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A Bibliometric Study in Advanced Manufacturing and Industry 4.0: What About the Sustainable Supply Chain?

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Abstract- Different ideas, approaches, and technologies have emerged during the past ten years, advancing industry toward what is now known as the fourth industrial evolution, or Industry 4.0 (I4.0) and Advanced Manufacturing (AM). Based on both, Supply Chain (SC) is described as a crucial concept in a sustainable approach to I4.0 since it is the pertinent process that establishes the sustainability of production. Nevertheless, no research has examined the development of science in both AM and I4.0. In order to fill this gap, the purpose of this study effort is to examine the tendencies of science research connected to I4.0 and AM by doing a bibliometric and network analysis and also to develop a new contribution through the analysis.

Keywords- Industry 4.0; advanced manufacturing; supply chain; sustainable supply chain; bibliometric analysis; network analysis

I. INTRODUCTION

The phrase I4.0 refers to the fourth industrial revolution, a consequence of the first three prior industrial revolutions, which lasted over 200 years, with the presence and use or implementation of the I4.0 concept currently being a reality in numerous industrial and economic environments.

A new manufacturing model known as Advanced Manufacturing (AM) emerged in production processes during the third industrial revolution as a prelude to I4.0. AM produced unique products through technology advancements and creative concepts [3]. Beginning in the mid-1990s, this new paradigm started to acquire traction in the scientific community [4,5]. As a result, several Advanced Manufacturing Technologies (AMT) or Advanced Manufacturing Systems (AMS) [7] were created in response to growing production volumes and personalized demands [6].

Despite the constant evolution of AM, which is more focused on physical manufacturing technology [8], due to the needs and changes in manufacturing processes and business models, the term I4.0 was born [9] in 2011, coined by the German government and focused on the analysis of data obtained through various automated and interconnected systems, designed to be of great help in decision-making processes and representing the main difference between the terms Industry 3.0 (I3.0) and I4.0 [10]. Increased efficiency, flexibility, manufacturing speed, and mass customization are achieved through the use of interconnected automated systems that provide real-time communication between people, equipment, and products; resulting in greater quality and productivity for companies [11]. Thanks to their technologies, I4.0 and AM have both continued to develop in recent years in search of production systems that can lower production costs and increase flexibility and productivity while overcoming various challenges arising from industrial globalization, customization, or product life cycle, among other issues [12]. Both I4.0 and AM are methodologies that enhance innovation [13].

Many industries have chosen to use the technologies resulting from this fourth industrial revolution, but the manufacturing and logistics sectors have been at the forefront of adopting or incorporating these new technologies [15] because I4.0 facilitates the exchange of information and the integration of Supply Chain (SC), along with the synchronization of production with suppliers to shorten delivery times and reduce information desynchronization or distortions [14].

Consequently, the automated processes and digitization obtained from I4.0 have caused various repercussions on both SC and, consequently, the Supply Chain Management (SCM) structure [16]. Ojo et al. define SC as "a network of organizations responsible for the production and distribution of products from conception to the final consumer" [17]. In order to achieve a sustained competitive advantage, SCM integrates and incorporates all operations produced by the SC, strengthening relationships along the SC [18]. Therefore, the achievement of sustainable competitive advantages leads to a Sustainable Supply Chain (SSC), focused on the improvement of environmental, social, and economic benefits [19], frequently referred to using a phrase that encompasses these three aspects: Triple Bottom Line (TBL) [20].In view of the following, it is important to emphasize that achieving sustainability in any manufacturing company begins with SCM, and that sustainability is only achievable if it is properly managed [21], and for this purpose, the different technologies belonging to I4.0 technologies (Cyber–Physical Systems (CPS), Big Data (BD), Cloud Computing (CC), Industrial Internet of Things (IIoT)) play a very important role, under cyber security guidelines, as highlighted by several authors [22,23].

We can determine the scientific evolution essential to comprehending each bibliometric analysis notion using a variety of analysis techniques [24]. As a result, Table 1 lists the primary scientific methodologies for measuring and analyzing the advantages and disadvantages of various approaches.

