Sustainable Manufacturing 4.0

Subjects: Engineering, Industrial | Engineering, Manufacturing | Engineering, Environmental

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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.

sustainable manufacturing | green production | lean implementation | Industry 4.0 technologies | sustainable value creation | circular economy | bibliometric analysis | VOSviewer | research agenda

1. Introduction

Riding on the machines that changed the world, the industry has undergone numerous revolutions (**Figure 1**); 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][5][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][13][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][17][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.

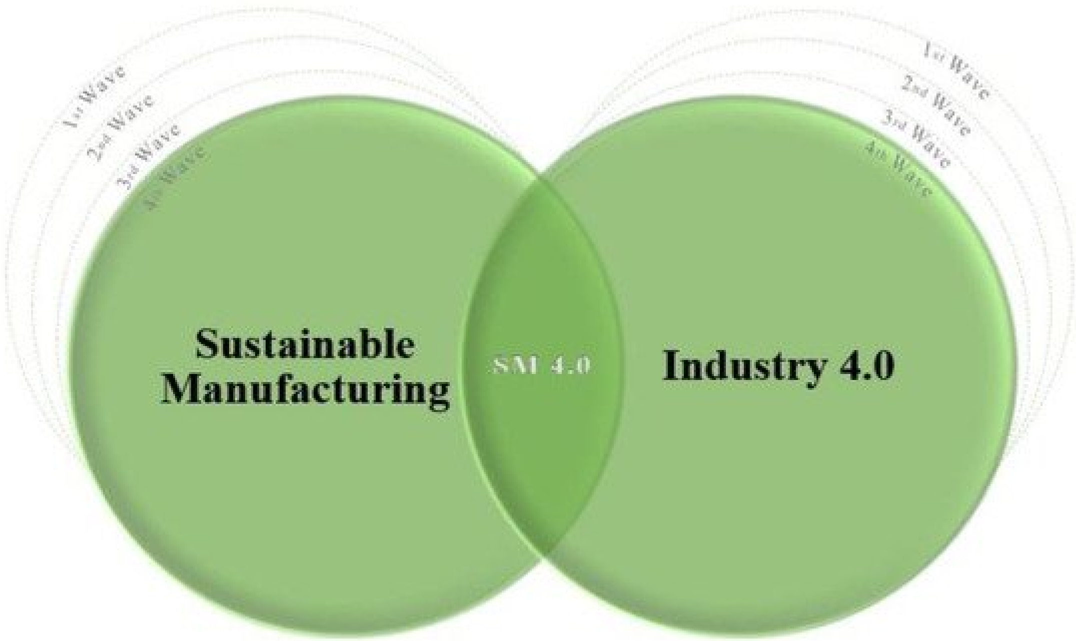

Figure 1. SM 4.0: A fully integrated concept of contemporary waves.

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.

2. 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. 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.

