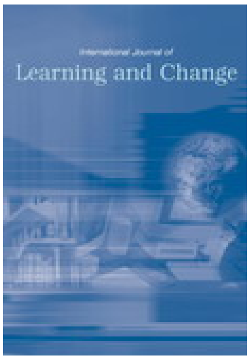


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# Past and future of Industry 4.0: a bibliometric review using bibliometrix and VOSviewer

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# Past and future of Industry 4.0: a bibliometric review using bibliometrix and VOSviewer


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**Abstract:** Industry 4.0 (I4.0) is a research field that accounted for an explosion of scientific publications since 2011. It is impractical to analyse the content of these many documents in a reasonable time (20,000). In these terms, the present research proposes a bibliometric review of this research field to identify its intellectual roots, research front, trends and gaps. The research settled for a must-read list, the past and current research themes and their evolution, and the supportive intellectual structure of the research field. It defined the research front under two general topics: 'I4.0 implementation' and 'I4.0 effects on sustainability', and it also presented thematic evolution trends and research gaps. Bibliometric analyses of the scientific field of I4.0 have several precedents: however, they have yet to embrace all the documents present in WOS and SCOPUS core collections. In this sense, the present article brings a novelty to the annals of the research field.

**Keywords:** Industry 4.0; I4.0; bibliometric review; digital transformation; manufacturing; intelligent manufacturing; trend analysis.

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This paper is a revised and expanded version of a paper entitled 'Digital transformation in manufacturing SMEs: a bibliometric analysis using VOSviewer' presented at *12th International Scientific Conference Business and Management 2022*, Vilnius – Lithuania, 12–13 May, 2022.

## 1 Introduction

The concept of *Industrie 4.0*, unveiled by the German government at the Hannover fair back in 2011, kick-started what would be the hottest research field for STEM knowledge disciplines (Ghobakhloo et al., 2021). Eleven years have passed, and the research field has grown exponentially (Machado et al., 2022). The present research encountered 19,917 documents, a tremendous sum which constitutes a barrier to literature review performance. Because of this, a bibliometric analysis was performed to better address the issue of selecting the most critical documents to analyse.

A systematic mapping review (Haddaway and Macura, 2018), also known as a bibliometric analysis, helps the researcher identify trends and gaps in a particular set of research documents referred to a specific research field (Muhuri et al., 2019). Haddaway and Macura (2018) consider this method capable of mapping out and categorising existing literature on a broad subject to commission primary research by identifying gaps in the literature or pursuing further research through cluster analysis. The authors also state that this method is 'accepted as the …'gold standard' form of evidence synthesis' (Haddaway and Macura, 2018).

The aim of the present article is two-fold. The first goal is to scrutinise and debate the descriptive properties of Industry 4.0 (I4.0) research field. The second goal is to identify the current trends in the research field. To achieve these goals, the researchers presented four research questions as follows:

RQ 1 What are the descriptive properties of the research field? To answer this question a performance analysis is the best form. This analysis makes it possible to determine which authors most influenced the research field, which journals have the most impact on the research stream, and identify the best performer documents among the dataset.

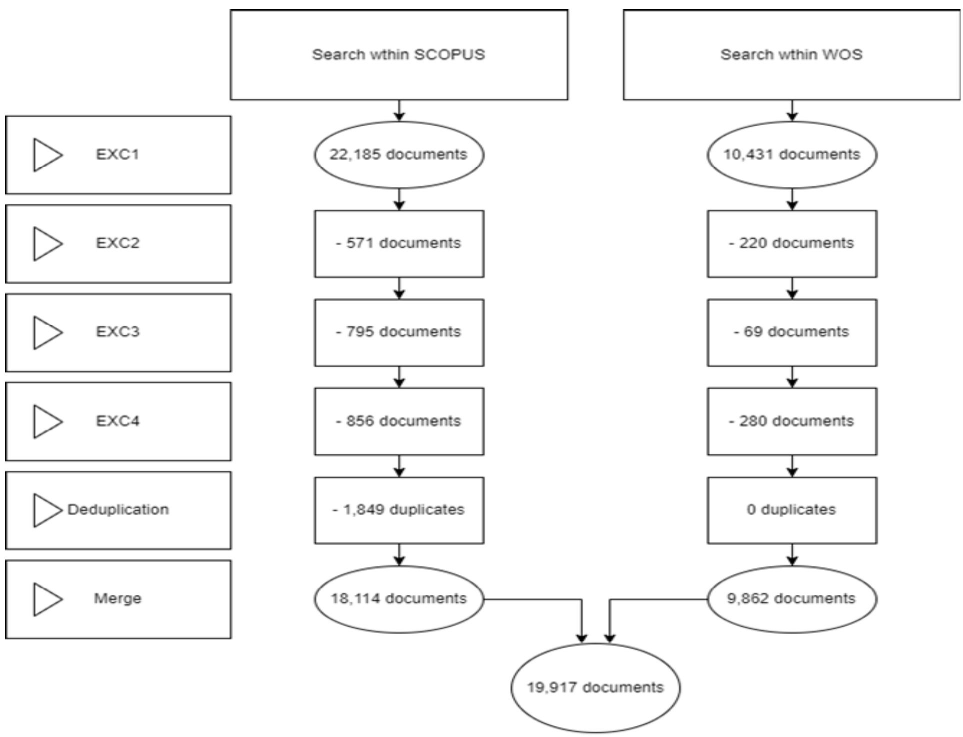
RQ 2 What is the intellectual structure of this research field? The present study will address the knowledge base of this research field through co-citation analysis. This bibliometric method makes it possible to identify who are the central researchers and what is the structure of the scientific community in this research field.

RQ 3 What is the conceptual structure of this research field? The present study will answer this question through a bibliographic coupling of the dataset. Through this bibliometric method, it is possible to examine the research front of this research field and identify recent/emerging literature.

RQ 4 What are the current trends in this research field? Through co-occurrence analysis of the most significant keywords normalised by Porter's stemming algorithm, it is possible to analyse the semantic map of this research field. It shows links among subjects in the research field and traces its development.

Because this research wants to embrace the entire research field, it was necessary to include all the different classifications academics have determined for the fourth industrial revolution paradigm. 'I4.0' is the direct translation of the strategic effort taken by the German government presented at the 2011 Hannover fair as 'Industrie 4.0' (Xu et al., 2018, 2021); this justifies the choice for the keyword 'industr* 4*'. 'Industrial internet' and 'intelligent manufacturing' were the USA' way of classifying this paradigm. In the first case, the push was given by a private corporation, general electric (Liao et al., 2017; Zhong et al., 2017; Xu et al., 2018, 2021); hence the choice for both keywords 'industrial internet' and 'intelligent manufacturing'. These concepts had some recent advancements based on the consideration that the issue has been being approached from an economic perspective, disregarding sustainability and human centricity, something that led to the European Commission coming forward with the concept of 'Industry 5.0', similar to the 'Society 5.0' presented by Japan (Ghobakhloo et al., 2021; Xu et al., 2021) – this justifies the choice for the keywords 'industr* 5*' and 'society 5*'.

**Figure 1** Article selection procedure




*Source:* Own

## 2 Methodology

### *2.1 Data collection*

Figure 1 represents the article selection procedure. 4 exclusion criteria were defined:

- EXC1: Articles should be available in WOS and SCOPUS
- EXC2: Articles published from 2011
- EXC3: Document should be article, proceeding, review, published, or preprint/early access
- EXC4: Document should be in English.

The following string was used for searching in both repositories:

- ‘industry* 4*’ or ‘industry* 5*’ or ‘society 5*’ or ‘industrial internet’ or ‘intelligent manufacturing’
- Both searches took place on September 3, 2022.

After applying the four exclusion criteria to the datasets, the authors performed deduplication. The WOS dataset had no duplicates, and the SCOPUS dataset, on the other hand, accounted for 1,849 duplicates. In the end, the datasets were merged, resulting in a final dataset of 19,917 documents.

The present research used the following metrics and methods to perform the bibliometric analysis.

## *2.2 The metrics for performance analysis*

The present research developed the following metrics related to performance analyses [Donthu et al., (2021), p.288 Figure 2]:

- Publication-related metrics (publication is a proxy for productivity):
  Total publications
  Number of contributing authors
  Sole-authored publications
  Co-authored publications
  Number of active years of publication
  Productivity per active year of publication.
- Citation-related metrics (citation is a measure of impact and influence):
  Total citations
  Average citations.
- Citation-and-publication-related metrics (combines both citations and publications to measure the performance of research constituents):
  Collaboration index
  Collaboration coefficient
  Number of cited publications
  The proportion of cited publications
  Citations per cited publication
  H-index
  G-index
  M-index.

It is essential to highlight two indicators in terms of citations: local and global citations. The first is calculated based on the references the documents that comprehend the dataset are citing. The latter refers to the metadata retrieved from the WOS and SCOPUS, indicating how many citations a particular document had. Local citations can be as much as global citations but not more.

### *2.3 Science mapping techniques*

The present research developed the following science mapping techniques (Zupic and Čater, 2015; Donthu et al., 2021):

- Co-citation analysis: relationships among cited publications and foundational themes. The purpose is to identify the intellectual structure of the research field (Persson, 1994).
- Bibliographic coupling: relationships among cited publications and periodical or present themes. The purpose is to identify the conceptual structure or research front (Price, 1965) of the research field.
- Co-word analysis (Callon et al., 1983): forecasts future research in the field and supports and enriches understanding of thematic clusters derived from co-citation analysis or bibliographic coupling.

