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Research Status and Trend of Digital Twin: Visual Knowledge Mapping Analysis

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Abstract

Digital twins are one of the promising digital technologies used to facilitate digital transformation. Therefore, it needs to continually be developed remain relevant in industry and academia. Consolidation of research is required to create a common understanding of the topic and to ensure that future research is built upon a solid foundation. Based on a bibliometric review and a thematic analysis of 217 publications on digital twins from the past two decades, this paper creates and analyzes a visual knowledge map and proposes areas for further research. To comprehensively analyze the development trends and research trends of digital twins, we performed statistical analysis of the relevant literature on digital twins within the core collection database of Web of Science. Through our research, we have shown that the current situation, trends, and hotspots of digital twin research were analyzed via CiteSpace. This study demonstrates that research on digital twins is rapidly growing in popularity, that the output of the research depends largely on the core group of authors conducting it, and that digital twins warrant cross-domain and cross-disciplinary research pathways.

Keywords: *Digital Twin, Bibliometrics, Web of Science, CiteSpace, Visual Knowledge Mapping*

1. Introduction

Digital twin technology is a rapidly emerging digital technology. It supports digital transformation by replicating and simulating new business models and decision support systems [1]. Many organizations have turned to commoditizing data, information, and analyses as part of their service offerings, and with the emergence of new information and communication technologies, major research and development activities have been conducted in emerging technology fields, such as Industry 4.0, Internet of Things (IoT), big data, cloud computing, block chain and artificial intelligence [2-8]. The internationally renowned IT consulting company Gartner has also listed digital twin technology as one of the top ten strategic technology trends in the "Emerging Technology Hype Cycle" report in the past two years, and predicted that digital twins would serve

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billions of people in 2020 [9-10]. Digital twin technology is used as a to enable technology and develop the concept of intelligent equipment. It can help engineer solutions for the problem of virtual and physical integration of intelligent equipment and systems [11]. The concept of the digital twin originated in the field of engineering and manufacturing. As one of the leading countries in the development of information technology, the United States of America adopted the concept of "twin" as early as 1969 in NASA's Apollo project, which produced a pair of identical spacecrafts [12].

In the past few years, academic and industrial interest in digital twins has greatly in-creased, which in turn has increased the number of related publications, processes, concepts, and expected benefits. Digital twins are increasingly being explored as a means to improve the performance of physical entities through the use of computing technologies, which have themselves been enabled by their virtual counterparts [13]. With the rapid development of Internet of Things technology, artificial intelligence technology, and virtual reality underway, the scope of application of digital twins has gradually expanded to include multiple concepts and models, such as manufacturing and services, in the entire product cycle [14]. Digital twin technology holds the advantage of having a wide range of applications; it can be applied in multiple stages of design, manufacturing, and service [15]. Under the large-scale attack of the COVID-19 pandemic, many domains such as education, transportation and entertainment have been strongly affected; the call for urban intelligence and service digitization has only increased [16].

Many in-depth studies and detailed examinations involving real world cases have already been conducted [17-18]. This paper focuses on the analysis of case studies in the field of digital twins and aims to investigate the academic contributions related to the digital twin. Scientific bibliometrics can reveal an overview of the development of a field or subject and theme from the macro, meso, and micro levels, which can subsequently allow us to comprehensively examine the structure, research hotspots, and key points of the subject from all angles [19]. This paper employed the bibliometric method to visually analyze case studies on digital twin technology that had been mapped using CiteSpace and explored the trend of research in this field through the number of papers. Then it explored the current status of the case studies and their relevant domains through the type of literature and the distribution of the research direction; and the co-occurrence network between research authors, institutions and countries using visualized knowledge graphs, analysis and research co-operation in the field. Finally, the knowledge evolution and hot trends of the case studies were analyzed by examining the co-citation and keyword co-occurrence network.

2. Related Works

2.1 The Digital Twin

As a result of digital transformation, many aspects of the industrial manufacturing processes are facing changes. The digital twin is "one of the main enablers for digital transformation" [20]. The concept of digital twins is still in its infancy. What a digital twin is and what it should do varies depending on the industry viewpoint. It originated from Michael Grieves' presentation on product lifecycle management based on his work with John Vickers [21]. The motivation for the development of this concept was wanting to transform paper-based and manually processed product data into a digital model of the product, which could become the basis of life-cycle management [22]. In the past two decades, many industries have become increasingly interested in digital twins, which has led to various definitions and characteristics, which this paper attempts to consolidate.

