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Application of Digital Twins and Building Information Modeling in the Digitization of Transportation: A Bibliometric Review

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Abstract: The industrial transformation led by digitization-related technologies has attracted research attention in recent decades, enhancing its application in different sectors. The transport industry is a crucial driving force for economic growth and social development. It is still necessary to make transportation infrastructure and services safer, cleaner, and more affordable to cope with increasing urbanization and mobility. This paper systematically examines the science mapping of building information modeling and digital twins technologies in the digitalization of transportation. Through the bibliometric and content analysis approaches, 493 related documents were screened and analyzed from the Web of Science and Scopus databases. The software programs VOSviewer and Bibliometrix were used to determine research trends and current gaps, which will be beneficial to future research in this vital field. The results showed that over 80% of the relevant documents have been published since 2018. China is the most productive country, followed by the United States and Italy, and Germany is the most cited and influential country. Moreover, research also revealed the leading authors, top journals, and highly cited papers. The findings may be used as a guide for: (1) improving the efficiency of intelligent transportation system element management; (2) the development and application of digital technologies; (3) the flow and goals of entire-life-cycle management; and (4) the optimization of related algorithms and models.

Keywords: building information modeling; digital twins; bibliometric analysis; research areas; applications; emerging technologies; development directions

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1. Introduction

Since the beginning of the 21st century, the application of new technologies has opened the door to the digital world. Nowadays, digital capabilities have been integrated into specific areas of people's daily lives, as well as having transformed and modernized different industries. The transportation industry is essential to every country's economy, security, and well-being. There is a critical need for more efficient and cost-effective technologies in order to keep up with the growing population [1]. As represented by building information modeling (BIM) and digital twins (DTs), digital technologies can bridge the gap between the real and virtual worlds from a spatial–temporal perspective. Moreover, they also have the potential to transform infrastructure and industry sectors such as manufacturing, production, transportation, and construction [2].

Digital technologies are affecting transportation in a similar way to other industries. More data means potentially better data-processing capability, which leads to improved decision-making as a result. The transportation industry contributes significantly to urban development. Currently, as smart cities are being constructed, the digitalization of transportation plays a crucial role in improving the economy, social well-being, and the environment [3]. It also directly impacts people's travel behaviors and lifestyles [4,5].

Roads are one of the central elements of transport systems, and governments have invested significant financial resources to develop and improve their road networks. As a result of digitalization, transportation infrastructure is being built, operated, and financed in new ways, having a profound impact on the entirety of its life cycle. Furthermore, digitalization provides an insightful direction for city development in the future. The joint usage of advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), blockchain (BC) technology, cloud computing (CC), and sixth-generation (6G) networks has led to the in-depth application of BIM and DTs [6,7]. Both play a crucial role in building life-cycle management. Among them, BIM simplifies the construction process for smart buildings. By using DTs, sectors can schedule work more efficiently, making complex spaces easier to manage [8]. They make the whole process easier, from conception to operation and maintenance. Digital technologies provide scientific and technological empowerment for intelligent transportation development while also boosting the transportation industry's transformation and upgrading [9].

BIM can inform early design decisions on project feasibility, energy analysis, and sustainability issues, and it can act as a pre-construction guide; BIM technology can also provide visual, 3D communications for DTs [10]. As for digital twin technology, it is a digital representation of an asset, process, or system in an infrastructure or natural environment that is as accurate as possible [11]. The respective features of BIM and DTs are compared in detail in Figure 1. Although BIM and DTs have different concepts and stages of development, they can both provide an important contribution to the intelligent and dynamic development of the transport construction industry [12].

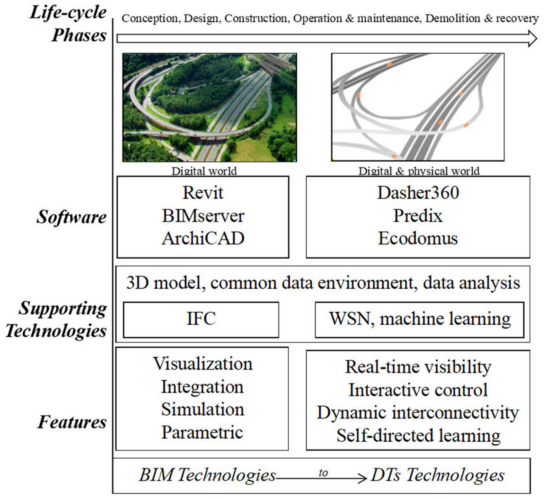


Figure 1. Research Objects.

Digital technologies have been regarded as the key to solving urbanization issues in smart cities for the past few years. Unfortunately, digitalization has become a buzzword or, even worse, an empty term used by vendors to sell expensive equipment and services to make any infrastructure, or even entire cities, "smart." This has led to a great deal of confusion. To address this issue, it is necessary to (1) identify the key elements of digital transformation and (2) ask and answer the question: what should infrastructure participants do to maximize the benefits of new technologies? These are important topics. Meanwhile, as academics and industries become more interested in the digitization of

transportation, this review examines more meaningful information that can be used to summarize the current intellectual structure.

