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Digital Twin Driven Intelligent Systems and Emerging Metaverse

Springer

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ISBN 978-981-99-0251-4 ISBN 978-981-99-0252-1 (eBook)
https://doi.org/10.1007/978-981-99-0252-1

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

The notion of digital twins represents a new stage in smart system development that has already shown to have a huge impact in recent years. This new topic has been made possible and accelerated by the developments and integration of various technologies such as the Internet of things, sensor technology, artificial intelligence, data science, and machine learning. As a result, a digital replica with rich representations of physical entities can be developed that maintains connectivity with the physical entity and enables living monitoring, control and simulations for intelligent decision-making. Rather than relying on direct observation and on-site manual tasks, digital twins provide remote control of processes based on (near) real-time digital information. This idea of a smart, connected digital replica offers innovative solutions to various problems in a broad range of application domains, including manufacturing, aerospace, smart farming, health care, and the automotive industry. Responsible innovations using digital twins can increase leverage and productivity and help create unprecedented value.

Clearly, the digital twin concept is not just a temporary hype but a long-term trend affecting an increasing number of application areas. The concept can be explained from a rationally sound, historical perspective and is part of the ongoing digital transformation process. However, despite its prevalence and growing popularity, there still seems to be a lack of understanding and consensus on the core concepts and implementation of digital twins in various application domain contexts. New concepts are validated, further developed and accepted through lessons learned from real case studies and experience in the practical context. Yet, while the digital twin concept has been proposed earlier in history, its application in a broader context is relatively new. Moreover, the number of applications reported on digital twins is limited to support further reflection on digital twin concepts and therefore help to learn from recent experience and increase understanding beyond the level of hype. Therefore, we need more insights into the diverse applications of digital twins concepts and reflect on the best practices for effective, responsible innovation. Of course, this is no easy task, given the multidisciplinary and interdisciplinary nature of digital twins. Developing digital twin-based systems requires a holistic systems engineering approach where multiple disciplines and often conflicting stakeholder concerns must be considered.

This book provides a timely and complementary contribution to current knowledge of digital twins, with valuable information on key concepts, concrete applications, and a vision for the future. I invite you to read this book and benefit from the valuable contributions reported in the separate chapters.

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Digital Twin Fundamentals

The Digital Twin Case in the Technological Transformation Process: Research Articles, Academic Collaborations, and Topics

Muhammet Damar and Güzin Özdağoğlu

1 Introduction

Technological developments that drive the world to the fourth industrial revolution create a significant competitive advantage for businesses that can keep up with these developments. Product and service producers who want to exist in this competition feel time pressure in new product development, product life cycles, and decision support processes. As a result of the opportunities provided by the technological transformations experienced, the medium or long-term waiting for the direct implementation of planning and designs and analysis of the results are no longer present. Much faster or rapid prototyping environments replaced these and real-time simulations years ago [2, 12, 16, 32, 44].

The primary source of these developments is the pairing technology that NASA developed and used many years ago. Bedding and mirrored technology create an exact virtual copy of a system, product, production, or service environment with the help of a sensor, artificial intelligence, Internet of things, machine learning, virtual and augmented reality, quantum computing, autonomous programming, and related technologies. It has become possible to create. Even if proposed at the beginning of the 2000s [24], it was 2010 when NASA defined this technology as the "digital twin" for the aeronautic sector [45], and this technology was highlighted as an essential component of the industrial revolution.

Digital twin has been more frequently related to systems engineering and, or specifically, to model-based system engineering. Like a virtual prototype, a digital twin is a dynamic digital representation of an existing system [39]. With the digital

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_1

twin technology, a mirror image of the physical world can be created in the virtual world so that analysis of decision processes, plans, product development, and customer experiences on the system, product, or service can be made instantly. With the advantage of the ability to run much more advanced analysis and optimization models, it is possible to design the most suitable product for the needs of the customer, come up with the best plans, and eliminate unwanted situations as soon as possible [1, 25]. For this purpose, various models have been developed to integrate the Internet of Things and the other technologies that Industry 4.0 has provided [30]. Cloud computing, artificial intelligence, machine learning, big data analytics, and cyber-physical systems are the prominent technologies needed to design digital twins. The most frequent application areas that utilize these technologies are smart manufacturing, automation, quality control, production control, uncertainty and analysis, risk assessment, supply chains, operation and maintenance, real-time monitoring, real-time simulation, product life cycle, control systems, manufacturing process, fault detection, cyber-physical system, product design, machine tools, maintenance, production system, manufacturing industries, additive manufacturing, production process, process control, computer-aided design, and optimization.

Since its launch, the source of the rapid developments in this technology is the positive exponential trend followed by research in this field. In addition to technological developments, widespread effects of the results of these studies, which examine the topic from many different perspectives, are revealed by the publications they present to the literature. In this regard, the purpose of this chapter is to present bibliometric research, including the basic statistics, network relationships, and topic structures of the portfolio of articles in the relevant literature on digital twin technology enhanced with advanced visuals. In this context, related text and network analytics approaches are used along with bibliometrics and scientometrics. The data sources of the analyses are the leading scientific databases Web of Science (WoS) and Scopus and thus the study focuses on research articles published between 2010 and 2021 (June). As a result of the analyses, many output dimensions are obtained, such as authors, co-authorship relationships, journals, citation relations, keyword networks, and prominent topics and publication metrics.

