sustainability

Article

Sustainable Manufacturing 4.0—Pathways and Practices

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Abstract: The manufacturing industry has undergone numerous revolutions over the years, with a unanimous acceptance of the greater benefits of being sustainable. The present industrial wave—Industry 4.0—by using its enabling technologies and principles holds great potential to develop sustainable manufacturing paradigms which require balancing out the three fundamental elements —products, processes, and systems. Yet, numerous stakeholders, including industrial policy and decision makers, remain oblivious of such potential and requirements. Thus, this bibliometric study is aimed at presenting an overview of the broad field of research on the convergence of sustainable manufacturing and Industry 4.0 under the umbrella of "Sustainable Manufacturing 4.0", which has yet to be developed. It includes the dissemination of original findings on pathways and practices of Industry 4.0 applied to the development of sustainable manufacturing, contributing a bibliometric structure of the literature on the aforementioned convergence to reveal how Industry 4.0 could be used to shift the manufacturing sector to a more sustainable-based state. An initial research agenda for this emerging area has accordingly been presented, which may pave the way for having a futuristic view on Sustainable Manufacturing 5.0 in the next industrial wave, i.e., Industry 5.0.

Keywords: sustainable manufacturing; lean production; Industry 4.0 technologies; sustainable value creation; circular economy; bibliometric analysis; VOSviewer

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1. Introduction

Riding on the machines that changed the world, the industry has undergone numerous revolutions: from the initial steam engine-powered machines to the advent of electricity in industrial processes for mass production, then the automated machines (set in around the 1970s), which involve advanced electronics and information technologies in automating the production process, and, today, the fourth industrial revolution—Industry 4.0 (I4.0)—which integrates smart machines with digital technologies to maximize industrial productivity [1,2]. This new industrial wave, which is perceived as a consequence of the increasing digitization of industries, particularly in manufacturing processes, fuses two fundamental components—Cyber-Physical Systems (CPS) and the Internet of Things (IoT)—to set in-depth connectivity in industrial systems [3]. Other technologies that are mainly deployed in I4.0 include Big Data Analytics, Industrial IoT, Simulation/Optimization, Additive Manufacturing, Horizontal/Vertical System Integration, Virtual/Augmented Reality, Autonomous Robots, the Cloud, and Cybersecurity [1,4–6]. The extant literature indicates that such connectivity can contribute numerous benefits to the industry and society at large. In the manufacturing context, machine–product communications empower manufacturers to have flexible and reconfigurable processes for customizing products, as well as for scrutinizing massive volumes of data in real-time and improving strategic and operational decision-making procedures [7,8]. Moreover, it is contended that I4.0 and its enabling technologies give the opportunity of moving towards industrial sustainability and, subsequently, a more sustainable society [9,10].

Considering the seminal report on "Our Common Future [11]" as a corporate sustainability reference, the common waves have also appeared in manufacturing (Figure 1); from the traditional substitution-based manufacturing to the advent of lean thinking for reducing waste and creating value in production processes, then green manufacturing (set in around the 1990s) which involves the 3R (reduce, reuse, and recycle) concept in greening product's supply chains, and, today, sustainable manufacturing (SM), which takes sustainability issues into three interrelated compartments—product, process, and system—using a broader innovation-based 6R methodology to not only meet the 3Rs but also to remanufacture, redesign, and recover the products over multiple life-cycles [12–14] This new paradigm wave, which is also regarded as an application of the circularity principle to manufacturing under the emerging concept of circular economy, enables creating sustainable value streams towards the triple bottom line (TPL) requirements [15]. Going through the leading literature revealed that the development of SM is mainly performed by compartmentalizing and developing manufacturing's fundamental elements, i.e., products, processes, and systems, which requires [16–18]: (1) the paradigm shifts from single life-cycle, open-loops to multiple life-cycle, closed-loops at the product level; (2) the optimization of technological advancements and process planning to reduce energy and resource intake, toxic wastes, and occupational hazards as well as to improve product life via the manipulation of process-driven surface integrity at the process level; and (3) the integration of the entire supply chain, i.e., from the major life-cycle stages to the multiple life-cycles at the system level. According to Jawahir and Bradley [15], many past attempts towards achieving this objective have fallen short owing to their failure to balance out the three fundamental elements.

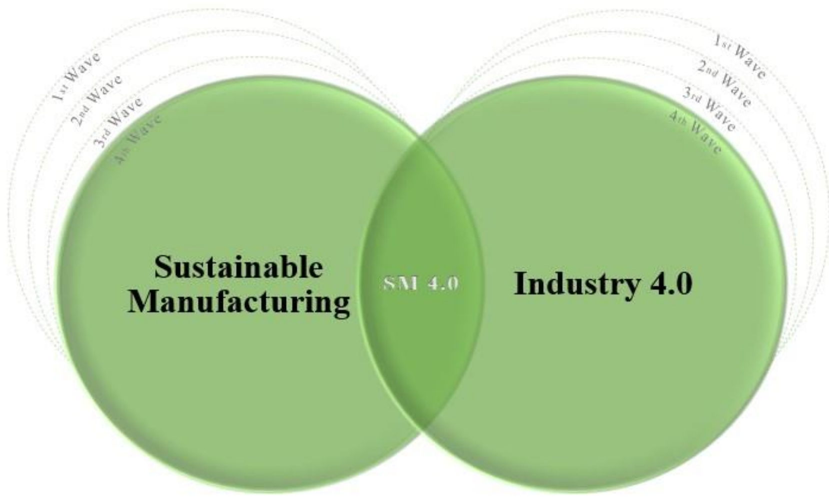

Figure 1. SM 4.0: A fully integrated concept of contemporary waves.

Due to these requirements and the expected benefits of I4.0, a number of scientific communities are becoming involved in investigating the applicability of implementing I4.0 technologies in addressing challenges and issues related to the TPL of sustainable manufacturing. It is evident that the integration of I4.0 technologies and principles to assess and develop SM can contribute to maximizing the economic, environmental, and societal values of I4.0 [6,18,19]. Yet, numerous stakeholders, including industrial policy and decision makers, remain oblivious of such endeavors and their integration. While research efforts have been contributed to the literature, which is analyzed and discussed in this article, there are opportunities for state-of-the-art research. As a new path of inquiry, it is believed there is a need for integrating and systematizing significant research efforts in order to have a better understanding of the topics of interest and also to expand collaboration networks. As one of the preliminary inquiries, this study is aimed at presenting an overview of the broad field of research on the convergence of contemporary waves under the umbrella of "sustainable manufacturing (SM) 4.0", which has yet to be developed (Figure 1). It includes the dissemination of original findings on pathways and practices of I4.0 applied to the development of SM, contributing a bibliometric structure of the literature on the contemporary waves to reveal how I4.0 could be used to shift the manufacturing sector to a more sustainable-based state. Contrary to the research that regarded sustainable manufacturing as an enabler for I4.0 [5], this study seeks to constitute SM 4.0 as a concept considering I4.0 technologies as expected enablers for the sake of developing SM.

To this end, the current study carried out a Bibliometric, or Scientometric, methodological approach, which is clarified in Section 2. Next, Section 3 presents the findings of the overview and discusses the results according to a bibliometric structure of the adopted approach. Section 4 provides an in-depth discussion on the topic and highlights potential pathways for further practices, and, finally, Section 5 outlines conclusions and limitations arising from this study.