2.2 The Societal Digital Twin

2.2.1 Digital Twin For a Smart City

In the field of urban analysis, more and more discussions related to urban digital twins are being held, with examples of existing projects in Rotterdam [23], Singapore [24] and Rio de Janeiro [25]. These systems provide real-time information access to the city—such as traffic volume on the road network, local temperature and air quality information, public transportation utilization and will eventually be developed in the direction of providing a complete digital implementation of the physical.

Due to the complexity of a city, developing a smart city is a complicated process [26]. Its concept has evolved from controlling the material growth of the city to a network comprising material, social and knowledge infrastructures [27-28]. However, although the city expressed by the 3D model provides a virtual representation of its physical elements, other uses of the 3D city model have been developed [29]. A smart city can be viewed through the lens of three components: technical, human, and institutional, within which exist the major areas of transport, environment, energy, healthcare, security, and education [30].

2.2.2 The Digital Twin for and of Humans

It is important to consider the human perspective in exploring the potential of digital twins. A common understanding that transcends disciplinary boundaries will become increasingly important if effective cooperation is to succeed [31-32]. For example, the conceptual Metaverse can create virtual experiences for humans in the physical world [33]. Digital twins also add structure and meaning to large amounts of data and combine various data in experimental scenarios to facilitate human creativity [32]. In order to obtain real-time information, work activities performed by a human must be recorded and historical data be compared with real-time data. Information describing human characteristics, abilities, and activities must be put into a form that digital twins can use. Therefore, there is a need for ideas on how to achieve this goal.

3. Method

3.1 Data Sources

The Web of Science (WOS) core collection database is the world's largest comprehensive academic information resource library covering the most disciplines. It is an information retrieval platform developed by Thomson Reuters, and includes databases such as SCIE, SSCI and A&HCI [34]. It contains more than 12,000 world-authoritative and high-impact academic journals in various research fields such as natural sciences, engineering technology, and biomedicine. WOS keeps a detailed record of all aspects of the publication of a paper. Many scholars and researchers use the WOS database as a data source and for literature analysis of bibliometrics [19, 35]. The input data for this study was collected using a combination of the research results from the multiple topic search queries into the WOS. The filters we used were: “article” for document type, “search” for retrieval method, and “English” for language; additionally, we used the following search formula: TS= (digital twin) AND TS= (case study) from 2000 to 2021. A total of 217 articles were retrieved, and the retrieval results were saved and output in text format. Then a search within the retrieved documents was performed to extract the authors’ names, organization, keywords, abstract, date, and other information. These search results were also saved and output in text format.

All bibliographic information was downloaded and saved as plain text files for subsequent data processing and analysis. Then the data was imported in CiteSpace and duplicates were removed in preparation for visualization.

3.2 Data Analysis Method

CiteSpace is a data visualization software developed by Chen Chaomei's team. The software is widely used in many fields such as information, science and bibliometrics. It can use the position and size of nodes in a visual knowledge network [36], visualize the knowledge context of a certain field for analysis, and identify the development and the structural relationships in the field [37]. Therefore, this study used CiteSpace 5.6.R3 (64-bit) to achieve visualization and gain insights into the development of digital twin technology in the field of empirical research on large amounts of data and the knowledge base in this field. This study used CiteSpace to analyze the knowledge base and research hotspots and development context through modules such as countries, institutions, authors, keywords, and references. The parameters were as follows: Node Type: Selection based on analysis; Time Period: 2000–2021; Time Slice Length: 1; Threshold Selection Criteria: Top 25 per analysis; the rest of the settings were set to the default.

4. Results of Visual Knowledge Mapping

Multiple authors are generally involved in contributing to the research literature in a particular field. They are located in different countries and regions, belong to different scientific research institutions, and collaborate with different researchers. In order to deeply analyze the academic cooperation in the field of digital twin technology, we divided the scientific research cooperation of the literature data into cooperation between countries, institutions and scientific researchers. Using CiteSpace analysis software to draw a map of research cooperation relationships at different levels and perform measurement statistics on the country, institution, and research personnel nodes involved in the literature data, we were able to obtain the distribution of case studies or the social cooperation between scholars in the field of digital twin technology.

