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Review

Digital Twins in Critical Infrastructure

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Abstract: This study aims to examine the use of digital twins in critical infrastructure through a literature review as well as a bibliometric and scientific mapping analysis. A total of 3414 documents from Scopus and Web of Science (WoS) are examined. According to the findings, digital twins play an important role in critical infrastructure as they can improve the security, resilience, reliability, maintenance, continuity, and functioning of critical infrastructure in all sectors. Intelligent and autonomous decision-making, process optimization, advanced traceability, interactive visualization, and real-time monitoring, analysis, and prediction emerged as some of the benefits that digital twins can yield. Finally, the findings revealed the ability of digital twins to bridge the gap between physical and virtual environments, to be used in conjunction with other technologies, and to be integrated into various settings and domains.

Keywords: digital twins; critical infrastructure; cybersecurity; security; review; bibliometric analysis; scientific mapping

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1. Introduction

Critical infrastructure can be composed of virtual and/or physical assets, systems, and processes and relies on technological advancements and applications to seamlessly be integrated and operate in various domains; hence, it is an integral component of modern societies which increasingly depend on them [1–3]. Critical infrastructure and its definition evolve along with the changes that take place to ensure the reliable, secure, and effective function of communities as well as economic welfare and social well-being [4]. As critical infrastructure is essential for a sustainable future [5], ensuring its resilience and continuous functioning, even under complex circumstances and threats, is crucial [1,6]. Cybersecurity issues, risks, and vulnerabilities are another major concern about critical infrastructure as it has been one of the main targets for various cyberattacks [7–9]. Hence, improving the security, availability, resilience, continuity, and performance of critical infrastructure has been an urgent national priority for many countries [3,10,11].

This fact comes as no surprise as critical infrastructure significantly affects everyday life due to the utilities that it offers [10]. Transportation and commuting systems, energy grids, communication networks, pharmacies, and healthcare clinics are just some examples. Additionally, it is regarded as an enormous public investment whose disruption can have important consequences [12]. As critical infrastructure involves both physical and virtual systems and assets, ensuring its cyber and physical security and resilience is a must [3,6–8,10,12,13]. In the context of critical infrastructure, resilience refers to the ability of a specific system to identify, withstand, adapt to, respond to, and recover from disruptive events and urgent conditions, as well as from internal and external threats, and directly impacts the reliability of the system [14,15].

There are 16 broad critical infrastructure sectors in which the destruction or malfunction of their physical or virtual systems, assets, and networks would have devastating implications [16]. Namely, these sectors involve the (1) chemical, (2) commercial facilities, (3) communications, (4) critical manufacturing, (5) dams, (6) defense industrial base, (7) emergency services, (8) energy, (9) financial services, (10) food and agriculture, (11) government facilities, (12) healthcare and public health, (13) information technology, (14) nuclear reactors, materials, and waste, (15) transportation systems, as well as (16) water and wastewater systems sectors [16]. However, geopolitical developments and economic changes may modify this list of sectors [17].

It is worth noting that critical infrastructure in the different sectors is not independent but mutually interconnected and interdependent [11]. The interdependency types of critical infrastructure can be described from different dimensions [2]. Hence, according to [2], various studies have presented different interdependency types of critical infrastructure, such as: (i) physical, cyber, geographic, or logical [11], (ii) functional or spatial [18], (iii) physical, geospatial, policy, or informational [19], (iv) input, mutual, shared, exclusive, or co-located [20,21], and (v) functional, physical, budgetary, or market and economic [22].

As digital twins are data-driven and precise virtual replicas of real-world entities, they can help bridge the gap between physical and virtual environments and be used in various settings and domains [23–25]. By receiving input from the physical entity [26] and through their diverse dimensions and capabilities, digital twins allow the optimization of services, products, and devices and improving cybersecurity [9] through constant and real-time monitoring and by capitalizing on the benefits of both horizontal and vertical approaches [27]. In the context of digital twins, horizontal approaches refer to the adoption and application of digital twins across different sectors and use cases while vertical approaches refer to the deep integration of digital twins and their optimization in specific domains or use cases. Digital twins have domain dependence, synchronization, autonomy, and self-evolution as their main properties [28]. Additionally, communication capabilities, unique identifiers, actuators and sensors, artificial intelligence, security and privacy, trust, and virtual representation are some of the main characteristics of digital twins [29]. These properties and characteristics render digital twins feasible to be integrated into different domains. Extended reality technologies, robotics, haptic devices, data-driven modelling, machine vision, cloud computing, tactile internet, 5G networks, artificial intelligence, and the internet of things are some of the various technologies that enable the realization of digital twins [24,30].

Digital twins have the potential to further improve the security, resilience, continuity, and functioning of critical infrastructure across all sectors. As the topic is advancing, it is important to present its evolution. Several systematic literature review studies have examined the role of digital twins in infrastructure [31–34]. Although studies have been conducted that examined the adoption, use, and role of digital twins in various domains, e.g., transportation [35], energy [36], infrastructure [37], smart industrial systems [38], manufacturing [39], smart building [40], health [41], transportation [42,43], power [44,45] to the best of our knowledge, there has not been any other study that presents the current state of the art regarding the adoption and integration of digital twins in the context of critical infrastructure while taking all critical infrastructure domains into account through a bibliometric and mapping analysis. To bridge this gap in the literature, this study aims to examine the use of digital twins in critical infrastructure through an overview and a bibliometric analysis and scientific mapping of the existing literature. The main research questions set to be explored were: what the role of digital twins in critical infrastructure is and what the current state-of-the-art is based on the existing literature. Therefore, the main contributions of the study can be identified as its representation of the existing literature, the bibliometric and mapping analysis of the related documents, the identification of the topic evolution and emerging themes, as well as recommend future research directions. The structure of the article is as follows: In Section 2, digital twins are presented and in Section 3, the methodology, query, and tools used are described. In Section 4, the results are separated into 7 categories and are analyzed. In Section 5, the findings of this study and the application of digital twins in critical infrastructure are discussed and directions for future research are provided. Finally, in Section 6, the limitations of this study and conclusive remarks are given.

2. Digital Twins

Digital twins consist of software services and models which capitalize on diverse data aspects [46] and represent a virtual copy of a physical object or system while focusing on the interaction between the physical and digital entities [47,48]. Hence, since digital twins can support real-time monitoring and optimization as well as simulation-based decision-making, they can be adopted and implemented throughout the product life-cycle as they [49–54].

Digital twins are in unison with their physical counterparts [55]. Hence, they change and evolve simultaneously as the life cycle of a product advances which, in turn, leads to enhanced usability, controllability, and fidelity [24,56–58]. Digital twins can be considered as living digital models of the physical entities represented in detail from micro to macro levels, they are constantly updated with new data and information about the status of the physical entity, and are able to predict future states as well as improve the overall security and productivity of the physical entity [53,55,59–61]. Hence, digital twins capitalize on data, processes, integrated simulations, cognitive services, and machine-readable representations to provide a formal one-to-one virtual representation of physical entities and their states, behaviors, resources, interactions, characteristics, and communication capabilities [24,51,62–67].

Through their intended application domains, content modularization, data integration, technologies, standards, and metamodels, digital twins can develop bi-directional dynamic mapping processes and high-fidelity digital representations [68,69] which provide constructive feedback and insight through real-time simulation and prediction of the state, behavior, and interactivity of the physical entities [48,70–73]. Moreover, digital twins enable advanced and autonomous decision-making, real-time monitoring and analysis, as well as interactive visualization which enable organizations to optimize their processes and operations, effectively evaluate how their assets will evolve in the future, increase their security and reliability, and address crucial issues [48,51,53,74]. Digital twins can be adopted into various domains and use cases while yielding benefits and improving processes [48,53]. For example, in built environments, digital twins can be used to assist in planning, building, operating, and maintaining built assets [75]. To ensure an effective integration, there are mission, safety, security, and time critical issues that must be thoroughly considered [74,76,77]. This is particularly true in the case of critical infrastructure.

3. Materials and Methods

Given the breadth of the topic concerning the use of digital twins in the context of critical infrastructures and to provide a cohesive representation of the state of the art and its evolution over the years, this study adopted a bibliometric analysis and scientific mapping approach [78]. To ensure the validity of the study and its meeting the requirements of a thorough bibliometric analysis and scientific mapping study [79,80], the guidelines of [81] and the approach of [82] were followed. Additionally, the databases used were Scopus and Web of Science (WoS) which are widely regarded as impactful and accurate and for that reason they are being used in various domains [82,83].

To aid this study, "Bibliometrix", which is an open-source R package, was used [81]. Specifically, R version 4.3.3 and Bibliometrix version 4.2.1 were used. To provide a thorough look at the use of digital twins in critical infrastructure, no limitations were set in the extensive search query which was applied on a topic level (title, abstract, and keywords) for both Scopus and WoS. The query integrated keywords from all domains that are regarded as critical infrastructures and used wildcards and logical operators to ensure that all the related documents would be identified. More specifically, the search query that led to the most accurate results after examining different combinations was: ("digital twin*") AND ("critical infrastructure*" OR "infrastructure*" OR "asset*" OR "facilit*" OR "service*" OR "material*" OR "structure*" OR "supply chain*" OR "chemical*" OR "commercial*" OR "communication*" OR "manufactur*" OR "dam*" OR "industr*" OR "emergenc*" OR "energy" OR "financ*" OR "food*" OR "agriculture" OR "government*" OR "health*" OR "hospital*" OR "medic*" or "information technolog*" OR "power" OR "transportation*" OR "water" OR "wastewater" OR "educat*" OR "national securit*" OR "environment*" OR "nuclear reactor*" OR "defense*" OR "defence*" OR "securit*").

To provide a more accurate and clearer depiction of the process that led to the creation of the document collection used, the flowchart from the PRISMA statement was used [84] and is depicted in Figure 1. More specifically, 15,572 documents were retrieved from Scopus and 9103 from WoS on 1 March 2024. In total, 24,675 documents were identified. Duplicate documents (7818) were identified both automatically through "Bibliometrix" and manually. Of the 16,857 documents that were assessed for eligibility, 1 document was removed as it was a book review, 6 were removed as they were retracted documents, 17 were removed as they were erratum, and 42 documents were excluded as they were missing most of the required information. The inclusion criterion for a document to be included in the document collection analyzed in this study was for the document to specifically refer to and focus on the use of digital twins in critical infrastructure. The inclusion criterion was purposefully kept generic to ensure that all documents related to the topic will be identified and included in the study. Owing to the number of documents identified and to improve reproducibility, an automatic approach was used to conduct the initial filtering of the documents. Taking the scope of the study and the number and nature of the keywords into account, the use of proximity operators was considered but not deemed appropriate. Specifically, proximity operators have strict rules regarding the position of words within a sentence or text. In the case of this study in which a complex query having multiple keywords was used, the proximity operator was too limited as the position of words could drastically differ. Hence, the existence of combinations of keywords based on the structure of the query within the title and abstract at any position was examined instead of conducting the initial document filtering (Reason 5). Thus, due to the extensive scope of the query as well as the fact that it was also applied to the keywords of the documents, 13,377 studies were excluded as they did not meet the inclusion criterion. Additionally, after manually examining the title and abstract of each document as well as the information retrieved from the Scopus and WoS databases and crosschecking the decisions made, the remaining documents were manually filtered based on Reasons 1–4 presented in Figure 2 and on the values reported by the databases. As a result, a total of 3414 documents were included in the document collection that was examined in this study. This study synthesizes the outcomes of other related works to provide an overview and carries out quantitative and qualitative analysis using bibliometric and scientific mapping analysis methods. Through this approach, a clear depiction of the current state-of-the-art can be achieved. The complete research process and the steps taken are showcased in Figure 2.

