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TOPICAL REVIEW

# Civil Infrastructure Digital Twins: Multi-Level Knowledge Map, Research Gaps, and Future Directions

HOSSEIN NADERI<sup>1</sup> AND ALIREZA SHOJAEI<sup>1</sup>

Myers-Lawson School of Construction, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

Corresponding author: Alireza Shojaei (shojaei@vt.edu)

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**ABSTRACT** Digital Twins (DTs) have received considerable attention as an emerging technology in recent years, which can offer advantages for improving the performance of infrastructures. However, the inherent complexity of infrastructures alongside the nascent nature of digital twins in the Architecture, Engineering, and Construction (AEC) industry hinders the adoption of infrastructure digital twins (IDTs). The lack of common understanding among different stakeholders has been noted as one of the most significant roadblocks to implementing IDTs in practice. This study is a quantitative attempt to address this gap by providing different stakeholders with a multi-layer knowledge map by analyzing 139 identified IDTs in three levels of bibliometric and social network analyses. First, knowledge themes are extracted from the most-frequent journals to provide an overview of IDT knowledge. Second, a combination of co-citation analysis and social network theories illustrated six clusters of IDT knowledge and their relationships. Third, the co-occurrence network of keywords revealed where, why, and what enabling technologies have been employed so far. These findings were synthesized into a three-layer knowledge map to not only illustrate the maturity level and evolution potentials of each layer but also serve as a hierarchical strategic plan recommending future direction to decision-makers, researchers, and practitioners.

**INDEX TERMS** Bibliometric analysis, civil infrastructures, digital twins, knowledge map, systematic review.

## I. INTRODUCTION

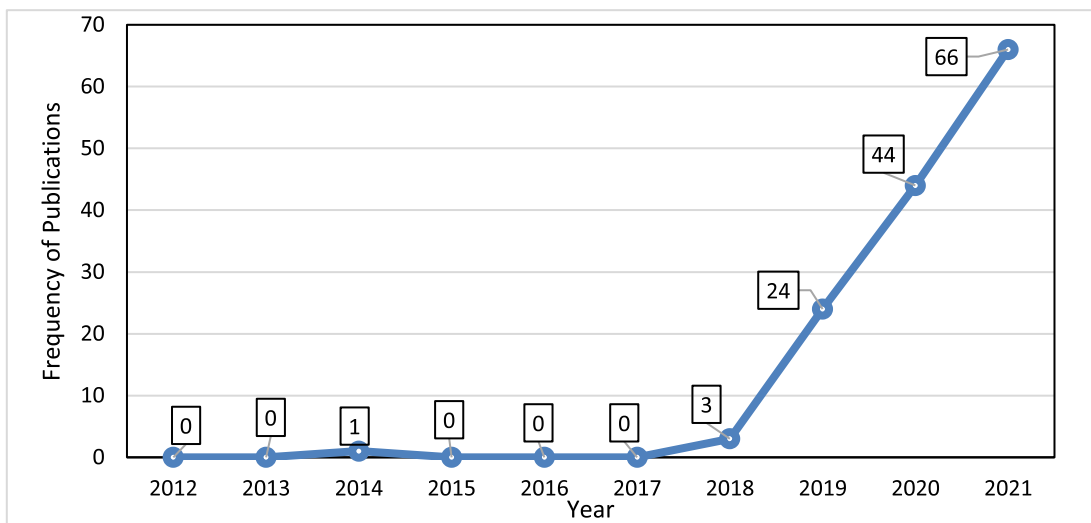
Since its first appearance in Michael W. Grieves's Product Lifecycle Management (PLM) model in 2002 [1], the term Digital Twins (DTs) has gained increasing popularity and is now considered a key aspect of Industry 4.0 [2], [3], [4]. As an up-to-date digital replica of the physical world [5], DT applications started growing with technological advancements of the Internet of Things (IoTs) in a wide range of industries [6], such as space [7] and manufacturing [8], [9], [10]. Likewise, civil infrastructures and the Architecture, Engineering, and Construction (AEC) industry have experienced the first generations of DTs in recent years [11], [12].