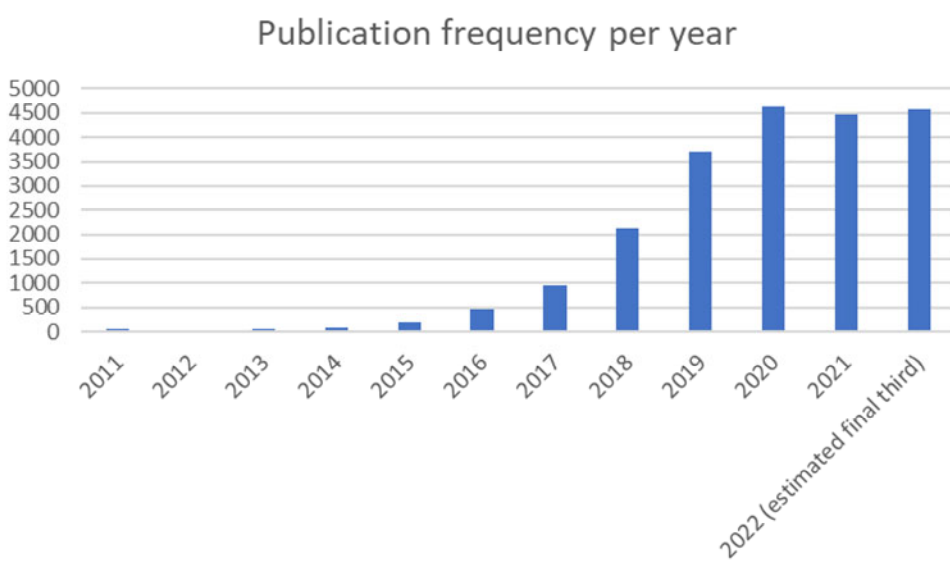
### *2.4 Network analysis – enrichment techniques*

- Network metrics:
  - a Normalised local citation score (NLCS): it is calculated by dividing the actual count of local citing items by the expected citation rate for documents with the same year of publication.
  - b Callon's centrality index: measures the intensity of links between a given community and other communities; it measures the importance of a theme in the whole collection (Callon et al., 1983, 1991).
  - c Callon's density index: measures the internal strength of the community; it measures the degree of development of a theme (Callon et al., 1983, 1991).
  - d (weighted) degree of centrality: is the number of relational ties a research constituent has in a network, – e.g., the number of co-cited documents within a dataset (Newman and Girvan, 2004).
  - e Betweenness centrality: a node's ability to carry information between unconnected groups of nodes or clusters (Newman and Girvan, 2004).
  - f Closeness centrality: refers to the capability of nodes to carry information effectively by being closer to other nodes in the network. The sum of the distance of such nodes from other nodes in the network indicates the relative ease for these nodes to carry information effectively.

g PageRank analysis (Ding et al., 2009): is an alternative measure of a publication's impact. Initially designed to prioritise web pages in a keyword search, it is now used to calculate the prestige publications that influence the research field by influencing highly-cited publications despite not being highly cited. High PageRank = high quality = must cite (Donthu et al., 2021).

- Normalisation: the Porter's stemming algorithm (Porter, 2006) was used for the creation of keyword Plus, by removing suffixes and merging synonyms.
- Clustering: is an enrichment technique whose primary goal is to create thematic or social clusters. Co-citation analysis and bibliographic coupling shed light on the significant themes underpinning the intellectual structure and their development over time in the research field. Several techniques can be used for clustering such as exploratory factorial analysis, hierarchical clustering, island algorithm, Louvain method, walktrap or other community detection algorithm, multidimensional scaling and simple centres algorithm. These can all be complementary to one another (e.g., one can use the walktrap algo for clustering and multidimensional scaling for layout) (Zupic and Čater, 2015). Yang et al. (2016) benchmarked 8 community detection algorithms (fastgreedy, infomap, leading eigenvector, label propagation, multilevel, walktrap, spinglass and edge betweenness). These authors concluded that the walktrap and the multilevel algorithms are the best suited in most situations (Yang et al., 2016). Bibliometrix accounts for several algorithms, including the walktrap, but not the multilevel. Therefore, the chosen algo was walktrap. VOSviewer only accounts for the smart local moving algo, which is an evolution of the Louvain algo, therefore it was the one used while using this software.

**Figure 2** Production of documents per year with current year of 2022 estimated (see online version for colours)




*Source:* Own

## 3 Findings and discussion

The following subsections present and debate over the key findings of the present bibliometric analysis.

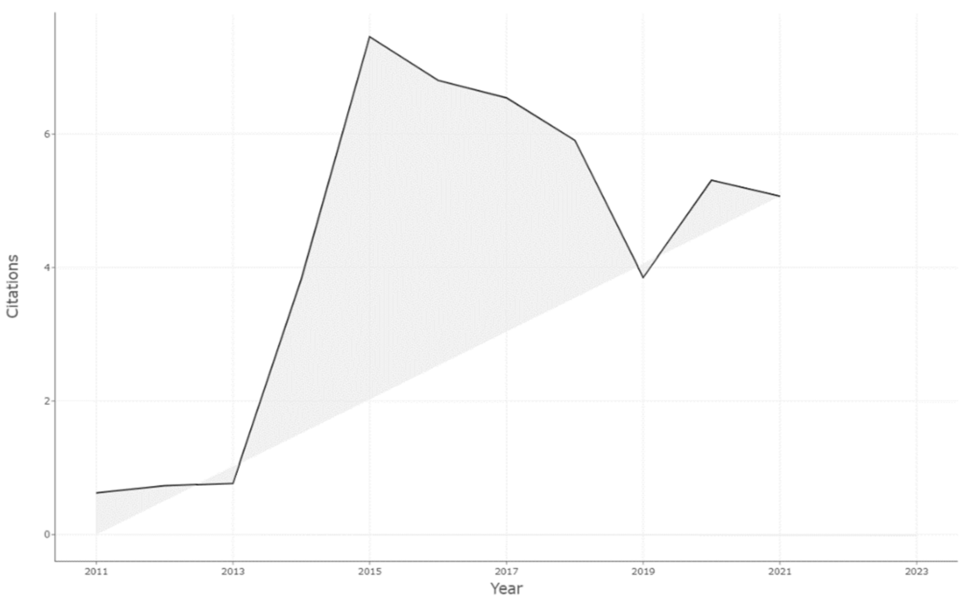
### 3.1 Performance analysis

The time span of the dataset comprehends the years between 2011 and 2023 (because of the early access and preprint articles that are already scheduled for publication); the dataset is composed of 19,917 documents from 3,646 sources, where only 1,505 were single-authored documents, from which 8,110 are journal articles, 790 are article reviews, 10,955 are proceedings, and 62 are early access or preprint articles; the dataset compounds 34,917 author's keywords; there are 37,288 authors from which 1,258 authored single-authored documents; international co-authorship accounts for 2.42% of the dataset; the total local citations account for 232,432; the average citation per document is 11.67.

Figure 2 represents the production of documents per year. The current year of 2022 has its final third estimated (by its mean value) to not give the impression that publications have decreased in the current year, which is not the case. By the estimate made, 2022 will have more publications than 2021. After the estimation, the dataset showed a compound annual growth rate of 54.44%.

Figure 3 represents the average citations per year. In this collection, one or more articles published after 2013 are collecting the highest nº of average total citations per year.

**Figure 3** Average citations per year (see online version for colours)




*Source:* Bibliometrix

Author's productivity through Lotka's Law. It affirms that as the number of published articles increases, authors producing many publications become less frequent. By applying this law, 1% of authors authoring 6 or more documents are considered the core authors on the research front. In the present dataset, occasional authors accounting for a single publication constitutes 74% of total authors. This discrepancy may indicate that the I4.0 research field is in its early stages.

Table 1 represents the top 20 authors sorted by their local H-Index. A particular remark for the author Wan J who has only 29 contributing documents to the field but has an H-Index of 22, which means that ¾ of its oeuvres have 22 citations or more. This author is also the most locally cited, with 3,954 citations.