4.1 Annual Publishing Trend

In order to conduct an in-depth analysis of case studies related to digital twin technology trends, we collected the publications produced between 2000 and 2021 from the WOS core collection is shown in Figure 1. We found that the number of publications case studies related to digital twin technology did not increase between 2000 and 2015 and did not show a significant growth trend until 2016, which indicates that research in the field of digital twins is still in its infancy.

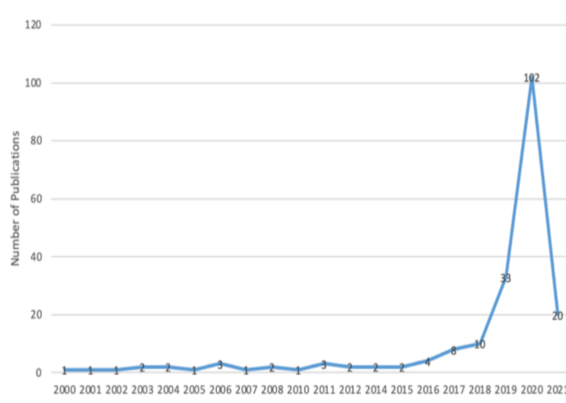

Figure 1. Trend of publication in the case studies related to digital twin technology

Between 2000 and 2015, the average annual output was 2, the average annual output between 2016 and 2018 was 7. With the introduction of information technology, Industry 4.0 and concepts and technologies related to IoT, research on digital twins rapidly developed. The number of related papers increased rapidly, and there has been a significant in-crease in publications since 2018, reaching the peak in 2020. The number of papers published in 2020 was 102, accounting for 47% of all papers.

4.2 Co-occurring Knowledge Graphs

Co-occurring knowledge graphs of authors, institutions, countries, etc. can effectively reveal the mutual cooperation relationship in the research field. We set each parameter value in CiteSpace as follows: the time interval was set to 2000-2021, the time slice was 1 year; the analysis object selected were Author, Institution and, Country; the connection strength of the object data was determined via cosine analysis; the node threshold value selected was the Top100 with the highest frequency in each time segment. The size of nodes in the graph is proportional to the number of posts, and the thickness of node connections is proportional to the strength of cooperation. The annual rings of nodes represent the changes in the period of posting, that is, the change from cold to warm tones rep-resents the change in time from the farther past to recent.

4.2.1 Country Analysis

The number of national/regional publications reflects the contribution of the country/region to research in the field. According to the literature data published by countries with case studies related to digital twin technology in the WOS core collection, the top 6 countries were ranked according to the number of publications. As shown in Figure 2, China ranked first (44 articles), accounting for 20.3% of the total data collected. Then came the United States (24 articles), England (21 articles), Germany (16 articles), Italy (15 articles), and Singapore (8 articles) which covered 38.7% of all publications in the dataset.

Centrality is an index that measures the importance of nodes in the network, and it is used to measure the importance of specific nodes in CiteSpace. The centrality of a country reflects the international recognition of a country in the field. According to Table 1, China had the highest degree of centrality (centrality= 0.53), and England came in second (centrality= 0.40). Although the United States was ranked second in the number of papers published, its centrality (centrality= 0.17) was lower than other countries.

According to these results, China has a large number of publications in this field, and this is reflected by the strong international influence of China's research results in case studies related to digital twin technology.

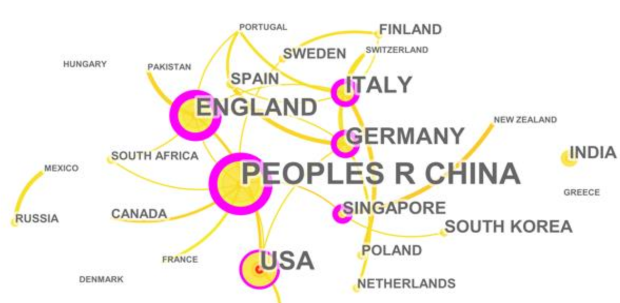

Figure 2. Knowledge map of country collaboration in the case studies related to digital twin technology