Once the advantages and cons have been assessed, the most appropriate technique to describe and quantify the academic performance of the defined field of research is through a bibliometric examination of the data received from a scientific database. Additionally, the analysis of networks, which produces pertinent data for the scientific community, is the best method for determining the primary collaborative groups or research areas, both within a particular organization and generally.

II. METHODOLOGY

The following three stages are used to accomplish the research work's goals: The first relies on data retrieval to create a database of I4.0 and AM-related scholarly articles. According to a number of studies, using several databases (such as Google Scholar (GS), Web of Science (WoS), and Scopus) yields better results. However, GS shows as many citations as Scopus and WoS, and those citations that differ or are unique have less scientific impact than those of Scopus and WoS [52,53]. Additionally, these two databases complement one another; nonetheless, in this instance, Scopus has been selected because it offers more records than WoS.

Nevertheless, because Scopus is one of the biggest databases of abstracts and citations in peer-reviewed literature (75 million documents indexed), it is used for this purpose [54].

The allocation was performed by constructing and iteratively testing multiple queries, comprising of distinct phrases for extracting data from the database's scientific papers. With the objective of establishing the main query terminology, the particular terms that arise in past AM- and I4.0-related work were established. In the search strategy, it is very crucial to design the search query and create a balance between recall and precision [55].Since the research field in this instance can encompass a variety of approaches, the query was constructed using "Advanced manufacturing or Industry 4.0" and both, depending on the situation, along with "technology or systems or overview or key" as keywords (groups Author Keywords and Index Terms derived from Elsevier's thesauri) in order to obtain a precise query with a greater recall (see Figure 1). The period between 2010 and 2019 was chosen for data collection. The main query used in Scopus retrieved a total of 6571 publications.

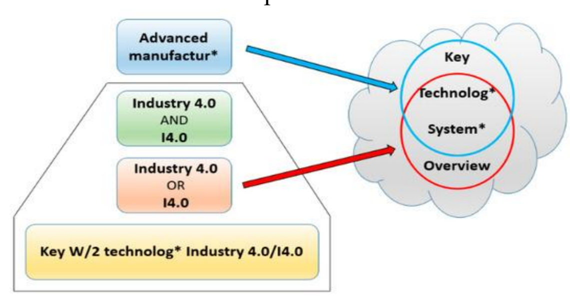

Figure 1. Scheme Followed in Defining the Search Query. *: wildcard character with which to represent and cover any other phrase, within our area of research, through the different existent possibilities of the character * onwards.

The second phase is the cleaning up of retrieved data, utilizing text mining technologies. For this, Vantage Point (VP) software [56] was employed, a text-mining software that helps us to clean up the data and then analyze it through a mix of statistics. This software comprises data cleaning methods based on fuzzy matching techniques or thesaurus, and additionally, it incorporates techniques for analyzing data, such as co-occurrences matrix, Social Network Analysis (SNA), natural language programming, etc.

The creation of the scientific research profile, which describes publishing patterns, academic achievement, and research themes, is the third phase. Based on the co-occurrence matrices generated in VP, a network analysis was performed to enhance and expand the analysis of scientific trends. The collaboration networks between nations, organizations, the most pertinent research topics generally or of a particular organization, or the organizations associated with a particular research area, among other things, can be visualized and identified thanks to the networks. Gephi software was used to create and visualize the networks [57]. Additionally, other results of the VP analysis were mapped and represented using Microsoft Power BI software [58].

III. RESULTS

3.1. Scientific Performance Profile

3.1.1. General Trends of Publications

The number of published documents has significantly increased over the past ten years, as seen in Figure 2, demonstrating the intense interest produced in the academic community. Conference papers and articles are the most published document kinds. The number of publications increased gradually between 2010 and 2014, and there was even a minor decline in 2012. But since 2015, the growth has been exponential, nearly doubling annually. As a result, businesses and the scientific and research community are focusing more on the technology aspects of I4.0 and AM.