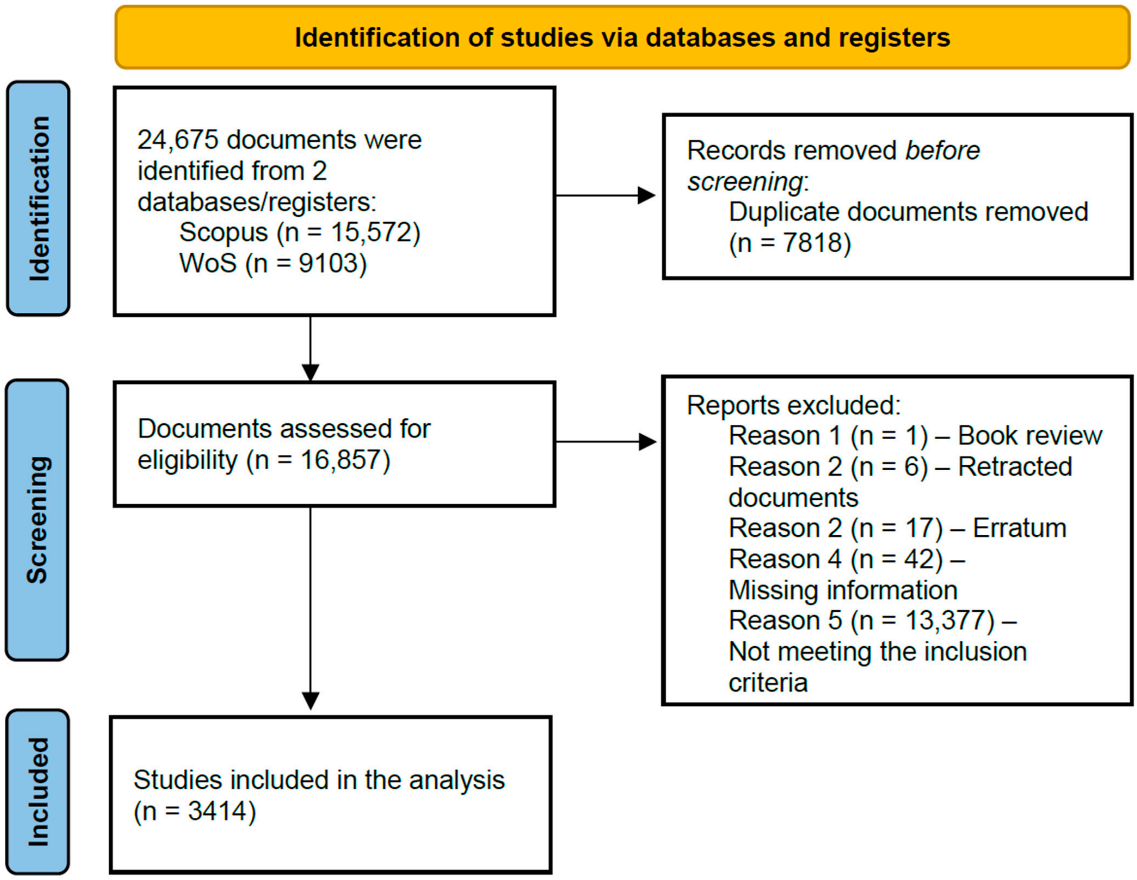

Figure 1. Document processing flowchart.

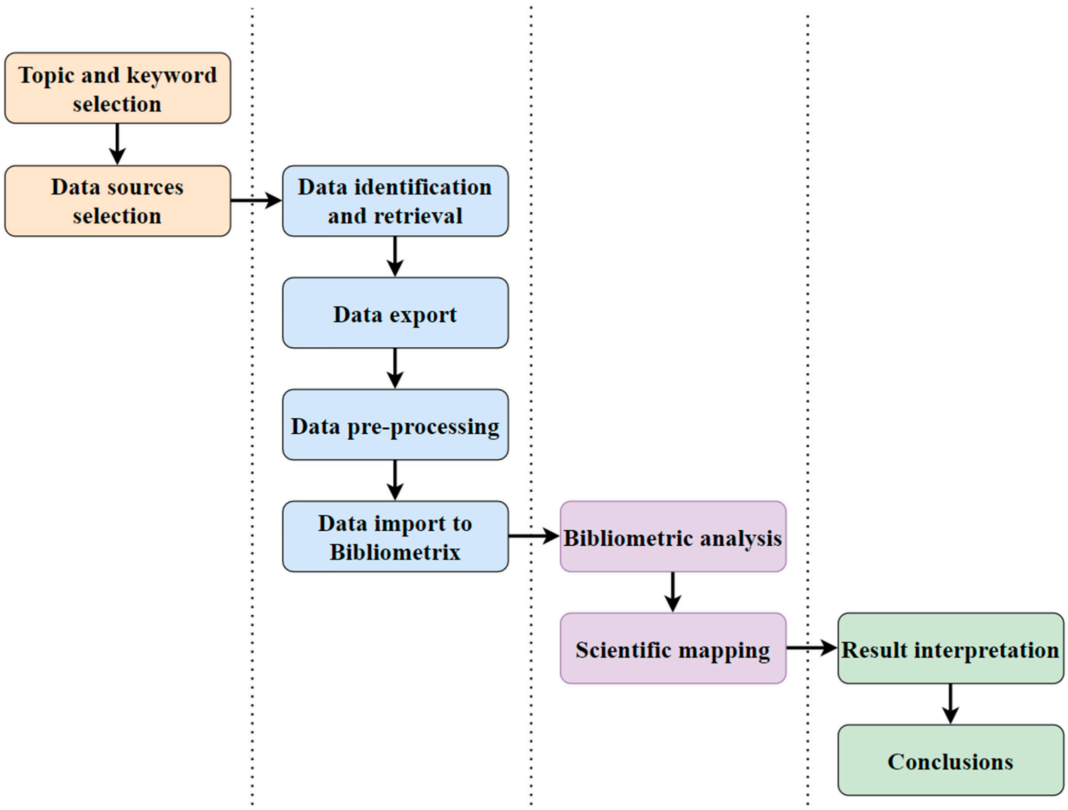

Figure 2. Research process.

4. Result Analysis

This section presents the analysis of the results using descriptive statistics, figures, diagrams, and tables. In order for the results to be more easily read, they are separated into the following categories: (i) descriptive information, (ii) citation analysis, (iii) source analysis, (iv) affiliation analysis, (v) country analysis, and (vi) document analysis.

4.1. Descriptive Information

The descriptive statistics of the collection of articles examined in this study, which consists of 3414 documents derived from 1447 sources, are displayed in Table 1. The documents were published from 2014 to 2023. It is worth noting that although the term digital twins was introduced prior to 2014, when taking into account the search query, the databases used, and the inclusion criterion, the first relevant to the topic published document was identified in 2014. The importance and recency of the topic can be justified by the average document age being 2.19 years, by the annual growth rate of 35.41%, as well as by the average citations for each document being 17.42. Authors from all continents, particularly 8827 authors from 75 countries, contributed to the creation of the documents examined. In total, there were 181 single-authored documents while the significant majority of documents were the result of collaboration among authors with an average of 4.27 co-authors for each document. Despite this fact, with the international co-authorship rate being 13.18%, it can be inferred that most of the collaborations involved authors from the same affiliation or country. Moreover, it is worth noting that the documents were published in various sources with conferences/proceedings (49.85%) and research articles in journals (39.81%) being the most prominent of the different document types, followed by book chapters (5.04%) and review articles (4.19%).

Table 1. Document collection information.

Description	Results	Description	Results
Main information about data		**Document types**	
Timespan	2014:2023	Article	1359
Sources (Journals, Books, etc.)	1447	Book	11
Documents	3414	Book chapter	172
Annual growth rate %	35.41	Conference/proceedings paper	1702
Document average age	2.19	Editorial	27
Average citations per document	17.42	Review	143
Document contents		**Authors collaboration**	
Keywords plus (ID)	14,787	Single-authored documents	181
Author's keywords (DE)	6908	Co-authors per document	4.27
Authors		International co-authorships %	13.18
Authors	8827		
Authors of single-authored documents	159		

4.2. Citation Analysis

The increasing interest and the variety of studies being conducted around the globe further highlight the potential of digital twins to be integrated in various domains and enrich critical infrastructure. As it can be seen in Figure 3, in which the number of documents published in each year is presented, the vast majority of documents have been published over the last few years and with the annual growth rate being 35.41%, it can be inferred that the interest in this topic will further increase in the coming years. Moreover, based on the annual scientific production, 2018–2019 was the period in which the interest in digital twins in critical infrastructure started to grow, the period of 2020–2021 was when the interest in the topic sparked, and the years 2022 and 2023 were the breakthrough years which also demonstrated the largest number of published documents (923 and 1386 respectively). Based on the scientific production and citations per year (Table 2), the articles published in 2017 (n = 14, 212.93), 2016 (n = 3, 183.67), and 2018 (n = 69, 18.25) had the largest mean total citations per document. Nonetheless, this can be justified when taking into account the citable years of the document and the number of documents published in the following years. When the mean total citations per year is being taken into consideration, the documents published in 2015 (n = 1, 101.3), 2017 (n = 14, 26.62), 2016 (n = 3, 20.41), and 2018 (n = 69, 18.25) were the most impactful. However, given the growth of the topic and the fact that most documents were published in recent years and have an average citable age of 2.19 years, these results can change in the future. Finally, it can be said that the most impactful document was published in 2015, and the year with the most documents published was 2023.

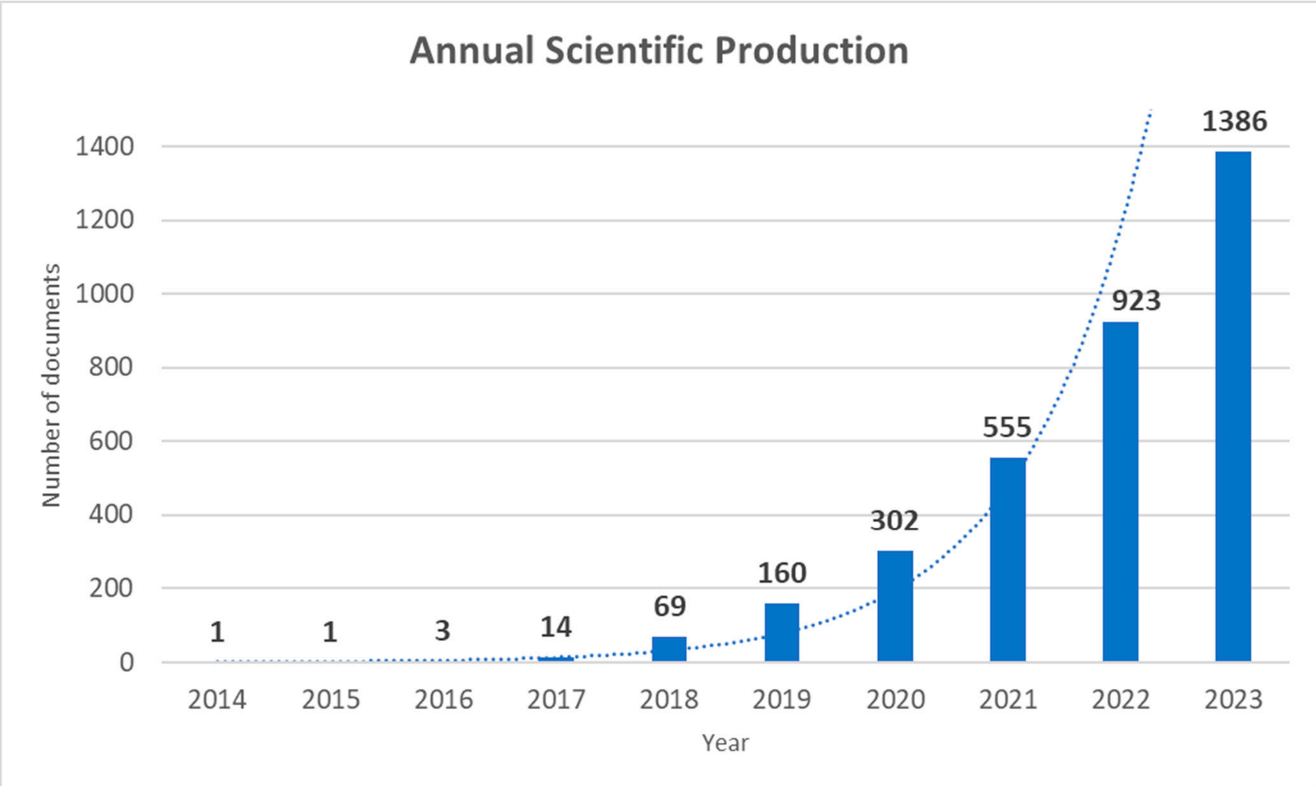

Figure 3. Annual scientific production.