Table 1. Top 6 country collaborations in the case studies related to digital twin technology

Count	Centrality	Year	Country
44	0.53	2018	PEOPLES R CHINA
24	0.17	2014	USA
21	0.4	2003	ENGLAND
16	0.21	2006	GERMANY
15	0.23	2019	ITALY
8	0.22	2018	SINGAPORE

4.2.2 Institutional Analysis

CiteSpace was used to establish an institutional cooperation network to reflect the contribution and degree of cooperation between institutions in the case studies related to digital twin technology. Figure 3 shows the Institution Collaboration Network, which consists of 26 nodes representing the institutes. The connection lines indicate the cooperation between institutions, and each link between two institutions is represented by a spectrum of colors corresponding to the years of occurrence.

A higher number of co-citations usually indicates a greater contribution and influence. The three highest ranked institutions by citation count were Univ Cambridge and Hong Kong Polytech Univ, each with a citation count of 5, followed by Nanyang Technol Univ, with a citation count of 4. Betweenness centrality was used to measure the importance of nodes in the network and identify the possible potential of cross-border and paradigm transitions that lead to revolutionary discoveries. The three highest ranked institutions by centrality were Hong Kong Polytech Univ, Univ Hong Kong, and Jinan Univ, each with a centrality of 3. The sigma value indicates the importance of structure and citation changes. The three highest ranked institutions by sigma were Univ Hong Kong and Northwestern Polytech Univ, each with a sigma of 0.08, followed by Hong Kong Polytech Univ, with a sigma of 0.04. It can be observed that Hong Kong Polytech Univ has made a huge contribution to this field.

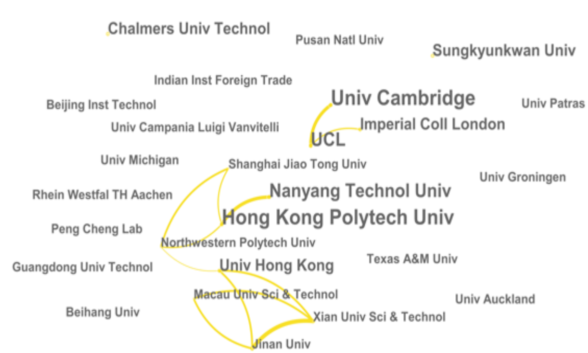

Figure 3. Knowledge map of institutional collaboration in the case studies related to digital twin technology

Table 2. Top 3 institutional collaboration in the case studies related to digital twin technology

Count	Institutional	Centrality	Institutional	Sigma	Institutional
5	Univ Cambridge	3	Hong Kong Polytech Univ	0.08	Univ Hong Kong
5	Hong Kong Polytech Univ	3	Univ Hong Kong	0.08	Northwestern Polytech Univ
4	Nanyang Technol Univ	3	Jinan Univ	0.04	Hong Kong Polytech Univ

4.2.3 Author Analysis

Authors' Cooperative Network analysis displays the core authors and their cooperative intensity and mutual citation in a certain field; it explores the important influence of team cooperation on academic research in this field [38]. Table 3 lists the 10 most productive authors. The results showed that QIUCHEN LU was the one with the most publications. Other relevant authors included AIJTH KUMAR PARLIKAD (3 articles), PAI ZHENG (3 articles), XIANG XIE (3 articles), and FEI TAO (2 articles). Figure 4 shows the knowledge map of author collaboration in the case studies related to digital twin technology. Each node in the author collaboration network represents the author; the number of papers published by the author is represented by the size of the nodes, and the connections between the nodes represent the cooperative relationship between the authors.

Table 3. Top 10 authors based on frequency

Author	Frequency	Year
QINCHEN LU	4	2020
AJITH KUMAAR PARLIKAD	3	2020
PAI ZHENG	3	2020
XIANG XIE	3	2020
GUOXIN WANG	2	2020
HAO ZHANG	2	2019
MARCELLO FERA	2	2020
FEI TAO	2	2018
MENG ZHANG	2	2018
CHUNHSI EN CHEN	2	2020

Figure 4. Knowledge map of author collaboration in the case studies related to digital twin technology

4.3 Hot Research Topics on the Case Studies Related to Digital Twin Technology Filed

4.3.1 Co-citation Literature Analysis

Co-citation deeply reflects the theoretical knowledge base of related research. High-frequency co-citation literature shows the results of basic research in different periods and plays an important role in the academic development of this field [36]. The co-citation network in the case studies related to digital twin technology field was composed of 144 nodes and 588 connections is shown in Figure 5. The node represents the cited literature, and the importance of the literature is expressed by its size. The label on the node is the first author and publication year of the article. 18 key literature nodes with important academic influence were selected as shown in Table 4. It lists the highly co-citation literature in Figure 5 with a frequency of ≥15.