2. Methods

There are three types of systematic reviews: domain-based reviews, theory-based reviews, and method-based reviews. Domain-based reviews include structured reviews, framework-based reviews, bibliometric reviews, and any hybrid types [20]. This study applied the bibliometric type, which is quantitative in nature and commonly used to provide a comprehensive overview of research trends, data and information visualization, network analysis and, consequently, to give a potential guide for future research [21].

2.1. Search Strategy

The most often used databases by researchers for document search are the Web of Science and Scopus. This study employed the Scopus database since it compiles the largest data sets of abstracts and citations of state-of-the-art literature [22], covering over 23,452 peer-reviewed journals, 294 trade publications, over 852 book series, and over 9.8 million conference papers from over 120,000 worldwide events [23]. Using Scopus, our search strategy was established on the following basis: (1) All electronic searches were performed on 19 June 2021 and were limited up until May 2021 for the analysis; (2) there is no time interval set for the search in order to determine the first document published for the keyword; (3) there is no limitation for both document and source types as the discourse upon SM 4.0 has just started to be developed; and (4) the language was restricted to documents that were written only in English.

2.2. Data Collection and Analysis

The data collection was organized by the following steps. Firstly, the search was conducted based on all major relevant keywords in pursuit of influential (highly cited) articles. The Scopus database was used as the search engine for the keywords pertaining to 6Rs-based manufacturing strategies (contemporary waves appeared in manufacturing)—"Sustainable Manufacturing", "Green Manufacturing", and "Lean Manufacturing", as well as for interchangeable terms including "Sustainable Production", "Green Production", and "Lean Production". Similarly, we identified the adopted terms for the keyword "Industry 4.0", i.e., "Fourth industrial revolution", "4th industrial revolution", "IR 4.0", and "I4.0". Table 1 presents the keywords as well as the summary of document types retrieved from articles, conference papers, review papers, and others (including abstract reports, books, book chapters, business articles, conference reviews, data papers, editorials, erratum, letters, notes, retracted, and short surveys). This is to ensure that we are not leaving any possible documents out of the sample.

Table 1. Summary of major keywords and document types retrieved.

No *	Keyword Search	Article	Conference Paper	Review Paper	Others	Total
(i)	"Sustainable production"	4089	856	749	698	6392
(i)	"Sustainable manufacturing"	936	741	115	162	1954
(i)	"Green production"	624	147	66	60	897
(i)	"Green manufacturing"	601	487	46	106	1240
(i)	"Lean production"	1092	798	96	154	2140
(i)	"Lean manufacturing"	1778	1454	273	373	3878
(ii)	"Fourth industrial revolution"	1134	1160	127	258	2679
(ii)	"4th industrial revolution"	226	250	18	54	548
(ii)	"Industry 4.0"	3341	5191	345	1017	9894
(ii)	"IR 4.0"	69	53	7	1	130
(ii)	"I4.0"	144	216	25	24	409
(iii)	Keywords' combination	96	119	13	20	**248**

* (i) indicates all keywords related to '6Rs-based Manufacturing'; (ii) indicates all keywords related to 'I4.0'; (iii) indicates the combination of keywords: ("sustainable manufacturing" OR "sustainable production" OR "green manufacturing" OR "green production" OR "lean manufacturing" OR "lean production") AND ("industry 4.0" OR "IR 4.0" OR "fourth industrial revolution" OR "4th industrial revolution" OR "I4.0"). The bolded value indicates the total of documents considered for the review in this study.

Next, it is sought to discover the bibliometric structure of the literature on the contemporary waves. Hence, in line with SM 4.0, the search strategy conducted was: (TITLE-ABS ("sustainable manufacturing" OR "sustainable production" OR "green manufacturing" OR "green production" OR "lean manufacturing" OR "lean production")) AND TITLE-ABS ("industry 4.0" OR "IR 4.0" OR "fourth industrial revolution" OR "4th industrial revolution" OR "I4.0") AND PUBYEAR < 2021 OR PUBDATETXT (("January 2021" OR "February 2021" OR "March 2021" OR "April 2021" OR "May 2021")) AND (EXCLUDE (PUBYEAR, 2022)) AND (LIMIT-TO (LANGUAGE, "English")), which resulted in identifying a total of 248 documents in the Scopus database (Table 1).

The inclusive documents were accordingly downloaded and saved in various file formats before proceeding to the analysis stage. Analysis indicators included (1) publication distribution based on document types; (2) yearly and accumulative document numbers; (3) publication distribution among countries, journals, institutions, and authors; (4) analysis of links, total link strength, and average citations among countries and frontier topics; and (5) visualization of co-authorship (countries) and co-occurrence network (keywords). In this regard, this study used Harzing's Publish or Perish software and VOSviewer as analysis tools. Harzing's Publish or Perish was used to compute the citation metrics, which are retrieved from indexing platforms such as Scopus [24]. VOSviewer (version 1.6.16) was accordingly utilized to construct and visualize bibliometric networks.

3. Results and Discussion

3.1. Growth of Research Interest

For 7 years since 2015, 248 documents had been published in 119 various sources. Of the total documents, 39% were published as journal articles, while 48% were published as conference papers, highlighting a great demand for state-of-the-art studies to further this new line of research. Moreover, 5% and 8% of the total documents were published as review papers and others (i.e., conference review, book chapter, book, editorial), respectively—see Table 1. The analyses indicate that there is no document written in the abstract report, multimedia, press release, and report. In addition, there were no documents published as multi-volume reference works, newsletters, newspapers, press releases, or report sources.

As shown in Figure 2, the first documents came out in 2015 with only one publication, i.e., Kolberg and Zühlke [7], discovering that the understudied topic is very young and has just started to develop. The highest number of annual publications was recorded in 2020 with 95 documents, 1.6 times higher than the previous year. Similar trends can be seen in 2016, 2017, 2018, and 2019, where their annual publications increased by 7, 20, 40, and 60 documents, respectively, revealing that the cumulative number of publications has dramatically soared in recent years.

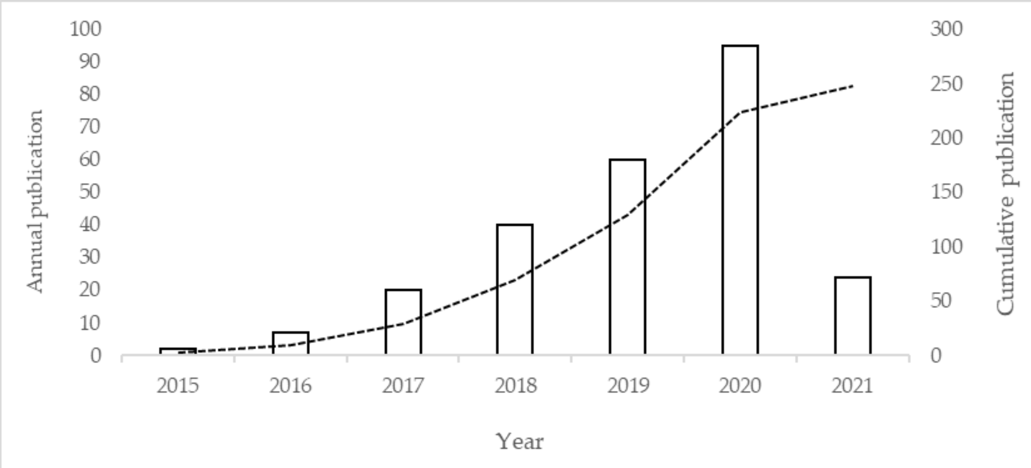

Figure 2. Trends in publications over the years.