This paper conducts a bibliometric analysis to assess the implementation of digital technologies like BIM and DTs. It provides long-term-interested scholars and policymakers with a vast amount of highly relevant literature, allowing them to gain a deeper understanding of transportation digitization's major challenges. To achieve the study's objectives, the literature review that has been described in this paper undertook and examined three research questions: (1) How have digitization technologies affected scientific publications in the transportation industry, and what information has been obtained from these changes? (2) How are BIM and DTs used in this field to represent digital capability in terms of transportation, and what countries, affiliations, or specialists are discussing this topic? (3) What are the current research gaps, and what are the most promising trends?

The sections of this review are arranged as follows. Section 2 elaborates on this review's methods, materials, and scope. Results are stated and interpreted in Section 3, which is the bibliometric analysis from the perspective of the two representative digital technologies' applications in the transportation industry. Section 4 discusses the main evolution of digital transportation and future directions. Lastly, there is the conclusion, which presents the main implications and research gaps.

2. Materials and Methods

The traditional methods of reviewing and evaluating related publications are meta-analysis and the systematic literature review. Both methods have analyzed the trend and direction of related research from a qualitative point of view in the transport [13] and logistics sectors [14]. These are both compelling methods, but they are limited in nature and breadth of study. With the development of the Information Age, quantitative analysis based on data is increasingly used in various fields. The science mapping approach, which is mainly bibliometric, is able to analyze research networks and trends, greatly deepening the breadth of research. To gain a better understanding of the latest research in transportation digitization, a bibliometric method was used as part of the study [15]. Furthermore, various methods, including keyword analysis, content analysis, and bibliographic coupling and clustering, are innovatively integrated to support the review.

Nowadays, researchers are increasingly using bibliometric analysis for science mapping to present a comprehensive overview of the knowledge structures in multiple scientific fields. The bibliometric analysis is used to delineate the science underlying the conceptual structure of science, dynamics, and paradigm developments in this review [16]. It can also handle large volumes of publications more efficiently than traditional literature reviews, which are based on statistical measures.

Figure 2 illustrates the overall framework design of this research, corresponding to the research questions and expected steps. The search protocol for data collection and analysis methods are explained in the following sub-sections.

2.1. Search Protocol: Data Collection Process

Previous studies have indicated that an appropriate search protocol is crucial to collect as many relevant and reliable research publications as possible [17]. In this regard, the necessary steps are (1) selecting a reliable database with sufficient coverage; (2) formulating a well-defined search query; and (3) identifying the publications to be included and excluded for quality of bibliometric reviews.

Taking the transportation industry into account for our study, we focus on how BIM and DTs technologies are applied to digital transformation. In addition, the Web of Science (WoS) Core Collection citations and Scopus databases were considered as the main databases for conducting this review [18]. The initial run of the search query on the topics of the publications (based on title, abstract, keywords, and keywords plus) returned 1081 articles. Then, based on the checking rules, 721 related papers were screened. Lastly, we manually checked the titles and abstracts of the remaining publications to see if they

were relevant to the topic. On this basis, 164 papers that had mainly focused on other topics were excluded from the sample. Data collection was completed on 20 July 2022 and was updated on 17 August to avoid data source deviation due to the publication of new papers. Records were exported as plain text files and tab-delimited files using the "full records and cited references" option. The search database, search query, and results are shown in Table 1.

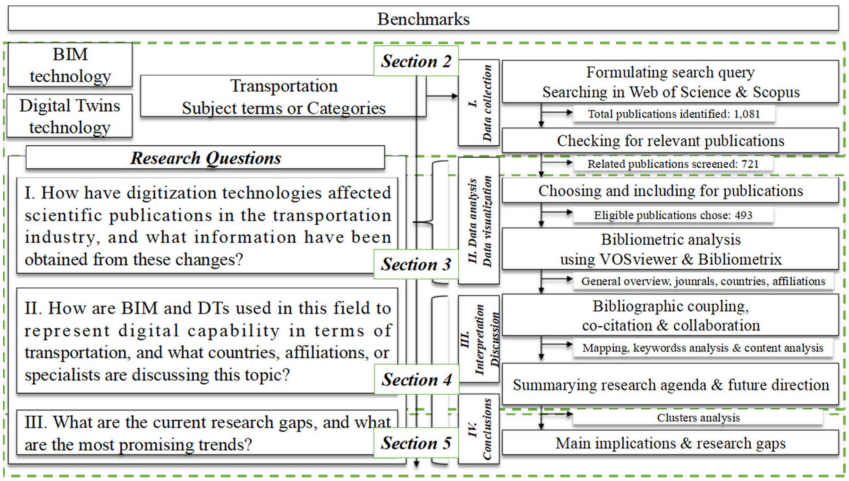


Figure 2. Research framework design.

Table 1. Collecting the final data results for analysis.

Database	Search Query	Results
Scopus	(TITLE-ABS-KEY ("digital twin*")) AND SUBJTERMS (3313)	74
	(TITLE-ABS-KEY ("BIM") OR TITLE-ABS-KEY ("building information modeling")) AND SUBJTERMS (3313)	220
Web of Science	"digital twin*" (Topic) and Transportation Science Technology or Transportation (Web of Science Categories)	65
	"BIM" (Topic) or "building information modeling" (Topic) and Transportation Science Technology or Transportation (Web of Science Categories)	139

* replacing multiple characters in a word (e.g., digital twin* returns digital twin, digital twins, digital twinning).