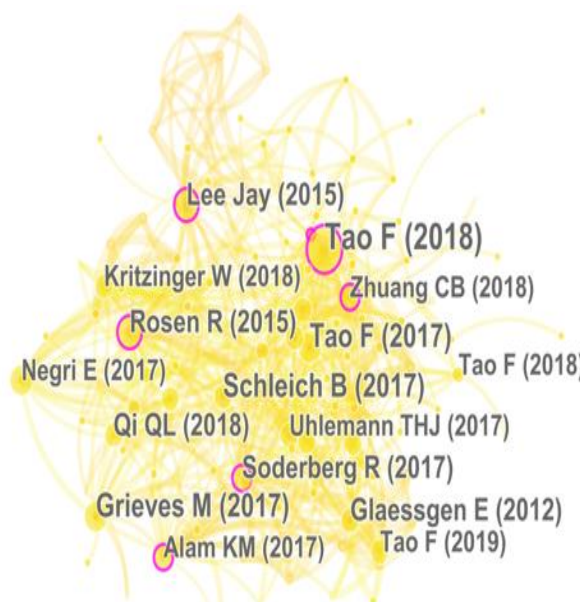

Figure 5. Knowledge map of co-citation literature in the case studies related to digital twin technology

Table 4. The first 18 pieces of co-citation literature in the case studies related to digital twin technology

Author	Frequency	Year	Source	DOI
Tao F	37	2018	INT J ADV MANUF TECH	10.1007/s00170-017-0233-1
Schleich B	26	2017	CIRP ANN-MANUF TECHN	10.1016/j.cirp.2017.04.040
Tao F	25	2017	IEEE ACCESS	10.1109/ACCESS.2017.2756069
Grieves M	25	2017	TRANSDISCIPLINARY PE	10.1007/978-3-319-38756-7_4]
Lee Jay	21	2015	MANUFACTURING LETTERS	10.1016/j.mfglet.2014.12.001
Qi QL	21	2018	IEEE ACCESS	10.1109/ACCESS.2018.2793265
Soderberg R	20	2017	CIRP ANN-MANUF TECHN	10.1016/j.cirp.2017.04.038
Glaessgen E	20	2012	…	DOI 10.2514/6
Rosen R	20	2015	IFAC PAPERSONLINE	10.1016/j.ifacol.2015.06.141
Uhlemann THJ	18	2017	PROC CIRP	10.1016/j.procir.2016.11.152
Negri E	18	2017	PROCEDIA MANUF	10.1016/j.promfg.2017.07.198
Tao F	18	2019	IEEE T IND INFORM	10.1109/TII.2018.2873186
Alam KM	17	2017	IEEE ACCESS	10.1109/ACCESS.2017.2657006
Kritzinger W	16	2018	IFAC PAPERSONLINE	10.1016/j.ifacol.2018.08.474
Zhuang CB	16	2018	INT J ADV MANUF TECH	10.1007/s00170-018-1617-6
Tao F	16	2018	CIRP ANN-MANUF TECHN	10.1016/j.cirp.2018.04.055
Boschert S	15	2016	MECHATRONIC FUTURES	10.1007/978-3-319-32156-1_5
Lu YQ	15	2020	ROBOT CIM-INT MANUF	10.1016/j.rcim.2019.101837

4.3.2 Co-occurrence of Keywords

Keywords are the condensation of the main content of the article, and can reflect the hot spots and development trends of the research field. We ran the “Keyword” module of CiteSpace, merged some semantic repetitions, and generated a graph of the keyword co-occurrence network in the case studies related to digital twin technology filed. CiteSpace provides the function of automatically tagging the cluster network, allowing three algorithms (LSI, LLR and MI) to extract noun phrases from titles, keywords or abstracts. Given the co-occurrence of keywords, the nodes were revised, and the Log-likelihood (LLR) algorithm was adopted for clustering calculation. The keywords of the same cluster are on the same horizontal line, and each node represents a keyword, the keywords are fixed in the year when they first appear, connected by lines. The visualization map obtained N = 117, E = 368 (density = 0.0542). The modularity Q and the mean silhouette scores are two important metrics that tell us about the overall structural proper-ties of the network. In this paper, the Modularity Q score was 0.578, the Mean Silhouette score was 0.5167, as presented in Figure 6. There were a total of 7 clusters as listed in Table 5.