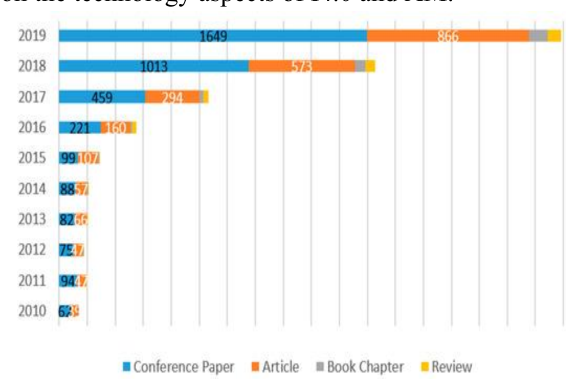

Figure 2. No. of Document Types and Total per Year.

3.1.2. Academic Achievement: Nation, Institutions, and Writers.

The most productive nations, institutions, and writers in the field of study were examined in terms of academic achievement. Regarding countries, the most productive countries were Germany (896 publications), followed by the United States (U.S.) (798), China (682), and Italy (636), as shown in Figure 3. It should be mentioned that over the past ten years, the United States and China have produced regularly; however, Russia (ranked #7) began publishing the findings of their research on AM and I4.0 in 2014.

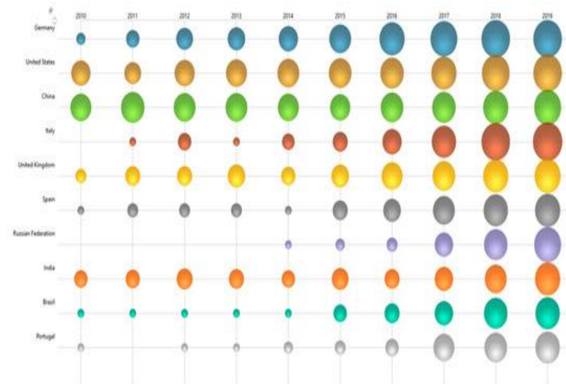

Figure 3. Publication Evolution by Top Countries per Year.

In order to identify the primary collaboration networks across countries, a network analysis was done. The size of the node represents the number of collaborations, and as shown in Figure 4, the most collaborative countries are located in the heart of the network and are U.S., China, United Kingdom (U.K.), Germany, and Italy. In addition, we also observed other countries such as Australia (ranked #10), Mexico (ranked #12), India (ranked #13), Malaysia (ranked #16), and Canada (ranked #18), which provide an essential level of collaboration. Therefore, in the sphere of research, the collaborations are located in what is known as the tri-polar world (America, Europe, Asia-Pacific), establishing the scientific powerhouse countries in the central zone of the network, surrounded by growing countries.

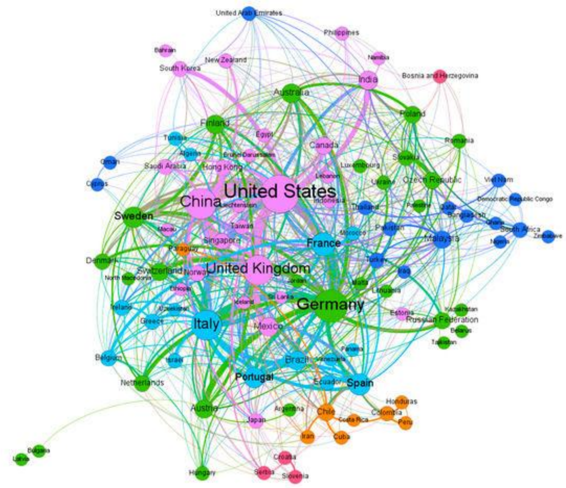

Figure 4. Network for Country Collaboration.

The weighted degrees of the various countries are shown in Table 2, which allows the number of collaborations between the various nations to be quantified (the size of the node in Figure 4). Emphasizing that the most productive countries are the most collaborative.