As a result, we chose 493 (five duplicate papers were removed) papers published between 2008 and August 2022 that were eligible for the review. Figure 3 shows the number of publications in the WoS and Scopus databases, respectively. Over the past few years, there have been fluctuating increases in the number of annual publications. 2021 already marked the peak. Moreover, the digitalization of transportation research based on digital twin technology and BIM technology is still an active research hotspot.

2.2. Analysis Methods

By using descriptive analysis, keyword analysis, content analysis, and bibliographic coupling analysis, a bibliometric review of the transportation digitization literature was conducted in three steps.

Firstly, a descriptive analysis was performed to provide a general overview of the performance of publications in the field of digitization transportation, including main information about data, document contents, and document types, addressing RQ1 and RQ2. Moreover, the leading journals, authoritative conferences, top specialists, contribution and collaboration information of countries, and affiliations were extracted from the target literature. The data cleaning for whole keywords was a critical step before conducting a keywords-based analysis, improving the analysis's reliability [19]. As a result, we have the following settings: (1) abbreviations of keywords are merged with the full form; (2) the

singular and plural forms of keywords are considered the same; and (3) brackets inside keywords are removed.

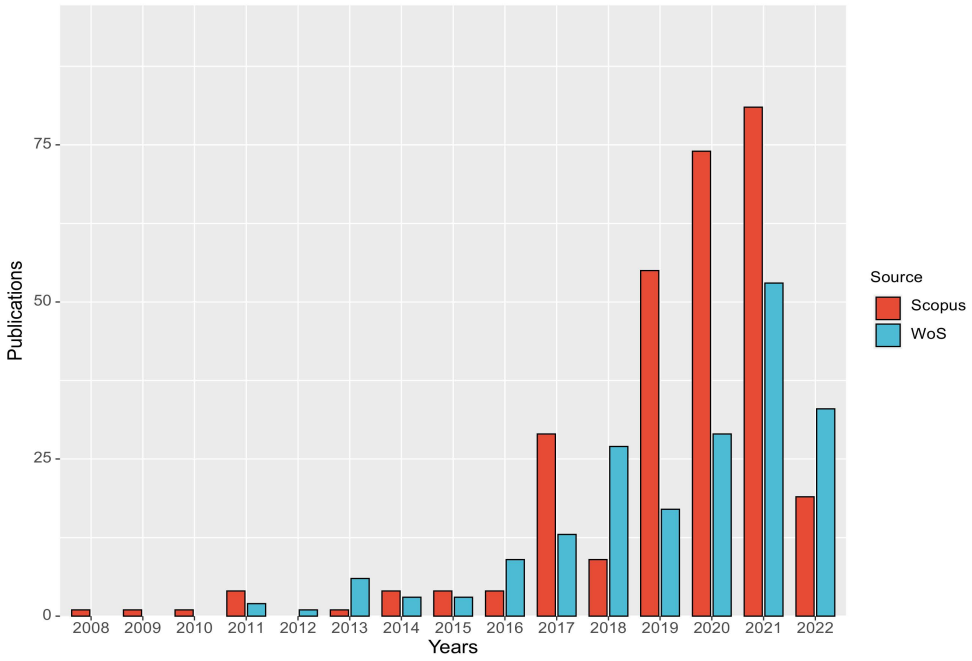


Figure 3. Annual Publications in the WoS and Scopus.

As the second step, we perform a keyword analysis using the Author's Keywords (n = 1537) and Keywords Plus (n = 1703) of the papers, combined with content analysis of the titles and abstracts of whole papers (n = 493) to discover the current research hotspots and research trends of the digitalization of transportation research and to formulate a theoretical basis for solving RQ2. The author's keywords represent the research's core concepts [20]. Keywords Plus data were used to supplement the clarification. The Bibliometrix R-Tool is designed to perform comprehensive science mapping analysis [21]. Nevertheless, further study of the text information of the papers can be conducted to enrich the knowledge obtained from keywords-based analysis [22] to gain more insights into the topics explored by the researchers. Researchers are using content analysis to find scholars' research tendencies and directions by analyzing large volumes of scientific literature and extracting context and meaning from texts [23]. From the titles and abstracts of papers, content analysis offers the possibility of extracting meaningful terms and patterns. Content analysis aims to identify phrase patterns, semantic structures, and potential research directions in existing transportation digitization research. Therefore, the VOSviewer software version 1.6.18 is used for content analysis to visualize relevant terms extracted from the scientific documents [24].

Finally, the data clustering technique is used to discover emerging themes in digitization of transportation research through bibliographic coupling networks. As a result of machine learning algorithms [25], four clusters are produced. Based on these analytical results and insights, potential directions for future research on transportation digitization are suggested to answer RQ3.

3. Results

3.1. Descriptive Analysis: Publication Development

Section 3.1 provides a descriptive analysis of the digitization of transportation research, including the evolution of publications over time, leading journals, authoritative conferences, and top specialists. Most importantly, national and institutional sources of contributions and collaborations are included. This section addresses RQ1 of this study.