It is anticipated to continue to grow significantly in the coming years as the diffusion of the concept and its adoption are evolving. However, I4.0 is understood as an issue of technology diffusion and adoption, and this diffusion–adoption process usually flows from leading countries [3,25]. In this regard, a number of countries have developed their own programs to accelerate the adoption and advance of I4.0 technologies. The birthplace of the concept, i.e., Germany, had developed a program named “High-Tech Strategy 2020”. The United States developed its “Advanced Manufacturing Partnership”, France with “La Nouvelle France Industrielle”, China with “Made in China 2025”, and Brazil with “Towards Industry 4.0” (Rumo à Indústria 4.0). Such local programs, whether in developed or emerging countries, have the objective of disseminating the concepts and technologies of I4.0 to local businesses [3]. This implies that such countries have already conceived I4.0 concepts and technologies and subsequently matured with regards to the two concepts of Industry 3.0—automation and ICT usage—which are now being incorporated in I4.0 [26].

3.2. Leading Countries, Productive Institutions, and International Collaboration

Going through the literature reveals that there is a growing global interest in maximizing the economic, environmental, and societal values of I4.0 through integrating I4.0 technologies and practices with sustainable paradigms in the manufacturing context. This will remain to rise due to the unique intellectual contributor of the matter to “our common future”; however, it is unanimously accepted, after the Earth Summit [27], that being sustainable is more beneficial [28].

Figure 3 shows the country-wise growth of publications on this topic of concern. A total of 59 countries contributed to the area of SM 4.0, with the top 10 leading countries responsible for 78% of the total publications. Italy (40 documents), Brazil (27 documents), Germany (26 documents), India (18 documents), and China (16 documents) had been the top 5 prolific countries in terms of the number of published documents. Among them, Malaysia, with 10 documents, was the only developing country which is ranked 12th and came across the topmost productive countries. Nowadays, the benefits of international collaborations not only extend the network and share knowledge and expertise but also promote the rank.

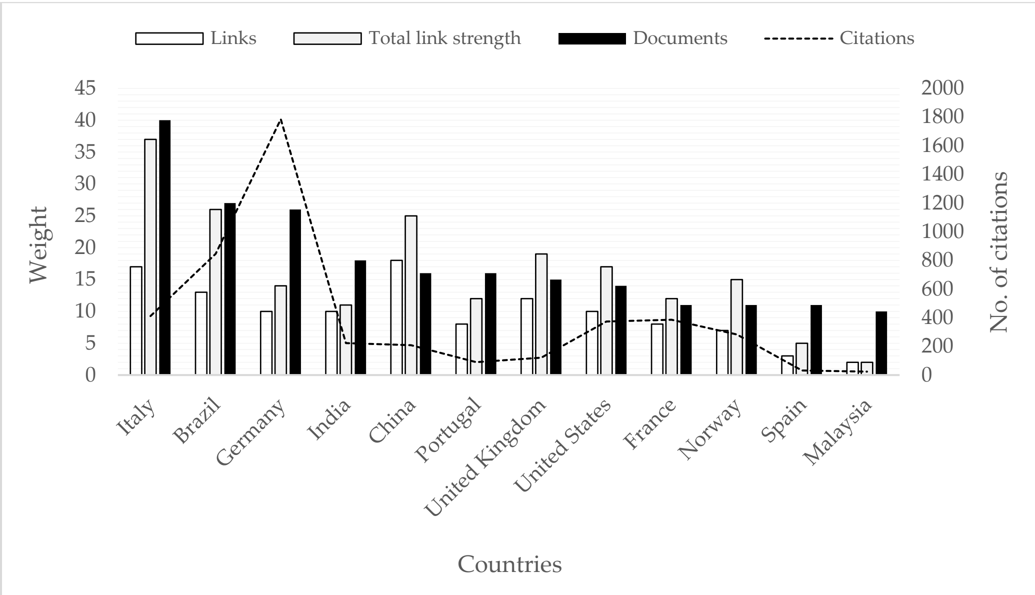

Figure 3. Dispersion of countries across the subject area.

Even though Italy had the most documents and international collaboration (total of 37 documents with 17 countries), Germany and Brazil have the greatest number of citations, i.e., 1785 and 846, respectively (Figure 3). This implies the documents published by leading countries received more attention and citations, e.g., Germany—where the I4.0 concept was born—has the earlier average publication year (2018.15) compared to Italy (2019.05) and Brazil (2019.26), as depicted in Figure 4. This figure presents the co-authorship network map of countries publishing scientific articles in the understudied area as well as shows the dynamic trend in time changing over the years. From the full map, it is revealed that only 73% (43 countries) were connected to others; in other words, they are countries that publish collaboratively. Estonia, Israel, Greece, Germany, and Mexico were accordingly ranked as the top five early countries investigating the subject in various institutions.

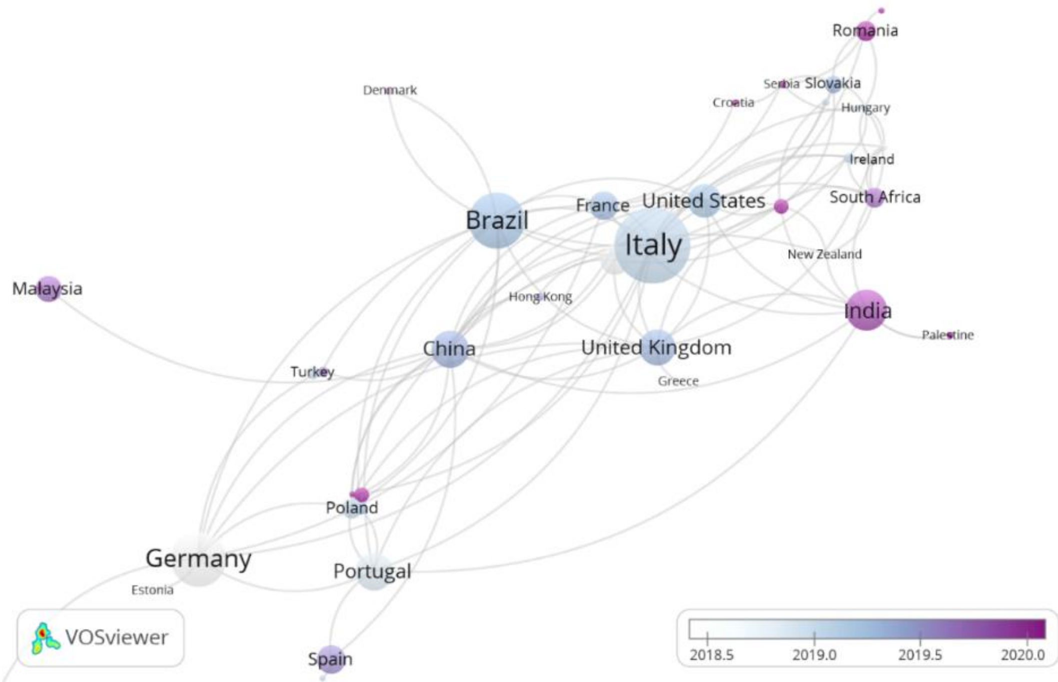

Figure 4. Co-authorship network map of the countries.

The analyses have also indicated that there were 160 academic institutions publishing papers in the area of SM 4.0. Table 2 compiles the top 10 most proactive institutions in terms of their publications. Based on the list, the most productive academic institution was the Universidade Federal de Santa Catarina in Brazil, contributing ninr publications—seven journal articles and two conference papers. Among the top 10 affiliations, institutions from developed countries had the highest contributions (31 documents), followed by emerging countries (14 documents) and developing countries with 10 documents. We found that there is no considerable difference in the number of documents published between institutions, indicating that there are no boundaries between developed, emerging, and developing countries on the research topic.