A timeline visualization depicts clusters along a horizontal timeline. The main 7 clusters are presented in Figure 7. Each one can indicate the evolution of research in the field by analyzing falls in the case studies related to digital twin technology between 2000 and 2021. The domains #0, #1, #2, #3, #4, #5, and #6 are cyber-physical systems, fatigue crack growth, internet of things, industry foundation classed, artificial intelligence, and interoperability, respectively. Digital twin technology has been proposed in recent years as an effective method of realizing real-time interaction between the physical world and the virtual world. By analyzing the titles, keywords, and other content of the cited documents of each module, we can observe that the documents in the above modules were all re-searched from the perspective of manufacturing, and the research was carried out via application and integration of artificial intelligence and other new technologies.

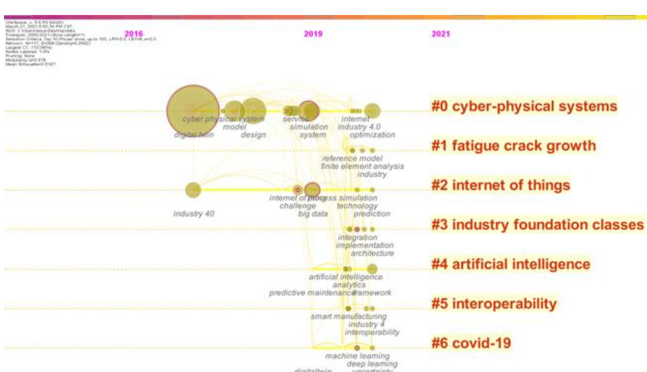

Figure 6. Knowledge map of keyword cluster in the case studies related to digital twin technology

Figure 7. A landscape view of keyword cluster analysis generated by Top N = 100 per slice from 2000 to 2021. (LRF = 3, LBY = 8, and e = 2.0)

Table 5. Subjects of cluster analysis

#	Size	Silhouette Value	Year	Top Term in LLR
0	23	0.86	2019	cyber-physical systems; virtual reality; manufacturing; artificial intelligence; big data; interoperability; covid-19; ergonomics
1	17	0.697	2020	fatigue crack growth; human factors; composite; mixed reality; digitization; asset management

2	17	0.77	2019	internet of things; databases; modeling; knowledge representation; block chain technology; sustainability
3	15	0.866	2020	industry foundation classes; anomaly detection; operations and maintenance; subway station; sustainable development
4	15	0.852	2019	artificial intelligence; predictive maintenance; decision support system; virtual physiological human; personalized medicine; autonomy
5	13	0.751	2020	Interoperability; standards; probabilistic logic; building information modeling; safety management; collaboration
6	13	0.887	2019	covid-19; big data; resilience; pandemic plan; deep learning; government

An internal uniformity (profile) value from 0.69 to 1 indicates that the top terms in the cluster match well and that the cluster is reliable. The results in Table 5 show that the realization of industrial IoT has led to smart manufacturing with the advent of the big data era. The industry 4.0 vision has been accelerated through the astute usage of IoT competencies. The collaboration of industrial IoT and transformative technologies such as artificial intelligence, blockchain, and digital twins can become an important symbol of the future of business giants. The rise of the sharing economy and its supporting technologies represents a paradigm shift in the access and consumption of IoT systems and services.

Digital twin technology can also be considered a knowledge representation, as when combined with blockchains. Using blockchains, the concept of digital transfers of value can be fully implemented in a decentralized manner. Digital twins are increasingly being stored on blockchains. In other words, blockchain technology is gaining the inherent capability to redefine the concept of digital twins.