**Table 1** Top 20 authors' local impact by H-index, G-index, M-index, and total citations, arranged hierarchically by the H index score

| *Author* | *H index* | *G Index* | *M index* | *Total citations* | *Number of documents* |
|---|---|---|---|---|---|
| Liu Y | 30 | 56 | 3 | 3,327 | 97 |
| Li D | 27 | 57 | 3,375 | 3,696 | 57 |
| Xu X | 25 | 62 | 2,5 | 3,906 | 63 |
| Wang X | 24 | 38 | 2 | 1,584 | 80 |
| Zhang X | 24 | 49 | 3 | 2,684 | 102 |
| Liu C | 23 | 51 | 3,286 | 2,698 | 53 |
| Wan J | 22 | 29 | 2,75 | 3,954 | 29 |
| Li Y | 21 | 38 | 2,625 | 1,588 | 81 |
| Lu Y | 21 | 44 | 2,625 | 3,536 | 44 |
| Rauch E | 20 | 34 | 2,857 | 1,281 | 60 |
| Chen C | 19 | 33 | 2,111 | 1,244 | 62 |
| Wang J | 19 | 35 | 1,583 | 1,323 | 76 |
| Wuest T | 19 | 43 | 2,714 | 2,683 | 43 |
| Chen Y | 18 | 33 | 2,571 | 1,302 | 74 |
| Matt D | 18 | 25 | 2,571 | 708 | 49 |
| Romero D | 18 | 39 | 2,571 | 1,543 | 41 |
| Wang L | 18 | 35 | 1,8 | 1,278 | 58 |
| Imran M | 17 | 27 | 2,429 | 1,586 | 27 |
| Li J | 17 | 35 | 2,429 | 1,374 | 68 |
| Wang H | 17 | 36 | 1,889 | 1,384 | 52 |

*Source:* Own

Following are the top manuscripts per global citations (reference-nº of global citations):

1 Lee et al. (2015)-2,660

2 Hermann et al. (2016)-1,447

3 Lu (2017)-1,430

4 Xu et al. (2018)-1,259

5 Zhong et al. (2017)-1,205
6 Stock and Seliger (2016)-944
7 Liao et al. (2017)-937
8 Sisinni et al. (2018)-835
9 Wang et al. (2016b)-801
10 Frank et al. (2019)-794
11 Liao et al. (2017)-937
12 Kang et al. (2016)-741
13 Schumacher et al. (2016)-666
14 Dalenogare et al. (2018)
15 Negri et al. (2017)-625
16 Oesterreich and Teuteberg (2016)-609
17 Li et al. (2018)-604
18 Sadeghi et al. (2015)-589
19 Thoben et al. (2017)-578
20 Oztemel and Gursev (2020)-563.

Following are the most relevant local cited references (reference-nº of local citations).

1 Lee et al. (2015)-634
2 Lu (2017)-469
3 Lasi et al. (2014)-427
4 Kagermann et al. (2013)-389
5 Stock and Seliger (2016)-362
6 Zhong et al. (2017)-358
7 Xu et al. (2018)-349
8 Hofmann and Rüsch (2017)-323
9 Frank et al. (2019)-286
10 Schumacher et al. (2016)-279
11 Lee et al. (2014)-254
12 Dalenogare et al. (2018)-242
13 Kamble et al. (2018)-226
14 Monostori (2014)-212
15 Qin et al. (2016)-212

16 Ghobakhloo (2018)-205

17 Xu et al (2014)-195

18 Oesterreich and Teuteberg (2016)-186

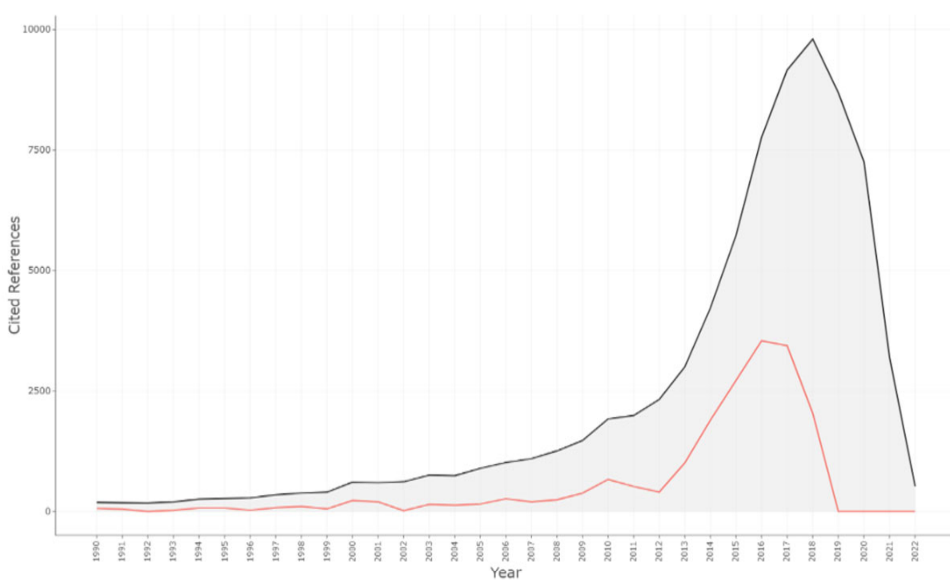
19 Atzori et al. (2010)-169

20 Liao et al. (2017)-168.

Most of the documents incorporating local and global top 20 most relevant manuscripts were not authored by the local top 20 most relevant authors to the research field, which may be another indicator to support that the research field of I4.0 is still in its early stages.

Figure 4 represents the references per year spectroscopy (RPYS). RPYS is a quantitative method for identifying the historical origins of research fields and topics. It creates a temporal profile of cited references for a set of papers that emphasises years where relatively significant findings were published, allowing for the identification of the temporal roots of the research field. The black line consists of the number of cited references per year, while the red line constitutes the deviation from the 5-year median.

**Figure 4** References per year spectroscopy (see online version for colours)




*Source:* Bibliometrix

According to the present research analysis, the 2016 spike may be justified by 4 highly cited proceedings papers and 6 highly cited journal articles published in that year (Hermann et al., 2016; Hossain and Muhammad, 2016; Kang et al., 2016; Monostori et al., 2016; Oesterreich and Teuteberg, 2016; Stock and Seliger, 2016; Wan et al., 2016; Wang et al., 2016a, 2016b). They are the results of government pushes, led by the German government with replicas all over the world, that started in 2013 with publications such as Kagermann et al. (2013), Acatech (2015), Ruessmann et al. (2015), and Hankel and Rexroth (2015). This explains the burst in publications starting from 2012 as an answer from academia after the German government presented the Industrie 4.0 concept at the 2011 Hannover fair (Xu et al., 2018). Moreover, the explosion of scientific production disrupted in 2016 until the present date is a result of these combined factors.

Figure 5 represents the source clustering through Bradford's Law. By applying this law, 26 sources are the most significant contributors among the 3,645 sources. According to this law, these are the central conference proceedings and the nuclear academic journals, and researchers should concentrate their analysis on the core source documents. They are (publication title-frequency):

1 *Procedia Computer Science*-648

2 *IEEE Transactions on Industrial Informatics*-503

3 *Procedia CIRP*-425

4 *IEEE Access*-343

5 *Procedia Manufacturing*-314

6 *Advances in Intelligent Systems and Computing*-311

7 *Lecture Notes in Computer Science*-310

8 *Sensors*-157

9 *IEEE Internet of Things Journal*-296

10 *IFIP Advances in Information and Communication Technology*-291

11 *Sustainability*-287

12 *IFAC-Papersonline*-267

13 *Lecture Notes in Mechanical Engineering*-252

14 *ACM International Conference Proceeding Series*-232

15 *Proceedings of the 23rd Pacific Asia Conference on Information Systems*-226

16 *Journal of Physics: Conference Series*-200

17 *IOP Conference Series: Materials Science and Engineeing*-183

18 *Applied Sciences*-181

19 *Lecture Notes in Electrical Engineering*-162

20 *International Journal of Advanced Manufacturing Technology*-157

21 *IOP Conference Series: Earth and Environmental Science*-156

22 *Proceedings of the International Conference on Industrial Engineering and Operations Management*-149

23 *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*-148

24 *2020 IEEE International Workshop on Metrology for Industry 4.0 and IOT, METROIND 4.0 AND IOT 2020-PROCEEDINGS*-142

25 *Lecture Notes in Networks and Systems*-136

26 *Smart Innovation, Systems and Technologies*, 143.

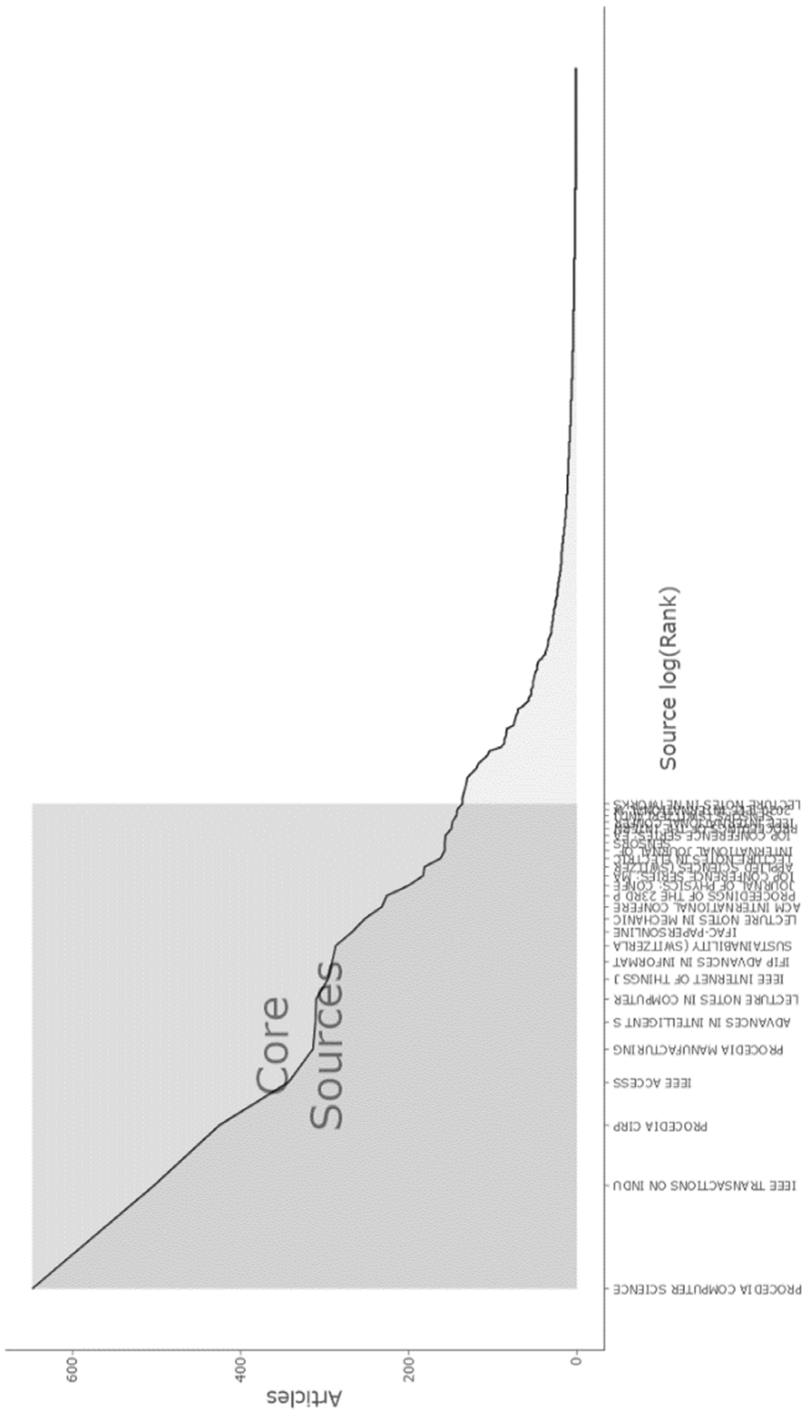
A special remark here given to the fact that 15 out of the 26 core sources are scientific journals, and only 11 are conference proceedings. This may indicate that the research field is starting to mature.