The backbone of any society is its civil infrastructures [13], while the current status of aging infrastructures has reduced

their services and created financial and societal burdens for communities [14]. For this reason, efforts should be concentrated on developing new ways of designing, building, operating, and maintaining civil infrastructure to better accommodate society's true needs [11]. Such an opportunity can be realized by utilizing DTs in civil infrastructures [15]. The complexity and breadth of civil infrastructure projects on one hand [16], and the nascent nature of the DT concept in the AEC industry on the other hand make it more challenging to adopt DTs within the context of civil infrastructures [17]. Although DTs are used in a wide range of infrastructures, including but not limited to civil, energy, and digital, this study focused on DTs for civil infrastructure to gain a clearer and more accurate picture of how DTs fit into civil systems.

DTs have received considerable attention recently, and the growing number of DT-related studies in the civil engineering domain is a good indication of this trend, which is illustrated

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**FIGURE 1.** Frequency of DT-related publications per year in the AEC field (Based on a search using “Digital Twin” in web of science and limiting).

in Fig. 1. As seen in this figure, the number of studies has nearly tripled in the past three years whereas DTs in infrastructures are still in their infancy [11]. The concept of DTs has been interpreted differently depending on the application or research area in which it is being applied [18]. For example, many researchers refer to DTs interchangeably with BIM. While some consider DTs to be a simple 3D representation of their assets [5], others view them as an extension of traditional simulations [19]. The lack of common understanding in this confusing environment has also been cited as a major problem to DT implementation within civil infrastructures [20]. As a result, a holistic and structured picture of IDT knowledge can bring about a deeper understanding of gaps and future needs in the body of knowledge, which leads to balanced research and development, adoption, and expansion of DT applications in civil infrastructures.

Some previous reviews have explored DTs within the context of civil infrastructure [11], [12], [21], which are primarily qualitative and based on manual interviews. Despite the undeniable potential of these reviews, they are typically incapable of producing an accurate, comprehensive, generalizable, and replicable picture of the body of knowledge [22] due to their potential for subjectivity and the limited number of studies they can review [23]. Furthermore, they are unable to determine the maturity level and relationships between different knowledge domains, which can unveil hidden barriers and potential solutions for the future development of IDT knowledge. This study seeks to address mentioned issues by quantitatively analyzing the intellectual core of the body of IDT knowledge.

In particular, the study reviews the existing literature through a combination of objective bibliometric analysis and graph theory to address following research questions (RQs): (RQ1) how the body of IDT knowledge has been developed so far? (RQ2) what is the current IDT gaps and what areas

of development have future? (RQ3) what should be done (in which level) to enhance IDT adoption in civil systems? As part of its contribution, the present review is the first of its kind that provides a multi-layer picture of the DT literature in infrastructures and identifies knowledge gaps and future directions in a hierarchical manner for decision-makers, researchers, and practitioners. This study aims to present a three-layered picture of IDT literature in order to provide decision-makers, researchers, and practitioners with a firm foundation and common understanding for the adoption of DTs in infrastructures (main research objective). This will also contribute to the future development of DT applications in civil infrastructures by identifying the key pillars on which existing IDTs are built as well as the gaps decision-makers, researchers, and practitioners must address.

The rest of the study begins with a background of previous DT-related review studies in section 2. Section 3 outlines the systematic review methodology, with steps to identify and select core studies between 2012 and 2022. This is followed by the bibliometric analysis in section 4, which introduces research findings in three levels of detail. Then, the findings in the previous section are synthesized in section 5 to provide an elaborative knowledge map and direction for future developments. Finally, we concluded the article in Section 6.