According to Table 3, the most productive organizations between 2010 and 2019 were the Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University (Germany) with 72 publications, Università degli Studi di Brescia (Italy) with 53 publications, and Saint Petersburg National Research University of Information Technologies, Mechanics, and Optics University (ITMO) (Russia) with 52 publications. However, it should be noted that the publications of Stuttgart University (ranked #6) have an average of three times more citations than those of first-ranked RWTH Aachen University, which indicates the influence that the research carried out by this organization has on the rest of the scientific community. Finally, within the Top 10, there is a majority presence of European organizations, differentiating the organizations from Russia and two American countries (Brazil and Mexico) within this ranking as non-European organizations and emphasizing the influence of the publications of the Tecnológico de Monterrey.

The most cooperative organizations are represented by the network of organizations shown in Figure 5. The institution that produces the most publications in partnership is the institution of Monterrey, even if it is the tenth (ranked #10) most productive company. Similarly, the University of Naples Federico II is dynamic and very collaborative. In addition, the high degree of collaboration with other groups of the University of Pennsylvania in its research activities is interesting. In addition, Plekhanov Russian University of Economics, Beihang University, Shanghai Jiao Tong University, and South China University of Technology are highly collaborative institutions.

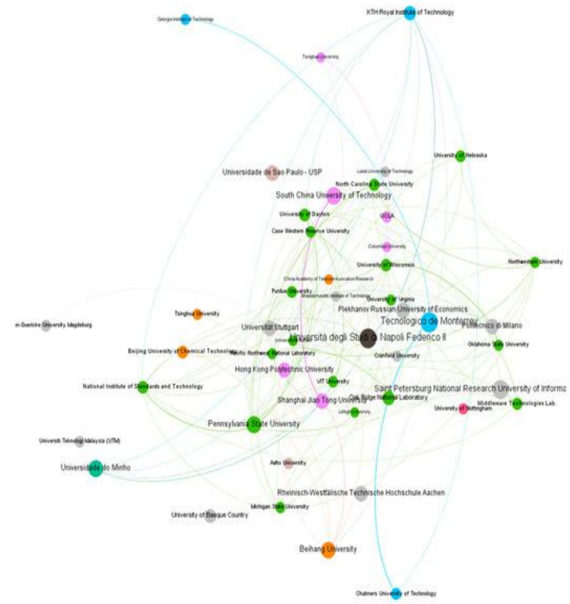

Figure 5. Network of Collaboration between Organizations.

Regarding the organizations, Table 4 quantifies the various nodes of organizations depicted in Figure 5 by displaying the levels of collaboration among the various organizations.

In terms of writers, ITMO University is home to the first three authors with the most publications (Zakoldaev, Danil A.; Zharinov, Igor Olegovich; and Shukalov, Anatoly Vladimirovich).

The geographic locations of the many authors listed in Table 5 are displayed in Figure 6. The larger the concentration of authors in that geographical area, the greater the diameter of the node that represents them, with Russia being the country with the most authors in the top 10 but, as indicated previously, with less impact. In actuality, four of the top five authors are from Europe, while the author with the greatest average citations per publication is from the United States.

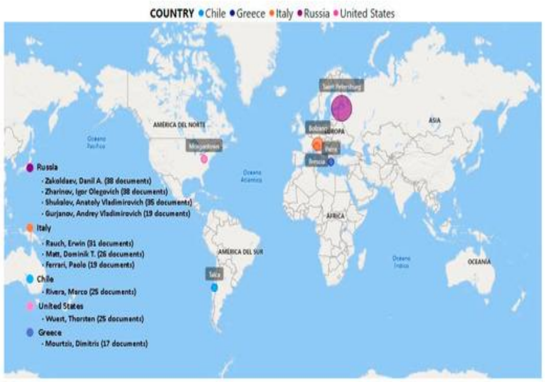

Figure 6. Location of the Top 10 Authors.

3.1.3. Sources and Subject Area Classification

The different sources with more documents related to I4.0 and AM were identified. As shown in Figure 7, the number of documents published by the top 10 sources is about the 19.7% of the publications on this subject. For example, the journal Procedia Computer Science (ranked #1) monopolizes 3.3% of the documents published. Of the total of documents, 58.3% are published in conference proceedings and 34.3% in journals, with the remaining percentage being published in book chapters, reviews, etc. It is worth noting the importance of Procedia in the number of documents published. Elsevier publishes an open source series called Procedia (Procedia Computer Science, CIRP (see footer of Figure 7), Manufacturing...) with the goal of disseminating suggested conference proceedings. Therefore, conferences become the most important source of dissemination of scientific research linked to I4.0 and AM.