**Table 2** Sources' local impact by H-index, G-index, M-index, and total citations, arranged hierarchically by the total number of produced documents

| *Source* | *H Index* | *G index* | *M index* | *Total citations* | *Number of documents* |
|---|---|---|---|---|---|
| *Procedia Computer Science* | 25 | 35 | 3.12 | 3,772 | 648 |
| *IEEE Transactions on Industrial Informatics* | 61 | 103 | 7.62 | 13,996 | 503 |
| *Procedia CIRP* | 40 | 85 | 4 | 8,848 | 425 |
| *IEEE Access* | 41 | 75 | 5.86 | 7,151 | 343 |
| *Procedia Manufacturing* | 41 | 81 | 5.12 | 7,969 | 314 |
| *IEEE Internet of Things Journal* | 35 | 55 | 5.83 | 4,310 | 296 |
| *Sustainability (Switzerland)* | 37 | 65 | 6.17 | 5,541 | 287 |
| *IFAC - PapersOnline* | 25 | 54 | 3.12 | 3,494 | 267 |
| *Sensors (Switzerland)* | 30 | 44 | 4.29 | 2,813 | 157 |
| *International Journal of Advanced Manufacturing Technology* | 27 | 43 | 3 | 2,436 | 157 |
| *International Journal of Production Research* | 44 | 102 | 4.33 | 10,551 | 130 |
| *International Journal of Production Economics* | 26 | 46 | 3.67 | 3,957 | 130 |
| *Computers in Industry* | 41 | 73 | 4.56 | 5,588 | 119 |
| *Technological Forecasting and Social Change* | 32 | 67 | 6.4 | 4,732 | 111 |
| *Journal of Manufacturing Systems* | 33 | 57 | 3.3 | 3,496 | 106 |
| *Computers and Industrial Engineering* | 32 | 56 | 3.2 | 3,253 | 104 |
| *Journal of Intelligent Manufacturing* | 26 | 51 | 2.17 | 2,772 | 84 |
| *Journal of Cleaner Production* | 34 | 52 | 5.67 | 2,863 | 70 |
| *Journal of Industrial Information Integration* | 20 | 42 | 3.33 | 3,046 | 52 |
| *Manufacturing Letters* | 35 | 39 | 2.25 | 4,224 | 41 |

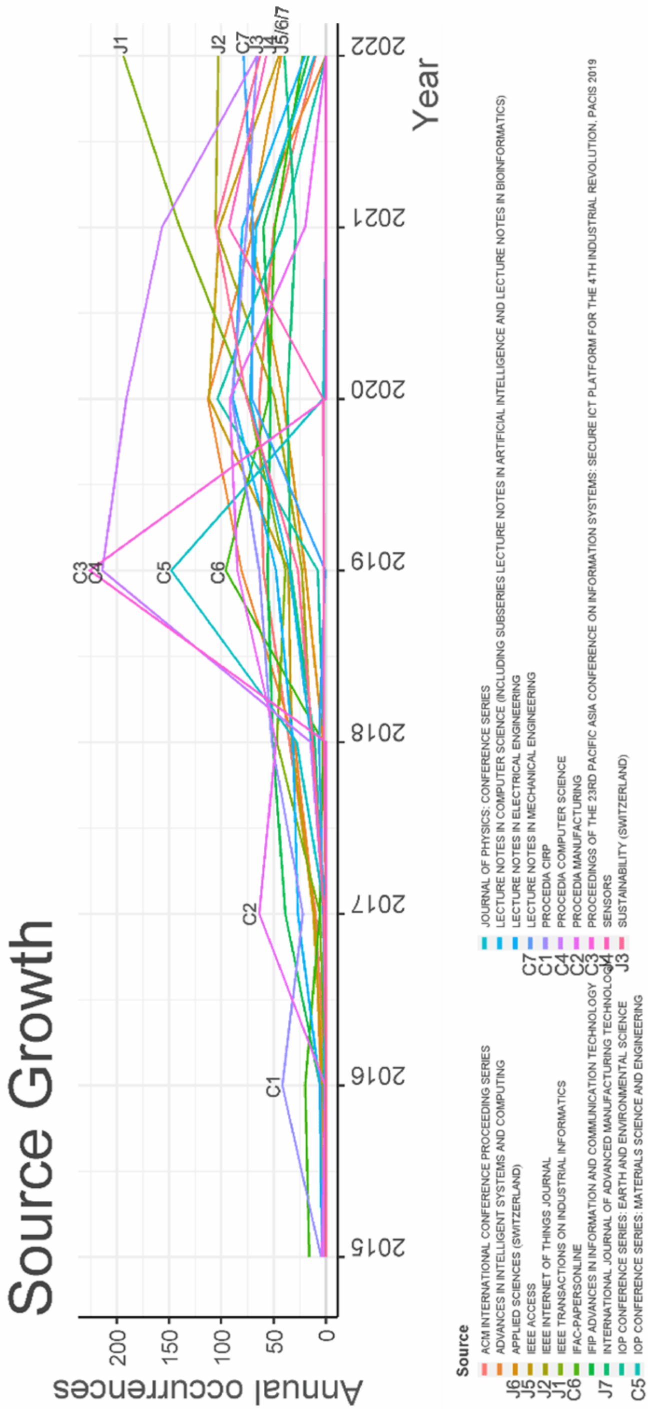
*Source:* Own

**Figure 5** Source clustering through Bradford's Law




*Source:* Bibliometrix

**Figure 6** Sources' growth per year (see online version for colours)

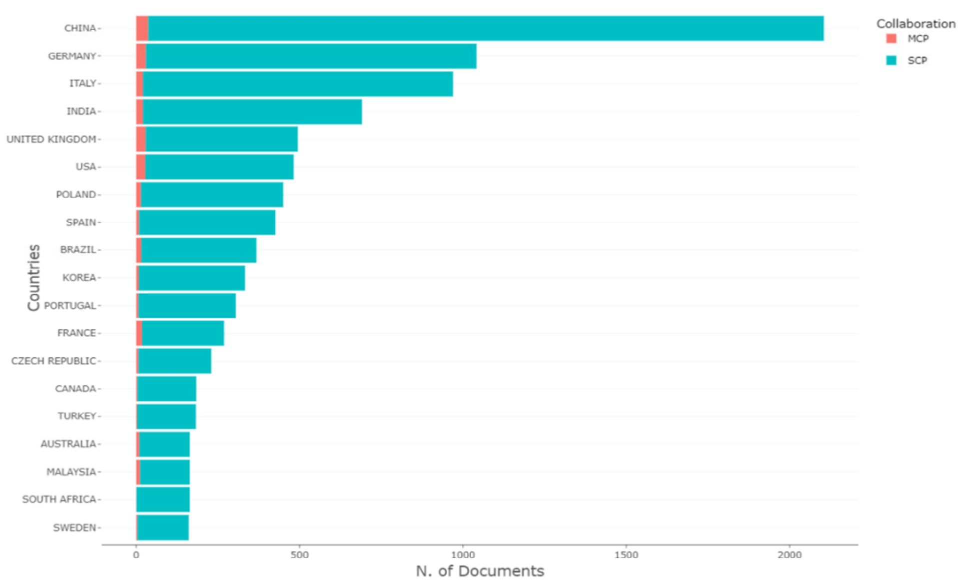



*Source:* Bibliometrix-edited

Bradford's law (a.k.a. Bradford's/Pareto distribution), is an efficient bibliometric analysis method, especially when addressing a significant amount of data. The underlying principle is that, in general, publication titles outside the core sources are most likely not focused on publishing relevant work for the research field in scope, while they might it will be scarce (Shenton and Hay-Gibson, 2009). If a researcher intends to grasp the pulse of a research field, especially when it accounts for thousands of titles and tens of thousands of documents, one should focus on the core sources documents; otherwise, it would be impractical to perform a systematic literature review under such conditions. Also, the fact that some of the titles that published highly cited documents are not all present on the list is not a surprise because the most significant contribution of this particular analysis is to the research front analysis and not to the intellectual structure analysis. A newcomer should focus on the titles publishing fresh and relevant content and the most recent advancements in the research field. Also, these contents will undoubtedly cite relevant intellectual structure.