## II. BACKGROUND

### A. BIBLIOMETRIC ANALYSIS IN THE DT LITERATURE

The bibliometric analysis can be defined as a tool for mapping and visualizing particular scientific studies in a knowledge domain [24]. Researchers are now able to uncover hidden connections and trends in the literature using the advancement of computing technology, scientific indexing, and data visualization techniques [25]. While bibliometric analyses within the context of DTs in the AEC industry have remained less investigated, this technique has been employed by several

review papers in the manufacturing field as their principal analytical technique. For example, Wang et al. [26] proposed a picture of DT literature by analyzing 514 studies from 2014 to 2021 to explore core outlets, most productive articles, authors, institutions, and relevant countries. This technique also can be used to evaluate DT applications in a narrower range. In order to enhance safety management in the manufacturing industry, Agnusdei et al. [27] looked into the capabilities of DTs using co-occurrence keyword analysis. In addition, Lo et al. [28] utilized a systematic review to provide an overview of DT knowledge areas with an emphasis on the process of product design and development. It should also be noted that the application of bibliometric analyses is not limited to the manufacturing industry, some studies used them as a way to develop an in-depth understanding of DTs in their industries. For example, in the field of internal transportation, Kosacka-Olejnik et al. [29] used bibliometric tools and graphical mapping to visualize the network of most significant journals, authors, countries (affiliations), and keywords.

### B. RELATED STUDIES IN THE AEC INDUSTRY

While the bibliometric analyses are rarely applied to evaluate the state of DT literature, most review papers have employed qualitative techniques coupled with the systematic review method as a kind of mixed method [30] to examine the use of DTs in the field. The content analysis method is a means of interpreting meaning from the text of identified studies [31]. A systematic review also can be defined as a way of objectively identifying relevant studies in a given field [32]. Table 1 lists some of the available review papers in the AEC industry. One group of studies is focused on DT basics in the AEC industry. For example, Deng et al. [33] discussed the evolution of DTs from BIM models through categorizing identified studies, and Jiang et al. [6] identified DT research clusters in the civil engineering sector. In a more foundational review study, Davila Delgado and Oyedele [34] explored the literature of the manufacturing industry to enrich the understanding of the DT concept in the AEC industry.

Another group of studies concentrates their reviews on a particular life-cycle of projects. For example, Boje et al. [35] qualitatively explored the literature and DT uses during the construction phase of projects. The operation and maintenance (O&M) stage was selected by Coupry et al. [36] to investigate the potential of integrating DT models and Extended Reality (XR) devices. Opuku et al. [37] also applied a combination of content analysis and bibliometric analysis to explore DT capabilities for the construction industry. However, the bibliometric analysis in this study is limited to 22 relevant studies, resulting in low-density networks with few nodes and connections. For this reason, the study was unable to move from network parameters to hidden knowledge behind DT literature. Furthermore, other studies have been focused on a specific scope, such as smart cities [38], [39], or a particular DT application, such as construction safety [40] and disaster prevention [41].

**TABLE 1. Identification of review studies focused on digital twins in the AEC industry.**

Category	Focus	Analysis Method	Ref.
DT basics in AEC	Civil engineering sector	Content Analysis	[6]
	DT evolution	Content Analysis	[33]
	DT definition	Content Analysis	[34]
DT for AEC lifecycles	Construction DT	Content Analysis	[35]
	Construction DT	Content Analysis Bibliometric Analysis	[37]
	Operation and Maintenance	Content Analysis	[36]
DT applications in AEC fields	Smart City	Thematic analysis	[38]
	Smart City	Framework development	[39]
	Construction Safety	Content Analysis	[40]
	Intelligence Disaster Prevention	Content Analysis	[41]
Infrastructure DT (IDT)	Infrastructures	Semi-structured interviews	[12]
	Infrastructures	Semi-structured interviews	[21]
	Infrastructures	Semi-structured interviews	[11]