Table 2. Annual scientific production and citations.

Year	MeanTCperArt	N	MeanTCperYear	CitableYears
2014	103	1	9.36	11
2015	1013	1	101.3	10
2016	183.67	3	20.41	9
2017	212.93	14	26.62	8
2018	127.75	69	18.25	7
2019	66.09	160	11.02	6
2020	34.72	302	6.94	5
2021	23.7	555	5.92	4
2022	9.02	923	3.01	3
2023	2.5	1386	1.25	2

4.3. Source Analysis

According to the number of documents published, the most relevant sources of the 1447 contained in this document collection are presented in Figure 4. The top-5 sources which published the most documents related to the topic were: "Procedia CIRP (75 documents)", "Applied Sciences (Switzerland) (56 documents)", "IEEE Access (54 documents)", "IFAC-PapersOnLine (51 documents)", and "Sensors (44 documents)". In Table 3, the most impactful sources based on their h-index on the specific topic are displayed. The top-5 most impactful sources were: "Journal of Manufacturing Systems (h-index: 24)", "Procedia CIRP (h-index: 23)", "IEEE Access (h-index: 20)", "Applied Sciences (Switzerland) (h-index: 19)", and "IEEE Transactions on Industrial Informatics (h-index: 18)".

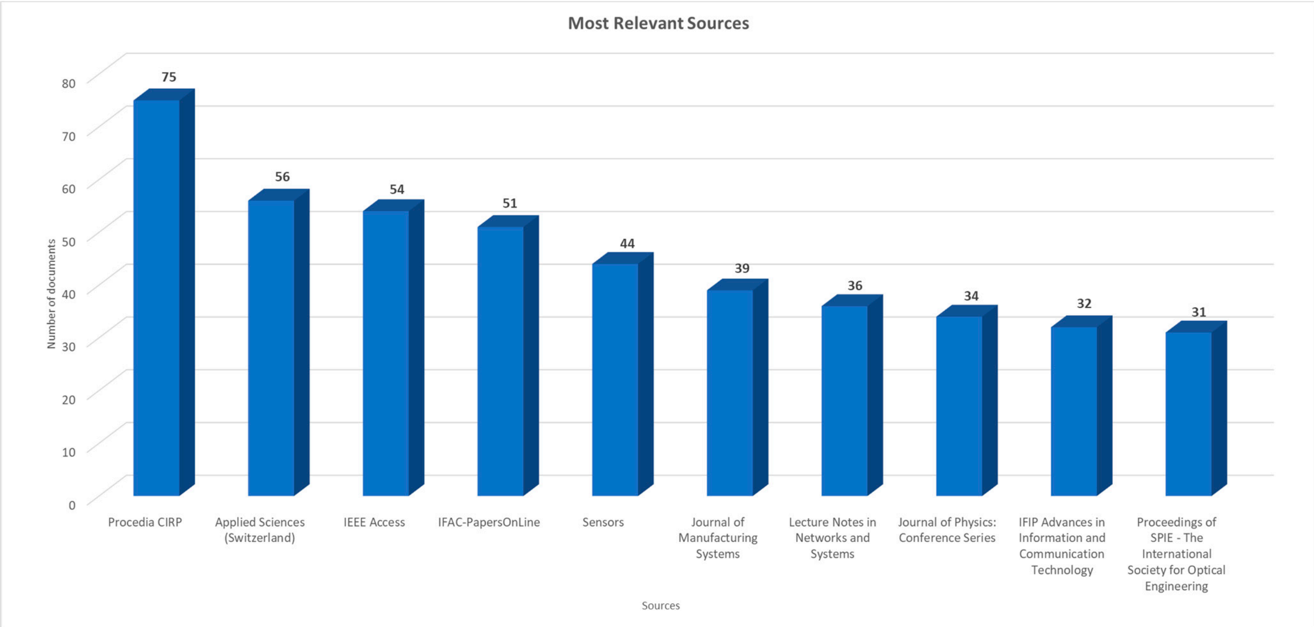

Figure 4. Sources with most documents published.

Table 3. Most impactful sources based on h-index.

Sources	h-Index	g-Index	m-Index	TC	NP	PY-Start
Journal of Manufacturing Systems	24	39	3.429	2882	39	2018
Procedia CIRP	23	50	2.875	2567	75	2017
IEEE Access	20	54	2.5	3467	54	2017
Applied Sciences (Switzerland)	19	33	3.8	1200	56	2020
IEEE Transactions on Industrial Informatics	18	30	2.571	3426	30	2018
International Journal of Computer Integrated Manufacturing	15	26	2.5	1067	26	2019
Robotics and Computer-Integrated Manufacturing	15	20	3	1727	20	2020
IFAC-PapersOnLine	14	51	1.4	3575	51	2015
International Journal of Advanced Manufacturing Technology	14	26	2	2152	26	2018
Procedia Manufacturing	14	18	1.75	852	18	2017

To further examine the sources and their impact, Bradford's law was used to cluster them into 3 clusters, with cluster 1 representing the most impactful sources. More specifically, cluster 1 (3.46%) was composed of 46 sources with 1136 documents, cluster 2 (22.53%) consisted of 326 sources with 1153 documents, and cluster 3 (74.29%) involved 1075 sources with 1125 documents. Based on the results depicted in Table 4, the top-5 most impactful sources following Bradford's law were: "Procedia CIRP", "Applied Sciences (Switzerland)", "IEEE Access", "IFAC-PapersOnLine", and "Sensors". The significance of the topic is further highlighted when considering that sources of various types are among the top-10 most impactful ones. Following Bradford's law, the production of the top-10 sources over time is displayed in Figure 5. Specifically, Figure 5 presents the number of documents published in each source per year. According to the results, it can be noted that most documents in the top-10 most impactful sources were published in 2023 (452 documents), 2022 (292 documents), and 2021 (170 documents).

Table 4. Most impactful sources based on Bradford's law.

Source	Rank	Freq	cumFreq	Cluster
Procedia CIRP	1	75	75	Cluster 1
Applied Sciences (Switzerland)	2	56	131	Cluster 1
IEEE Access	3	54	185	Cluster 1
IFAC-PapersOnLine	4	51	236	Cluster 1
Sensors	5	44	280	Cluster 1
Journal of Manufacturing Systems	6	39	319	Cluster 1
Lecture Notes in Networks and Systems	7	36	355	Cluster 1
Journal of Physics: Conference Series	8	34	389	Cluster 1
IFIP Advances in Information and Communication Technology	9	32	421	Cluster 1
Proceedings of SPIE—The International Society for Optical Engineering	10	31	452	Cluster 1

Year	Procedia CIRP	Applied Sciences (Switzerland)	IEEE Access	IFAC-PapersOnLine	Sensors	Journal of Manufacturing Systems	Lecture Notes in Networks and Systems	Journal of Physics: Conference Series	IFIP Advances in Information and Communication Technology	Proceedings of SPIE - The International Society for Optical Engineering	Total published documents per year
2015	0	0	0	1	0	0	0	0	0	0	1
2016	0	0	0	2	0	0	0	0	0	0	2
2017	1	0	1	2	0	0	0	0	0	0	4
2018	4	0	2	5	0	1	0	0	2	0	14
2019	18	0	3	10	0	1	0	2	3	0	37
2020	30	8	11	18	0	2	1	4	7	0	81
2021	37	19	20	26	9	23	2	15	18	1	170
2022	53	33	34	47	26	29	11	25	25	9	292
2023	75	56	54	51	44	39	36	34	32	31	452
Total published documents per source	143	60	71	111	35	56	14	46	55	10	

Figure 5. Production of the top-10 sources over time based on Bradford's law.

4.4. Affiliation Analysis

In total, the authors that contributed to this document collection were from 3266 affiliations. The affiliations whose authors published the most documents on the topic are displayed in Figure 6. Based on the number of published documents on the topic, the top-5 most prolific affiliations were: Shanghai Jiao Tong University (49 documents), Beihang University (45 documents), The Hong Kong Polytechnic University (40 documents), Nanyang Technological University (38 documents), and the University of Cambridge (38 documents). The collaboration network among the different affiliations is presented in Figure 7. In particular, the nodes of the network map correspond to affiliations, the lines that connect them represent their relationships in terms of collaboration, and the different colors reflect the clusters of affiliation whose authors collaborate more actively.

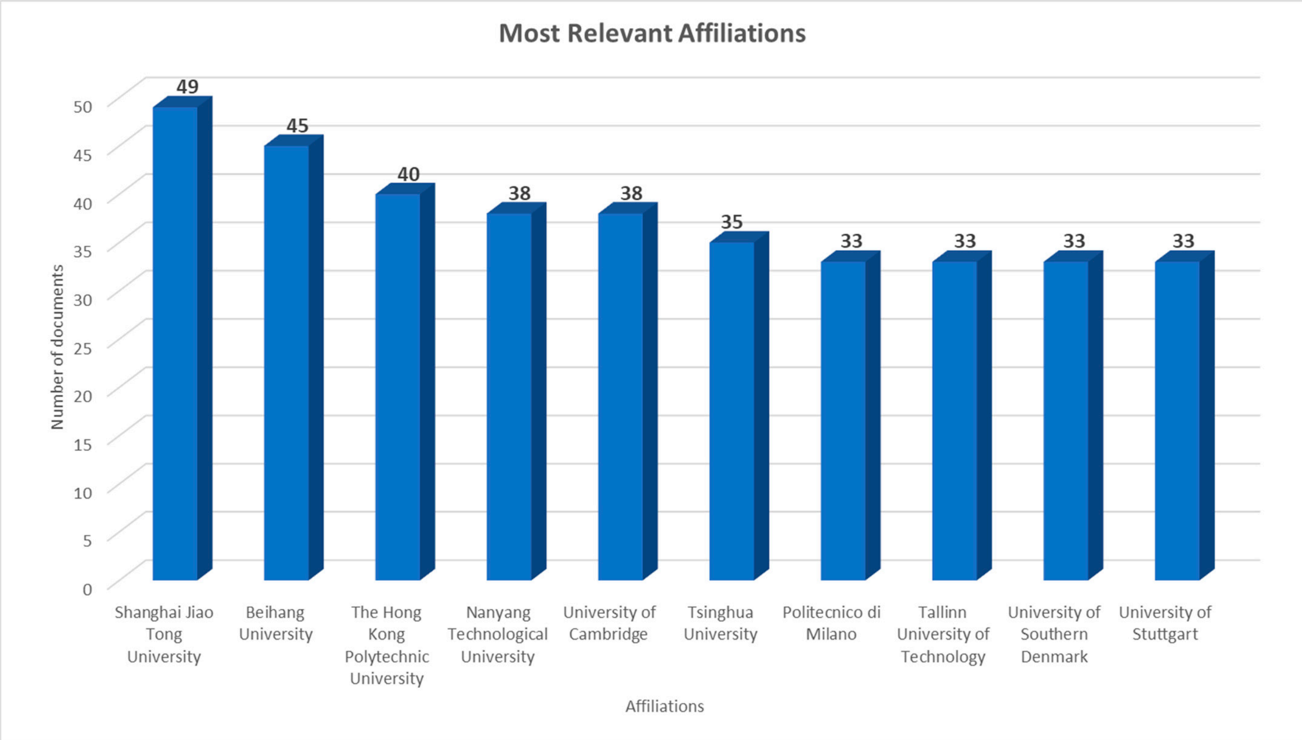

Figure 6. Top affiliations based on the number of documents published.