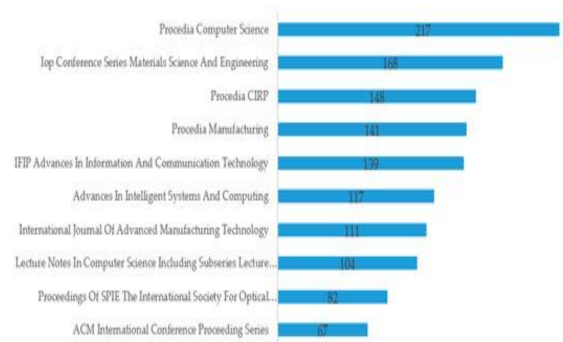

Figure 7. The quantity of publications based on the best sources. The Institute of Physics (IOP); the College International pour la Recherche en Productique (CIRP); the International Federation for Information Processing (IFIP); the Society of Photographic Instrumentation Engineers (SPIE); and the Association for Computing Machinery (ACM).

According to the Scopus database's categorization, engineering accounts for 30% of all publications, followed by computer science (24%) and mathematics (7%).

Additionally, a network analysis based on the co-occurrence matrix has been conducted to identify the University of Stuttgart's primary research areas, taking into consideration that the university has been identified as the most influential of the top 10 (see Figure 10). I4.0, CPS, digitalization, manufacturing, data analytics, process optimization, IoT, SM, IIoT, Cloud Manufacturing (CMfg), data mining, production systems, and Petri nets are some of the primary study subjects.

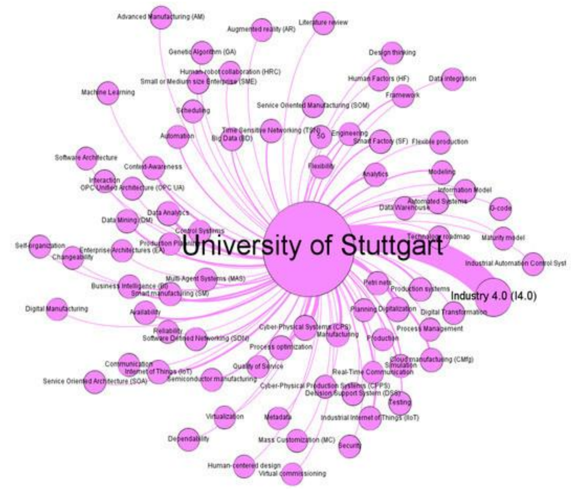

Figure 10. Keywords used by the author and the University of Stuttgart Co-Occurrence Network.

The different nodes or study areas of the network do not offer a considerable variation in size, except in the case of I4.0, as indicated by the weighted degree of the major terms displayed in Table7.

3.2. What about the Sustainable Supply Chain?

In order to study the academic–scientific behavior of SC or SSC in the scientific environment of I4.0 and AM, we have analyzed, on the one hand, the evolution of these terms (and others connected to them) based on the first year that these terms emerge in the scientific research. On the other hand, based on a network analysis, the research topics that co-occur in this field of research have been identified, and in addition, both the organizations and countries that research in the area have been recognized.

In terms of terms or keywords, it has been determined which year the terms related to SC initially surfaced. The phrases related to SC have changed over the past ten years, as Table 8 illustrates. In 2018, the sustainable and SC research model emerged as the keyword "Sustainable Supply Chain." Please note that the first reference in our SC dataset is from 2011; however, it may be older since a drawback of the study is that not all publications have been evaluated, only those published in the recent 10 years.

The author's keyword co-occurrence matrix indicates that SSC is not a phrase that frequently co-occurs with other research topics, which may be the reason for the recent definition of SSC as a research topic (see Figure 9). As a result, as Figure 11 illustrates, the network analysis identifies the phrases that have the most impact on "Supply Chain," including sustainability, Logistic 4.0, digitalization, data mining, optimization, simulation, Decision Support Systems (DSS), and process control.