In comparison to other studies, the research design is unique. The research, for example, includes not only the related papers in the WoS or Scopus databases but in both. This study handles these databases and provides findings comparatively. Even though the dimensions, criteria, and analyses are comparable to the previous research, none of them covers most of these dimensions together.

Digital twin technology is an integral part of the fifth industrial revolution [15], where personalized designs, cognitive programming, and collaborative robots are expected to be forefront. In this context, the findings presented reflect the structure of the existing literature on digital twin technology from a holistic perspective and have the qualities to support researchers and practitioners in this field in their research processes and accelerate this process.

2 Related Work

The research paper portfolio, rapidly amassed in the literature within the notion of a digital twin, is summarized using various approaches and serves as a reference for future research on this topic. These studies provide information extraction from different datasets, criteria, details, and dimensions in light of methods such as review, systematic review, and bibliometrics.

Krüger and Borsato [32] implemented the ProKnow-C method on a bibliometric dataset to filter the papers for further analysis and then discussed the recent studies in digital manufacturing and digital twin after presenting the descriptive statistics about the related work. Jones et al. [31] conducted a systematic review to recall the digital twin concept and characterize it over critical processes and terminology, along with knowledge gaps in the broader area. Agostino et al. [2] presented bibliometric research to reveal the application of simulation models in production and logistic systems related to digital twins before introducing their conceptual model. Chinotaikul and Vinayavekhin [16] examined digital transformation as a business research subject. They identified guiding publications and utilized co-word network analysis to reveal the intellectual structure of the selected papers. Kumar et al. [33] evaluated the papers from Scopus to infer key insights such as publishing volume, co-authorship networks, citation analysis, demographic distributions, concept proposals, keywords, affiliations, journals, and funding information. Ciano et al. [17] clarified the importance of digital twin in realizing smart industrial systems by discussing its role in implementing real-time systems, integration of digital twin, and Industry 4.0 technologies. Ante [5] conducted bibliometric research to identify the impact of digital twin on smart manufacturing and Industry 4.0 and applied exploratory factor analyses to categorize the implementation areas. Agnusdei et al. [1] assessed digital twin-oriented engineering and computer science studies to identify research clusters and future trends and discussed the findings from safety issues.

As evidenced by the cited research, as the number of studies centered on the notion of the digital twin grows, publications from other domains, authors, analyses, and models begin to appear in the literature. Another notable feature is that bibliometric or review studies published in the same year focus on various elements of the subject and produce diverse results. In this regard, this chapter puts forth another bibliometric research, including the basic statistics, network relationships, and topic structures of the portfolio of articles in the relevant literature on digital twin technology enhanced with advanced visuals.

3 Methodology

Focusing on the concept and technology of the digital twin, the main objective of this research is to reveal the statistics and patterns regarding authors, co-authorship relationships, collaborations, journals, citations, keyword networks, and prominent topics and publication metrics in the relevant literature. Basic statistics, network relationships, and topic structures of the portfolio of articles are developed with advanced visuals. Thus, the research plan depends on these objectives and the related techniques of bibliometrics and scientometrics. The analyses were set to answer the following outcomes regarding the research on the concept of the digital twin:

- General distribution of the document types by years,
- Number of original articles by years,
- Impact of the articles in the related literature,
- Authors, countries, organizations and institutions, and collaborations among them,
- Journals and most cited articles,
- Thematic structures over author keywords.

In this context, related text and network analytics approaches are used along with bibliometrics and scientometrics methodologies. The study's data sources are the leading scientific databases Web of Science (WoS) and Scopus; the analyses focus on research articles published between 2010 and 2021 (June). We retrieved data based on the query "digital twin*" in a topic search.

3.1 Bibliometrics, Scientometrics, and Related Tools and Techniques

Activities to reveal the basic patterns of a particular subject in the literature, different topics and fields, connection points, and demographic elements are included in bibliometrics, scientometrics, informetrics, and webometrics as the techniques used within these methods. Although there are similarities in the focus, topics, and dimensions within the analysis, there are differences in the focus topics and dimensions within the analyses [8, 19, 28, 51]. Summary statistics on authors, keywords, and citations are provided in scientometric research. Furthermore, relationships such as co-authorship, co-citation, common keywords, and findings of advanced data analysis within the scope of time and clusters can be presented using network and density graphics in addition to summary statistics. Although the content and types of analyses are very similar in all similar methods, differences can be seen in the handling and details. For example, in the analyzes made within the scope of scientometrics, it is seen that the outputs are found in more dimensions [3]. In addition to descriptive statistics, network models and text analytics are employed in analyses [29]. Garfield [22] explained the historical development of scientometrics in detail in a chronological structure.

3.2 Preprocessing and Analysis

Different application environments such as Oracle database, WoS and Scopus analysis tools, Bibliometrix library in R [6], and spreadsheets were used for preprocessing, visualizations, and analysis. Several summary tables were organized to provide descriptive statistics for the selected dimensions. Also, appropriate software was utilized for further analyses, such as VOSviewer, i.e., the software package for analyzing and visualizing large bibliographic datasets. VOSviewer applies its modularity-based clustering similar to the multidimensional scaling based on the smart local moving algorithm [48, 49]. Within the scope of advanced data analysis, integrated network models with clustering analyzes have been developed to reveal the source perspectives of the research area, present the collaborations, thematic structure of keywords, and the journals in which the articles were published. These analyses first segment the raw data set, captured as plain text, using text analytics, create the network image over the metrics used in network analysis, and cluster it based on partnership levels and similarities. The findings were also discussed through the perspectives of fundamental laws of bibliometrics, i.e., Bradford's and Lotka's laws [13, 37].