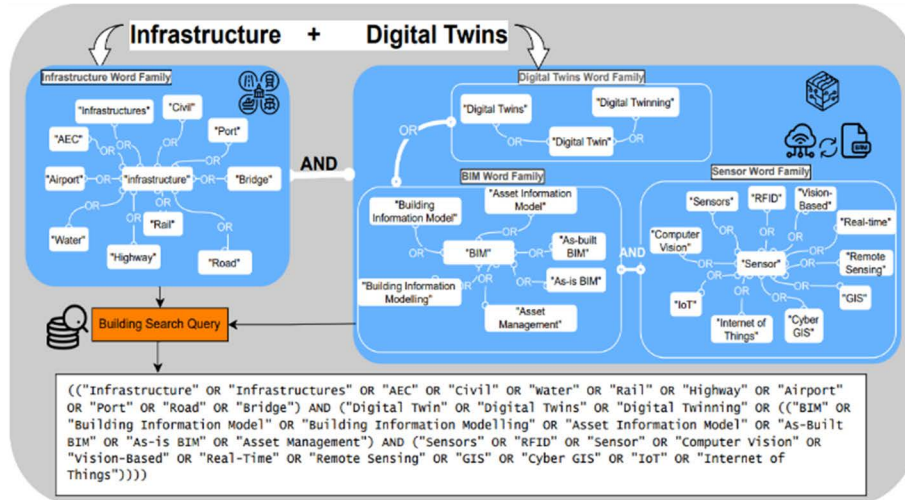
Few studies have been conducted on the review of DTs within civil infrastructures and to our knowledge no studies have been found to explore this body of knowledge in a quantitative manner. Broo and Schooling [11] conducted semi-structured interviews with professionals in the UK infrastructure industry and identified some strategies and challenges for DT adoption within the infrastructure sector. Callcut et al. [12] explored DT applications across various types of infrastructures and proposed a set of recommendations for the future. Similarly, semi-structured interviews are utilized by Shahzad et al. [21] to identify DT use cases in infrastructure fields. Despite the inevitable value of these reviews, they failed in mapping the domains, connections, and contours of DT literature. As a result, these studies could not fully identify where research gaps and opportunities for future research lie. This study mainly aims to address these remaining issues.

### III. METHODOLOGY

This section is divided into 4 steps, explaining the systematic review approach followed in this study. It involves selecting an appropriate database and the process of building search strings as the first step. Then, the next steps are collecting and preparing records. In the final step, methods and tools employed for the bibliometric analysis are explored.

#### A. IDENTIFICATION OF DATABASE AND SEARCH QUERY

The outcome of systematic reviews is influenced by the sample selection of relevant studies, which necessitates the use of objective and reproducible search systems to identify



**FIGURE 2.** The process of building search query for identifying studies related to infrastructure digital twins (IDTs).

as many relevant studies as possible [42]. This review collected bibliometric records from the Web of Science (WoS) for three reasons: (1) it is one of the most comprehensive datasets [43] and it has the most accurate citation data-banks [44], serving as the major tool for bibliometric analyses. (2) In the fields of natural sciences and engineering, there are more unique journal titles in the WoS database than in Scopus [45]. (3) In spite of Google Scholar having the largest size of articles, it is considered to be an inappropriate search engine for systematic reviews as it cannot provide essential reproducibility [46].

For finding studies relevant to a field of research, query-based search is one of the most prevailing approaches [47]. However, formulating an acceptable search query to capture a wide range of DT-related studies in infrastructures is challenging, mainly because the term “Digital Twins” is frequently used in a blurred manner [5]. To address this issue, we built a comprehensive search query based on the study scope.

Fig. 2 illustrates the process of building the infrastructure digital twins (IDTs) search query. The search query is mainly constructed from two compulsory terms “Digital Twins” and “Infrastructure”, which should be linked together using AND command. The infrastructure word family (left block) contains different equivalents of the infrastructure word, such as “Highway”, “Bridge”, etc., which are linked together using the OR command. To cover DT related words (right block) in the search query, we considered two connected sub-families by OR command: (1) “Digital Twins” and its other forms as Digital Twins Word Family; (2) a combination between “BIM Word Family” and “Sensor Word Family” coupled with the AND command. The sub-family of BIM/Sensors was included as part of our search query because, in many studies, it represents a DT model without directly mentioning the actual term.

**B. DATA ACQUISITION STAGE**

Having identified potential databases and constructed search queries, we can seek out relevant studies. Fig. 3 depicts three stages of the research methodology adopted in this study, the first of which is discussed in this section. The developed search query from the previous section was applied in the “Title” and “Abstract” fields of identified search engines (WoS) with the OR command. This approach enabled us to find any studies in the WoS database that include query keywords in their abstract or title. The number of identified study records in WoS databases on March 1, 2022, was 808.