3.1.1. General Overview

Figure 3 shows the trend in the number of papers published in the field of digitization of transportation using BIM and DTs technologies. As can be seen in Tables 2 and 3, the first paper published in Scopus dates back to 2008, while WoS saw its first such paper published in 2011. The number of published papers in the two databases from 2008 to 2016 remained between 0 and 10 per year, but in 2017, this number more than tripled. Continuous growth started in 2011 (except in Scopus for 2018) and, through an exponential increase, the number of published papers in the year 2020 reached 134.

Table 2. Main information of Scopus's publications.

Main Information about Data		Document Contents		Document Types	
Timespan	2008:2022	Keywords Plus (ID)	1477	Article	73
Sources	79	Author's Keywords (DE)	952	Book chapter	48
Documents	287	Authors	804	Conference paper	147
Annual growth rate %	23.41	Authors of single-authored docs	37	Review	13
Doc average age	2.62	Single-authored docs	44		
Average citations per doc	8.564	Co-authors per doc	3.33		
References	8097	International co-authorships %	12.5		

Table 3. Main information of Web of Science's publications.

Main Information about Data		Document Contents		Document Types	
Timespan	2011:2022	Keywords Plus (ID)	226	Article	80
Sources	89	Author's Keywords (DE)	585	Early access	10
Documents	206	Authors	662	Conference paper	113
Annual growth rate %	29.03	Authors of single-authored docs	14	Review	3
Doc average age	2.65	Single-authored docs	14		
Average citations per doc	7.024	Co-authors per doc	3.67		
References	5502	International co-authorships %	23.3		

Continuous growth in WoS started in 2011 (except for 2016) and, through an exponential increase, the number of published articles in the year 2020 reached 125. The leap between 2017 and 2021 is also noticeable, probably because many countries issued guidance documents and standards aimed at promoting the application of BIM and DTs technologies in the transportation industry that would sharply boost the number of digital transportation subscribers around the world. The number of published articles only in the first half of 2022 (from 1 January to 20 July) was 52, which is expected to lead to a higher record than in 2021 by the end of the year. Therefore, this field seems to be in its expansion period. Other main information (like main information about data, document contents, and document types) from Scopus and WoS can be seen in Tables 2 and 3. It also gives some interesting indicators (Scopus in front, WoS in back) of the digitization technologies in transportation-related papers, which indicate the publication annual growth rate (23.41%, 29.03%), international co-authorships (12.5%, 23.3%), and average citations per document (8.564, 7.024).

3.1.2. Leading Journals, Authoritative Conferences, and Top Specialists

A total of 168 sources contributed to the publication of whole papers in the studied field. It was listed among the top 10 journals and conferences, as shown in Figure 3. These relevant sources have a total of 377 papers, including 217 journal articles and 60 conference papers, which is about 56.19% of the publications in our sample.

Figure 4 also shows the top 10 journals and conferences, such as *Computer-Aided Civil and Infrastructure Engineering*, *Transportation Research Procedia*, *IEEE Transactions on Intelligent Transportation Systems*, *The Journal of Advanced Transportation*, *The China Journal of Highway and Transport*, *The Transportation Research Record*, The COTA International Conference of Transporta-

tion Professionals, etc., directly focusing on the transportation field of study. The other sources are focused on sustainable cities, the built environment, and engineering infrastructure.

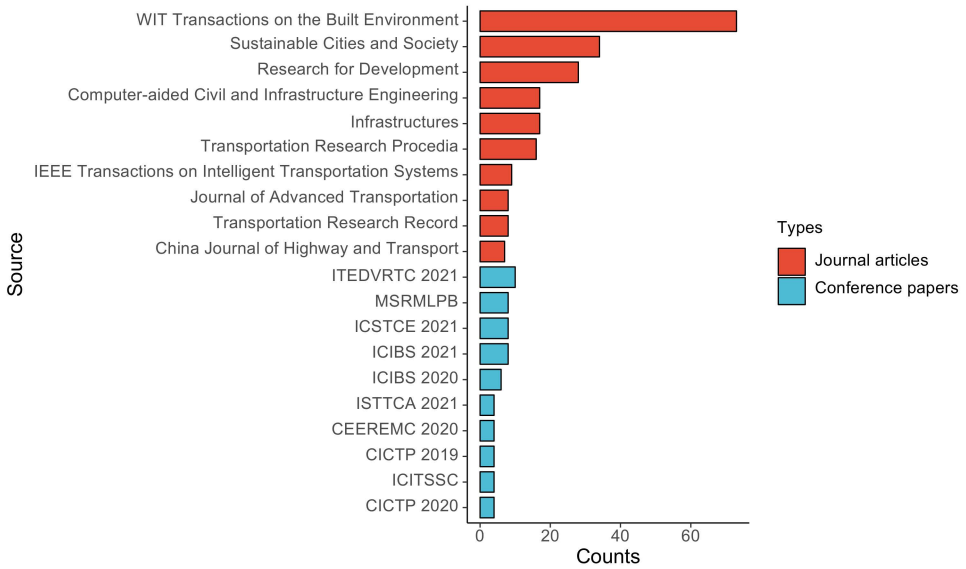


Figure 4. Most Relevant Journals and Conference Sources.