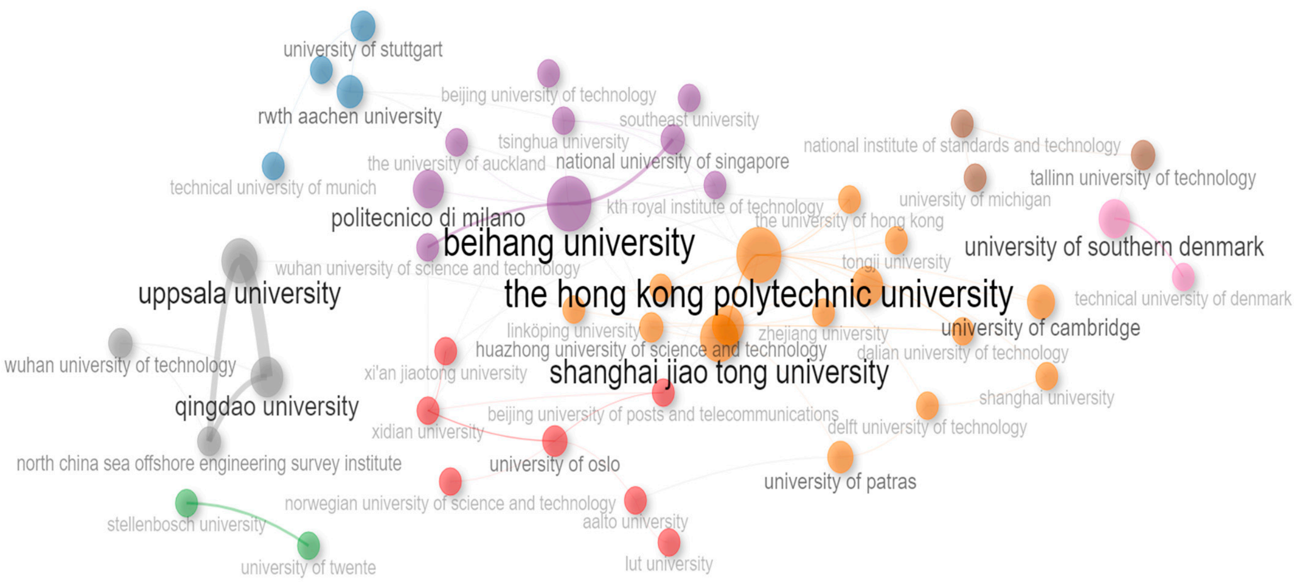

Figure 7. Collaboration network based on affiliations.

4.5. Country Analysis

In total, authors from 75 countries contributed to this document collection. When taking into account the number of documents published on this topic, China (820 documents), the United States (378 documents), Germany (327 documents), the United Kingdom (205 documents), and Italy (193 documents) were the countries with the most published documents, as it can be seen in Figure 8. Figure 9 presents the countries that received the most citations. Based on the results, China (17,297 citations), Germany (4218 citations), the United States (3170 citations), Italy (2245 citations), and the United Kingdom (2011 citations) were the top-5 countries that received the highest number of citations. Furthermore, the collaboration between the countries is showcased as a network in Figure 10 and as a map in

Figure 11. Specifically in Figure 10, the nodes of the network map correspond to countries, the lines that connect them represent their relationships in terms of collaboration, and the different colors reflect the clusters of countries whose authors collaborate more actively.

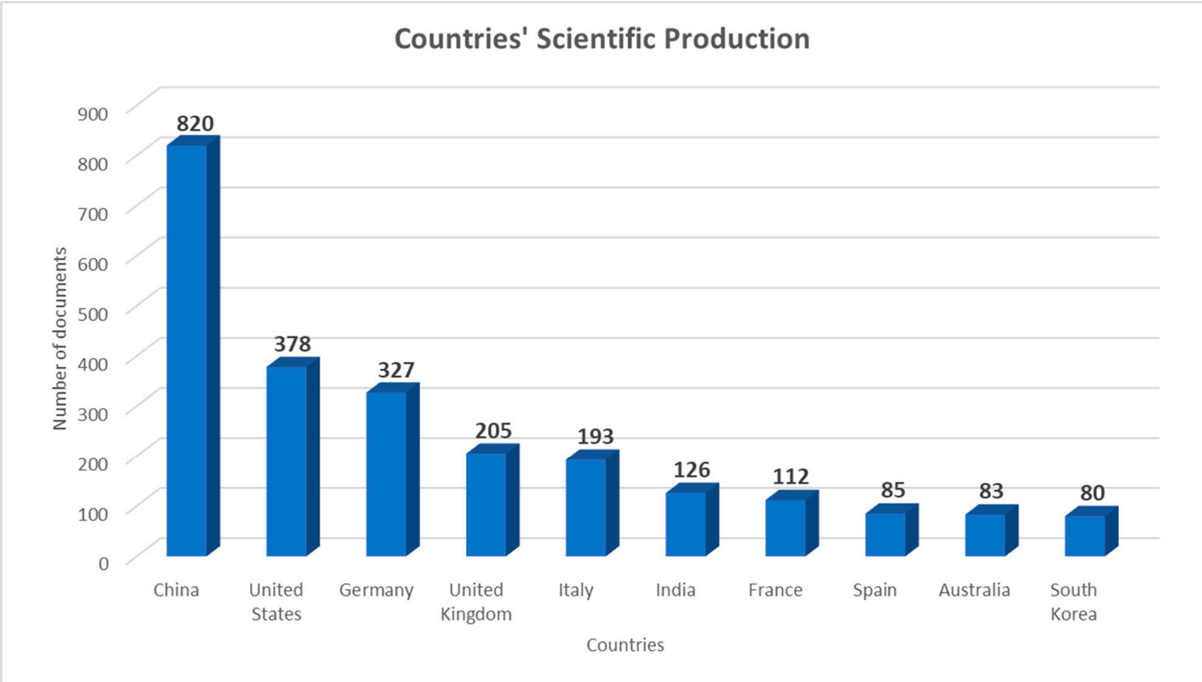

Figure 8. Top-10 countries that published the most over time.

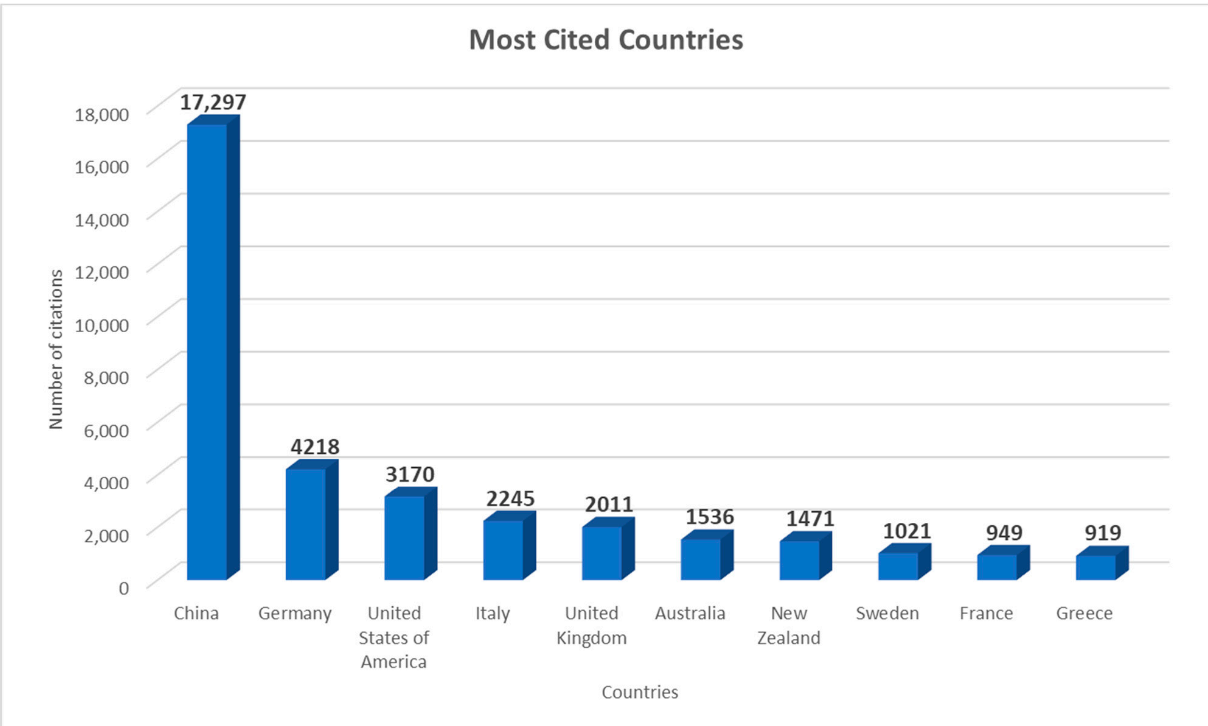

Figure 9. Top-10 countries that received the most citations.

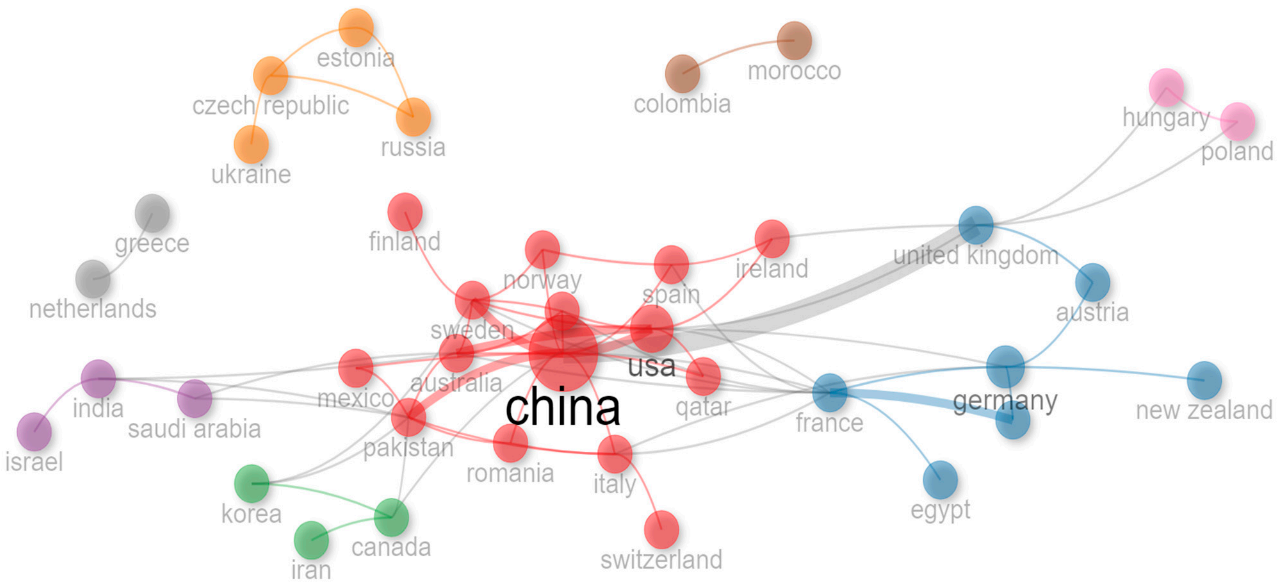

Figure 10. Country collaboration network.