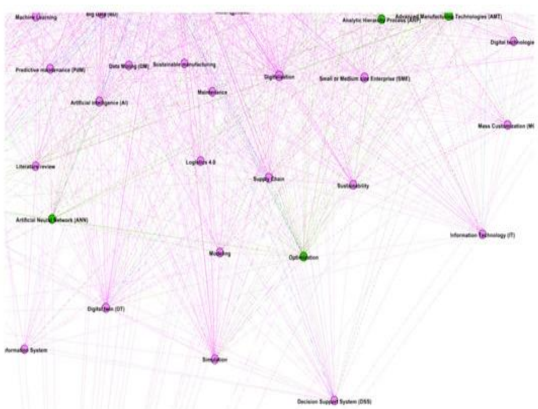

Figure 11. Network of Terms that Co-Occur with Supply Chain.

The network analysis has enabled the identification of the nations and institutions that do research on SC and SSC (see Figure 12). Due to the wide background of the SC research field, its scientific progress is found throughout America, Asia, Africa, and Europe, with a focus on nations like the United States, China, Germany, Spain, Italy, India, Indonesia, Brazil, and South Africa. However, because of its short history in scientific progress, the SSC study field has a more constrained expansion (see Table 8). However, it conducts research in a number of nations, including the United States, India, Spain, Iran, Lithuania, South Africa, Denmark, China, the United Kingdom, and Brazil.

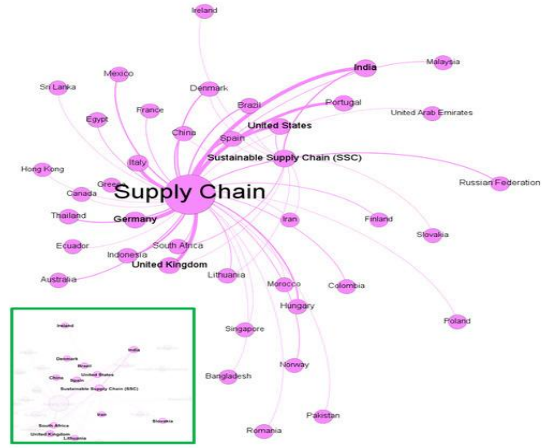

Figure 12. SC and SSC and Country Co-Occurrence Network.

A network based on the matrix of co-occurrences of terms and organizations was developed to identify the organizations that do research in the fields of SC and SSC. VIT University (Vellore Institute of Technology) of India stands out for its research in both fields (see Figure 13). Furthermore, the following institutions have a significant presence in the field of SC research: Chulalongkom University, Berlin School of Economics and Law, Universidade do Minho, University of Bozen-Bolzano, and St. Petersburg Institute for Informatics and Automation of the RAS (SPIIRAS). In turn, research related to SSC is also present in University of Sevilla, Columbia University, Beijing University of Technology, and Copenhagen Center for IoT Economy, among others.

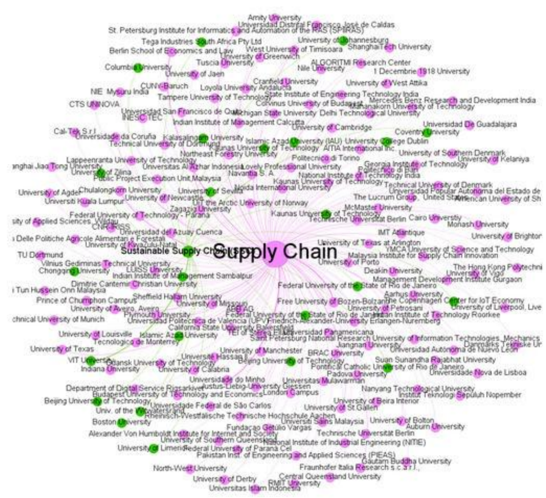

Figure 13. SC and SSC and Organization Co-Occurrence Network.