Search outputs were refined in three ways to bring identified studies closer to the study scope. (1) “English” was selected as the only acceptable language for identified studies in the database. As illustrated in Fig. 1, the emergence of DTs is still in its early stages, and there is no need for a wide date range to find relevant studies. (2) We narrowed the identified search results to the last decade, with dates ranging from 2012 to 2022. The most influential records for systematic reviews are journal articles [48] and they improve the quality of review studies [35]. Additionally, it is widely recognized that, in the computer science field, many important research findings are published as conference papers [49] and that many of DT’s enabling technologies originate from this field. As a result, (3) we limited document types of identified studies in WoS to the journal and conference proceedings articles to end up with a comprehensive and generalizable database. These limits reduce the number of records from 808 to 689.

**C. DATA PREPROCESSING STAGE**

According to second stage of research methodology (see Fig.3), a set of eligibility criteria is developed as follows to ensure that identified studies meet our review scope: (1) identified studies must be carried out within the



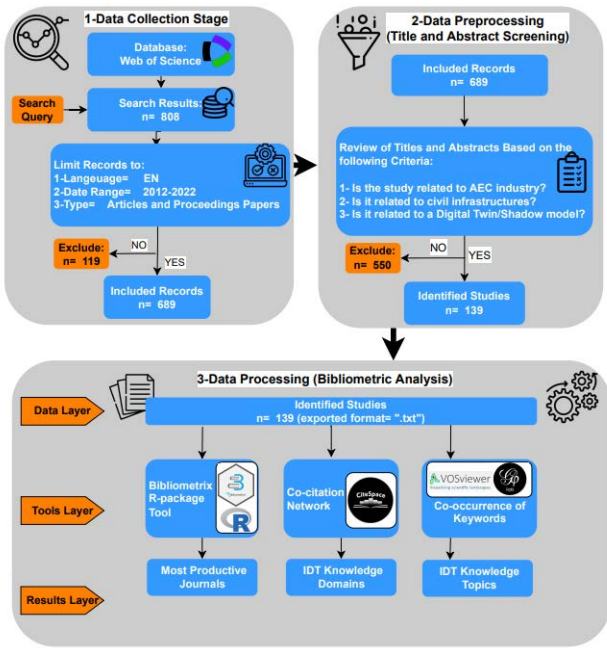


FIGURE 3. Methodology of systematic review (three stages).

AEC industry; (2) the developed DT must relate to at least one particular physical infrastructure, such as bridges, water and wastewater systems, roads, and railways. The reason for this restriction is that many DT models developed for buildings are not applicable in the complex environment of civil infrastructures; (3) the identified studies must include a digital twin or shadow twin according to the Kritzinger’s classification [50]. This restriction is mainly due to the fact that despite the use of the Digital Twins term in titles or abstracts of many studies, the term is merely a synonym for a 3D model without any data flow.

**D. DATA PROCESSING TOOLS AND METRICS**

Third stage of research methodology (see Fig.3) seeks to discuss the tools and techniques that were used for the bibliometric analyses. Various methods and software packages have different capabilities and strengths, which should be applied carefully depending on the desired type of analysis and outcome [25]. In this review, the identified studies were analyzed from three perspectives: (1) most productive journals, (2) document co-citation network, and the keyword co-occurrence network.

The Bibliometrix in the R programming language is an open-source tool providing features for quantitative research in a bibliometric analysis [51]. We used the capabilities of this tool in terms of analyzing core journals among the identified studies. To identify knowledge domains in the literature, we used CiteSpace as a mapping and analysis tool to visualize and explore the scientific literature [52]. This software also was applied to identify knowledge domains using features, such as clustering literature, and time-zone views. VOSviewer is another open-source tool to visualize

TABLE 2. Essential definitions of network metrics.

Metrics	Definition
Degree Centrality	the total number of edges connected to the node [55]. The higher this metric is, the more central the node in the network is.
Network Modularity (Q)	Modularity measures a network's ability to be divided into well-structured clusters, with a range of scores from 0 to 1. [56]
Network Density	The ratio of actual links among nodes to all the possible links, with the value of 0 to 1 [57].
Betweenness Centrality	It is defined for each node in a network and measures the possibility that an arbitrary shortest path in the network will pass the node [58].
Silhouette score	Cluster homogeneity is measured by silhouette scores, which is between -1 and 1; a high value indicates that the node is fitted its cluster while it is poorly matched to adjacent clusters [59].

and explore network data, which provides basic capabilities required for visualizing bibliometric networks and further analyses by network analysis techniques [24], [53].