Table 2. Top 10 most productive academic institutions.

Affiliation	Country	National Context	No. of Documents	Total Citations	Most Cited Article (Times Cited)
Universidade Federal de Santa Catarina	Brazil	Emerging country	9	334	Tortorella and Fettermann [29] (199)
Norges teknisk-naturvitenskapelige universitet	Norway	Developed country	8	268	Buer et al. [30] (220)
Universidade do Minho	Portugal	Developed country	6	69	Varela et al. [31] (38)
University of Johannesburg	South Africa	Developing country	6	61	Bag and Pretorius [32] (31)
Universidade Federal de São Carlos	Brazil	Emerging country	5	245	Jabbour et al. [10] (214)
Politecnico di Milano	Italy	Developed country	5	84	Matteo et al. [33] (55)
Università degli Studi di Bergamo	Italy	Developed country	5	43	Powell et al. [34] (20)
Politechnika Poznanska	Poland	Developed country	4	248	Mrugalska and Wyrwicka [35] (180)
Universiti Teknikal Malaysia Melaka	Malaysia	Developing country	4	5	Ito et al. [36] (3)
Technical University of Berlin	Germany	Developed country	3	690	Stock and Seliger [19] (674)

3.3. Most Proactive Journals, Highly Cited Articles, and Prolific Authors

Table 3 ranks the top 10 journals reporting SM 4.0 research by the number of publications and citations. *Procedia Manufacturing* was ranked the first with 15 documents (Total Citations: 270), which is closely followed by the journals of *Procedia CIRP* (TC: 869) and *Sustainability* (TC: 145) with 14 publications each. Since publishing in top-quartile journals is considered important for many researchers and/or institutions, we also presented the information in terms of journal quartile. CiteScore Quartiles are derived from CiteScore Percentiles and are defined as Quartile 1 (75–99th percentiles), Quartile 2 (50–74th percentiles), Quartile 3 (25–49th percentiles), and Quartile 4 (0–24th percentiles). The results have shown that among the 10 leading journals on the list, there were 4 journals of Q1, 1 journal of Q2, 2 journals of Q3, and 3 journals of Q4. The quartile-based information, however, cannot be used to make a direct comparison between journals of different subject fields, even though they share the same subject area. This is because the CiteScore value is not field-normalized; the different publication and citation behavior of researchers in different fields affects the values [22,23].

Table 3. Top 10 most productive journals.

Source Title	No. of Documents	Total Citations	Publication Year of Documents	Scopus Cite Score 2020 (Highest Percentile)	WoS Quartile 2020 (Impact Factor)	Total H-Index of Documents
Procedia Manufacturing	15	280	2017–2020	13.1 (98%)	-	7
Procedia CIRP	14	869	2015—2020	3.3 (68%)	-	5
Sustainability	14	145	2018–2021	3.9 (84%)	Q2 (3.251)	5
IFAC-PapersOnLine	10	294	2015–2020	2.1 (43%)	-	5
Proceedings of The International Conference on Industrial Engineering and Operations Management	9	22	2017–2021	-	-	2
IFIP Advances in Information and Communication Technology	8	42	2017–2021	1.0 (26%)	-	3
Proceedings of the Summer School Francesco Turco	8	1	2018–2020	-	-	1
International Journal of Production Research	7	729	2017–2020	10.8 (97%)	Q1 (8.568)	7
Journal of Cleaner Production	5	31	2020–2021	13.1 (98%)	Q1 (9.297)	5
IOP Conference Series: Materials Science and Engineering	5	4	2017–2020	0.7 (23%)	-	1

Moreover, the findings indicate that only three leading journals were indexed in the Web of Science (WoS) database—*Sustainability*, the *International Journal of Production Research*, and the *Journal of Cleaner Production*. This may be due to the significant contribution of conference papers to the development of the topic; however, as mentioned earlier, 48% of the total documents were published as conference papers. In terms of total citations, *Procedia CIRP* has the most total citations (869 citations) from 14 documents, notably owning the most cited article (i.e., Stock and Seliger [19]) with 674 citations. It is followed by the *International Journal of Production Research* (729 citations), although it has only published seven articles regarding the topic. In this regard, Piwowar-Sulej et al. [20] by using Harzing's Publish or Perish computed the h-index indicator, which marks document visibility according to the number of citations reported from the identified documents to classify the most proactive journals. Interestingly, *Procedia Manufacturing* had a total h-index value of 7, the same as the *International Journal of Production Research* (Table 3).

Next, we identified the highly cited articles up until May 2021. This subgroup analysis uncovered that 248 documents had received a total of 4468 citations, with nearly 745 citations per year and 18 citations per paper. Table 4 presents the list of the 10 highly cited articles in Scopus. The investigation of Stock and Seliger [19], which was aimed at presenting an overview of opportunities for SM 4.0 in macro and micro perspectives, is topped by the highest number of 674 citations. According to Abu et al. [21] and Piwowar-Sulej et al. [20], citation count is effective to assess the influence of articles. However, it should be noted that newer articles have a shorter period to be cited.

Table 4. Top 10 highly cited articles.

Authors	Year of Publish	Title	Cites	Cites Per Year
Stock and Seliger [19]	2016	Opportunities of Sustainable Manufacturing in Industry 4.0	674	134.8
Sanders et al. [37]	2016	Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing	275	55
Li [38]	2018	China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0"	257	85.67
Kolberg and Zühlke [7]	2015	Lean Automation enabled by Industry 4.0 Technologies	249	41.5
Buer et al. [30]	2018	The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda	220	73.33
Jabbour et al. [10]	2018	When titans meet—Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors	214	71.33
Tortorella and Fettermann [29]	2018	Implementation of industry 4.0 and lean production in Brazilian manufacturing companies	199	66.33
Mrugalska and Wyrwicka [35]	2017	Towards Lean Production in Industry 4.0	180	45
Wagner et al. [39]	2017	Industry 4.0 Impacts on Lean Production Systems	143	35.75
Machado et al. [5]	2020	Sustainable manufacturing in Industry 4.0: an emerging research agenda	101	101

The most effective authors have been also examined and identified in terms of the number of documents and citations. In total, 159 scholars (excluding 9 undefined authors) have contributed to publishing the 248 documents. Table 5 presents the 10 most prolific authors who are affiliated to 6 countries—Brazil (1 author, total publications: 8), Italy (4 authors, total publications: 15), Norway (1 author, total publications: 5), South Africa (1 author, total publications: 3), Germany (2 authors, total publications: 6), and France (1 author, total publications: 3). As listed in the table, Tortorella, G.L., who is affiliated with the Universidade Federal de Santa Catarina, situated in Brazil, was ranked first, with eight articles published. Going through the institutional contribution reveals that he was the main contributor to putting his institution at the highest ranking among the other 160 institutions. The authors' affiliations have demonstrated that the primary focus of SM 4.0 research was in areas related to Engineering (systems, industrial, manufacturing, technology), Computer Science, Decision Sciences, Business and Management, Environmental Science, and Energy.

Table 5. Top 10 most prolific authors.