Table 2 represents the sources' local impact by H-index and its generalisations. A remark that only nine titles considered core sources according to Bradford's Law made it the top 20 most productive sources. In this leader board, there are only three conference proceedings, and the rest are composed of journals. Nevertheless, the three conference proceeding titles made it to the top 5.

**Figure 7** Most productive countries (see online version for colours)




*Source:* Bibliometrix

Figure 6 represents the sources' growth per year, where the year 2023 was excluded. This representation confirms that despite the intellectual structure started to grow with conference proceedings, the research front is now shifting to journal articles, like the *IEEE Transactions on Industrial Informatics Journal*, the *IEEE Internet of Things Journal, Sustainability, Sensors*, *IEEE Access*, *Applied Sciences*, and the *International*

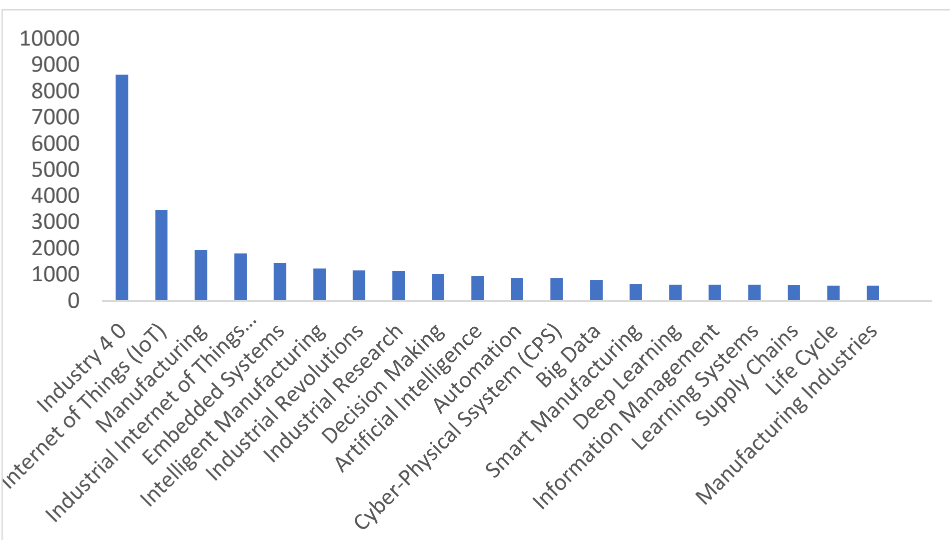
*Journal of Advanced Manufacturing Technologies*, titles that grew significantly from 2020 to 2022.

Figure 7 represents the most productive countries. Caption SCP stands for Single Country Publication (the vast majority), and MCP stands for multiple country publication. It is noticeable that the research contributions to the field have a global expression, but there are few multiple-country endeavours, only 2.42% of the dataset, as previously mentioned on the performance outline.

Considering the most frequent author's keywords, it is undoubtful that the central theme is I4.0, and the other topics revolve around its core technologies. To better analyse the research field with greater depth, this research normalised the keywords with Porter's stemming algorithm. Garfield (1990) claimed that keywords plus terms could capture an article's content with greater depth and variety. Zhang et al. (2016) defended that bibliometric analyses of the structure of scientific fields should use Keywords Plus because the significant number of terms and their broad meanings confer advantages over author keywords.

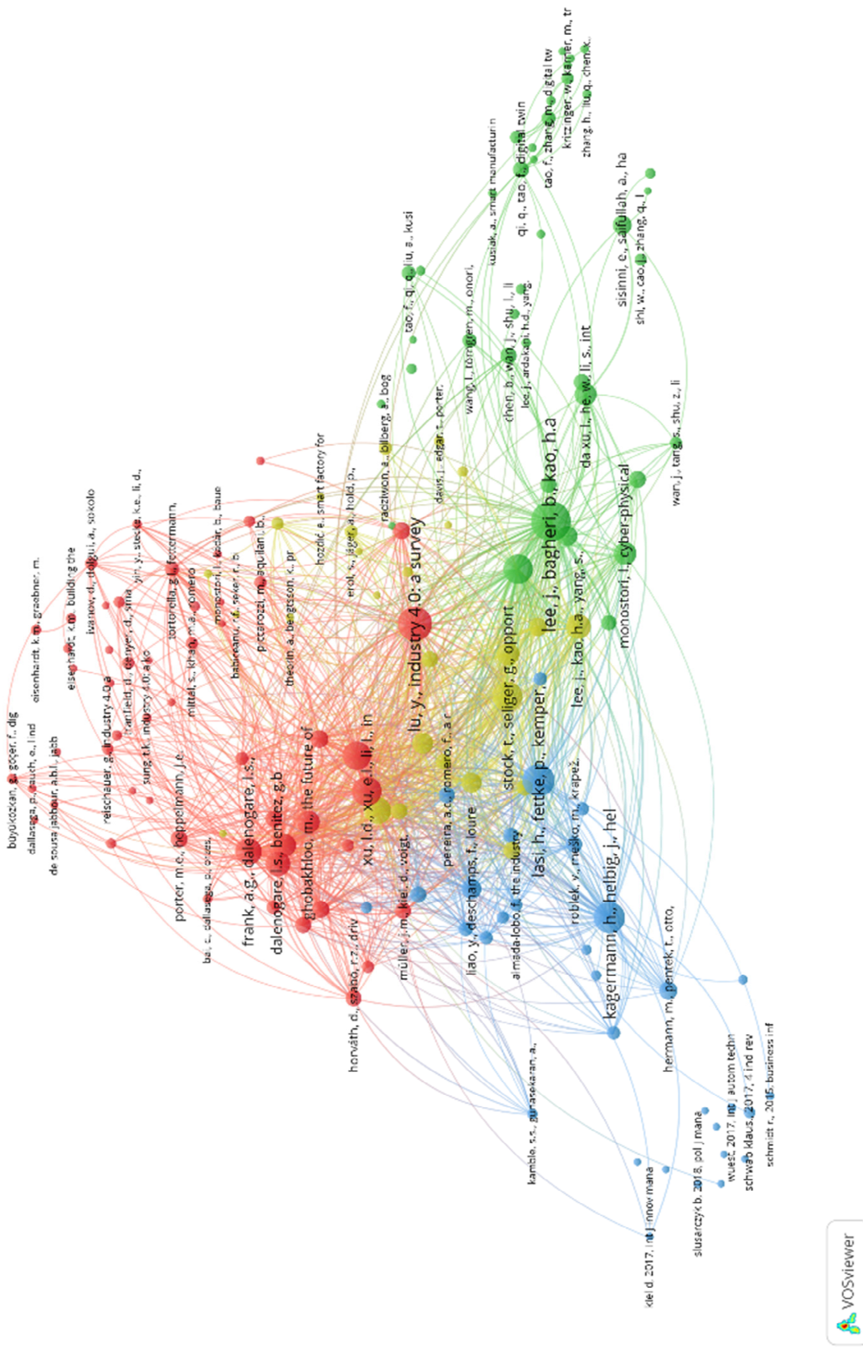
Figure 8 represents the most relevant keywords normalised by Porter's stemming algorithm. It removes suffixes and merges synonyms. This representation shows the effectiveness of the algorithm in normalising author keywords. The Relevance of I4.0 becomes less prominent by comparison, leaving more space for other themes and topics to arise. Themes regarding developing topics, such as automation and supply chain. It is also noticeable that the life cycle appears as a relevant research approach.

**Figure 8** Most relevant keywords plus (see online version for colours)




*Source:* Own

**Figure 9** The intellectual structure of the research field represented by a co-citation network (see online version for colours)