IV. DISCUSSION

The number of publications has increased exponentially in recent years, according to the examination of the scientific profile used by I4.0 and AM. Furthermore, we can estimate the degree of technological growth by looking at the number of terms or research topics that emerge for the first time during the dataset's time span [59]. Based on this, we can conclude that the scientific field related to I4.0 and AM is expanding, producing up to nearly 4500 new terms in 2019.

RWTH Aachen University in Germany, the origin of I4.0, has the most papers pertaining to cooperation in the spatial patterns when it comes to organizations. Although they are not in the top 5 organizations with the most publications, the University of Stuttgart and Tecnologico de Monterrey should be emphasized as the organizations with the most scientific impact because they have the highest average citations per publication. Nonetheless, the most cooperative institutions are the University of Naples Federico II (Italy) and Technological de Monterrey (Mexico). This enables us to assess these organizations' capacity for relation, diffusion, or scientific-technological transfer, pointing out that increased cooperation and linkage (over time) among organizations leads to above-average productivity and has a greater effect on the citation impact of individual (non-collaborative) publications, which in turn generates more visibility and, consequently, greater dissemination [61].

The three authors with the most publications are members of the same study group at ITMO University (Russia), yet their papers have little influence. With an average of more than twice as many citations per publication as the second most important author, Thorsten Wuest of West Virginia University (U.S.) stands out in terms of research impact.

In addition to other research areas like CPS, digitalization, manufacturing, data analytics, process optimization, IoT, SM, IIoT, CMfg, data mining, and so on, the network analysis of the research topics enables us to conclude that there are two main research areas grouped in two clusters, the main cluster being the one formed by the I4.0 field, in which the SC- and SSC-related topics are grouped. Additive manufacturing, RP, and AHP are cluster terms associated with the AM group. We can observe that the topics observed in the network effectively correspond with the technological bases that the various authors use as a foundation in the process of technological and digital transformation of SC directed toward I4.0 through their technologies when we compare these topics with the works produced by other authors, such as Da Silva et al. [63] and Cimini et al. [64]. Therefore, it can be stated that, in terms of scientific advancement, the study domains associated with I4.0 and AM are obviously distinct, even though they exhibit the same strategy to boost competitiveness in various production systems.

Lastly, Table 9 lists all of the research that has been conducted using a bibliometric analysis pertaining to I4.0 in order to elucidate the academic–scientific significance of this study.

Therefore, by representing and identifying the most cooperative and exceptional nations and institutions, as well as assessing their capacity for dissemination and relationships, our study and analysis not only fills the gap mentioned at the outset of this work, but also offer the scientific community new avenues for collaboration, both in terms of I4.0 and AM. In a similar vein, we are helping to identify the scientific trends of SSC and SC, particularly in relation to I4.0 and its technologies. We are also identifying the nations and organizations that conduct more research in this field, paving the way for further investigation and cooperation in the pursuit of increased sustainability in the manufacturing sector.

V. CONCLUSIONS

Based on the evidence presented in this study, we can infer that scientific research on I4.0 and AM is expanding at an exponential rate, with China, the United States, and Germany being the most active nations. Furthermore, scientific articles are created cooperatively throughout the world (Europe, America, and Asia-Pacific), with the most collaborative members of the network being the scientific powerhouses. In terms of organizations, RWTH Aachen University is the most productive, but the University of Stuttgart and Tecnologico de Monterrey, with Technological de Monterrey being the most cooperative, have a big impact on scientific output. The network of one of the most powerful universities enables us to identify a number of primary research areas associated with I4.0 technologies, including

CPS, digitalization, manufacturing, data analytics, process optimization, IoT, and SM, among others.

Therefore, it can be concluded that this is a very active field of research, opening the way to new investigations that make it possible to further the transfer of the knowledge generated (as co-citation analysis), in order to facilitate and promote new research to the scientific community.

SSC will remain a focus of ongoing research due to the environmental, social, and economic advancements it has brought about as well as governmental pressure and consumer demands regarding environmental issues. As a result, it will be crucial to employ the technologies that have arisen from I4.0 and AM, especially I4.0. In fact, some papers have already linked I4.0 to sustainability through the circular economy, with acronyms like Green Supply Chain Management (GSCM) emerging.

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