4 Results and Findings

4.1 Overview of the Studies

The research on digital twin with Industry 4.0 was included in the analysis, as described in the methodology section. First and foremost, regardless of the category, the number of publications and summary visuals is displayed.

WoS databases comprise the following document types and frequencies (f); Articles (f:1,359), Proceedings Papers (f:921), Review Articles (f:123), Early Access (f:103), Editorial Materials (f:81), Book Chapters (f:26), Meeting Abstracts (f:7), News Items (f:5), Books (f:3), Corrections (f:2), Letters (f:2), Data Papers (f:1), respectively. In comparison to WoS, Scopus has a broader portfolio, i.e., Conference Paper (f:2266), Article (f:1757), Review (f:152), Conference Review (f:144), Book Chapter (f:141), Note (f:24), Editorial (f:21), Short Survey (f:13), Book (f:6), Erratum (f:2), Letter (f:2), Business Article (f:1), Data Paper (f:1), respectively.

There has been an upward tendency in recent years when we evaluate the impact of this article portfolio in WoS as evidenced by citation-based metrics such as Citing Articles (5091), Citing Articles Without self-citations (4352), Times Cited (10,028), Times Cited Without Self-Citations (6363), Average Citation Per Item (*ACP*) (7.38), *H*-Index (43). When we evaluate the impact of this article portfolio in Scopus as evidenced by citation-based metrics such as Times Cited (16,763), *ACP* (9.54), and *H*-Index (58), at this stage, we can speak of a significant effect in a relatively short timeframe, such as 2010–2021. This condition can be explained by exemplary studies

Table 1 Article counts by years

Years	Scopus		Web of Science	
	N	% in 1757 articles	*N*	% in 1359 articles
2021	762	43.36	537	39.51
2020	622	35.40	526	38.70
2019	256	14.57	206	15.15
2018	69	3.92	62	4.56
2017	41	2.33	24	1.76
2016	3	0.17	1	0.07
2015	2	0.11	2	0.14
2014	1	0.05	1	0.07
2013	0	0	0	0
2012	0	0	0	0
2011	1	0.05	0	0
2010	0	0	0	0

conducted by key industry sectors, research and development institutions, and, of course, academicians.

Further analyses are presented to see the field's detailed research patterns, focusing on the research articles created within the context of this topic after giving a broad overview of the number of publications (Table 1).

In keeping with the general profile, annual changes in the number of research articles within the selected period demonstrate an increasing trend, as seen in Table 1. As a result of this pattern, approximately, 79% of the chosen portfolio dates from the last two years. With new research in the coming months, this rate is expected to reach at least 80% by the end of the year. Preliminary studies on innovations and current issues in the scientific field are usually presented and discussed as proceedings or conference papers in symposiums, conferences, and similar scientific meetings. As a result, the number of articles published in proceeding books can also provide antecedent clues about the level of interest in a given subject and field. The statistics show a similar trend in the digital twin, reflected in conference papers in the same direction. From this vantage point, it is reasonable to expect this trend to continue to rise in the following years with positive momentum.

Another intriguing conclusion is that before 2017, just a few studies were included in the chosen portfolio. Although the literature review claims that the concept of a digital twin has been introduced and discussed since the early 2000s and that the idea of a digital twin has gained even more importance and interest since the announcement of the fourth industrial revolution in 2010, the dissemination of relevant research has accelerated when the required technology has become available.

4.2 Authors

The top 25 authors in both WoS and Scopus are given in Table 2 regarding the number of articles published (*N*) along with the total number of citations (*C*), *ACP*, and the percentage of the article count in the selected portfolio.

Generally, 4644 authors picked from WoS databases produced 1359 publications in the publication portfolio. While there are scholars dedicated to this topic, there are also those who have recently developed an interest in it or have published only a few papers on it as part of broader studies. The number of authors who publish ten or more publications within the context of the digital twin concept, for example, is ten. These leading authors, regarding the number of articles published, can be listed as Liu Q. (*f*:14; *C*:526; *ACP*:37.57); Soderberg R. (*f*:14; *C*:243; *ACP*:17.36), Tao F. (*f*:14; *C*:1,695; *ACP*:121.07), Leng J.W. (*f*:12; *C*:514; *ACP*:42.83), Warmefjord K. (*f*:12; *C*:190; *ACP* 15.83), Zhang H. (*f*:12; *C*:913; *ACP*:76.08), Zhang Y. (*f*:12; *C*:30; *ACP*:2.50), Chen X. (*f*:11; *C*:448; *ACP*:40.73), Li J. (*f*:10; *C*:86; *ACP*:8.60), Park K.T. (*f*:10; *C*:94; *ACP*:9.40), respectively. 59 researchers are observed in the list when the threshold is lowered to five.

1757 articles from the Scopus database yielded a total of 5727 authors. The number of writers with five or more publications is 154, which appears to be greater than WoS when adjusted by article count. In parallel with WoS, ten authors create ten or more articles. The WoS database has a higher proportion of authorial records than the other one on this level. Top ten authors regarding article counts are Tao, F. (*f*:31; *C*:3092; *ACP*:99.74), Qi, Q. (*f*:16; *C*:2128; *ACP*:133.00), Liu, J. (*f*:14; *C*:519; *ACP*:37.07), Liu, X. (*f*:13; *C*:264; *ACP*:20.30), Cheng, J. (*f*:11; *C*:1334; *ACP*:121.27), Leng, J. (*f*:11; *C*:629; *ACP*:57.18), Liu, Q. (*f*:11; *C*:768; *ACP*:69.81), Zhang, M. (*f*:11; *C*:2002; *ACP*:182.0), Zhuang, C. (*f*:11; *C*:358; *ACP*:32.54), Qu, T. (*f*:10; *C*:168; *ACP*:16.80), respectively.