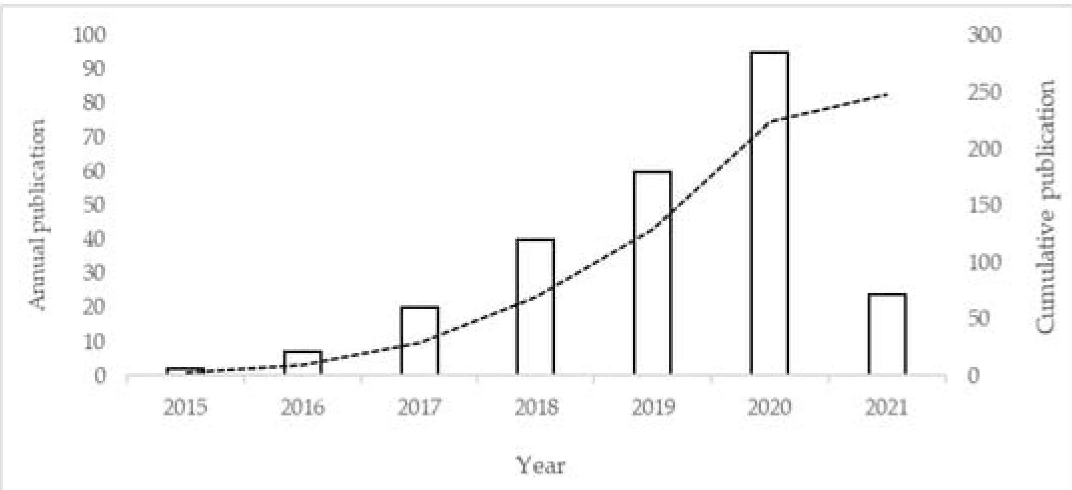

Figure 2. Trends in publications over the years.

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][20]. 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 [21].

3. 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 [22], that being sustainable is more beneficial [23].

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.

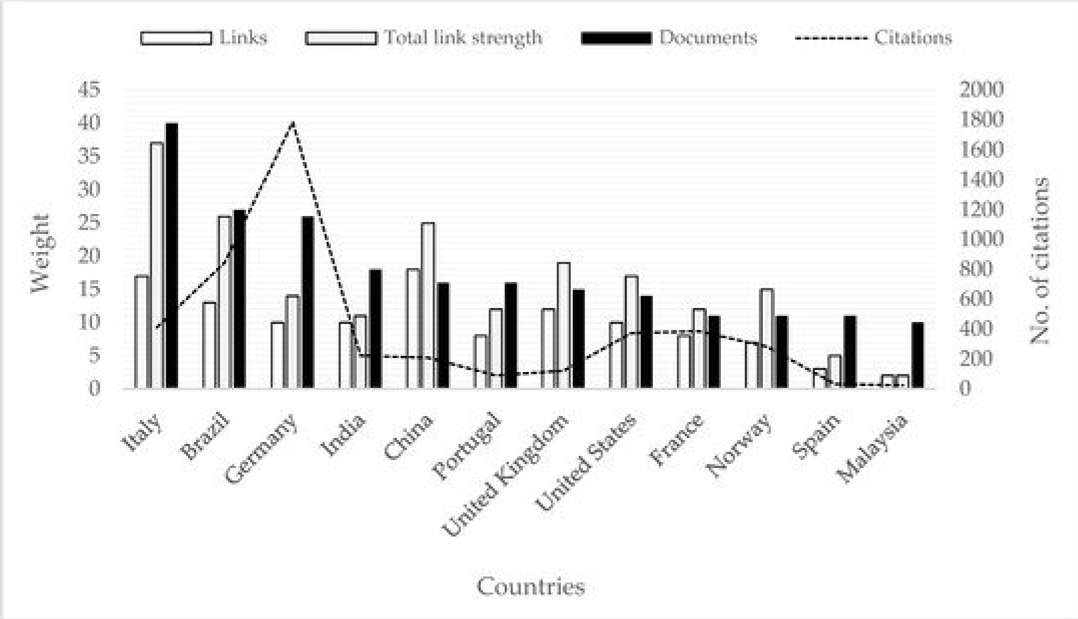

Figure 3. Dispersion of countries across the subject area.

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.