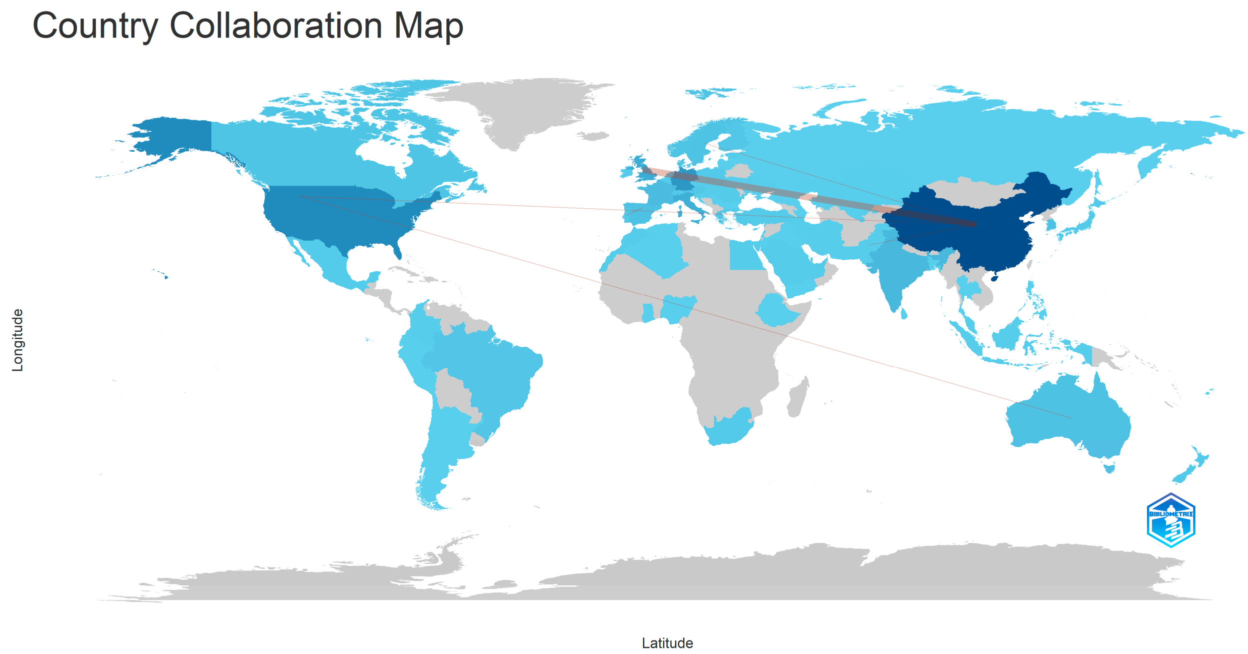

Figure 11. Country collaboration map.

4.6. Document Analysis

In the context of the document analysis, the most impactful documents, the keywords used, the trend topics, and the thematic evolution of the topic were explored. Table 5 presents the most impactful documents based on the number of global total citations they have received. The top-5 most impactful documents were: [68,72,85–87].

Table 5. Most impactful documents of the document collection based on the total number of citations they received.

Document	DOI	Total Citations	Total Citations per Year	Normalized Total Citations
[85]	10.1109/TII.2018.2873186	1785	297.5	27.01
[72]	10.1007/s00170-017-0233-1	1752	250.29	13.71
[68]	10.1016/j.ifacol.2018.08.474	1550	221.43	12.13
[86]	10.1016/j.ifacol.2015.06.141	1013	101.3	1
[87]	10.1109/ACCESS.2018.2793265	986	140.86	7.72
[88]	10.1109/ACCESS.2017.2756069	884	110.5	4.15
[89]	10.1016/j.rcim.2019.101837	782	156.4	22.53
[54]	10.1016/j.jmsy.2020.06.017	720	180	30.38
[90]	10.1016/j.procir.2016.11.152	710	88.75	3.33
[91]	10.1016/j.eng.2019.01.014	668	111.33	10.11

Various types of documents were included in this collection. The most common among them were: conferences/proceedings papers (49.85%), research articles in journals (39.81%), book chapters (5.04%), and review articles (4.19%). Due to the applicability of digital twins and the various categories of critical infrastructure, the large number of review studies in comparison to other topics should be highlighted. The keywords used can be categorized into author keywords and keywords plus. Although both categories of keywords can satisfactorily present the document knowledge structure of Scopus and WoS data, keywords plus results in a more representative depiction [92]. However, both categories of keywords are reported in this study. The frequency of the keywords plus used is presented in Figure 12 and the related co-occurrence network is displayed in Figure 13. Particularly in Figure 13, the nodes of the network map correspond to keywords plus, the lines that connect them represent their relationships, and the different colors reflect the clusters of keywords plus co-occurrence. In total, three main clusters are identified, with one of them being mostly related to digital twins and related key technologies (e.g., artificial intelligence, the internet of things, virtual reality, blockchain, etc.) and aspects, the other one being related to cyber-physical systems and manufacturing, and the third one being related to advanced monitoring, adapting, and decision-making methods. The most commonly used keywords plus were: “digital twin”, “cyber-physical system”, “industry 4.0”, “internet of things”, “life cycle”, and “decision making”. Figure 14 depicts the frequency of the author’s keywords while Figure 15 presents their co-occurrence network. Specifically in Figure 15, the nodes of the network map correspond to author’s keywords and the lines that connect them represent their relationships. In contrast to the three clusters identified when examining keywords plus co-occurrence, only one cluster of keywords was identified when exploring author’s keywords. This outcome is directly correlated with the use of more specific and targeted keywords by authors. Nonetheless, the interrelationship and interconnection of digital twins with other aspects and technologies, such as cyber-physical systems, blockchain, and the industrial internet of things, is clear. For example, digital twins are closely related to extended reality technologies (e.g., virtual reality and augmented reality) and the metaverse. Additionally, it supports the realization of Industry 4.0 and Industry 5.0 while also enriching manufacturing. It can integrate artificial intelligence and machine learning methods to further amplify its potentials and it can lead to the optimization of processes and to a positive digital transformation. The most commonly used author’s keywords were: “digital twin”, “industry 4.0”, “internet of things”, “machine learning”, “simulation”, and “artificial intelligence”. In addition, the relationship among countries, keywords, and sources is displayed in Figure 16.

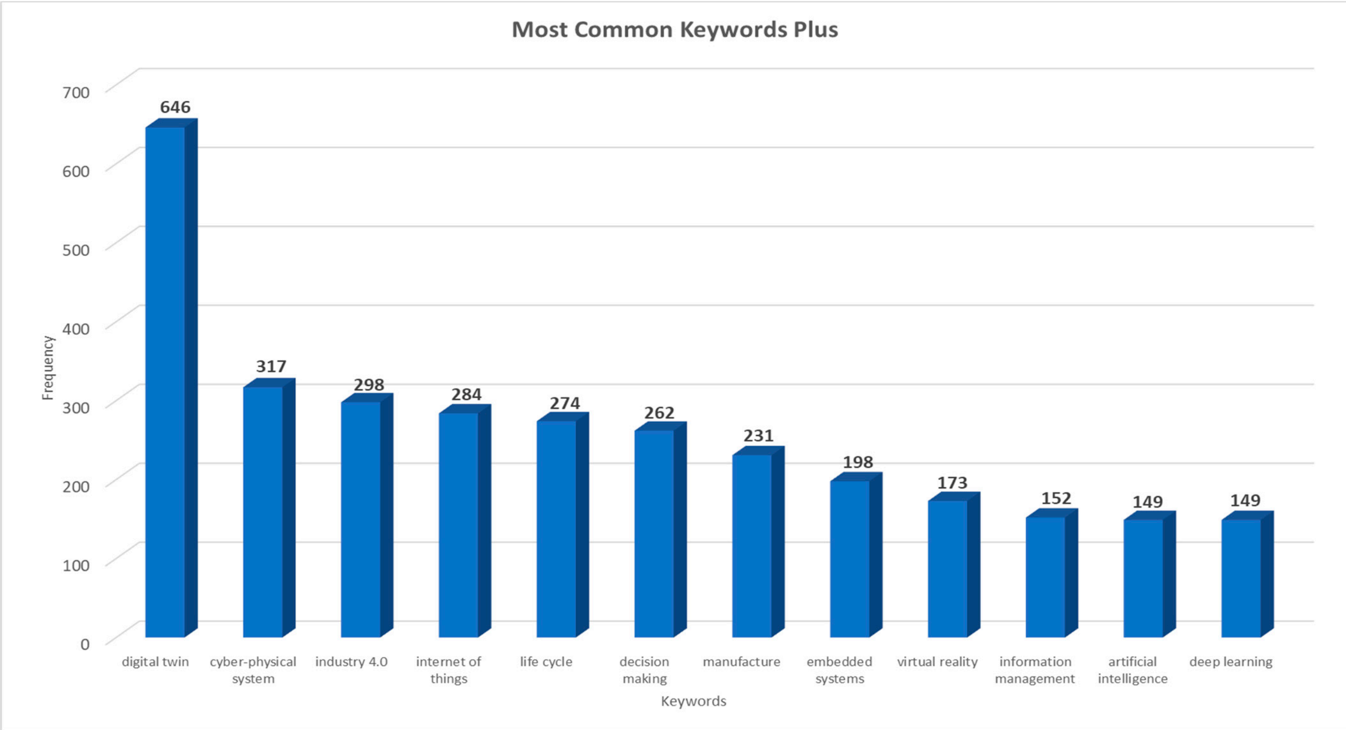

Figure 12. Most frequent keywords plus.

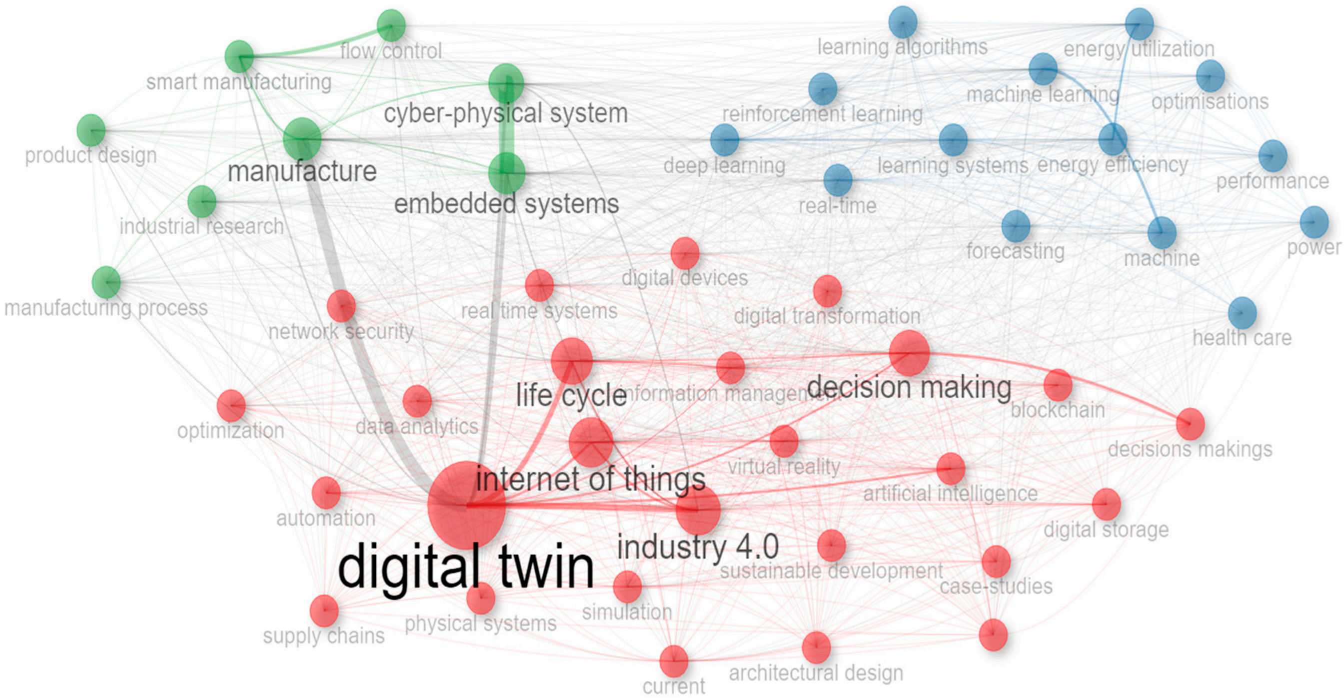

Figure 13. Keywords plus co-occurrence network.