It is also striking that the WoS and Scopus databases contain a significant difference between the top ten author lists, which have the intersection set in terms of the journals they host.

Lotka's law is one of the laws proposed in bibliometrics. It refers to the frequency with which authors in a given field publish. It shows that "*y* authors contributing *x* articles in a given period is a fraction of the number contributing a single article, based on the formula $x^n y$, where *n* nearly always equals two, i.e., an approximate inverse-square law, where the number of authors publishing a certain number of articles is a fixed ratio to the number of authors publishing a single article" [37: 323].

Lotka's law attempted to forecast the scientific productivity process to determine what contributions authors who wrote in a particular subject made to the literature and how their articles were quantitatively distributed in that field's literature [52: 62]. A Pareto-like distribution emerges when the number of contributions is plotted according to the number of authors [9: 23]. It is possible to assess the author's productivity status in the specified portfolio using the Bibliometrix library, available in the R coding environment. The findings of the analyses performed in this context are shown in Table 3.

Table 2 Top 25 authors according to the number of publications

Rank	Scopus					Web of Science				
	Authors	*N*	*C*	*ACP*	% in 1757 articles	Authors	*N*	*C*	*ACP*	% in 1359 articles
1	Tao, F.	31	3092	99.74	1.76	Liu, Q.	14	526	37.57	1.03
2	Qi, Q.	16	2128	133.00	0.91	Soderberg, R.	14	243	17.36	1.03
3	Liu, J.	14	519	37.07	0.79	Tao, F.	14	1695	121.07	1.03
4	Liu, X.	13	264	20.30	0.73	Leng, J. W.	12	514	42.83	0.88
5	Cheng, J.	11	1334	121.27	0.62	Warmefjord, K.	12	190	15.83	0.88
6	Leng, J.	11	629	57.18	0.62	Zhang, H.	12	913	76.08	0.88
7	Liu, Q.	11	768	69.81	0.62	Zhang, Y.	12	30	2.50	0.88
8	Zhang, M.	11	2002	182.00	0.62	Chen, X.	11	448	40.73	0.80
9	Zhuang, C.	11	358	32.54	0.62	Li, J.	10	86	8.60	0.73
10	Qu, T.	10	168	16.80	0.56	Park, K. T.	10	94	9.40	0.73
11	Hu, T.	9	473	52.55	0.51	Noh, S. D.	9	69	7.67	0.66
12	Liu, Z.	9	196	21.77	0.51	Zhang, M.	9	1004	111.56	0.66
13	Lu, Y.	9	422	46.88	0.51	Lu, Y. Q.	8	183	22.88	0.58
14	Park, K. T.	9	274	30.44	0.51	Rosen, R.	8	3	0.38	0.58
15	Söderberg, R.	9	285	31.66	0.51	Xu, X.	8	281	35.13	0.58
16	Wärmefjord, K.	9	285	31.66	0.51	Zhang, D.	8	321	40.13	0.58
17	Zhang, D.	9	444	49.33	0.51	Zhang, K.	8	23	2.88	0.58
18	Zhang, Y.	9	19	2.11	0.51	Chen, C. H.	7	163	23.29	0.51
19	Chen, X.	8	576	72.00	0.45	Lindkvist, L.	7	175	25.00	0.51
20	Noh, S. D.	8	105	13.12	0.45	Strube, J.	7	17	2.43	0.51

(continued)

Table 2 (continued)

Rank	Scopus					Web of Science				
	Authors	*N*	*C*	*ACP*	% in 1757 articles	Authors	*N*	*C*	*ACP*	% in 1359 articles
21	Stark, R.	8	109	13.62	0.45	Tan J. R.	7	25	3.57	0.51
22	Strube, J.	8	20	2.50	0.45	Zhang, C.	7	82	11.71	0.51
23	Xu, X.	8	382	47.75	0.45	Zheng, P.	7	175	25.00	0.51
24	Zhang, H.	8	1317	164.62	0.45	Huang, G. Q.	7	26	3.71	0.51
25	Bao, J.	7	101	14.42	0.39	Qu, T.	7	15	2.14	0.51

Table 3 Author productivity through Lotka's law

No. of articles	Scopus		Web of Science	
	No. of authors	Proportion of authors	No. of authors	Proportion of authors
1	3972	0.855	4358	0.832
2	439	0.095	506	0.097
3	123	0.026	141	0.027
4	50	0.011	79	0.015
5	22	0.005	43	0.008
6	12	0.003	21	0.004
7	9	0.002	25	0.005
8	5	0.001	16	0.003
9	2	0.000	8	0.002
10	2	0.000	5	0.001
11	1	0.000	5	0.001
12	4	0.001	1	0.000
13	0	0.000	6	0.001
14	3	0.001	3	0.001
15	0	0.000	4	0.001
16	0	0.000	1	0.000
17	0	0.000	4	0.001
18	0	0.000	2	0.000
19	0	0.000	2	0.000
20	0	0.000	1	0.000

When the WoS and Scopus data in Table 3 are evaluated, the number of researchers writing an article in the field is between 80 and 85% of the total researchers, while the number of researchers producing two documents in the area is between 9.5 and 9.7% and the number of researchers producing three articles is between 2.6 and 2.7%. When these results are evaluated together with the increasing trend in publications and citations, the digital twin is a current and open subject that has attracted significant attention from many authors in various fields.