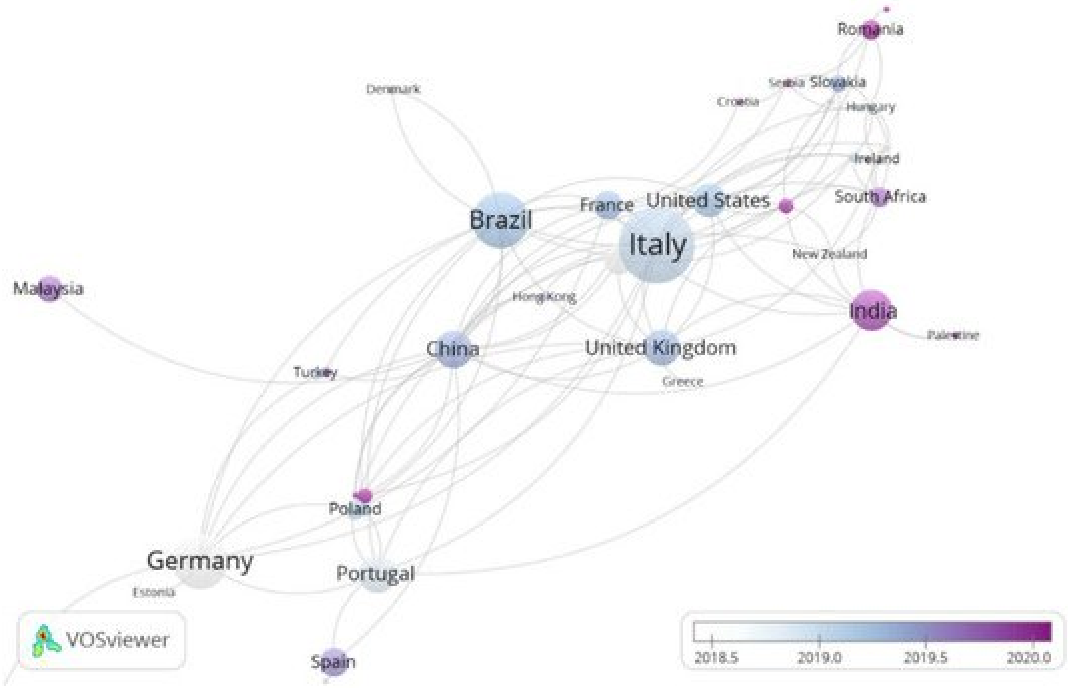

Figure 4. Co-authorship network map of the countries.

The analyses have also indicated that there were 160 academic institutions publishing papers in the area of SM 4.0. **Table 1** 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 1. 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 [24] (199)
Norges teknisk-naturvitenskapelige universitet	Norway	Developed country	8	268	Buer et al. [25] (220)
Universidade do Minho	Portugal	Developed country	6	69	Varela et al. [26] (38)

Affiliation	Country	National Context	No. of Documents	Total Citations	Most Cited Article (Times Cited)
University of Johannesburg	South Africa	Developing country	6	61	Bag and Pretorius [27] (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. [28] (55)
Università degli Studi di Bergamo	Italy	Developed country	5	43	Powell et al. [29] (20)
Politechnika Poznanska	Poland	Developed country	4	248	Mrugalska and Wyrwicka [30] (180)
Universiti Teknikal Malaysia Melaka	Malaysia	Developing country	4	5	Ito et al. [31] (3)
Technical University of Berlin	Germany	Developed country	3	690	Stock and Seliger [19] (674)

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Table 2 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 [32][33].

Table 2. 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

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
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

...ce (WoS) ...*roduction*. ...wever, 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. [34] 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 2**).

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 3** 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. [35] and Piwowar-Sulej et al. [34], 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 3. 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. [36]	2016	Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing	275	55
Li [37]	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. [25]	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 [24]	2018	Implementation of industry 4.0 and lean production in Brazilian manufacturing companies	199	66.33
Mrugalska and Wyrwicka [30]	2017	Towards Lean Production in Industry 4.0	180	45
Wagner et al. [38]	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 4** 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 4. 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

5. 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**.