*Source:* VOSviewer

**Table 3** Top 20 most local cited references per cluster

| *Reference* | *Cluster* | *Citations* | *PageRank* |
|---|---|---|---|
| Lu, Y., Industry 4.0: a survey…(2017) | Red | 469 | 0.02927 |
| Xu, L.D. ..., Industry 4.0: state of the…(2018) | Red | 349 | 0.029343 |
| Hofmann, E. and Rusch, Industry 4.0 and the…(2017) | Red | 323 | 0.026473 |
| Frank, A.G. ..., Industry 4.0 technologies: im…(2019) | Red | 286 | 0.022042 |
| Dalenogare, L.S. …, The expected contributio…(2018) | Red | 242 | 0.021186 |
| Kamble, S.S. …, Sustainable industry 4.0…(2018) | Red | 226 | 0.014237 |
| Ghobakhloo, M. …, The future of manuf…(2018) | Red | 205 | 0.018469 |
| Moeuf, A. …, The industrial management…(2018) | Red | 141 | 0.013205 |
| Kusiak, A., Smart manufacturing (2018) International… | Red | 125 | 0.00855 |
| Porter, M.E., Heppelmann, J.E., How smart…(2014) | Red | 119 | 0.008608 |
| Müller, J.M., …Fortune favours…(2018b) | Red | 118 | 0.015294 |
| Luthra, S., Mangla, S.K., Evaluating cha…(2018) | Red | 112 | 0.014446 |
| Müller, J.M. …What drives the impl…(2018a) | Red | 112 | 0.015294 |
| Barreto, L. …Indusrty 4.0 implications…(2017) | Red | 108 | 0.006271 |
| Horváth, D. and Szabó, R.Z., Driving forces…(2019) | Red | 103 | 0.011142 |
| Tortorella, G.L. and Fettermann, D., Implementat…(2018) | Red | 85 | 0.007291 |
| Buer, S.V. …, The link between industry 4.0…(2018) | Red | 75 | 0.006821 |
| Tjahjono, B. …What does industry 4.0 mean…(2017) | Red | 71 | 0.006137 |
| Ghobakhloo, M., Industry 4.0, digitisation…(2020) | Red | 66 | 0.009486 |
| Piccarozzi, M. …Industry 4.0 in management…(2018) | Red | 64 | 0.008608 |
| Lee, J. …A cyber-physical systems...(2015) | Green | 634 | 0.041139 |
| Zhong, R.Y. …Intelligent manufact...(2017) | Green | 358 | 0.021447 |
| Monostori, L., Cyber-physical prod...(2014) | Green | 212 | 0.010779 |
| Xu, L.D. …Internet of things in ind...(2014) | Green | 195 | 0.015755 |
| Atzori, L. …The internet of things...(2010) | Green | 169 | 0.010727 |
| Sisinni, E. …Industrial internet of...(2018) | Green | 153 | 0.008233 |
| Wollschlaeger, M. …The future of in...(2017) | Green | 124 | 0.007276 |
| Qi, Q. and Tao, F., Digital twin and big data tow...(2018) | Green | 112 | 0.009415 |
| Boyes, H. …The industrial internet...(2018) | Green | 111 | 0.006688 |
| Chen, B. …Smart factory of industry 4.0: key...(2017) | Green | 106 | 0.003384 |
| Xu, X., From cloud computing to cloud man...(2012) | Green | 106 | 0.009732 |
| Gubbi, J. …Internet of things (IoT): a vision...(2013) | Green | 102 | 0.007412 |
| Tao, F. and Zhang, M., Digital twin shop-floor...(2017) | Green | 88 | 0.006986 |
| Wang, L. …Current status and advancement...(2015) | Green | 85 | 0.007488 |
| Tao, F. …Data-driven smart manufacturing (2018) Jo… | Green | 80 | 0.015948 |
| Wan, J. …Software-defined industrial internet...(2016) | Green | 68 | 0.004048 |
| Negri, E. …A review of the roles of digital tw...(2017) | Green | 66 | 0.006382 |
| Shi, W. …Edge computing: vision and challen…(2016) | Green | 63 | 0.004497 |
| Kritzinger, W. …Digital twin in manufacturing...(2018) | Green | 62 | 0.00649 |
| Christidis, K. and Devetsikiotis, M., Blockchains...(2016) | Green | 51 | 0.002091 |

**Table 3** Top 20 most local cited references per cluster (continued)

| *Reference* | *Cluster* | *Citations* | *PageRank* |
|---|---|---|---|
| Lasi, H. ...Industry 4.0 (2014) Business and Informatio… | Blue | 427 | 0.033893 |
| Kagermann, H. …Recommendations for Impl…(2013) | Blue | 389 | 0.040281 |
| Liao, Y. …Past, Present and Future of ind...(2017) | Blue | 168 | 0.015652 |
| Hermann, M. …Design Principles for Indust...(2016) | Blue | 137 | 0.021679 |
| Pereira, A.C. and Romero, F., A Review of the | Blue | 114 | 0.007675 |
| Roblek, V. …A complex view of industry 4.0 (2016) | Blue | 114 | 0.009333 |
| Oztemel, E. and Gursev, S., Literature review of in...(2020) | Blue | 109 | 0.00924 |
| Drath, R. and Horch, A., Industrie 4.0: hit or hype...(2014) | Blue | 97 | 0.008487 |
| Wang, S. ...Implementing smart factory of Ind...(2016a) | Blue | 88 | 0.014368 |
| Kang, H.S. ...Smart manufacturing: past Resea...(2016) | Blue | 78 | 0.004994 |
| Leitão, P. …Industrial automation based on...(2016) | Blue | 73 | 0.004509 |
| Vaidya, S. …Industry 4.0 – a glimpse (2018) Procedi… | Blue | 73 | 0.005073 |
| Weyer, S. …Towards industry 4.0-standar...(2015) | Blue | 70 | 0.004878 |
| Almada-Lobo, F., The industry 4.0 revolution...(2016) | Blue | 66 | 0.00905 |
| Benešová, A. and Tupa, J., Requirements for educ...(2017) | Blue | 60 | 0.003727 |
| Schwab, K., Fourth industrial revolution (2017) … | Blue | 56 | 0.004592 |
| Frey, C.B. and Osborne, M.A., The future of emp...(2017) | Blue | 55 | 0.003477 |
| Rojko, A., Industry 4.0 Concept: Background...(2017) | Blue | 47 | 0.006546 |
| Kamble, S.S. …Analysis of the Driving and…(2018) | Blue | 46 | 0.014237 |
| Longo, F. …Smart operators in industry 4.0...(2017) | Blue | 43 | 0.005305 |
| Stock, T. and Seliger, G., Opportunities of sust...(2016) | Yellow | 362 | 0.027082 |
| Schumacher, A. …A Maturity Model for Ass...(2016) | Yellow | 279 | 0.02013 |
| Lee, J. …Service innovation and smart anal...(2014) | Yellow | 254 | 0.021068 |
| Qin, J. …A categorical framework of man...(2016) | Yellow | 212 | 0.014485 |
| Oesterreich, T.D. and Teuteberg, F., Understandi…(2016) | Yellow | 186 | 0.014303 |
| Brettel, M. …How virtualisation, decent...(2014) | Yellow | 158 | 0.017607 |
| Wang, S. …Towards smart factory for ind...(2016b) | Yellow | 140 | 0.014368 |
| Hecklau, F. …Holistic approach for human...(2016) | Yellow | 115 | 0.007613 |
| Kolberg, D. adn Zühlke, D., Lean automation ena...(2015) | Yellow | 110 | 0.007951 |
| Mrugalska, B. and Wyrwicka, M.K., Towards lean...(2017) | Yellow | 109 | 0.006322 |
| Sanders, A. …Industry 4.0 implies lean...(2016) | Yellow | 106 | 0.010431 |
| Wagner, T. ...Industry 4.0 impacts on lean...(2017) | Yellow | 101 | 0.006377 |
| Radziwon, A. …The smart factory...(2014) | Yellow | 77 | 0.006086 |
| Erol, S. …Tangible industry 4.0...(2016) | Yellow | 73 | 0.006845 |
| Ivanov, D. …A dynamic model and an algo…(2016) | Yellow | 63 | 0.008113 |
| Davis, J. …Smart manufacturing, manufac…(2012) | Yellow | 51 | 0.006313 |
| Thames, L. and Schaefer, D., Software-defined...(2016) | Yellow | 47 | 0.005838 |
| Faller, C. adn Feldmüller, D., Industry 4.0 lear…(2015) | Yellow | 43 | 0.003708 |
| Hozdić, E., Smart factory for industry 4.0...(2015) | Yellow | 32 | 0.005034 |
| Kolberg, D. …Towards a lean automation...(2017) | Yellow | 30 | 0.005168 |

## *3.2 Intellectual structure analysis*

Knowledge base or intellectual base (Persson, 1994) is the set of articles most cited by the current research. The knowledge base or intellectual structure refers to the examined scientific domain's research traditions, disciplinary composition, influential research topics, and the pattern of their interrelationships (Zupic and Čater, 2015). The bibliometric method suited for analysing the intellectual structure of a research field is co-citation analysis (Aria and Cuccurullo, 2017).

Co-citation analysis is the past (Donthu et al., 2021). It is performed for mapping older papers (prospective analysis-dynamic and best performed between or within different time slices) (Zupic and Čater, 2015). Since co-citation is applied to the cited articles, it can identify the knowledge/intellectual base of a topic/research field and is suited for answering the second research question.

Figure 9 presents the co-citation network with documents as the unit of analysis formulated by the SLM algorithm with 150 nodes. It clearly shows 4 different clusters: the *red cluster* is the most prominent. At the core, we have the most cited references. The focus is on the implementation and deployment of I4.0 technologies and how to promote digital transformation benefitting from the 'new' paradigm. Most articles that compound the red cluster are from 2018. The research documents are mostly overviews, scope reviews, and systematic reviews, the reason why among the cited references there is the article authored by Tranfield et al. (2003). There are also some case studies for theory building.

The *green cluster* revolves around the top-tier technologies of I4.0, like CPS, IoT, Digital Twin and Big Data, and their importance for the future of manufacturing industries and their business models (mass personalisation vs mass production). Most of the documents were published in 2017.

The *blue cluster* is more concerned with defining the scope of the research field paradigm and its design principles, which justifies the incorporation of the research document that was first named the paradigm 'Industrie 4.0' (Kagermann et al., 2013).

The smaller *yellow cluster* is focused on the effects of digital transformation and its possible benefits. Effects of automation and digitisation on existing jobs, opportunities are made possible through I4.0 technologies for achieving sustainable development goals, lean and flexible manufacturing, and opportunities for service innovation. Most of the documents that compound the yellow cluster are from 2016.