We also list the top 15 most locally cited sources from all the reference lists. It was found that 18 journals or proceedings, as listed in Table 4, had been cited at least 50 times as of July 2022. *Energy and Buildings* (Q1, CiteScore 11.5, impact factor 7.201), *Advanced Engineering Informatics* (Q1, CiteScore 10.1, impact factor 7.862), and *Computer-Aided Civil and Infrastructure Engineering* (Q1, CiteScore 17.2, impact factor 10.066) are the most popular journals for scholars related to BIM and DTs technologies. These journals especially focus on recent improvements in computer and information technologies. They also encourage the development and use of emerging computing paradigms and technologies, with a focus on knowledge and engineering applications.

Table 4. Most Locally Cited Sources in the WoS and Scopus (from Reference Lists).

No.	Journals	Papers Cited
1	*Energy and Buildings*	308
2	*Advanced Engineering Informatics*	91
3	*Computer-Aided Civil and Infrastructure Engineering*	83
4	*IEEE Access*	81
5	*Journal of Cleaner Production*	78
6	*Building and Environment*	76
7	*Sustainable Cities and Society*	75
8	*International Journal of Production Research*	74
9	*Journal of Computing in Civil Engineering*	65
10	*Journal of Construction Engineering and Management*	59
11	*IEEE Intelligent Transportation Systems Society*	57
12	*Journal of Management in Engineering*	55
12	*Transportation Research Procedia*	55
12	*Procedia Engineering*	55
13	*Vehicle System Dynamics*	53
13	*Transportation Research Part C-Emerging Technologies*	53
14	*IEEE Transactions on Industrial Electronics*	51
15	*Renewable and Sustainable Energy Reviews*	50

Table 5 shows the local impact of authorship. Within the top three, we find that the author Salvatore Antonio Biancardo from Italy has published seven scientific works related to BIM in road design [26] and modeling [27], railway design [28], and the expansion of

airport facilities [29]. These four works have each received at least five citations, so they have an H-Index of 5. Biancardo received 64 total citations. He is followed by the authors Di Giuda and Paleari, both with an H-Index of 4 and the same total citations of 31. Farzad Jalaei has contributed many interesting and influential research works, with the highest citation count of 292, including analyses of entire-life-cycle costs from the conceptual stage [30], full-life-cycle environmental impacts to manage waste [31], development of integrated multi-technology systems for the conceptual design phase of buildings [32], and cost estimation of building projects [33]. Farzad Jalaei's research began in 2015, mainly focusing on sustainable design and life-cycle assessment.

Table 5. Top 10 Specialists' Local Impact in the WoS and Scopus.

No.	Author	h_index	g_index	m_index	TC	NP	PY_start
1	Biancardo Sa	5	7	1	64	7	2018
2	Di Giuda Gm	4	5	1.333	31	5	2020
3	Paleari F	4	5	1.333	31	5	2020
4	Schievano M	4	5	1.333	31	5	2020
5	Viscione N	4	5	1.333	39	5	2020
6	Jalaei F	4	4	0.5	292	4	2015
7	Daniotti B	2	2	0.667	5	3	2020
8	Giana Pe	2	3	0.667	9	3	2020
9	Oreto C	2	3	0.667	9	3	2020
10	Wang Zr	2	2	0.333	5	3	2020

3.1.3. Contributions and Collaborations of Countries and Affiliations

Forty-nine countries or territories contributed to the digitization of transportation literature in the WoS and Scopus databases. The collaboration of countries is illustrated in Figure 5.

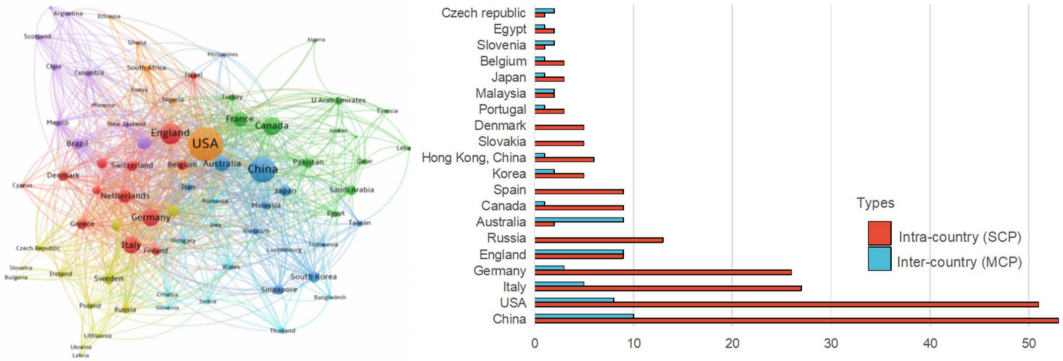


Figure 5. Collaboration of Countries. Intra-country (SCP) and Inter-country (MCP) Collaboration of Top 20 Countries or Territories.

The sizes and colors of the countries are based on their numbers of publications and their collaborating groups. Those with the highest numbers of publications are China (63), the United States (59), Italy (32), and Germany (29). Moreover, we also find in first place China, where the inter-country (MCP) publications numbered 53, followed in second and third place by the United Kingdom (18) and Australia (10). They have published 18 papers and 10 papers, respectively. They both have nine international co-publications. In the fourth position is the United States, with 59 papers and eight foreign collaborations. Comparatively, Germany (29) and Russia (13) have many scientific publications but less external collaboration. In terms of cooperation between countries, United States–China (8), China–Singapore (7), Australia–China (7), and Canada–China (6) are the top-ranked combinations. International collaborative research is well regarded in China.