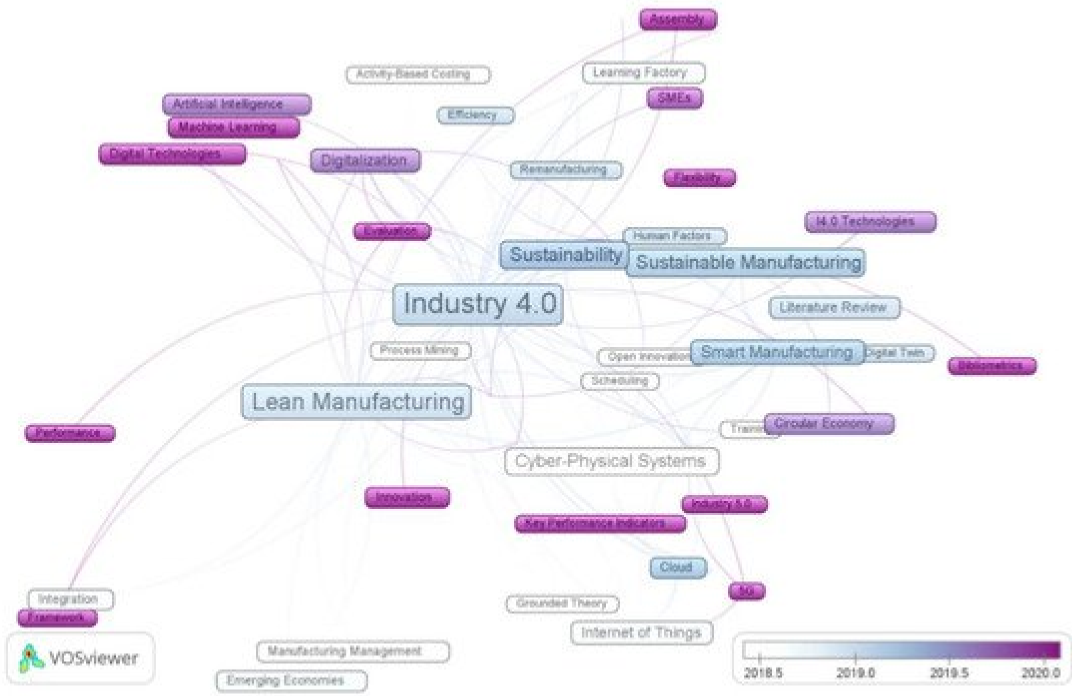

Figure 5. Co-occurrence network map of the keywords.

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 [39][40].

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)'.

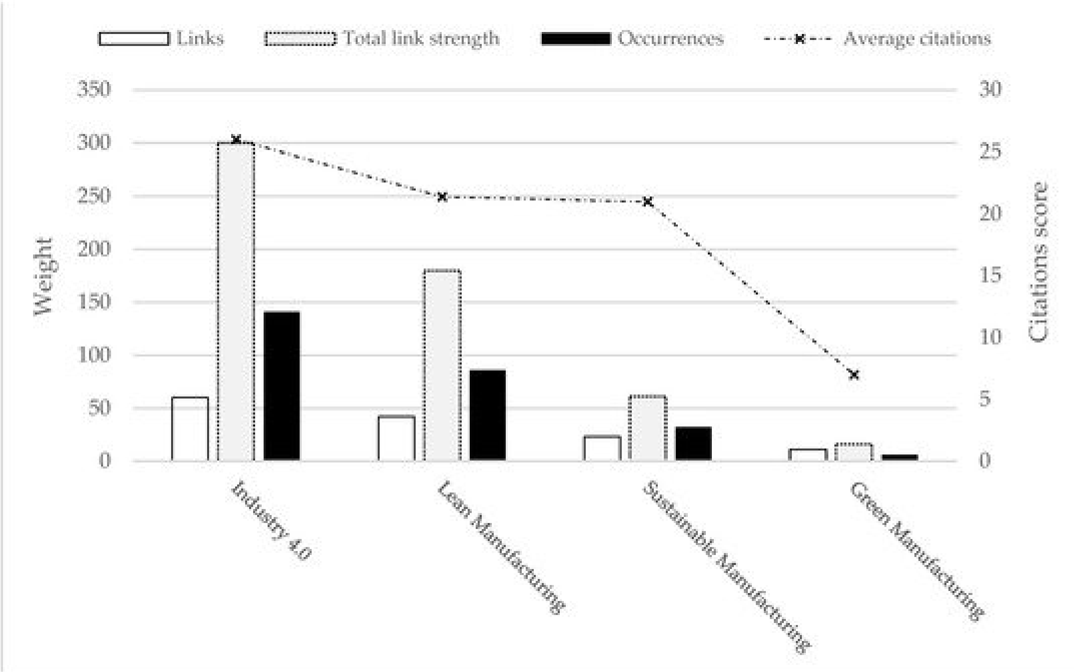

Figure 6. Dispersion of publications across the major keywords.