A co-authorship network was developed to reveal the collaborations at the author level, as depicted in Fig. 1. The related clustering analysis was conducted in VOSviewer with the help of its original algorithm. The primary use parameter for co-authorship networks is the minimum number of documents as a threshold to appear on the network; therefore, two articles for WoS and four articles in Scopus were used by considering the total number of articles in each portfolio. In Fig. 1, the most productive authors in terms of the number of articles published seem to be the centroids of the corresponding clusters; moreover, the author groups in high collaboration are indicated in different colors.

Fig. 1 Co-authorships analysis by authors-based Web of Science and Scopus data countries

The article portfolio from WoS and Scopus databases has 72 different countries at its address. Although there are slight differences in the rankings, the top five countries are China, Germany, the USA, the UK, and Italy in both databases. These five countries remain dominant in half of the portfolio (Table 4). Countries in the top ten by the number of publications in Scopus are China (f:2,040), Germany (f:845), USA (f:628), UK (f:422), Italy (f:327), Spain (f:241), South Korea (f:239), France (f:189), Australia (f:112), Sweden (f:109), whereas in WoS, China (f:674), Germany (f:372), USA (f:363), UK (f:223), Italy (f:151), South Korea (f:120), France (f:109), Russia (f:109), Spain (f:102), Sweden (f:82), respectively. China is the leading country having 25% of the portfolio. Table 4 exhibits more countries in the top list to emphasize the other leading countries and the position of Turkey in this portfolio.

Table 4 Distribution of article counts by countries

Rank	Scopus				Web of Science			
	Countries/regions	*N*	*C*	% in 1757 articles	Countries/regions	*N*	*C*	% in 1359 articles
1	China	441	1982	25.09	China	290	3579	21.33
2	Germany	255	352	14.51	USA	204	1123	15.01
3	USA	210	265	11.95	Germany	192	1083	14.12
4	UK	144	439	8.19	UK	116	491	8.53
5	Italy	100	394	5.69	Italy	88	448	6.47
6	Russia	96	154	5.46	France	65	122	4.78
7	South Korea	68	145	3.87	South Korea	64	221	4.70
8	Spain	68	108	3.87	Spain	63	193	4.63
9	France	66	57	3.75	Sweden	50	294	3.67
10	Sweden	42	185	2.39	Russia	49	27	3.60
11	Hong Kong	40	34	2.27	Australia	37	242	2.72
12	Australia	39	143	2.21	India	36	86	2.64
13	India	35	53	1.99	Switzerland	35	47	2.57
14	Switzerland	35	53	1.99	Singapore	33	274	2.42
15	Norway	34	121	1.93	Netherlands	32	125	2.35
16	Singapore	32	94	1.82	Norway	32	123	2.35
17	Canada	31	13	1.76	Denmark	29	137	2.13
18	Denmark	28	62	1.59	Finland	28	112	2.06
19	Finland	28	24	1.59	Canada	27	222	1.98
20	Netherlands	28	42	1.59	Austria	22	48	1.61
21	Austria	26	66	1.47	Belgium	22	33	1.61
22	Belgium	22	9	1.25	Brazil	22	76	1.61
23	Greece	21	56	1.19	Greece	21	94	1.54
24	Poland	21	26	1.19	Poland	18	52	1.32
25	Japan	18	30	1.02	New Zealand	17	174	1.25
41	Turkey	6	5	0.34	Serbia	6	1	0.44
42					Turkey	6	6	0.44

Since more than one author mainly produces the articles, cross-country collaborations are worth examining within the scope of international partnerships. The country-based collaboration map and network in Fig. 2 were created due to the analyses carried out with the help of the Bibliometrix library in R. Figure 2 is consistent with Table 4 regarding the leading countries such that those countries constitute the cores of the clusters in the network. They also have most of the incoming flows in the collaboration map (Scopus). This map was developed using only the bibliometric data Scopus provided since the visualizations in WoS and Scopus are too close to each other. Presenting both of them might result in redundant figures in the text.

China, Hungary, Norway, Australia, Singapore, Canada, New Zealand, and Saudi Arabia are the highly collaborating countries in the red cluster around China. In the blue cluster, the UK and the USA are in the center of the clusters. Still, the USA has a more significant portfolio in the field where Korea, Sweden, Italy, Finland, Spain, Denmark, Belgium, Luxemburg, Thailand, Ireland, Estonia, United Arab Emirates, India, Cyprus, Greece, Switzerland, South Africa, and Pakistan are placed around these countries. The last and green cluster hosts Portugal, Czech Republic, Slovakia, Brazil, France, Austria, Romania, Germany, Netherlands, and Japan location Germany in the center. The numerous interactions of cluster centers should not be overlooked and considered when evaluating collaboration between more than two countries in detail.