Table 6 shows the total number of citations in selected papers by countries or territories. We found that Pakistan, Egypt, and Germany's publications received high numbers of citations and had the greatest impact. In addition, as part of North America, Canada and the United States excel in total citations, while their average paper citations need to be improved. Publications in China and Hong Kong, China, need to gain more influence as well.

Table 6. Most Cited Countries and Average Paper Citations in Scopus and WoS.

No.	Countries	Total Citation	Average Paper Citations
1	Germany	708	40.81
2	China	326	2.99
3	Canada	241	26.85
4	Italy	233	4.05
5	Hong Kong, China	194	27.71
6	United Kingdom	164	9.19
7	United States	135	5.05
8	Australia	134	15.42
9	Pakistan	117	58.5
10	Egypt	114	57

In addition, it is worth noting that in the 493 related publications, case studies of mega infrastructure projects are also concentrated in the high-citation countries. In Germany, this category includes the Frankfurt Airport Terminal 3 Construction Project and the Stuttgart 21 Project [34]. In China, the Sichuan–Tibet railway and the Hong Kong–Zhuhai–Macao railway [35] are the most representative projects. As for other countries, the HS2 and the Thames Tideway Tunnel in the United Kingdom [36] and California High-Speed Rail [37] in the United States are also widely mentioned.

Table 7 shows the classification of scientific publications by author affiliation. The following are the top five affiliations: University of Naples Federico II (Italy), Cornell University (United States), The Hong Kong Polytechnic University (China), Jiangsu University (China), and Beijing Jiaotong University (China). A total of 15% of publications were attributed to the top five affiliations. Half of the most relevant affiliations are from China, while the United States and Italy each have two universities in top 10.

Table 7. Most Relevant Affiliations in Scopus and WoS.

No.	Affiliation	Country	Papers
1	University of Naples Federico II	Italy	17
2	Cornell University	USA	17
3	The Hong Kong Polytechnic University	China	16
4	Jiangsu University	China	13
5	Beijing Jiaotong University	China	11
6	Duke University	USA	11
7	The University of Hong Kong	China	11
8	Chang'an University	China	10
9	University of Padova	Italy	10
10	Sapienza University of Rome	Germany	9

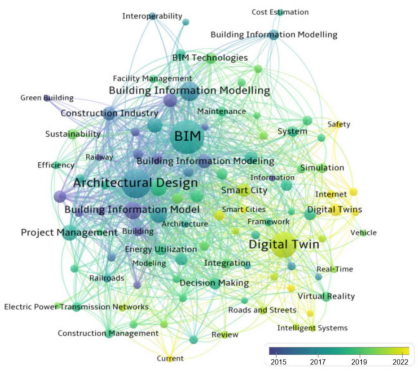
3.2. Research Hotspots, Tendencies, and Orientations

In this section, keyword analysis and the contents of the publications' titles and abstracts were utilized to address RQ2 of this study.

3.2.1. Keywords Analysis

Analyzing keywords can give us an idea of the hotspots in the research field. The VOSviewer software is used to analyze the keywords of the BIM and digital twins technologies involved in the digitalization of transportation; 1703 keywords were used in the retrieval of 493 papers. After deleting meaningless words, merging synonyms, and

performing cluster analysis on more than 40 occurrences of keywords, the final results are shown in Figure 6, which presents the collaborations of 100 keywords and the evolution of the top 20 items.



No.	Item	Frequent	Begin	End	2015	2016	2017	2018	2019	2020	2021	2022
1	architectural design	84	2018	2021								
2	building information model(ling) -BIM	46	2017	2020								
3	life cycle	27	2019	2021								
4	information management	24	2018	2021								
5	bim	23	2021	2022								
6	information theory	19	2016	2020								
7	construction	18	2017	2019								
8	sustainable development	16	2017	2020								
9	building(s)	13	2016	2022								
10	model	13	2017	2021								
11	system	11	2018	2021								
12	design	9	2018	2022								
13	management	9	2021	2022								
14	safety engineering	8	2019	2021								
15	structural design	8	2015	2020								
16	infrastructure	7	2019	2020								
17	railroad transportation	7	2018	2020								
18	internet	6	2019	2022								
19	challenges	5	2019	2022								
20	machine learning	5	2021	2022								

Figure 6. Keyword Collaborations from 2015–2022 and the Evolution of TOP 20 Items.

In addition to the retrieval of keywords for BIM and digital twins, by integrating the high-frequency keywords in the research on transportation digitization, we can see that there are three phases of the timeline of the development of transportation digitization. As part of the first stage (2015–2017, color purple), the research directions are as follows: Information (2015.4), Buildings (2016.4), Structural Design (2016.5), Surveys (2017.5), Railways (2017.8), Information Theory (2017.8), and Sustainable Development (2017.9).

