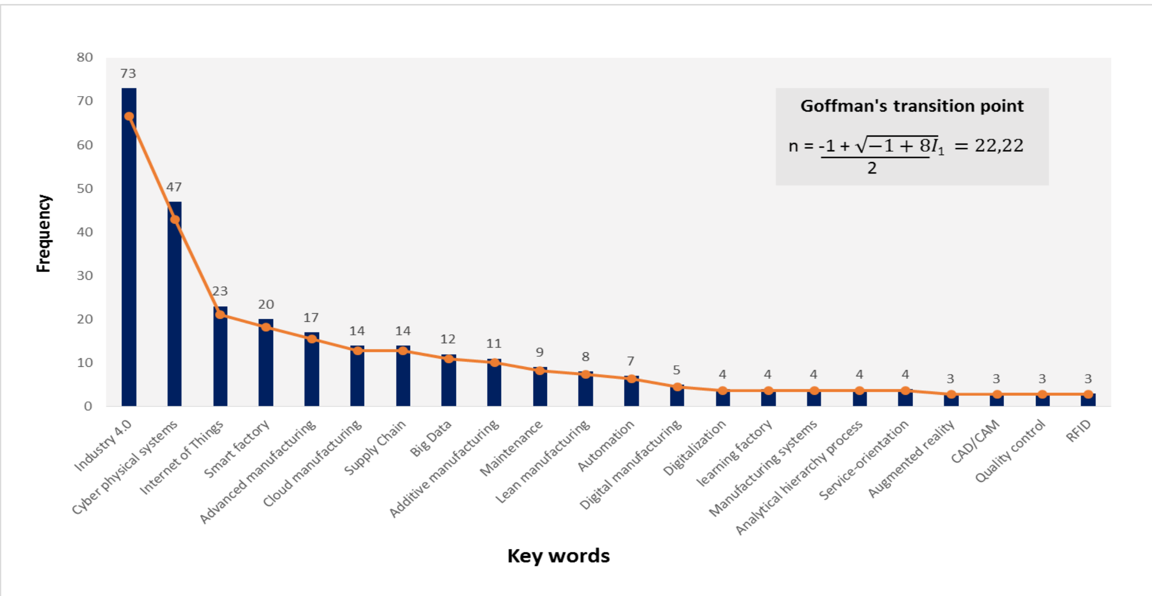

Figure 6. Pareto chart with the most frequent keywords

Figure 7 shows a word cloud encompassing the 47 words most frequently associated with the i4.0 concept. The size of each word is related to the frequency observed in the records, ranging from 2 words (minimum frequency), such as "Simulation" up to 73 words (maximum frequency). It is possible to observe that the approach given to the technologies associated with the i4.0, such as CPS, additive manufacturing, Big Data Analytics, Smart Factory, IoT, etc., were addressed in the Pareto chart.

Following the same procedure, the analysis of the words presents in the titles allowed the identification of 156 words. After filtering these words, 101 terms were then selected to perform the word cloud. Figure 8 illustrates the word cloud based on the most used words in the titles of the 235 papers analysed. Knowing that the research topic has a wide field of application even within operations management and that the titles reflect this range of studies, there is no further analysis in this sense.

Figure 7. Word cloud formed by the keywords present in the articles

5. CONCLUSIONS

Although the i4.0 issue appears incipient in scientific research, its importance for operations management is present in several economies. For this reason, the growth in the number of studies focused on the topic reflects the importance given to the digital transformation in recent years. The technologies associated with the fourth industrial paradigm are exploited in an integrated way, connecting technologies stemming from the third industrial revolution, also called digital technologies, with the vast amount of data and devices perfected in the internet age.

The use of bibliometric techniques allowed an understanding of some specificities of international scientific production. In addition to highlighting the relevance of the theme to the scientific community, the study revealed the efforts of countries such as the United States, Germany, China, and the United Kingdom concerning the volume of papers published, as well as contributions from other countries, including India, Italy, Japan, and Hungary regarding the number of works cited worldwide.

Figure 8. Word cloud formed by the words present it the title of the articles

The analysis of the sources revealed that the distribution of the articles approximates the Bradford Law since the core of the sample consists of 29.36% of the articles published in the four most prolific journals. On the other hand, it was not possible to prove the Law of Lotka, generally used to analyse the authors' contribution to the number of publications. However, the study presented the ten most cited articles and the network of co-citations among authors present in the 20 most cited articles, revealing connections between them. Otherwise, the analysis of the keywords and words in the articles' titles provided an understanding of the interaction between the various concepts and techniques associated with the central theme for the research agenda.

The main limitation of this work is the number of papers used in the bibliometric analysis. This limitation is due to the application of the search criteria described above, since the study focused on the selection and analysis of works on i4.0, which led to the exclusion of important articles on the subject published in other areas of engineering, such as chemistry, mechanics, computing, etc. Thus, as a suggestion for future research, it is recommended to extend this work to other databases, as well as bibliometric analyses on i4.0 in other areas of science.

5.1 Research Agenda

The bibliometric analysis results allow us to identify some ideas for future research in the context of the i4.0. The first proposed research agenda concerns the interaction between i4.0 technologies and business processes, including supply chain, maintenance, and quality control, as observed in the keywords contained in Goffman's transition point. In this context, practices inherent to the shop floor management, such as lean manufacturing, manufacturing systems, and learning factory could be investigated in light of the fourth industrial revolution paradigm.

Another aspect for future research addressing the central theme of this paper would be the proposal of frameworks aimed at teaching and disseminating topics related to i4.0, both in the academic and business environment. In this context, the word "framework" is highlighted in figure 8, revealing the main keywords in the titles of the articles analysed. In the same figure, it is also possible to observe the highlighted word "integration," understood here, as a possibility of investigation between two or more digital technologies inherent to the i4.0.

As this is a developing issue, the bibliometric analysis revealed that several studies have the objective of investigating the challenges, opportunities, and trends that may offer a better understanding of the future of operations management. As examples of this approach, we can address a study that highlights the identification of the leading technologies related to Smart Manufacturing through the analysis of policies and roadmaps developed by Germany, the US, and Korea in order to support the conversion to the new industrial paradigm (Kang et al., 2016). Another research survey applied in Mexican industries points out the main problems of implementing i4.0 technologies in assembly plants (Alvarado & Garcia, 2013). Finally, in the scope of operational excellence, we also observed a study presenting the main trends inherent to the improvement processes for organizations that adopt Cyber-physical Systems, Big Data, and IIoT (Tamás & Illés, 2016).

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