Author Name	Institutions	Country	No. of Documents	Total Citations
Tortorella, G.L.	Universidade Federal de Santa Catarina	Brazil	8	328
Powell, Daryl John	Norges teknisk-naturvitenskapelige universitet	Norway	5	44
Gaiardelli, Paolo	Università degli Studi di Bergamo	Italy	5	43
Costa, Federica	Politecnico di Milano	Italy	4	71
Iung, Benoît	Université de Lorraine	France	3	144
Facchini, Francesco	Politecnico di Bari	Italy	3	78
Bag, Surajit	College of Business and Economics	South Africa	3	53
Bauer, Dennis	Universität Stuttgart	Germany	3	3
Draghici, Viorel Petrut	Fraunhofer Institute for Manufacturing Engineering and Automation IPA	Germany	3	3
Ciano, Maria Pia	Università Carlo Cattaneo	Italy	3	0

3.4. Topmost Keywords and Influential Publications Distributed to Major Keywords

In this study, the minimum number of occurrences of a keyword was set at two for the mapping in VOSviewer (Figure 5); a software program that was used in this case to create and visualize a co-occurrence network map of author keywords. The frequency of articles in which two keywords occur together is determined by the link strength between author keywords in co-occurrence analysis. Based on the co-occurrence networks, there were a total of 665 author keywords reported, among which 107 keywords have met the threshold. We exported the selected keywords so that we can create a thesaurus file to group similar keywords. After re-labeling synonymic and congeneric keywords, a total of 67 keywords were taken into careful consideration, as shown in Figure 5.

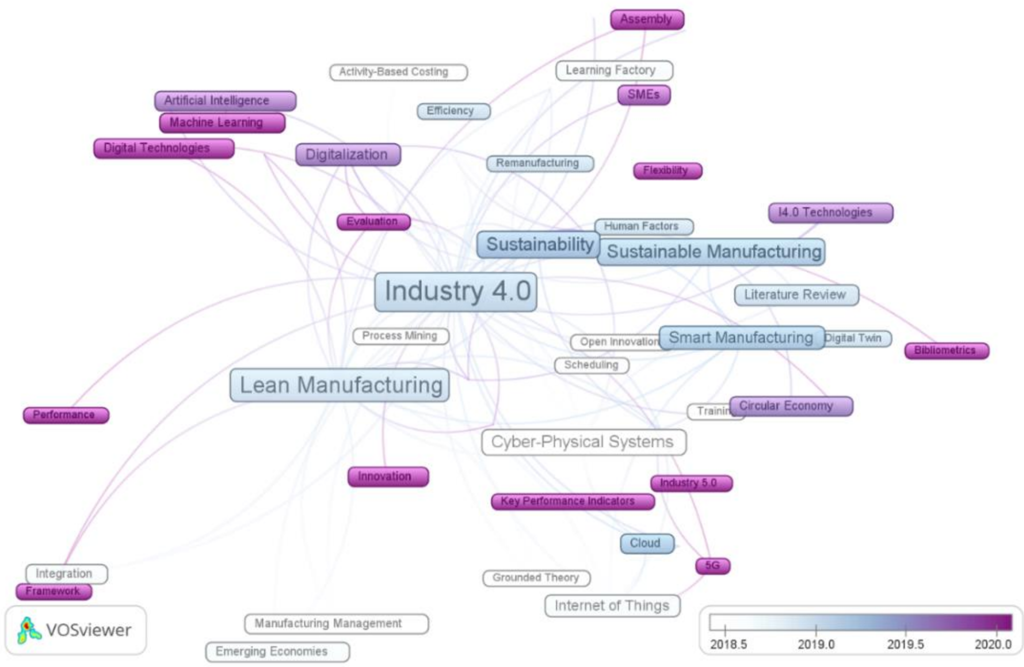

Figure 5. Co-occurrence network map of the keywords.

Going through the map shows the development of keywords which was initiated in 2015.5 (average publication year) on the CPS keyword. The purple in the color box displays the recent hotspot keywords. It was observed that Industry 4.0 (2019.1) has significantly directed towards two major keywords, including 'sustainable manufacturing' (2019.2) and 'lean manufacturing' (2019.0). This implies that this understudied field is likely to remain relevant in the coming years. Moreover, there is a futuristic view on the subject as researchers have begun to discuss the transition of manufacturing sectors under I4.0 for the sake of Industry 5.0 [40,41].

The analyses showed that 'Industry 4.0' was the most frequently encountered keyword with 141 occurrences and 300 total link strengths, as illustrated in Figure 6. We also came across the utilization of major keywords—'sustainable manufacturing' (32 occurrences, 61 total link strengths), 'green manufacturing' (6, 16), and 'lean manufacturing' (86, 180). The results of the analysis of the major keywords revealed that 'Industry 4.0', 'Lean manufacturing', and 'Sustainable manufacturing' were the most linked keywords in total. Noticeably, there were three link strengths exceeding 20, which have been made between 'I4.0 and Lean manufacturing with link strength of 67', 'I4.0 and Sustainable manufacturing with link strength of 23', and 'I4.0 and Cyber-Physical Systems with link strength of 22'. In addition, I4.0 was co-occurred with technological keywords: 'Internet of Things (15 occurrences, 49 total link strengths)', 'Big Data Analytics (9, 18)', 'Autonomous Robots (8, 25)', 'Optimization (7, 22)', 'Simulation (7, 26)', 'Additive Manufacturing (5, 10)', 'Cloud (4, 17)', and 'Industrial Internet of Things (3, 11)'.

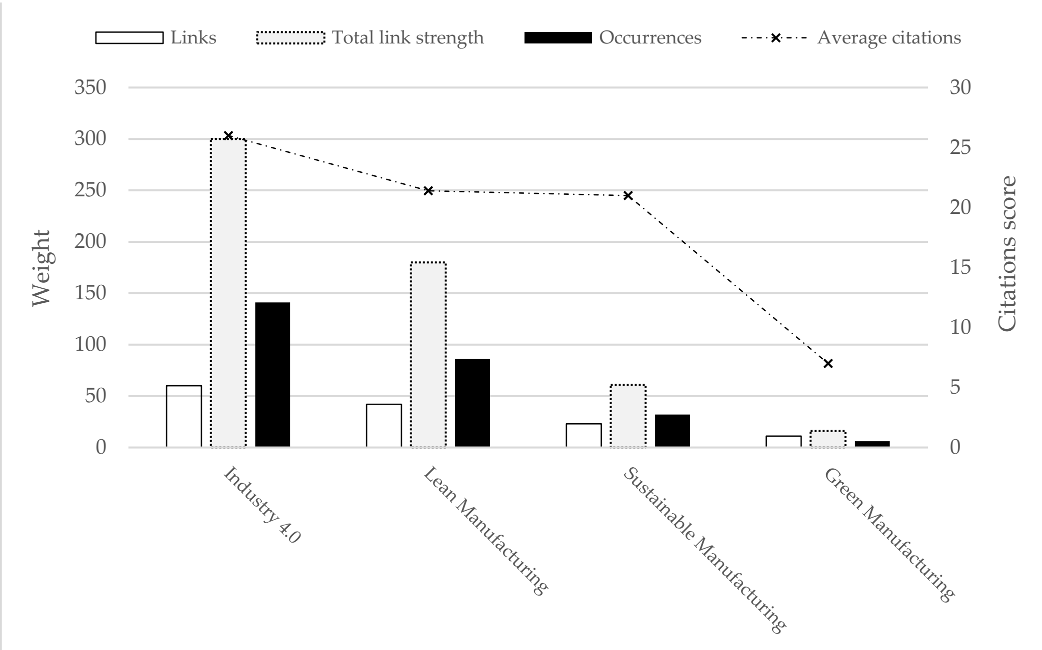

Figure 6. Dispersion of publications across the major keywords.