Table 3 accounts for the top 20 documents per cluster. The PageRank score is given according to a set of 150 references.

## *3.3 Conceptual structure analysis*

The third research question regards the conceptual structure of the I4.0 research field. The present study used bibliographic coupling of the dataset to answer this question. Through this bibliometric method, it is possible to examine the research front of the I4.0 research field and identify the intellectual structure of recent/emerging literature.

The analysis produced a map. The x-axis measures the cluster centrality (by Callon's Centrality index), while the y-axis measures the cluster impact by mean normalised local citation score (MNLCS). A document's NLCS is calculated by dividing the actual count of local citing items by the expected citation rate for documents with the same year of publication.

**Table 4** Top 40 documents per cluster

| *Document* | *Cluster* | *Document* | *Cluster* |
|---|---|---|---|
| Frank AG, 2019, Int. J. Prod. Econ. | Red | Jagatheesaperumal SK, 2022, ieee inter… | Red |
| Ghobakhloo M. 2020, J. Clean Prod | Red | Obermayer n, 2022, meditari account res | Red |
| Kumar R, 2020, J. Clean. Prod. | Red | Brodeur j, 2022, sustainability | Red |
| Zheng T, 2021, Int. J. Prod. Res. | Red | Kumar r, 2022, sensors | Red |
| Bueno A., 2020, Comput. Ind. Eng. | Red | Gupta a, 2022, int j manpow | Red |
| Hahn GJ, 2020, Int. J. Prod. Res. | Red | Thekkoote r, 2022, int j qual reliab m… | Red |
| Ghobakhloo M, 2021, J. Clean. Prod. | Red | Ramadan m, 2022, sustainability | Red |
| Ciano MP, 2021, Int. J. Prod. Res. | Red | Gadekar r, 2022, sustain prod consum | Red |
| Mittal S, 2020, int j prod res | Red | Jayashree s, 2022, sustain prod consum | Red |
| Dieste m, 2022, int j prod econ | Red | Jena a, 2022, int j adv manuf technol | Red |
| Torres da rocha ab, 2022, heliyon | Red | Kumar v, 2022, benchmarking | Red |
| Sahu a, 2022, j enterp inf manage | Red | El baz j, 2022, j clean prod | Red |
| Baran e, 2022, sustainability | Red | Jałowiec t, 2022, sustainability | Red |
| Rocha-jácome c, 2022, lect notes elec… | Red | Demirkesen s, 2022, eng constr archit… | Red |
| Suleiman z, 2022, cogent eng | Red | Ramanathan k, 2022, j manuf technol… | Red |
| Bueno a, 2022, smart innov syst tech…. | Red | Tutak m, 2022, j open innov : technol… | Red |
| Bokhorst jac, 2022, int j prod econ | Red | Benitez gb, 2022, supply chain manage… | Red |
| Bhatia ms, 2022, ieee trans eng manage | Red | Gadekar r, 2022, intl j syst assur eng… | Red |
| Senna pp, 2022, comput ind eng | Red | Gadekar r, 2022, ann oper res | Red |
| Núñez-merino m, 2022, technol forec… | Red | Nimawat d, 2022, int j interact des… | Red |
| Xu ld, 2018, int j prod res | Blue | Galati f, 2019, comput ind | Blue |
| Dalenogare ls, 2018, int j prod econ | Blue | Ghobakhloo m, 2020, int j prod res | Blue |

*Source:* Own

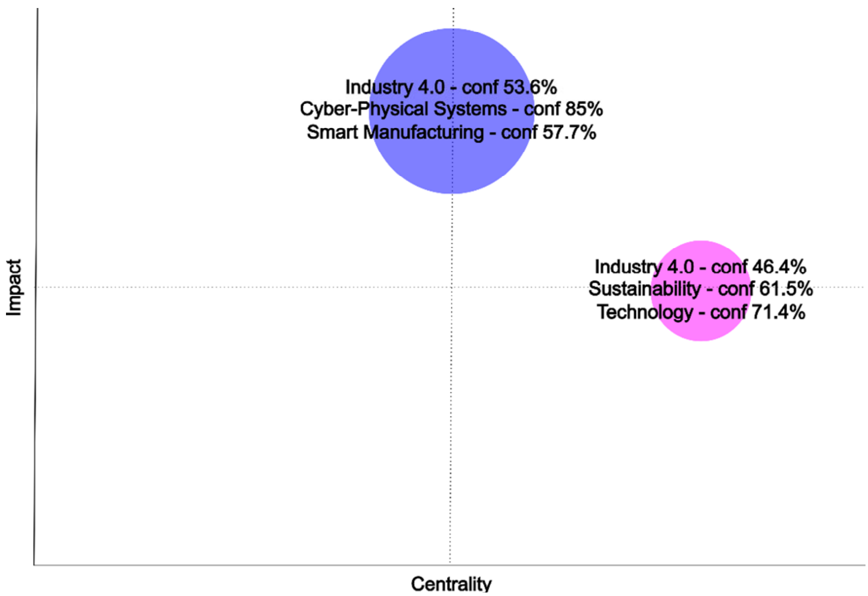
**Table 4** Top 40 documents per cluster (continued)

| *Document* | *Cluster* | *Document* | *Cluster* |
|---|---|---|---|
| Manavalan e, 2019, comput ind eng | Blue | Osterrieder p, 2020, int j prod econ | Blue |
| Kamble ss, 2018, comput ind | Blue | Semeraro c, 2021, comput ind | Blue |
| Beier g, 2020, j clean prod | Blue | Silvestri l, 2020, comput ind | Blue |
| Machado cg, 2020, int j prod res | Blue | Anumbe n, 2022, sensors | Blue |
| Culot g, 2020, int j prod econ | Blue | Salih kom, 2022, sensors | Blue |
| Ben-daya m, 2019, int j prod res | Blue | Nimawat d, 2022, int j ind syst eng | Blue |
| Sony m, 2018, prod manuf res | Blue | Gajdzik b, 2022, j open innov : technol… | Blue |
| Sony m, 2020, benchmarking | Blue | Rikalovic a, 2022, ieee syst j | Blue |
| Fettermann dc, 2018, j ind prod eng | Blue | Sureshchandar gs, 2022, int j qual… | Blue |
| Kamble s, 2020, int j prod res | Blue | Castellani d, 2022, j ind bus econ | Blue |
| Winkelhaus s, 2020, int j prod res | Blue | Saniuk s, 2022, sustainability | Blue |
| Maresova p, 2018, economies | Blue | Dhamija p, 2022, scientometrics | Blue |
| Pilloni v, 2018, future internet | Blue | Lampropoulos g, 2022, j softw evol… | Blue |
| Kipper lm, 2020, int j prod res | Blue | Demir s, 2022, emj eng manage j | Blue |
| Vinodh s, 2021, tqm j | Blue | Khan s, 2022, ieee access | Blue |
| Garrido-hidalgo c, 2019, comput ind | Blue | Abdullah fm, 2022, ieee access | Blue |
| Rejikumar g, 2019, benchmarking | Blue | Han h, 2022, technol forecast soc… | Blue |
| Lins t, 2020, comput ind eng | Blue | Cañas h, 2021, comput ind eng | Blue |

Bibliographic coupling is the present (Donthu et al., 2021). It maps the current research front (retrospective analysis – it does not change over time) (Zupic and Čater, 2015). The conceptual structure or research front (Price, 1965) describes the current scientific papers that cite the publications in the dataset. Examining the research front is best suited for the bibliographical coupling technique since this method uses reference lists for coupling and does not require the documents to be cited to connect them (Zupic and Čater, 2015).

Figure 10 represents the bibliographic coupling map. It shows 2 clusters. The blue cluster is the core cluster, focused on I4.0 implementation, cyber-physical systems and smart manufacturing. It is a motor theme with very high impact and high centrality. It has the most attention from academics but is proven to be less specific than the other cluster. The red cluster is gaining momentum with very high centrality in the research field. It is related to the effects of I4.0 on sustainable development and how I4.0 technologies will promote sustainability and sustainable development goals. Academics believe that I4.0 has the potential to unlock a series of practices that will help manufacturing companies achieve their sustainability goals, benefitting their ecosystems and, ultimately, their societies. I4.0, through this targeted scientific research, can unlock sustainable practices vertically and horizontally (Xu et al., 2021).

**Figure 10** Bibliographic coupling map (see online version for colours)




*Source:* Bibliometrix-edited; impact measured by NLCS and centrality measured by the Callon's centrality index)

The top 40 documents that incorporate the 2 clusters best represented in Figure 10 are enumerated in Table 4. According to the present research's findings, these 80 documents and the 80 documents identified co-citation network analysis should be considered in a further systematic literature review for content-centric and thematic analysis.