Incorporating organizations and countries into the purview of bibliometric analysis yield valuable sub-dimension data. As a result, institutions to whom academics

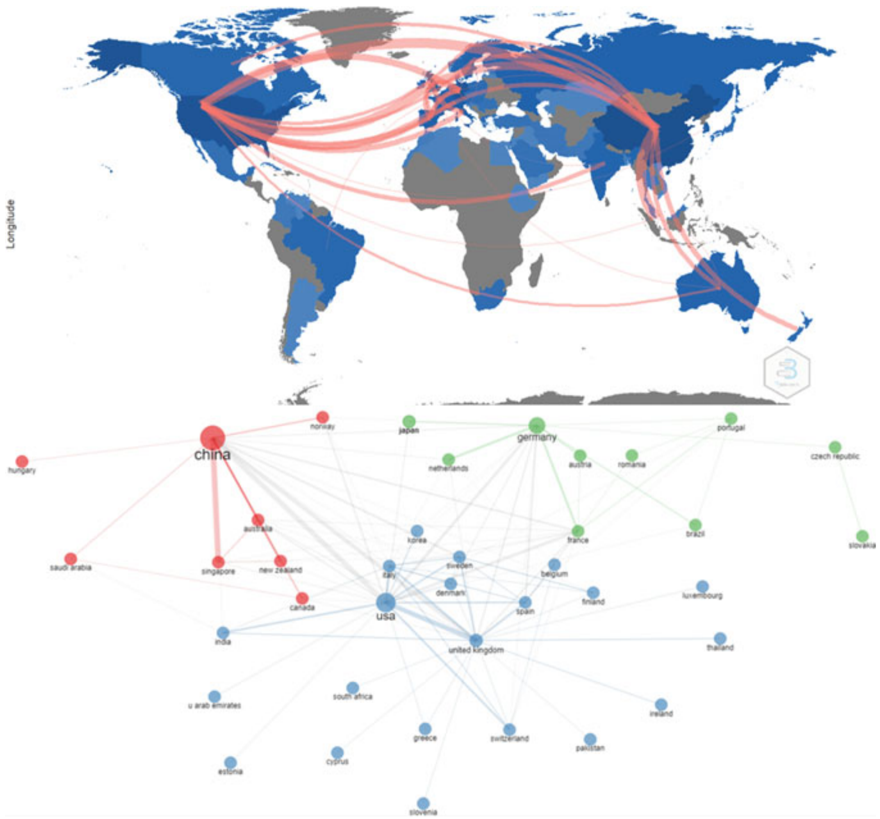

Fig. 2 Country-based collaboration map (minimum four edges) and collaboration network institutions and organizations

who desire to advance in this discipline can turn or examine collaboration options are offered. In this regard, gathering the information for institutions and organizations in WoS and Scopus regarding the digital twin concept, it is clear that German institutions stand out among those that provide a research environment for producing articles in both databases (Table 5 and Fig. 3). Rheinisch-Westfälische Technische Hochschule Aachen, Siemens AG, Universität Stuttgart, Technical University of Munich, Technische Universität Darmstadt, Friedrich-Alexander-Universität Erlangen-Nuremberg are some of Germany's most prestigious institutions. Furthermore, as illustrated in Fig. 2, European institutions have begun to collaborate more globally.

The other confronting institutions listed in Table 5 are China (Beihang University, Shanghai University, Shanghai Key Laboratory of Intelligent Manufacturing and Robotics), the UK (University of Cambridge, Cranfield University, The University of Sheffield), Russia (Peter the Great St. Petersburg Polytechnic University Russia, Saint Petersburg National Research University of Information Technologies, Mechanics and Optics University), in Italy (Politecnico di Milano, Politecnico di Torino), Norway (Norwegian University of Science Technology, DNV GL—Det Norske Veritas and Germanischer Lloyd—AS). It also stands out in digital twin scientific production with Finland, France, Hong Kong, Singapore, Greece, Sweden, Hungary, and New Zealand institutions.

Another notable discovery in Fig. 3 is that, while institution-level collaborations in Europe emerged as small clusters of two or three, more substantial and multiple links have been developed in clusters in the Far East, with locations like Hong Kong and China at the center.

4.3 Sources and Top Articles

The journals that distinguish out in bibliometrics research, as well as the articles published in these journals, are crucial in the analysis dimensions. Bradford's law is one of the first things that comes to mind at this point. Bradford's law defines how publications on a given topic are distributed. It is concerned with the submission of works to journals. Separation can be realized in core and other journals if scientific publications are managed according to this Law [13, 14]. According to Bradford, most publications on a given subject are published in a few journals devoted particularly to that topic or the main topic of which it is a part, and these journals constitute the field's core journals [13]. Doan (2019) emphasized this fact, stating that when a bibliography on a specific subject is sought, a small core set of journals will always contain a significant share (1/3) of the papers published in that subject or discipline. Therefore, sources can be categorized concerning Bradford's law, resulting in distinct zones. This law can also be adopted for managing and budgeting library resources, managing publications in order of priority and resource allocation, and deciding which journal databases to join on a field basis.