Tables 6–8 list the 10 most influential articles on the pathways of SM 4.0 and rank them in terms of the highest citation using Scopus. The discourse on the capability of I4.0 in implementing lean manufacturing was given by Sanders et al. [37] with 275 citations, which is topped in Table 6, where 6 papers with a citation count greater than 100 were included. Although some studies have linked I4.0 technologies to lean tools [22], the integration of these inter-links and the TBL requirements is still in its infancy. With its emphasis on waste elimination at all production stages, the applicability of lean practices has been extended to include all TBL aspects, e.g., the application of value stream mapping (VSM), which has recently evolved into the environmentally based VSM—'Green-VSM', 'Energy-VSM', 'Environmental-VSM'—then 'Socio-VSM', which is societally based and directed towards enhancing the operational and social performance, and, today, 'Sustainable-VSM', which combines the conventional VSM with a sustainability indicator set to visualize and evaluate the environmental impact and societal well-being [13,22]. Jamil et al. [14], by drawing on the lean and environment toolkit of the US Environmental Protection Agency (US EPA), described the objective of environmentally extended lean production as "to develop the highest quality products, at the lowest cost, with the shortest lead time by systematically and continuously eliminating waste, while respecting people and the environment", which, in the context of this current study, is rather extensive. To this end, effective approaches integrating the concepts of green and lean are being developed such as 'Green Lean Six Sigma', to minimize the green waste at all production stages, improve the environmental and operational performance, and maximize productivity.

Such capability has also been studied to enable green manufacturing, as shown in Table 7—an article by Li [38] had the highest citation count of 257 as such. There are also some significant efforts in the literature discussing the potentials and limitations of the convergence of I4.0 and the sustainable manufacturing paradigm, which is also considered as an application of the circularity principle to manufacturing under the emerging concept of circular economy. In this regard, the work of Stock and Seliger [19] was noticeably cited 674 times, ranked first among all the lists/studies, followed by Jabbour et al. [10] and Machado et al. [5], with total citations of 214 and 101, respectively. These are the three most influential practices that fall into the SM 4.0 area, with a citation count exceeding 100 (Table 8).

Table 6. Top 10 most influential articles on I4.0-enabled lean manufacturing.

Rank	Authors	Year	Title	Source Title	Times Cited	Document Type
1.	[37]	2016	Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing	Journal of Industrial Engineering and Management	275	Article
2.	[7]	2015	Lean Automation enabled by Industry 4.0 Technologies	IFAC-PapersOnLine	249	Conference Paper
3.	[30]	2018	The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda	International Journal of Production Research	220	Article
4.	[29]	2018	Implementation of industry 4.0 and lean production in Brazilian manufacturing companies	International Journal of Production Research	199	Article
5.	[35]	2017	Towards Lean Production in Industry 4.0	Procedia Engineering	180	Conference Paper
6.	[39]	2017	Industry 4.0 Impacts on Lean Production Systems	Procedia CIRP	143	Conference Paper
7.	[42]	2017	Towards a lean automation interface for workstations	International Journal of Production Research	99	Article
8.	[43]	2020	Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies	International Journal of Production Research	69	Article

Table 6. *Cont.*

Rank	Authors	Year	Title	Source Title	Times Cited	Document Type
9.	[44]	2017	Review of Socio-technical Considerations to Ensure Successful Implementation of Industry 4.0	Procedia Manufacturing	65	Article
10.	[33]	2019	The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers	International Journal of Advanced Manufacturing Technology	55	Article

Table 7. Top 10 most influential articles on I4.0-enabled green manufacturing.

Rank	Authors	Year	Title	Source Title	Times Cited	Document Type
1.	[38]	2018	China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0"	Technological Forecasting and Social Change	257	Article
2.	[45]	2018	Green production planning and control for the textile industry by using mathematical programming and industry 4.0 techniques	Energies	20	Article
3.	[46]	2018	Green production planning and control model with ABC under industry 4.0 for the paper industry	Sustainability (Switzerland)	16	Article
4.	[47]	2020	Industry 4.0 and the circular economy: Resource melioration in logistics	Resources Policy	15	Article
5.	[48]	2016	Toward dynamic energy management for green manufacturing systems	IEEE Communications Magazine	11	Article
6.	[49]	2017	Enhancing the competitiveness of manufacturers through Small-scale Intelligent Manufacturing System (SIMS): A supply chain perspective	2017 6th International Conference on Industrial Technology and Management, ICITM 2017	10	Conference Paper
7.	[50]	2020	Modified Carroll's pyramid of corporate social responsibility to enhance organizational performance of SMEs industry	Journal of Cleaner Production	8	Article
8.	[51]	2019	Business Logistics Optimization Using Industry 4.0: Current Status and Opportunities	IEEE International Conference on Industrial Engineering and Engineering Management	5	Conference Paper
9.	[52]	2021	Leveraging Optimized and Cleaner Production through Industry 4.0	Sustainable Production and Consumption	3	Article
10.	[53]	2021	Industry 3.5 for optimizing chiller configuration for energy saving and an empirical study for semiconductor manufacturing	Resources, Conservation and Recycling	2	Article

Table 8. Top 10 most influential articles on I4.0-enabled sustainable manufacturing.

Rank	Authors	Year	Title	Source Title	Times Cited	Document Type
1.	[19]	2016	Opportunities of Sustainable Manufacturing in Industry 4.0	Procedia CIRP	674	Conference Paper
2.	[10]	2018	When titans meet—Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors	Technological Forecasting and Social Change	214	Article
3.	[5]	2020	Sustainable manufacturing in Industry 4.0: an emerging research agenda	International Journal of Production Research	101	Article
4.	[54]	2017	On sustainable production networks for industry 4.0	Entrepreneurship and Sustainability Issues	71	Article
5.	[55]	2018	Manufacturing in the fourth industrial revolution: A positive prospect in Sustainable Manufacturing	Procedia Manufacturing	66	Conference Paper
6.	[56]	2018	Biologicalisation: Biological transformation in manufacturing	CIRP Journal of Manufacturing Science and Technology	56	Article
7.	[57]	2017	Enabling Circular Economy Through Product Stewardship	Procedia Manufacturing	44	Article
8.	[58]	2018	Maintenance for Sustainability in the Industry 4.0 context: a Scoping Literature Review	IFAC-PapersOnLine	43	Conference Paper
9.	[59]	2019	Industry 4.0—challenges to implement circular economy	Benchmarking	32	Article
10.	[60]	2018	Exploring gamification to support manufacturing education on industry 4.0 as an enabler for innovation and sustainability	Procedia Manufacturing	31	Conference Paper

4. Pathways for Further Practices

All the mentioned investigations are beneficial when seeking to realize the importance and capability of I4.0 to shift the manufacturing industry to a more sustainable-based state. It is believed the integration of I4.0 technologies to SM assessment, development, and/or management can help maximize the economic, environmental, and societal values of I4.0. According to Enyoghasi et al. [18], this integration would contribute to addressing the requirements relating to SM development, as mentioned earlier (Section 1). However, it is also revealed that such a synergy depends on critical success factors—see Jabbour et al. [10]. To clarify this, a visual representation is manifested in Figure 7, where I4.0 technologies together with other critical success factors are depicted to enable the development of processes, products, and systems based on the 6Rs-based approach to fulfill the TBL requirements of SM. Therefore, new technologies together with other critical success factors and mental models on which the manufacturing encompasses interrelated elements, with interconnected processes, units, norms, values, behaviors, individuals, and groups, which are influencing and being influenced by one another, are requested to sustainable manufacturing development so as to sustainably address challenges and issues related to eco-system destruction and numerous other unsustainable paradigms. There were many significant efforts as such; however, the development is generally traced by compartmentalizing the manufacturing's integral elements—products, processes, and systems. This is due to sustainable manufacturing is a complex systems problem [15] and which is being relied highly on the analytical approaches that make learning and development through reductionist thinking and mechanism interpretation.