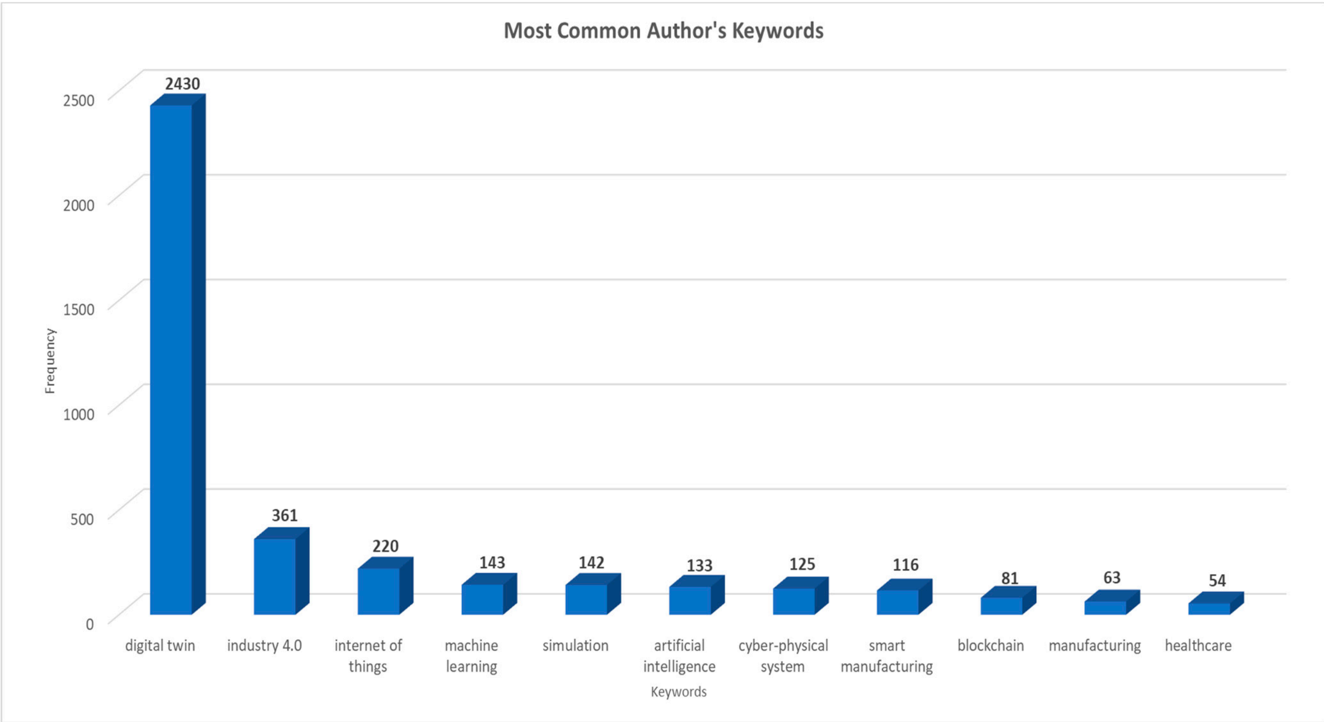

Figure 14. Most frequent author's keywords.

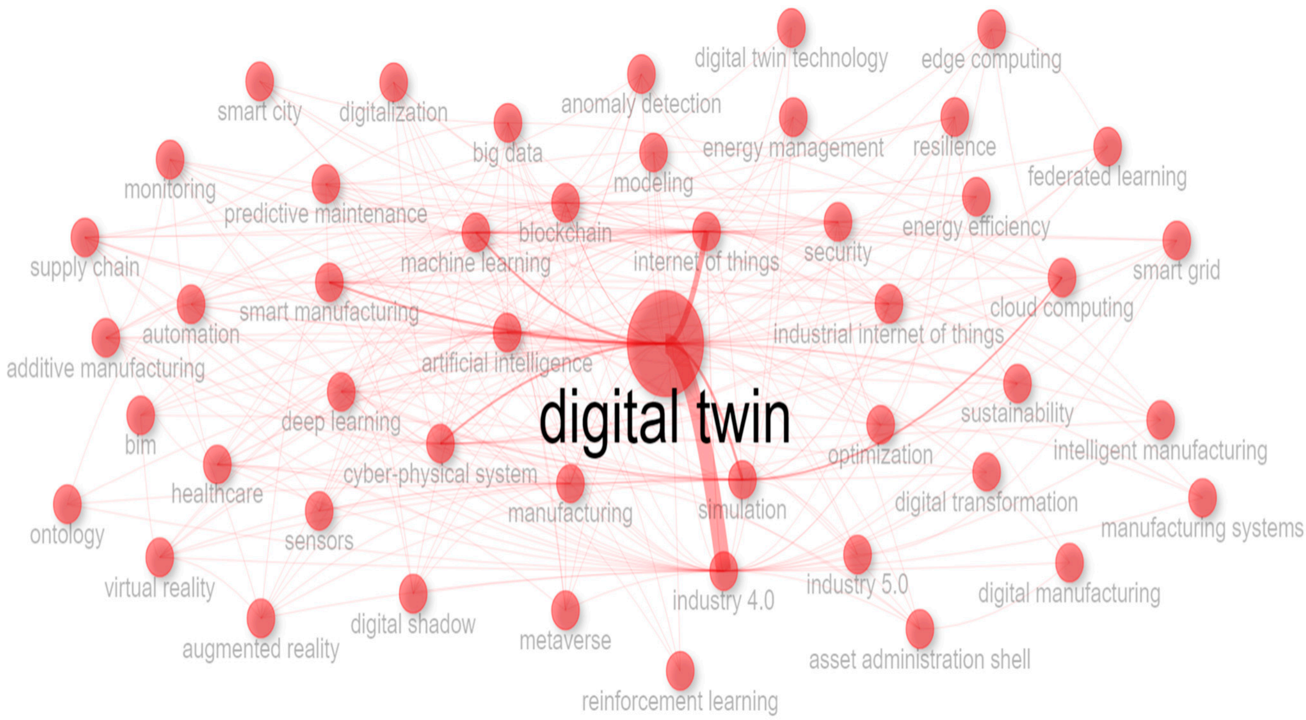

Figure 15. Author's keywords co-occurrence network.

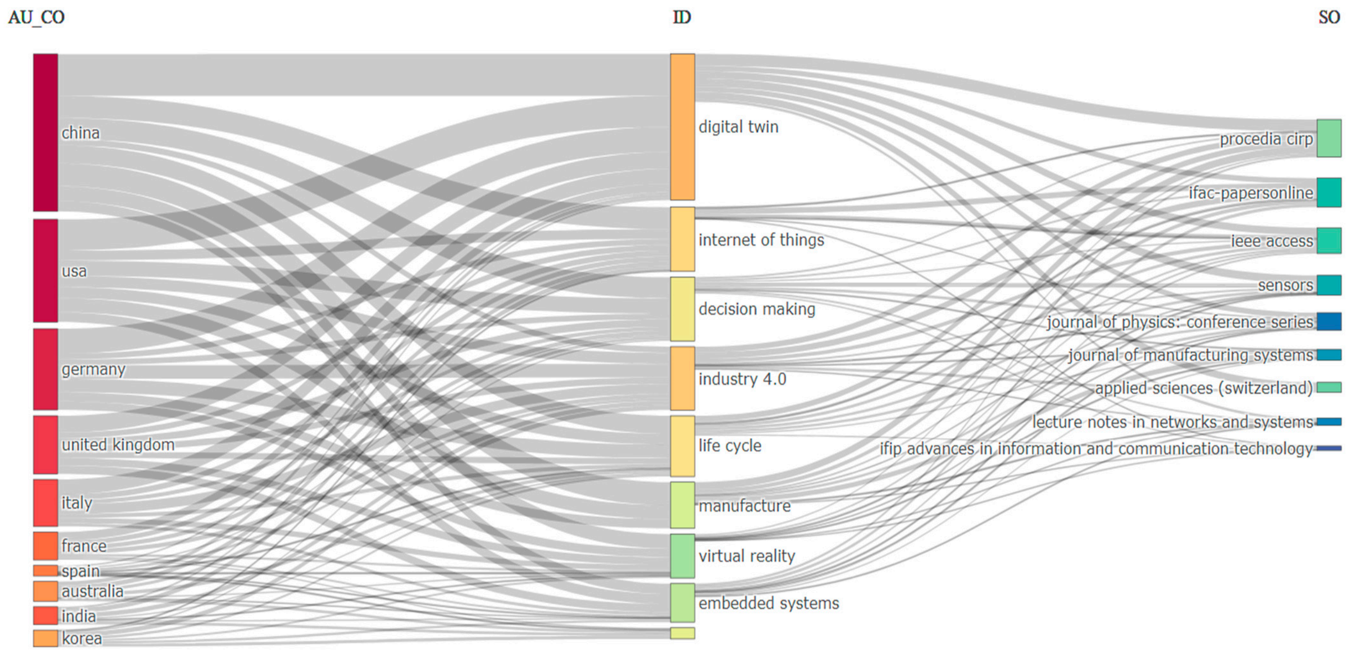

Figure 16. The relationships among countries, keywords, and sources source relationships.

Keywords were also used to examine the trend topics over the years as it can be seen in Figure 17 using keywords plus and in Figure 18 using author's keywords. Due to the distribution of the documents published, trend documents emerged over the period of 2018–2023. More specifically, the transition and convergence to cyber-physical systems, digital twins, and embedded systems is observed. Additionally, the focus on the role of digital twins in industry 4.0, artificial intelligence, and the internet of things was evident. Lastly, the emphasis on using digital twins in the context of blockchain, virtual reality, and the metaverse is observed. Using the global citation score as the impact measure, keywords plus as the coupling measure, and Walktrap as the clustering algorithm, the documents were clustered. In total, 3 clusters emerged (Figure 19), which were related to (i) the internet of things, Industry 4.0, and digital twins; (ii) life cycle, manufacture, and digital twins; (iii) cyber-physical systems, embedded systems, and digital twins.

Furthermore, given the breadth and diversity of the topic, its thematic structure was also explored as it can be seen in Figure 20. Four themes emerged in total. The first theme was related to the internet of things, energy utilization, real time, machine learning, and learning systems. The second theme involved digital twins, industry 4.0, life cycle, decision-making, and manufacture. The third theme referred to power, smart power grids, electric power transmission networks, power grids, and energy management, while the fourth one was related to architectural design, semantics, building information modeling, structural health monitoring, and three-dimensional computer graphics. The first two themes emerged as motor themes while the other two were categorized as emerging or declining topics. Due to the recency of the topic and given the distribution of published documents, the evolution of the topic over the years was examined during short time periods. In Figure 21, the thematic evolution is displayed. The applicability of digital twins in various domains and its potential to transform them throughout the life cycle of products, services, or assets are highlighted. The close relationship of digital twins with critical infrastructure and the industrial domain is evident. The focus on digital twins and their role in the energy domain in recent years is also highlighted.