The statistics gathered at this level of the investigation are presented in three tables. Table 6 lists the journals that have published the most articles on digital twin,

Table 5 Distribution of article counts by institutions and organizations

Rank	Scopus				Web of Science			
	Institutions and organizations	Country	*N*	% in 1757 articles	Institutions and organizations	Country	*N*	% in 1359 articles
1	Rheinisch-Westfälische Technische Hochschule Aachen	Germany	50	2.84	Beihang University	China	29	2.13
2	Siemens AG	Germany	43	2.44	Centre National De La Recherche Scientifique	France	27	1.98
3	Peter the Great St. Petersburg Polytechnic University	Russia	40	2.27	University of Cambridge	UK	22	1.61
4	South Ural State University	Russia	31	1.76	Polytechnic University of Milan	Italy	20	1.47
5	Universität Stuttgart	Germany	30	1.70	Siemens AG	Germany	19	1.39
6	Technical University of Munich	Germany	27	1.53	Chalmers University of Technology	Sweden	18	1.32
7	Technische Universität Darmstadt	Germany	22	1.25	Helmholtz Association	Germany	18	1.32
8	The Saint Petersburg National Research University of Information Technologies, Mechanics and Optics University	Russia	20	1.13	Norwegian University of Science Technology	Norway	18	1.32
9	Chalmers University of Technology	Sweden	18	1.02	University of Hong Kong	Hong Kong	18	1.32
10	Norwegian University of Science Technology	Norway	18	1.02	National University of Singapore	Singapur	16	1.17
11	Politecnico di Milano	Italy	18	1.02	Siemens Germany	Germany	16	1.17

(continued)

Table 5 (continued)

Rank	Scopus				Web of Science			
	Institutions and organizations	Country	*N*	% in 1757 articles	Institutions and organizations	Country	*N*	% in 1359 articles
12	Budapest University of Technology and Economics	Hungary	17	0.96	University of Michigan	USA	16	1.17
13	Friedrich-Alexander-Universität Erlangen-Nürnberg	Germany	16	0.91	University of Michigan System	USA	16	1.17
14	University of Cambridge	UK	16	0.91	Guangdong University of Technology	China	15	1.10
15	Beihang University	China	15	0.85	US Department of Energy Doe	USA	15	1.10
16	Panepistimion Patron	Greece	15	0.85	University of Auckland	New Zealand	15	1.10
17	Aalto University	Finland	15	0.85	Beijing Institute of Technology	China	14	1.03
18	Cranfield University	UK	14	0.79	Northwestern Polytechnical University	China	14	1.03
19	Centre National de la Recherche Scientifique	France	13	0.73	Russian Academy of Sciences	Russia	14	1.03
20	Politecnico di Torino	Italy	13	0.73	Rwth Aachen University	Germany	14	1.03
21	Shanghai University	China	13	0.73	Sungkyunkwan University	South Korea	14	1.03

(continued)

Table 5 (continued)

Rank	Scopus				Web of Science			
	Institutions and organizations	Country	*N*	% in 1757 articles	Institutions and organizations	Country	*N*	% in 1359 articles
22	DNV GL (Det Norske Veritas and Germanischer Lloyd) AS	Norway	13	0.73	Cranfield University	UK	13	0.95
23	Shanghai Key Laboratory of Intelligent Manufacturing and Robotics	China	13	0.73	Fraunhofer Gesellschaft	Germany	13	0.95
24	The University of Sheffield	UK	12	0.68	Hong Kong Polytechnic University	Hong Kong	13	0.95
25	The University of Auckland	New Zealand	12	0.68	Jinan University	China	13	0.95

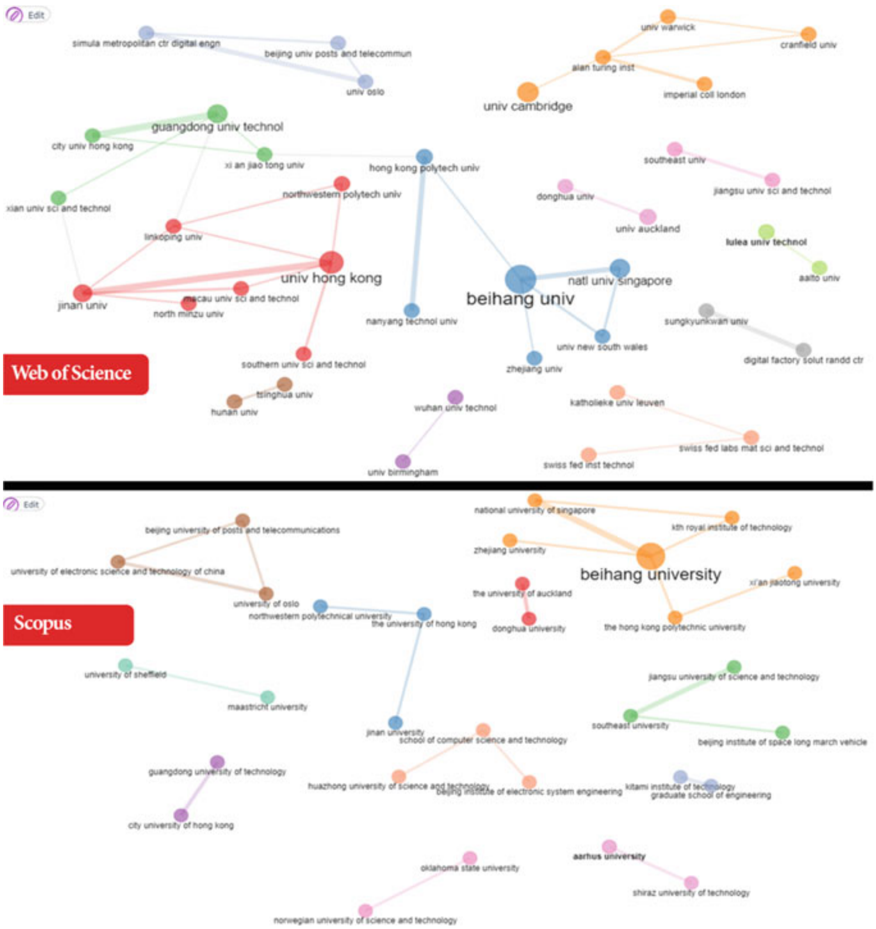

Fig. 3 Institutions and organizations-based collaboration networks

while Tables 7 and 8 list the top articles published in these journals as well as the most cited, or in other words, the top publications with the most significant influence in this subject. The journals were classified into different zones as a consequence of additional analyses of journal data within the scope of Bradford's law. It was observed that the portfolio of articles was published in 539 different journals in WoS and 691 in Scopus.