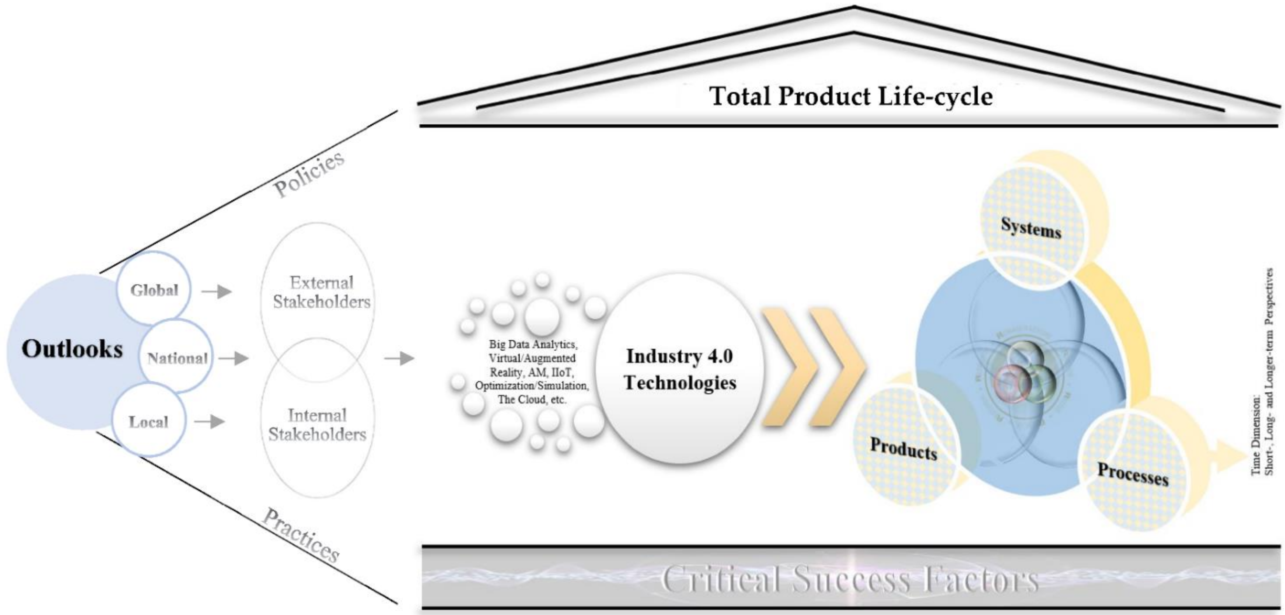

Figure 7. Sustainable Manufacturing 4.0.

In this regard, the most effective approaches have been aimed at assessing the sustainability performance of these elements using appropriate indicators; they are parameters or variables that represent the state (content indicator) or behavior (performance indicator) of a structure and require a metric to establish a comparison with a baseline or to a sustainable outcome, since the objective of the assessment is to develop the sustainability characteristic of the elements [61,62]. However, determining which indicators to use and how to analyze them in order to evaluate is always a challenge. It may not be practical to achieve the ideal levels of each indicator due to cost and technological constraints and also the growth of strong interactions among them, which typically necessitates a trade-off [63]; what can be accomplished are the optimal conditions with a minimal effect on the ecosystem. Going through the significant efforts made to assess the sustainability at all product, process, and system levels considering all TBL aspects and 6Rs, some early research has discovered the indicators that can be used to this end [16,64]. One of the most thorough is the Product Sustainability Index (ProdSI) presented by Shuaib et al. [65], who proposed an index-based hierarchical method based on measuring, normalizing, weighting, and aggregating indicators to product sustainability assessments. Sensitivity analysis (SA) was also used by them in the decision-making process when developing future generations of the product; an outlook for the future of modern SA is provided by Razavi et al. [66], underlining how SA must underpin a wide variety of activities to better serve science and society. Following this hierarchical approach, the Process Sustainability Index (ProcSI) [67] and the production Line, Plant, and Enterprise Sustainability Index-based methods (LiSI/PlaSI/EnSI) [68,69] were devised to assess and develop the sustainability performance of manufacturing processes and systems, respectively. Many other considerable quantitative and qualitative investigations have been devoted to the literature, using multi-criteria decision-making (MCDM) techniques [70], sustainability-extended lean tools, and life cycle assessment (LCA) [22,71–73]; however, the disadvantage of these methods over the others is the inconsideration of 6Rs and/or the total product life-cycle while holding the great potential to improve the sustainability performance in the manufacturing context. Taking steps to address these flaws and using more comprehensive approaches as the aforementioned hierarchical techniques, a challenge that still remains in the present industrial wave—Industry 4.0—is how I4.0 technologies and theories can be deployed and integrated in a deeper and more holistic way to SM development taking into account the 6Rs and the total product life-cycle, in addition to the TBL. Contrary to the research that regarded sustainable manufacturing as an enabler for I4.0 [5], it is stressed that future studies investigate the SM 4.0 as a concept considering I4.0 technologies as expected enablers for the sake of developing SM. Delving into I4.0 technologies, the impact of some of them on SM elements has been potentially exposed in the literature, as follows:

- 1. *Big Data Analytics*—capable of improving direct/indirect costs, waste and emissions, and product end-of-life management at the product level [18,59,74,75]; energy consumption and environmental impact at the process level [9,18,76,77]; and net profit, operational performance, material use and efficiency, energy use and efficiency, and water use and efficiency at the system level [4,9,18].
- 2. *Virtual and Augmented Reality*—capable of improving product quality and durability, functional performance, and safety and health impact at the product level [18,77,78]; manufacturing cost, personnel health, and operational safety at the process level [4,18,79]; and net profit, operational performance, health and safety, and stakeholder engagement at the system level [18,80].
- 3. *Optimization and Simulation*—capable of improving functional performance at the product level [18,81]; manufacturing cost, energy consumption, environmental impact, personnel health, and operational safety at the process level [18,74,77]; and capital charge, manufacturing cost, operational performance, material use and efficiency, energy use and efficiency, water use and efficiency, waste and emission, and stakeholder engagement at the system level [4,18,82].
- 4. *Additive Manufacturing*—capable of improving initial investments, material use and efficiency, energy use and efficiency at the product level [4,18,19,75,83]; personnel health and operational safety at the process level [4,18]; and net profit, operational performance, health and safety, and stakeholder engagement at the system level [18,74].
- 5. *Cloud*—capable of improving functional performance, product end-of-life management, and safety and health impact at the product level [18,84]; manufacturing cost and waste management at the process level [18,77]; and net profit, manufacturing cost, operational performance, health and safety, and stakeholder engagement at the system level [18,74,85].
- 6. *Industrial Internet of Things*—capable of improving benefits and losses, product quality and durability, and product end-of-life management at the product level [8,18,78,84]; manufacturing cost, waste management, personnel health, operational safety at the process level [4,18,59,76,81]; and net profit, capital charge, operational performance, health and safety, and stakeholder engagement at the system level [18,59,76,86].