Second comes the development stage (2018–2019, color green), with research directions including Green Building (2018.1), Construction Projects (2018.1), CAD (2018.2), Railroad Transportation (2018.4), Automation (2018.5), Interoperability (2018.6), Traffic Management (2018.8), Computer Simulation (2018.8), Point Clouds (2019.1), Construction (2019.1), Railroads (2019.1), Architecture (2019.1), Numerical Model (2019.2), Energy Efficiency (2019.2), Project Management (2019.2), Optimization (2019.1), Safety Engineering (2019.3), Cost Estimation (2019.4), Intelligent Buildings (2019.4), Model (2019.5), Decision Making (2019.5), Framework (2019.6), Planning (2019.6), Energy Utilization (2019.6), Efficiency (2019.6), Life Cycle (2019.7), Systems (2019.7), Construction Management (2019.7), Maintenance (2019.7), Artificial Intelligence (2019.8), Performance (2019.8), Climate Change (2019.8), Infrastructure (2019.8), Data Visualization (2019.8), Costs (2019.8), Facility Management (2019.8), Bridges (2019.8), and Virtual Reality (2019.9).

Currently, related research is in its third phase (2020-2022, color yellow), in which research works on Integration (2019.1), GIS (2019.4), IoT (2019.5), Three-Dimensional Computer Graphics (2019.5), Information Use (2019.7), Visualization (2019.9), Big Data (2019.10), Sustainability (2019.11), Simulation (2019.12), Vehicles (2020.2), Highway Planning (2020.4), Safety (2020.7), Real-Time (2020.9), Data Acquisition (2020.12), Traffic Control (2021.3), Smart City (2021.6), Digital Storage (2021.12), Monitoring (2022.4), Deep Learning (2022.5), and Machine Learning (2022.6) are being widely viewed.

Therefore, in the present and future, building as a research object, design and management as links within the entire life cycle, and machine learning as the key digital development technology will continue to play a critical role.

3.2.2. Content Analysis

With the help of the Bibliometrix software's content analysis and word segmentation tools, a list of 271 noun phrases was identified, providing potential terms to describe research tendencies and orientations in the field of digital transportation. Following this, we screened the list using manual processing. To avoid omission due to word segmentation, 39 terms were summarized into three categories: unigram words, bigram words, and trigram words (consisting of one/two/three words, respectively). The content analysis using unigram, bigram, and trigram words illustrated in Table 8.

Table 8. Content Analysis in Unigram, Bigram, and Trigram Words.

Unigram Words	Bigram Words	Trigram Words
BIM	building information	building information model(ling)
construction	digital twin(s)	entire life cycle
information	BIM technology	digital twin technology
building	life cycle	green space planning
design	construction industry	life cycle assessment
data	AEC industry	urban green space
management	construction management	building column base
model	management system	common data environment
digital	green building	geographic information system
project	information management	indoor environmental quality
system(s)	project management	active safety systems
research	smart city	ancillary building facilities
process	artificial intelligence	architecture engineering construction

As shown in Table 8, unigram words analysis focuses on research objects (building, project, data), link processes (design, management), and development goals (digital, system). As for bigram words, they mainly focus on management links, including construction management, project management, and information management. The entire life cycle, smart city, and green development are all outlined as clear development goals, and AI technology is also a major research orientation. Finally, trigram words provide additional details on microscopic application scenarios and analysis objects, including active safety systems, ancillary building facilities, and indoor environmental quality.

In general, transportation digitization research seems to be moving far from the applications of traditional technology, such as information theory (2017.8), construction (2019.1), and infrastructure (2019.8). It is more likely that researchers will integrate multiple technologies in order to build green, safe, and smart cities.

4. Discussion and Future Directions

In Section 4, cluster analysis is used to identify the main emerging themes in transportation digitization research to address RQ3. Based on the fundamental research themes, hotspots, and theoretical and practical contributions of previous studies, four main directions have been identified, as shown in Figure 7.

There can be no doubt that smart cities are advancing rapidly. To help with the digitalization of cities, future research directions for the integrated application of BIM and DTs technologies can be summarized as follows.

4.1. Cluster 1 (Blue): Improving the Efficiency of Intelligent Transportation System Element Management

The intelligent transportation system (ITS) has played a crucial role in allowing societies to cope with rapid urbanization. It connects all core transportation elements, facilitates information exchange and sharing, and ensures the optimal configuration and efficient use of various elements of transportation. ITS management can help improve transportation efficiency, reduce traffic congestion and environmental pollution, and ensure safety. In light of this, various researchers have become increasingly interested in it [38].

Future research is mainly concerned with research objects and management methods. According to the study objects, different types of transportation infrastructure are gaining widespread attention, such as bridges, buildings, railroads, roads and streets, urban transportation, and supporting smart power grids. Moreover, as for management methods, future ITS research will focus on traffic control and traffic management, seeking new technology development and collaboration based on the Internet of Vehicles [39].