According to Bradford's law, 457 articles in Zone 1, home to 14 journals, account for 26% of the portfolio. WoS indexed journals in Zone 1 are IEEE Access (f:65), Applied Sciences-Basel (f:60), Journal of Manufacturing Systems (f:45), International Journal of Advanced Manufacturing Technology (f:40), Sensors (f:39), Sustainability (f:32), International Journal of Computer Integrated Manufacturing

Table 6 Top 25 journals in Scopus and WoS

Rank	Scopus			Web of Science		
	Publication titles	*N*	% in 1757 articles	Publication titles	*N*	% in 1359 articles
1	Jisuanji Jicheng Zhizao Xitong Computer Integrated Manufacturing Systems	74	4.21	IEEE Access	65	4.78
2	Applied Sciences Switzerland	64	3.64	Applied Sciences Basel	60	4.41
3	IEEE Access	57	3.24	Journal of Manufacturing Systems	45	3.31
4	Journal of Manufacturing Systems	54	3.07	International Journal of Advanced Manufacturing Technology	39	2.87
5	ZWF Zeitschrift Fuer Wirtschaftlichen Fabrikbetrieb	38	2.16	Sensors	39	2.87
6	International Journal of Advanced Manufacturing Technology	35	1.99	Sustainability	32	2.35
7	Sustainability Switzerland	30	1.70	International Journal of Computer Integrated Manufacturing	26	1.91
8	International Journal of Computer Integrated Manufacturing	28	1.59	International Journal of Production Research	26	1.91
9	Sensors Switzerland	27	1.53	Robotics And Computer Integrated Manufacturing	23	1.69
10	IEEE Transactions on Industrial Informatics	23	1.30	CIRP Annals Manufacturing Technology	22	1.61
11	Robotics And Computer Integrated Manufacturing	23	1.30	Ercim News	21	1.54
12	Energies	20	1.13	Energies	20	1.47

(continued)

Table 6 (continued)

Rank	Scopus			Web of Science		
	Publication titles	*N*	% in 1757 articles	Publication titles	*N*	% in 1359 articles
13	International Journal of Production Research	20	1.13	Processes	20	1.47
14	Processes	18	1.02	Journal of Cleaner Production	17	1.25
15	CIRP Annals	17	0.96	ATP Magazine	16	1.17
16	Journal of Computing and Information Science In Engineering	16	0.91	Journal of Computing And Information Science in Engineering	15	1.10
17	Sensors	14	0.79	IEEE Transactions on Industrial Informatics	14	1.03
18	Advances In Biochemical Engineering Biotechnology	13	0.73	Journal of Intelligent Manufacturing	14	1.03
19	IEEE Internet Computing	13	0.73	Automation in Construction	12	0.88
20	Journal of Cleaner Production	13	0.73	Advances in Computers	10	0.73
21	Automation In Construction	12	0.68	Digital Twin Paradigm for Smarter Systems and Environments The Industry Use Cases	10	0.73
22	IEEE Internet of Things Journal	12	0.68	Journal of Management in Engineering	10	0.73
23	Journal of Intelligent Manufacturing	11	0.62	Engineering Fracture Mechanics	9	0.66
24	Russian Engineering Research	11	0.62	Journal of Ambient Intelligence and Humanized Computing	9	0.66
25	Journal of Management in Engineering	10	0.56	Advances in Civil Engineering	8	0.58

Table 7 Most cited articles in Scopus

Rank	Title	Journal	Authors	Year	*C*
1	Digital twin-driven product design, manufacturing, and service with big data	International Journal of Advanced Manufacturing Technology	Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F.	2018	746
2	Shaping the digital twin for design and production engineering	CIRP Annals—Manufacturing Technology	Schleich, B., Anwer, N., Mathieu, L., Wartzack, S.	2017	406
3	Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison	IEEE Access	Qi, Q., Tao, F.	2018	377
4	A Review of the Roles of Digital Twin in CPS-based Production Systems	Procedia Manufacturing	Negri, E., Fumagalli, L., Macchi, M.	2017	372
5	Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing	IEEE Access	Tao, F., Zhang, M.	2017	351
6	Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case	Transportation Research Part E: Logistics and Transportation Review	Ivanov, D.	2020	348
7	Reengineering aircraft structural life prediction using a digital twin	International Journal of Aerospace Engineering	Tuegel, E. J., Ingraffea, A. R., Eason, T. G., Spottswood, S. M.	2011	338
8	Digital Twin in Industry: State-of-the-Art	IEEE Transactions on Industrial Informatics	Tao, F., Zhang, H., Liu, A., Nee, A. Y. C.	2019	281
9	C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems	IEEE Access	Alam, K. M., El Saddik, A.	2017	261
10	Toward a Digital Twin for real-time geometry assurance in individualized production	CIRP Annals—Manufacturing Technology	Soderberg, R., Warmefjord, K., Carlson, J. S., Lindkvist, L.	2017	214

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