This performance appraisal approach, which is regarded as a vital part of sustainable development, can assist industrial decision and policy makers in deciding what developmental actions are required to be considered to make their manufacturers more sustainable [28,70,87]. They must also decide whether new technologies are necessary in order to reach a more sustainable state [28,61]. As said by Garetti and Taisch [88], the initiation of a new technology may modify the description of "what is sustainable". To prevent any uncertainties throughout the appraisal, short-, long-, and longer-term effects of current policy decisions and strategic practices to capture local, national, and global outlooks should accordingly be addressed by effectively involving stakeholders. However, a sound assessment of sustainability performance should meet the requirements and satisfaction of the stakeholders, who can affect or be affected by the company [28,68,89]. According to Labuschagne et al. [89], "the company must thus empower the stakeholders by ensuring structures to distribute the information". This may draw several of the other fundamental research agendas, i.e., to identify and involve stakeholders to avoid any uncertainty, and, more importantly, to assess the extent to which the organization incorporates stakeholders' input into operational decision-making.

We hereby invite scholars representing different disciplines, in particular, the fields related to Engineering (systems, industrial, manufacturing, technology), Computer Science, Decision Sciences, Business and Management, Environmental Science, and Energy, to contribute to enlarging the SM 4.0 area by addressing the questions presented in Figure 8. These formulated questions highlight the pathways for further research in a holistic manner. Based on Bell et al. [90], the most effective technique for highlighting and guiding future studies is to formulate research questions. This may also pave the way for having a futuristic view on Sustainable Manufacturing 5.0 in the next industrial wave, i.e., Industry 5.0.

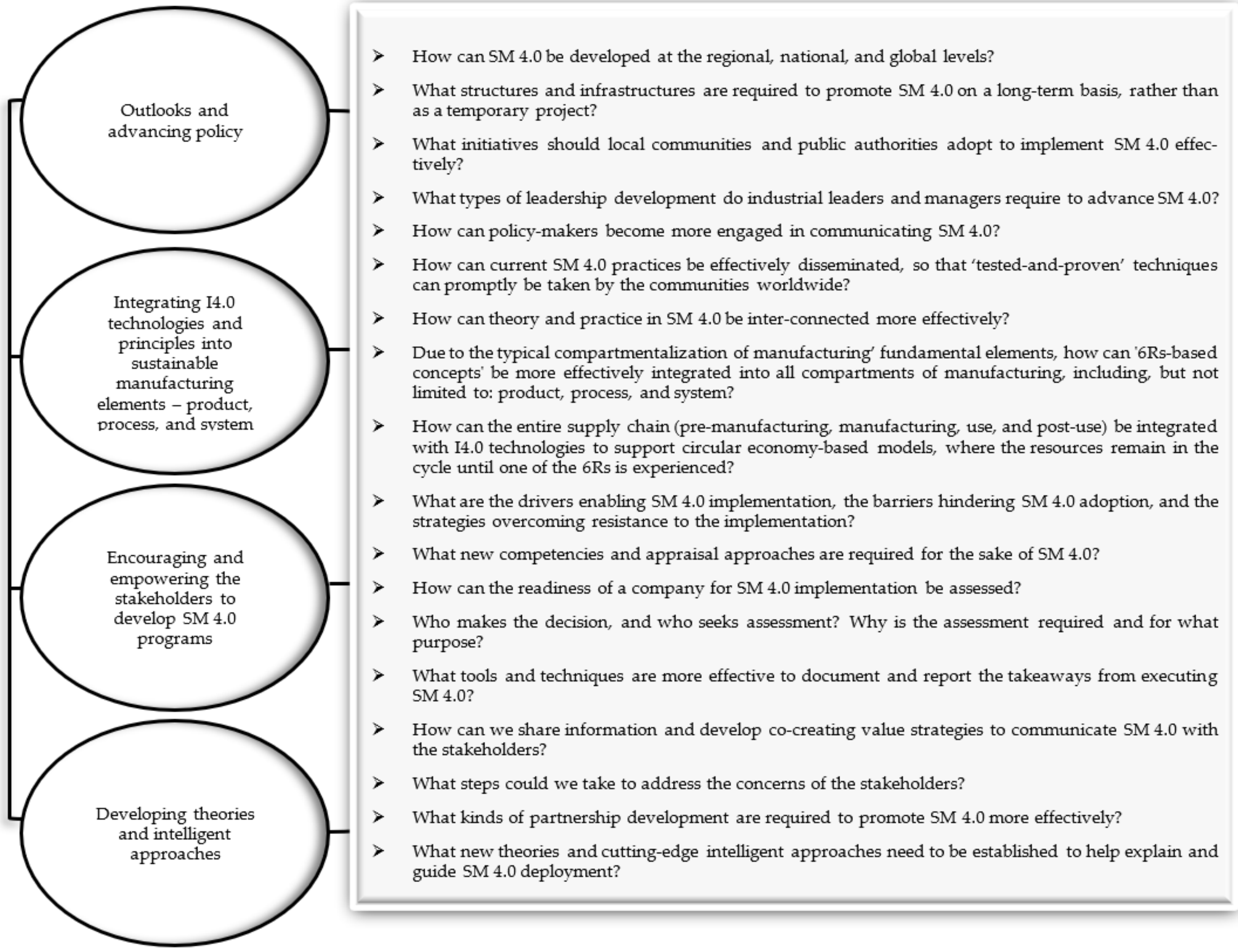

Figure 8. Research agenda in SM 4.0.

5. Conclusions

In the manufacturing context, there is a growing global interest in maximizing economic, environmental, and societal values of I4.0 through integrating I4.0 technologies and principles with sustainable paradigms. This paper investigates the research patterns in this integrated area—Sustainable Manufacturing (SM) 4.0—through performing a bibliometric analysis on articles derived from the Scopus database, which compiles the largest data sets of abstracts and citations of cutting-edge literature. It extracted descriptive publication outputs from the database up until May 2021, resulting in the retrieval of 248 documents published over the period from 2015 to 2021. This analysis, which is quantitative in nature, allowed the identification of the structures and developments in SM 4.0, which would, in turn, enable the scientific community to explore the available publications related to this field. Based on the analysis, there has been a rapid growth in the publication of articles on the topic since 2015, and it is believed that this surge is projected to continue due to its unique intellectual contributor to 'our common future'. Following the bibliometric structure, this paper has also identified the main contributing countries, journals, academic institutions, authors. In terms of countries, although Italy had the most publications (37 documents) and international collaborations (with 17 countries), Germany and Brazil had the most citations. This may motivate researchers from other countries and academic institutions to expand their research collaborations. The major concentration of SM 4.0 research was in fields linked to engineering (systems, industrial, manufacturing, technology), computer science, decision sciences, business and management, environmental science, and energy, as found by examining the authors' affiliations. The most prominent keywords, I4.0 technologies, and some new research areas in SM 4.0, which may potentially become the leading topics in future research were also discussed. While we have taken comprehensive measures to ensure that our search strategies would be able to cover all relevant literature on SM 4.0 topics available on Scopus, we also acknowledge the fact that there may still be a possibility of missing out on certain relevant documents due to the usage of less common terms by the authors. Additionally, this study had only used Scopus for the bibliometric analysis; future studies may expand their search by using other databases, e.g., Web of Science. By doing so, the outputs of various databases including Scopus and Web of Science can be compared to achieve richer findings.

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