The dual concepts of digital twins and machine-to-blockchain networks are portrayed as key technology facilitators for intrinsically empowering industrial IoT devices to participate in the fast-evolving sharing economy [40]. Healthcare is another industry that widely uses digital twin paradigms. Due to the requirement of large-scale IT resources to help big data and data flow analysis, the cloud computing domain is the first choice to support and sustain the idea of digital twins. These concepts can support and maintain the unique ideals of the sharing economy.

5. Research Trends Analysis

The trends of research in a field can reflect direction of future research development. The burst of keywords can reflect the changes in research topics and hotspots in one field. By using the burst detection function in CiteSpace, sudden increases or decreases in the number of citations of specific keywords or papers can be revealed [41].

Based on the statistical results are shown in Table 6, we made a list of the top 10 most popular vocabularies in the case studies related to digital twin technology according to two indicators: starting year and strength. The results showed that the research frontier of digital twin in the past decades has changed with time, and the strongest burst words excluding ‘digital twin’ are ‘service’ and ‘sustainability’. The latest burst words, ‘big data’, ‘cloud computing’, ‘management’, ‘future’, ‘internet of things′, represent some of the prevalent discourses in 2019 and will continue to be followed.

From the results, it can be observed that the digital twin currently has a negligible share of contribution in the domain of social sciences and requires an in-depth study of sustainability. Social digital twins need access to appropriate data to ensure that they reflect social processes in the real world. Recent work has seen that Metaverse is gaining more and more attention in association with other methods, such as statistics and machine learning, for model behavior calibration, optimization, and evaluation. The digital twin is playing an increasingly important role in the conceptualization of Metaverse. By capturing data on physical systems through a networked device and pushing them to the cloud, decision makers can more accurately understand the current status of these systems than ever before. They now have the ability to connect different parts of the enterprise systems in an interactive manner to visualize and understand how external forces influence the efficiency of these systems.

Table 6. Keywords with the strongest citation burst in the case studies related to digital twin technology fields

Keywords	Strength	Year
digital twin	4.7885	2017
service	2.2396	2018
sustainability	2.1224	2018
model	1.6887	2018
industry4.0	1.3354	2019
big data	1.0612	2019
cloud computing	1.0612	2019
management	0.7728	2019
future	0.7609	2019
internet of things	0.7328	2019

6. Conclusions

Through bibliometric analysis using CiteSpace, we observed that the number of papers related to digital twins began to show an increasing trend in 2016 and reached the peak of single-year publications in 2020. China, the United States, the United Kingdom, Germany, Italy, and Singapore rank within the top six of all countries/regions for papers related to digital twins. At the same time, these countries actively participate in the international research of digital twins and contribute the most to digital twin research. At present, research on digital twins is still in its infancy, and the number of papers and citations is relatively small. However, it is precisely because it has such a wide range of applications and much potential for further exploration that it can attract more scholars to conduct further in-depth research in the future.

Digital twins are important means to connect the physical and the virtual world, and as the maturity of information technology and world's demand for intelligent manufacturing increase, digital twin technology can increasingly be applied to manufacturing processes. In addition, if the digital twin technology can be used to aid in solving social problems, it will be a very big contribution to the field. The results of the literature analysis conducted in this study also show relevance to the social science and business management domains. Academic research on the subject is still lacking, and we aim to continue conducting in-depth research on digital twins in the social science domain.

The world's current technological development poses some limitations to the possibilities presented in this paper. However, in recent years, the trend of virtual reality has been set off in the internet industry, the concept of Metaverse has been proposed, and immersive virtual reality games have become its first application scenario. The idea of the Metaverse was inspired by the concept of the digital twin. As a key tool for digital transformation, the digital twin should meet the needs of the fast and dynamic transformation of human society and economy in the coming era and help realize a smart society.

Some challenges of digital twin implementation are technical in nature and can be solved through continuous research and development. Other challenges are cultural and require subversion of current operating models and ways of thinking. The concept of digital twins is clearly still evolving, as reflected in the diversity of new industries and use cases to which digital twins are applied. Due to the current lack of concrete examples to demonstrate the advantages of digital twins in practice, this continuous conceptual evolution is also a given. Therefore, we can safely hypothesize that digital twin technology can contribute greatly to the social sciences domain.

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