## *3.4 Trend analysis*

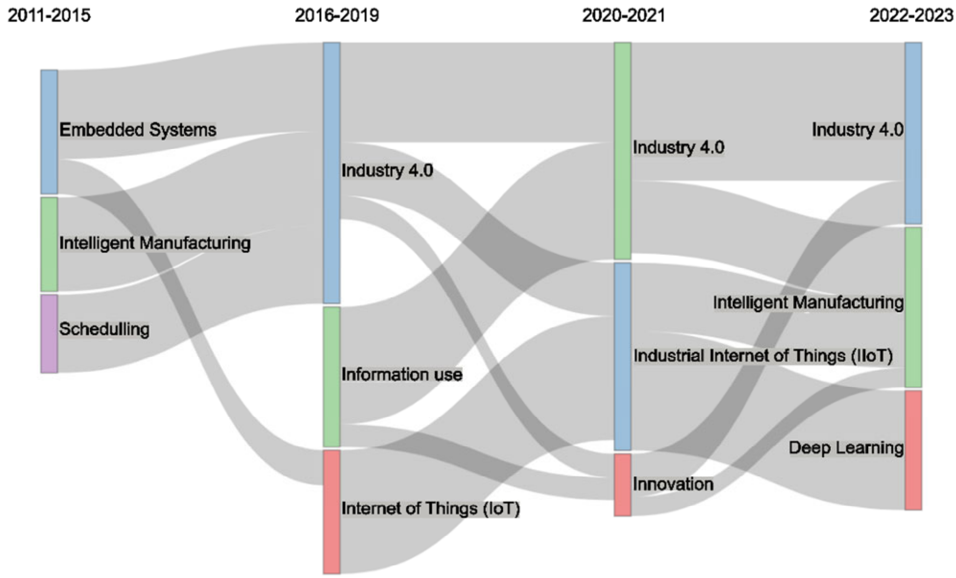
The fourth and last research question intends to unveil the current trends and research gaps in the I4.0 research field. To answer this question, the authors performed a co-occurrence analysis technique. Using the most significant keywords normalised by Porter's stemming algorithm as the unit of analysis, it is possible to analyse the semantic map of the research field. It shows links among subjects in the research field and traces its development.

Figure 11 gives a graphical representation of the thematic evolution over 4 time slices. I4.0 have become a motor theme of the research field after 2016. It has been fed by three themes that emerged in 2011: *Embedded Systems, Intelligent Manufacturing and Scheduling. Embedded Systems* also branched to a new theme named IoT.

An *Information Use* theme also emerged from 2016 until 2019. Most of this theme, coupled with the I4.0 theme, built this last in 2020 and 2021. The *I4.0* theme, on the other hand, branched to other themes*: IIoT* (an evolution of IoT, i.e., the implementation of IoT on the shop floor) *and Innovation*. This last branched in 2022 to the *I4.0* theme and the *Intelligent Manufacturing* theme, which reappeared in this last time slice.

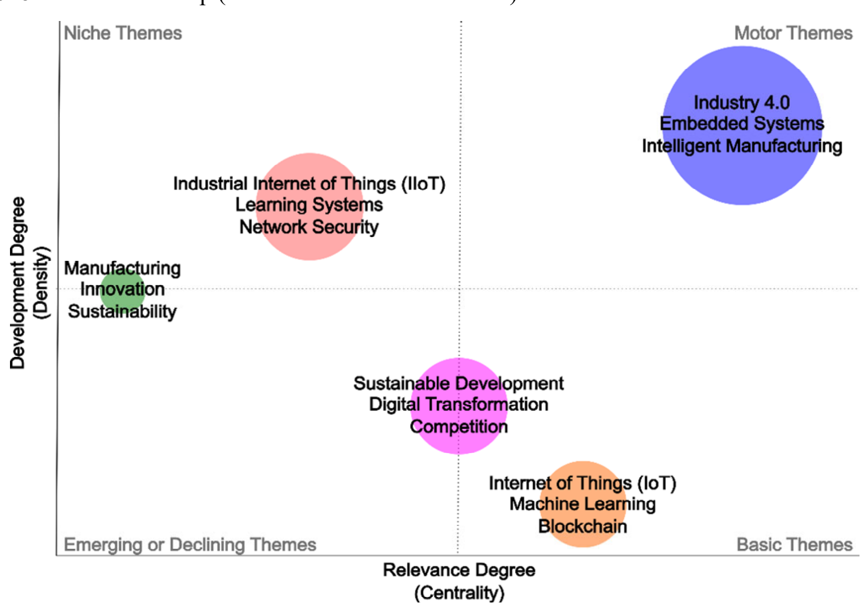
Also, a new theme emerged in 2022, called *deep learning*. An indication that may support the assumption that the research field is starting to mature because this type of analysis needs quality data in enough quantity to be effective. These conclusions end up supporting the following thematic map analysis in Figure 12.

**Figure 11** Thematic evolution of the research field in 4 time slices (see online version for colours)




*Source:* Bibliometrix-edited

**Figure 12** Thematic map (see online version for colours)




*Source:* Bibliometrix-edited

Figure 12 represents the thematic map produced in bibliometrix through the walktrap algorithm. The x-axis measures the cluster centrality (by Callon's Centrality index), while the y-axis measures the cluster impact by MNLCS. The NLCS is calculated by dividing the actual count of local citing items by the expected citation rate for documents with the same year of publication.

The thematic map shows the *I4.0* theme as a motor theme with the highest density and centrality. It also shows the *IoT* theme losing momentum/density but maintaining some traction with high relevance degree. It also identified 2 clusters related to sustainability as emergent themes. One is more focused on *Innovation*, and the other is more focused on *Sustainable Development* as a competitive advantage. It also presented an *IIoT* cluster, centred in learning systems. Despite its large size, which is quite apart from the other themes, therefore, considered a niche theme.

## 4 Conclusions and future research

The purpose of this article was to analyse the I4.0 research field through the lens of bibliometric analysis. This bibliometric review started with a dataset of 19,917 documents and settled on a must-read list of 160 for a future systematic literature review; it is the most significant contribution of the present article.

Through the lens of bibliometric analysis, it is possible for a researcher, without prior knowledge and experience in a specific research topic/theme/field, to identify critical literature and, with confidence, perform a systematic literature review. It is a method in which both the intellectual structure and the research front documents are flagged, generating a pool of must-read documents. One only needs to replicate these steps to acquire the same depth of results in any research topic/theme/field. Besides settling for a significantly reduced must-read documents list, it may help the researcher to identify research themes to which he can contribute with a research project or a PhD thesis and even encounter research gaps where he can explore new research routes. The replicability of the present research, allied with the possibility of adapting it to any research field, is of great value for academics, researchers and students alike.

Regarding the descriptive properties of the research field, it is growing at an accelerated pace with a compound annual growth of 54.44%. Those early documents still significantly impact the research front, accounting for a high degree of average citations per year. Almost ¾ of the authors only published one article. The top 20 most relevant authors have a local H index above 17, which indicates high productivity and relevance. Also, it was clear that the boom in productivity started in 2016 and that publications have been growing exponentially since then. Notably, only 26 publication titles, less than 1% of the sources, are responsible for many produced documents in this research field. It is also worth noting that, despite the early stages of the research field, it is now shifting from conference proceedings to journal articles, as shown in Figure 6. Also, the research field can be considered global, although international contributions are still scarce. Notwithstanding, Germany started to be the most productive country, but it got overtaken by China, which now accounts for almost twice as more publications than Germany. Unsurprisingly, the most frequent author keyword and keywords plus is I4.0, with a massive gap between the other top keywords that relate mainly to I4.0 technologies.

Regarding the intellectual structure of the research field, the co-citation analysis produced 4 distinctive clusters. The most prominent red cluster accounted for a significant number of review documents and focused mainly on implementing and deploying I4.0 technologies. The green cluster is more technology-focused, revolving around the I4.0 top-tier technologies like CPS, IoT, Digital Twin and Big Data and their impact on the future and the industrial business models. The blue cluster focused on the definition of scope and the design principles of the I4.0 paradigm. The smaller yellow cluster focuses on the potential benefits and drawbacks of I4.0 implementation.

The research front of the research field has been identified through bibliographic coupling. It identified 2 clusters. A core cluster focused on I4.0 implementation, CPS and smart manufacturing. This cluster can be considered a motor theme, with very high impact and high centrality. The other cluster is gaining momentum, showing a very high centrality in the research field. It focuses on sustainable development and how the I4.0 technologies can help manufacturing industries achieve sustainability goals.

Both the co-citation network analysis and the bibliographic coupling identified the most relevant documents of the research field, constituting the must-read list for further research efforts.

Also, by the compound analysis of these research findings regarding the intellectual structure and the research front documents' mean publication date, it is evident that they are very close. Therefore, we can affirm that the research field is still in its early stages. It also justifies that 2/3 of authors only contributed with a single document to the field. Therefore, there are expected more contributions to the research field in the upcoming years. It is also worth noting that, despite these early stages, the research field is starting to mature. The research front most contributing sources in 2022 are journals, something that has not yet happened before.

The thematic evolution of the research field was also revealed. Sustainable development is a major identified trend. The sustainability theme is expected to gain greater prominence, with two sub-themes already developed, one linked to innovation and the other to competitiveness.

By analysing the thematic evolution map, there are signs that the research field is maturing at an accelerated pace, and in the near future, more targeted scientific research can be expected. Through this analysis, it can be observed that in the present time, deep learning is a research topic trend. A considerable amount of consolidated data is needed to explore this research route. It is yet an indicator that, despite the early stages of the research field, it is becoming mature enough to nurture these kinds of developments. Also, the theme of sustainable development will be one of the hottest topics, as well as the possible ways of integrating this concept with the fourth industrial revolution paradigm. As gaps, we can indicate the lack of research directed to the role of the human being in the smart factory, as well as new forms of resilience and flexibility that will directly impact the survival of manufacturing organisations, consequently impacting their ecosystem and society in general.

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