Table 5, **Table 6** and **Table 7** 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. [36] with 275 citations, which is topped in **Table 5**, where 6 papers with a citation count greater than 100 were included. Although some studies have linked I4.0 technologies to lean tools [32], 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][32]. 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 6**—an article by Li [37] 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 7**).

Table 5. Top 10 most influential articles on I4.0-enabled lean manufacturing.

Rank	Authors	Year	Title	Source Title	Times Cited	Document Type
1.	[36]	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.	[25]	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.	[24]	2018	Implementation of industry 4.0 and lean production in Brazilian manufacturing companies	International Journal of Production Research	199	Article
5.	[30]	2017	Towards Lean Production in Industry 4.0	Procedia Engineering	180	Conference Paper
6.	[38]	2017	Industry 4.0 Impacts on Lean Production Systems	Procedia CIRP	143	Conference Paper
7.	[41]	2017	Towards a lean automation interface for workstations	International Journal of Production Research	99	Article
8.	[42]	2020	Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies	International Journal of Production Research	69	Article
9.	[43]	2017	Review of Socio-technical Considerations to Ensure Successful Implementation of Industry 4.0	Procedia Manufacturing	65	Article
10.	[28]	2019	The interrelation between Industry 4.0 and lean production: an	International Journal of Advanced	55	Article

Rank	Authors	Year	Title	Source Title	Times Cited	Document Type
			empirical study on European	Manufacturing		
1.	[37]	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.	[44]	2018	Green production planning and control for the textile industry by using mathematical programming and industry 4.0 techniques	Energies	20	Article
3.	[45]	2018	Green production planning and control model with ABC under industry 4.0 for the paper industry	Sustainability (Switzerland)	16	Article
4.	[46]	2020	Industry 4.0 and the circular economy: Resource melioration in logistics	Resources Policy	15	Article
5.	[47]	2016	Toward dynamic energy management for green manufacturing systems	IEEE Communications Magazine	11	Article
6.	[48]	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.	[49]	2020	Modified Carroll's pyramid of corporate social responsibility to enhance organizational performance of SMEs industry	Journal of Cleaner Production	8	Article
8.	[50]	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.	[51]	2021	Leveraging Optimized and Cleaner Production through Industry 4.0	Sustainable Production and Consumption	3	Article
10.	[52]	2021	Industry 3.5 for optimizing chiller configuration for energy saving	Resources, Conservation and Recycling	2	Article

Table 7. 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.	[53]	2017	On sustainable production networks for industry 4.0	Entrepreneurship and Sustainability Issues	71	Article
5.	[54]	2018	Manufacturing in the fourth industrial revolution: A positive prospect in Sustainable Manufacturing	Procedia Manufacturing	66	Conference Paper
6.	[55]	2018	Biologicalisation: Biological transformation in manufacturing	CIRP Journal of Manufacturing Science and Technology	56	Article
7.	[56]	2017	Enabling Circular Economy Through Product Stewardship	Procedia Manufacturing	44	Article
8.	[57]	2018	Maintenance for Sustainability in the Industry 4.0 context: a Scoping Literature Review	IFAC-PapersOnLine	43	Conference Paper
9.	[58]	2019	Industry 4.0—challenges to implement circular economy	Benchmarking	32	Article
10.	[59]	2018	Exploring gamification to support manufacturing education on industry 4.0 as an enabler for innovation and sustainability	Procedia Manufacturing	31	Conference Paper

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