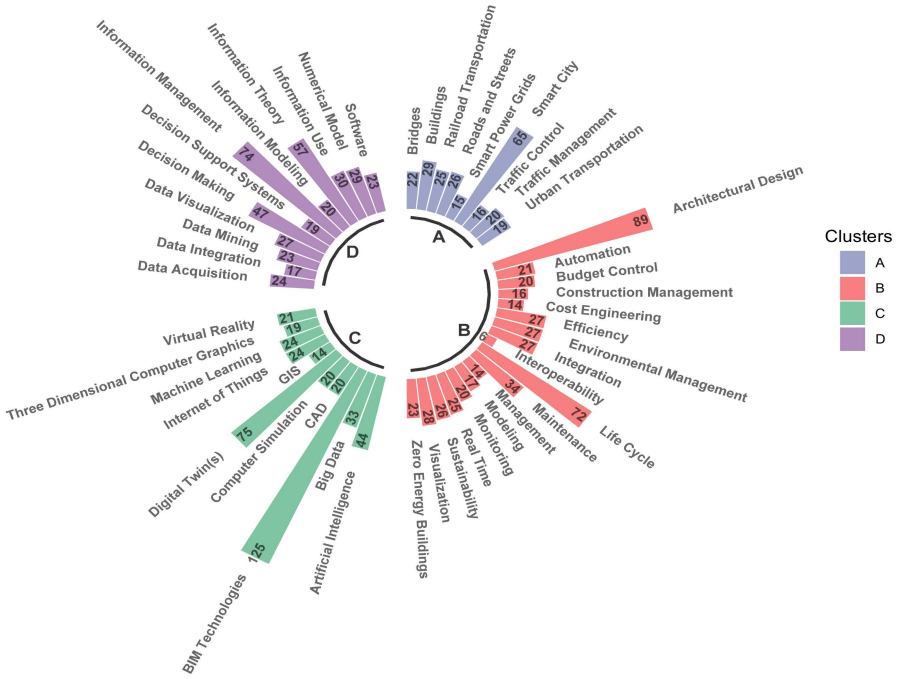


Figure 7. The research agenda for future research in the field of digitization of transportation.

4.2. Cluster 2 (Purple): Development and Application of Digital Technologies

Nowadays, a single digital technology is no longer sufficient for modern transportation development. The future of transportation digitization will require comprehensive improvements in safety, efficiency, and user experience. For this reason, in the future digitization of the transportation scene, it will be necessary to integrate the advantages of various advanced technologies as well as attain an overall perception of people, vehicles, roads, environments, and information.

During this early stage, the relevant research is conducted based on specific business scenarios. Big data and GIS are representative technologies in this regard. The Internet of Things, sensors, and computer simulations are becoming increasingly popular over time. The main force behind the growth of digitalization in transportation is the further development of BIM and DTs, which is the main research topic of this paper. Lastly, artificial intelligence, virtual reality, and machine learning will be the future directions for this field.

4.3. Cluster 3 (Red): Flows and Goals of Entire Life-Cycle Management

Planning, designing, building, operating, maintaining, and other stages of the transportation industry currently belong to different management departments. As a result, it is challenging to implement concepts and requirements such as project optimization, data sharing, and life-cycle benefits optimization. The overall needs must be considered at the beginning of each stage in order to treat all stages as organic wholes. Suppliers are seeking out engineering solutions with the greatest comprehensive benefits over the entire life cycle of transportation infrastructure. Furthermore, establishing appropriate technical and theoretical systems to guide engineering practices at different stages of sustainable development is also important.

This section focuses on two main aspects. To begin with, consider the entire life cycle of transportation technology, which encompasses: (1) pre-time design, including budget control, cost engineering, and architectural design; (2) mid-time modeling and construction management; and (3) post-time inspection and maintenance. Secondly, consider the ultimate goals of management, which include automation, efficiency, integration, interoperability, real-time, sustainability, visualization, and zero-energy buildings.

4.4. Cluster 4 (Green): Optimization of Related Algorithms and Models

Optimization of related algorithms and models is essential to the future development of transportation. They will fundamentally alter traditional business, management, marketing, and service models. As transportation moves forward, data will become more valuable for updating service models and seeking inspiration from industry changes. New transportation modes transform the flow of people, materials, and capital. In order to achieve more efficient scheduling of future traffic modes, travel modes, and transportation systems, it will be necessary to develop smarter ways of empowering future modes.

In this section, the main research focus is on related optimization algorithms and models. There are studies focusing on data itself, including data acquisition, data integration, data mining, and data visualization. In addition, there are studies on the informatization of the transportation industry, such as information management, information modeling [40], information theory [41], information use [42], and highly integrated software development. Furthermore, decision-making and decision-support systems [43] will serve as directions for future research.

5. Conclusions

With the development of digital technologies, the transportation industry is facing new challenges and gaining new opportunities. Using a bibliometric review, we investigate the application of BIM and DTs in the transportation industry, which indicates that the integration and utilization of multiple technologies can improve the schemes of mega engineering projects, improving the efficiency of such projects' digital management over their whole life cycle. We also believe that it is necessary to further improve the research design and present the results as clearly as possible in a future study.

Our findings will be beneficial to scholars involved in the field of transportation digitization by helping them better understand future research directions and trends. It is currently impossible to solve significant issues with a single form of technology. Multiple technologies must be integrated to find a complete solution. Further research may utilize other study aspects by using more related databases and bibliometric methods. In addition, Altmetrics is a new comprehensive bibliometric method for evaluating the academic and social impact of research outcomes. It can be used in combination with scientometric analysis to explore new areas for research on digital transportation.

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