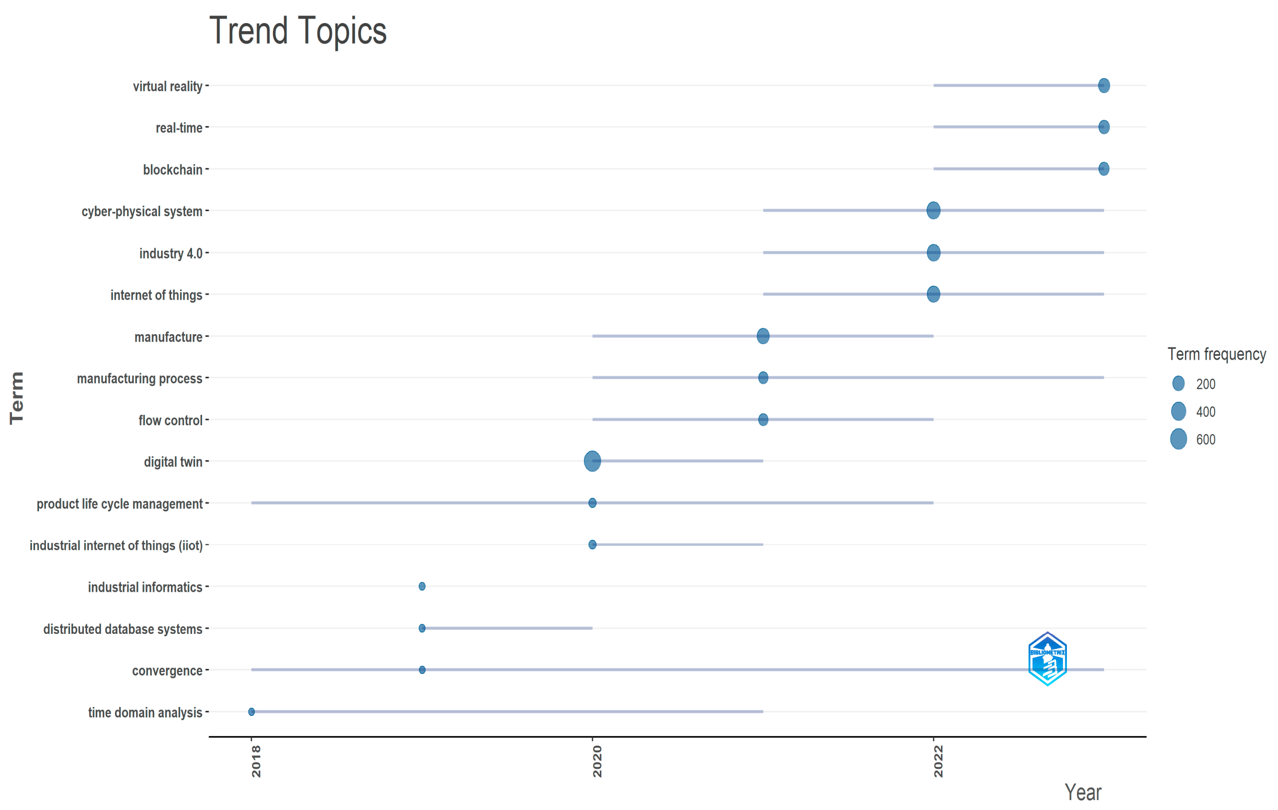

Figure 17. Trend topics based on keywords plus.

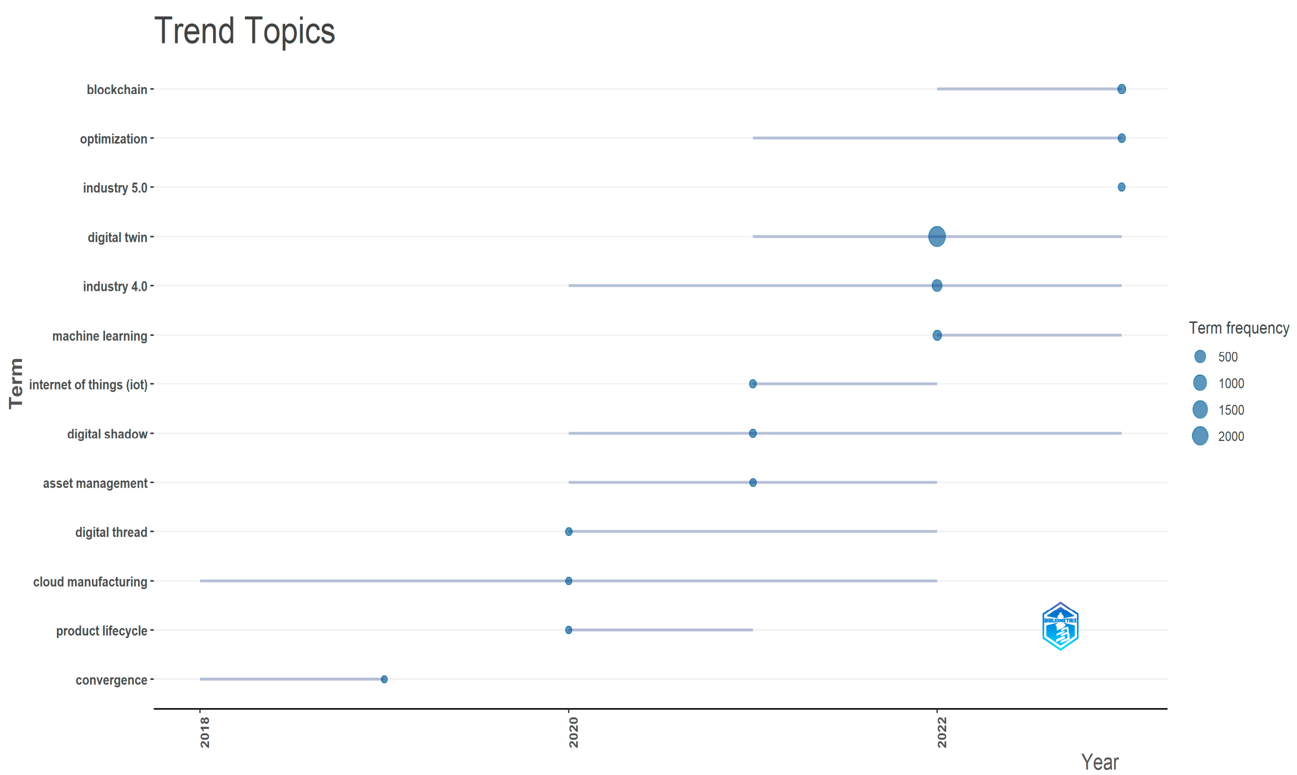

Figure 18. Trend topics based on author's keywords.

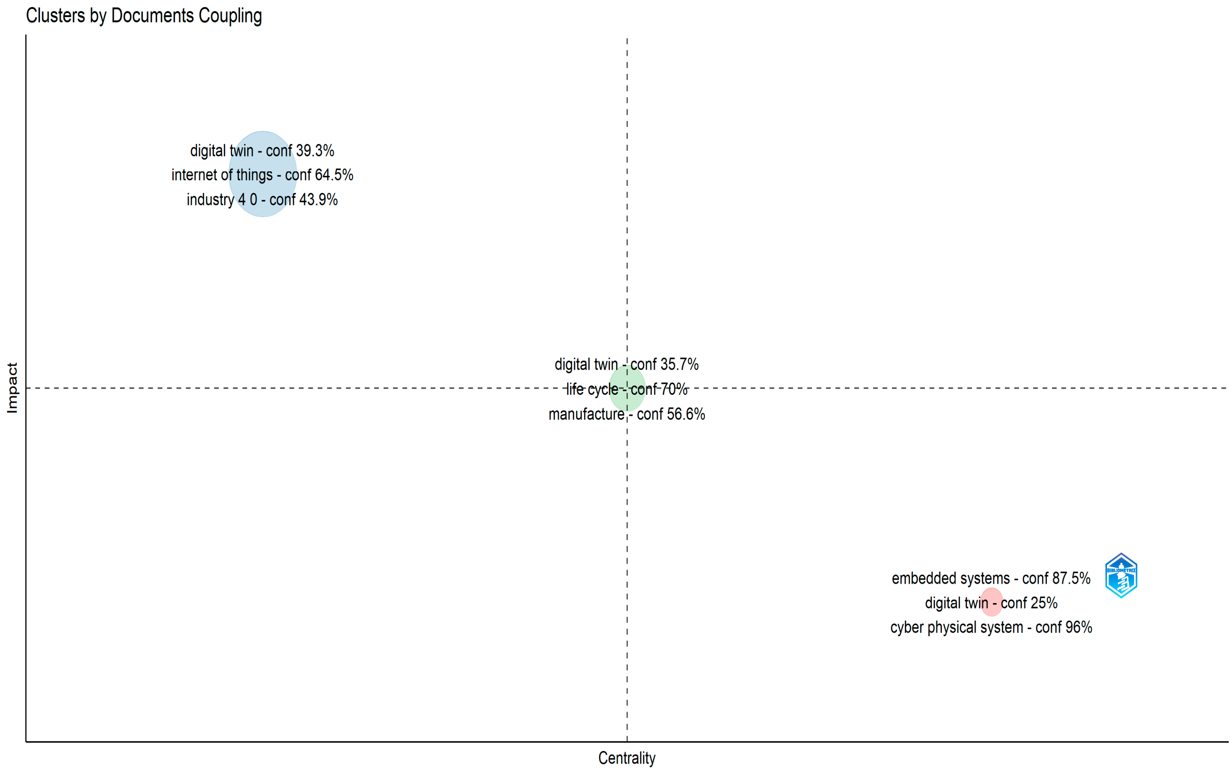

Figure 19. Documents clustered by coupling.

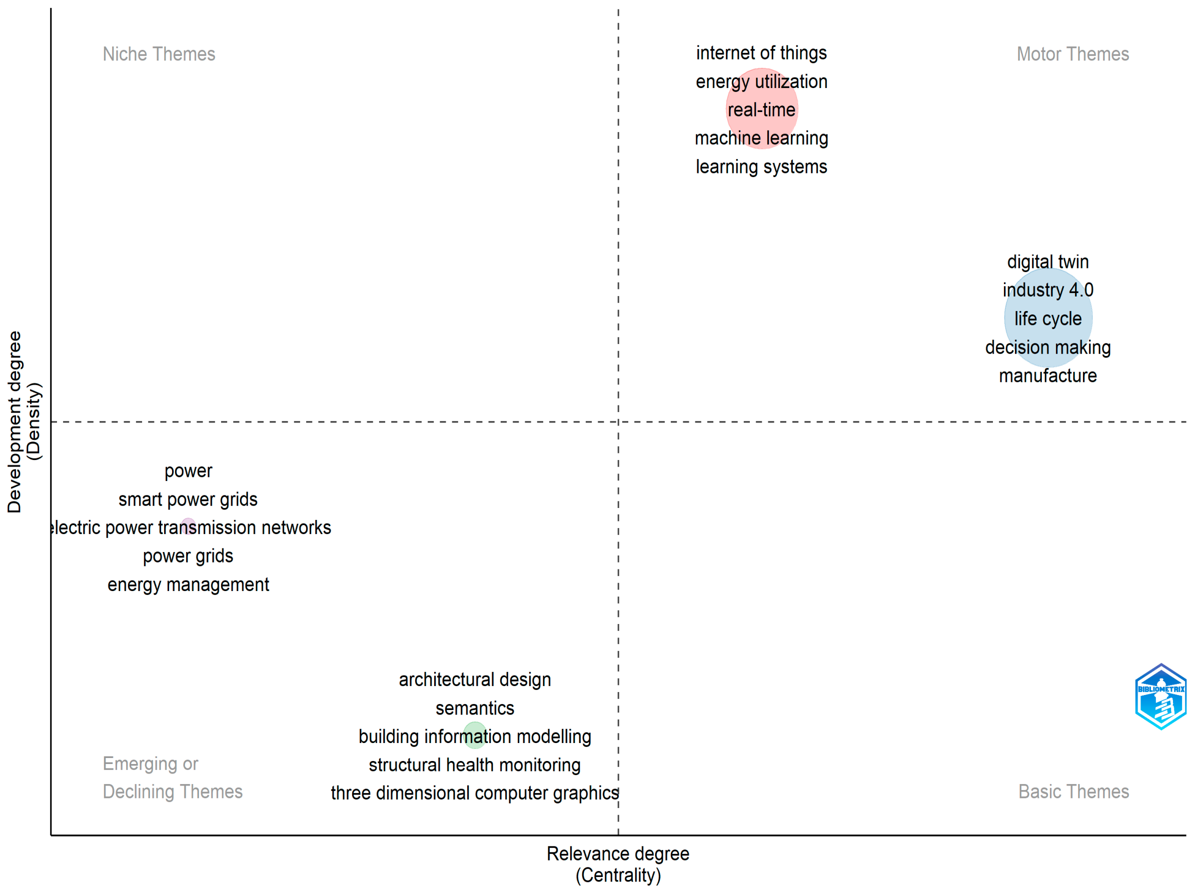

Figure 20. Thematic map of the topic.

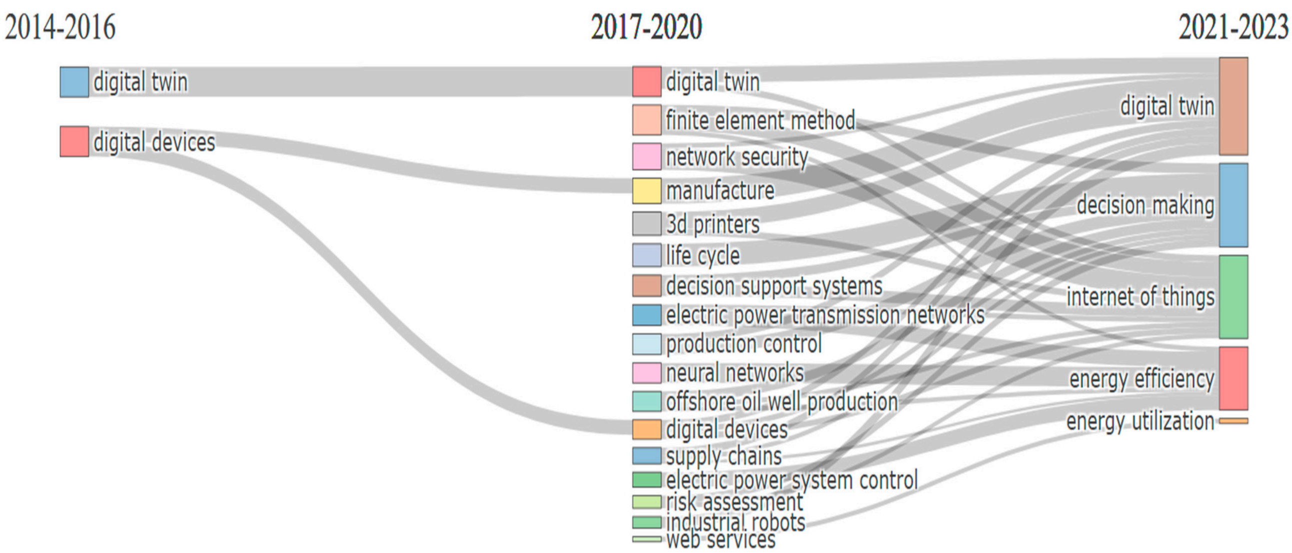

Figure 21. Thematic evolution of the topic.

5. Discussion

Ensuring the sustainability and security of critical infrastructure is imperative as they constitute a core aspect of society, communities, and well-being and a vital factor in achieving a sustainable future [1–5,10]. However, as technology advances, new cybersecurity issues and attacks arise which in many cases target critical infrastructure [7–9]. Since the interconnected and interdependent critical infrastructure [11] of the 16 broad sectors [16] consists of both virtual and physical assets, it is essential to enhance its resilience, security, and availability [3,6–8,10–13].

Digital twins are a novel solution that can potentially address crucial issues and increase the continuity, security, performance, and resilience of critical infrastructure in all 16 broad sectors [24,25,47,52] through their ability to provide autonomous and simulation-based decision-making, interactive visualization, and real-time predictions and monitoring [27,28,47,49–52,74], as well as to increase controllability, transparency, fidelity, and usability [25,55–58]. Being data-driven and consisting of software services and models [46], digital twins represent precise virtual copies of real-world entities with which they are in unison and focus on the interaction between the replica and the real entity [23–25,47,48,53]. Hence, they can enhance human-computer interaction [93] and play a vital role in shaping up smart city infrastructure [94]. Additionally, digital twins are closely related to Industry 4.0 and the internet of things [95,96]. However, there still remain several open challenges that need to be addressed for digital twins to be more widely used in industrial settings [97].

As this study involved a bibliometric analysis and scientific mapping of the literature, various aspects were explored, such as the document collection descriptive statistics and the citation, source, author, affiliation, country, and document analysis. The analysis initially involved 24,675 related documents from Scopus and WoS and after following the steps specified in the PRISMA statement as well as the inclusion and exclusion criteria set, the document collection examined was composed of 3414 documents which were published in 1447 sources. A total of 8827 authors from 75 countries contributed to this document collection which consisted mainly of conference/proceeding documents (49.85%), followed by research articles published in journals (39.81%).

To summarize the outcomes of this analysis, it is clear that the interest in this topic is constantly increasing. Although the overwhelming majority of documents were published in 2020 and afterwards, the recency and importance of the topic and the significance of integrating digital twins in critical infrastructure can be further justified by the average document age being 2.19 years, with the average citations for each document being 17.42, and the annual growth rate being 35.41%. When taking the h-index of each source into account, “Journal of Manufacturing Systems”, “Procedia CIRP”, “IEEE Access”, “Applied

Sciences (Switzerland)", and "IEEE Transactions on Industrial Informatics" emerged as the most impactful sources. When considering the total number of published documents, "Procedia CIRP", "Applied Sciences (Switzerland)", "IEEE Access", "IFAC-PapersOnLine", and "Sensors" were the top-5 sources with the highest number of documents published on the topic. It is worth noting that different types of sources are among the top which further justifies the scope and breadth of the topic.

The studies of Tao et al. [85], Tao et al. [72], Kritzinger et al. [68], Rosen et al. [86], and Qi et al. [87] received the most citations throughout the years. Specifically, the study of Tao et al. [85] looked into the role of digital twins and cyber-physical systems in the context of industry 4.0 and smart manufacturing and focused on comparing and correlating them. In another study, Tao et al. [72] looked into the use of big data within digital twin-driven product design, service, and manufacturing to create more intelligent, sustainable, and effective product life cycles. Kritzinger et al. [68] analyzed the role of digital twins in manufacturing while also examining the concepts of digital models and digital shadows through a categorical literature review. Rosen et al. [86] put emphasis on the significance of digital twins and autonomy in the realization of intelligent and sustainable manufacturing. Qi et al. [87] explored the use of digital twin services in the context of smart manufacturing as it can drastically transform several processes, such as design, usage, maintenance, repair, operations, and manufacturing.

Shanghai Jiao Tong University, China, Beihang University, China, The Hong Kong Polytechnic University, Hong Kong SAR, Nanyang Technological University, Singapore, and the University of Cambridge, the United Kingdom were the most prolific affiliations based on the number of published documents on this topic. Of the 75 countries whose authors contributed to this topic, China, the United States, Germany, the United Kingdom, and Italy were the countries with the highest number of published documents. When taking the total number of citations received into account, China, Germany, the United States, Italy, and the United Kingdom were the countries whose authors received the most citations. Although it is not possible to determine the development of critical infrastructure nor the implementation level of digital twins in critical infrastructure of each country based solely on the published documents, it is worth highlighting that authors from different countries across continents have focused on exploring this topic. This fact highlights the global significance of exploring different methods, tools, and approaches to improve critical infrastructure as they constitute an integral part of a functioning society. The topic and thematic analysis revealed the focus on integrating digital twins into various sectors and their capabilities to transform and enrich each domain. In addition, the gradual transition and convergence to cyber-physical systems, digital twins, and embedded systems across the involved sectors was observed. The use of digital twins in the context of artificial intelligence, the internet of things, industry 4.0, blockchain, virtual reality, and the metaverse also emerged. In each of the time periods and settings explored, the close relationship between digital twins, critical infrastructure, and the industrial domain was evident. The role of digital twins in transforming the power sector was also noticed.

In order to effectively integrate digital twins in critical infrastructure, there are several challenges and mission, safety, security, and time-critical issues that must be addressed [74,76,77]. Other issues involve challenges in simulation and modeling, in creating comprehensive architectures, as well as data and metric-related concerns [11]. Some of the open issues, whose solution would render the research on digital twins more coherent, are the development of innovative services, the unification of model and data standards, the creation of forums, and the open sharing of models and data [25]. In this context, there is a need for a more specific definition of digital twins that will cover the concept and use of digital twins in different application domains [28,85,89]. Due to the potential of digital twins being integrated into critical infrastructure, different domains, and industries, universal, common, holistic, and refined techniques, approaches, strategies, and regulations for security and data sharing must be developed [8,28]. Other open issues in securing critical infrastructure involve security, trust, privacy, and governance management, designing effective and secure network and communication channels, advancing self-healing, simulation, decision-making, modeling, and situational awareness [3]. On that note, it is important to develop appropriate evaluation and resilience metrics and reference models and conduct concrete case studies [28,68,98]. Additionally, the recent advances in generative artificial intelligence highlight its potential to further enhance the capabilities of digital twins as well as to empower and transform critical infrastructure systems [99–103]. Despite this fact, little is known regarding the impact of generative artificial intelligence in critical infrastructure and digital twins as well as the most optimal methods and approaches to integrate it in various sectors while reinforcing cybersecurity and improving performance, resilience, sustainability, and reliability. Hence, to increase the effectiveness and security of critical infrastructure and to better comprehend the potentials of integrating digital twins in various domains, future research should focus on further examining these challenges, open issues, and research directions and improving the efficiency, capabilities, processes, and accuracy of digital twins. Moreover, there is a need for meta-analysis studies to be conducted to examine the different types of digital twins used across critical infrastructure, to identify specific challenges associated with their integration and use, as well as to analyze and compare the specifications of integrating digital twins in different critical infrastructure sectors. Finally, it is important to examine in more detail how key aspects within critical infrastructure, such as resilience, reliability, security, continuity, functionality, and maintenance, can be affected when adopting and integrating digital twins.

6. Conclusions

Critical infrastructure plays a vital role in modern society and communities as well as in well-being and a sustainable future. Hence, ensuring the effective operation and security of critical infrastructure is essential. Due to their nature and capabilities, digital twins can be integrated into critical infrastructure to further improve their security and efficiency. Therefore, this study aimed at providing an overview about the adoption and integration of digital twins in critical infrastructure. Particularly, this study involved a bibliometric analysis and systematic mapping of the existing literature. The use of two databases and the inclusion of documents written only in English can be regarded as the main limitations of this study.

The analysis revealed 3414 related documents that were published in 1447 sources from 2014 to 2023. Most of the documents were published in conferences/proceedings or scientific journals. Some of the documents were in the form of book chapters or review articles. Only a few documents were editorials or books on the specific topic. In total, 8827 authors from 75 countries contributed to the creation of the documents and an international co-authorship rate of 13.18% was identified. The fact that authors from different countries across continents have collaboratively focused on exploring this topic further highlights its impact and the importance of improving critical infrastructure as they are vital parts of society. Additionally, the most productive and impactful sources, authors, affiliations, and countries were identified. The evolution, the trends, and thematic map of the topic were also examined and revealed the current state of the use of digital twins in critical infrastructure.

All in all, it can be inferred that critical infrastructure is closely related to technological advancements and digital twins are no exception to that. When integrated into critical infrastructure, digital twins can offer several benefits, such as advanced traceability, autonomous decision-making, real-time monitoring, analysis, and prediction, process optimization, increased productivity and user satisfaction, improved product quality, reduced risks, and time constraints. Hence, although there still remain open challenges and issues that must be addressed, digital twins, due to their overall capabilities and their ability to bridge the virtual and real environments, have the potential to increase the security, resilience, reliability, maintenance, continuity, and functioning of critical infrastructure in all sectors.

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