Network analysis theory was selected in this study to extract insights by measuring various metrics of networks. Our study utilized a variety of metrics, namely, the degree centrality, density, betweenness centrality, modularity, and silhouette score, which are defined in Table 2. Further, we applied Gephi [54] software as an open-source network graph and analysis tool to uncover patterns in networks. This tool allowed us to extract network metrics from the VOSviewer networks and facilitate reasoning based on the previously defined metrics. Using these tools and different bibliometric analyses, the current state of IDT knowledge was interpreted in different levels of detail.

**IV. BIBLIOMETRIC ANALYSIS**

**A. CORE JOURNALS (KNOWLEDGE TERRITORIES)**

There are particular journals in every field that publish more studies due to the tight relationship between the subject of the journals and the scope of research efforts in that field [60]. These journals can be classified as core journals that can provide authors and readers with useful information, allowing them to identify the best journals for publishing their studies or for gaining the most credible information. This information can also be vital to journal editors looking to expand their market and libraries seeking to allocate funds efficiently when investing in journals [61].

Bradford’s Law of Scattering provides the basis for the concept of core journals [62]. According to this law, a few journals account for the significant studies on a particular topic, and the rest of the studies are distributed to other journals to such a degree that, if the set of relevant articles is subdivided into zones containing the same number of studies, an exponentially increasing number of journals will be required to fill the succeeding zones [63]. Using this law and bibliometrix R-package, we identified core journals among the identified studies. Fig. 4 presents the most influential journals, ranked based on the frequency of published papers

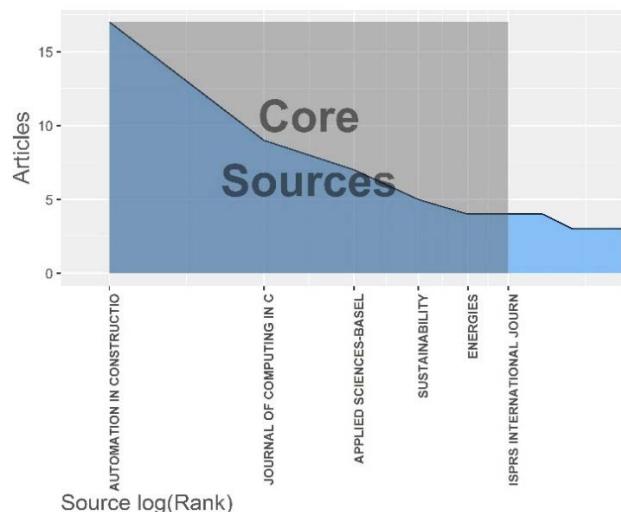


FIGURE 4. Identification of core journals among core studies.

in journals. The analysis indicates that “Automation in Construction,” is ranked first among the most productive journals, with a total output of 17 papers. Following that, “Journal of Computing in Civil Engineering” with 9 relevant studies, “Applied Science” with 7 reviews, “Sustainability” with 5 studies, “Energies”, and “ISPRS International Journal of Geo-Information” both with 4 studies represent the other core journals in descending order. These journals can most clearly reflect the conceptual essence of the studies undertaken in this field’s body of knowledge [64], considering the fact that being well-aligned with journal objectives is one of the basic prerequisites of journal selection [65]. Thus, these findings address RQ1 in an upper-level perspective.

In Fig. 4, “Automation in Construction” and “Journal of Computing in Civil Engineering” are the first and second top-ranked journals that both focused on the application of information technology (IT) and computing science in the AEC industry. Accordingly, it can be deduced that the major efforts in the literature are devoted to the technological characteristics of IDTs. Thus, technical support for DTs plays a crucial role in infrastructure projects, similar to the top priority for this issue in the BIM industry [66], [67]. Another interesting observation is the presence of “Sustainability” and “Energies” journals among the core journals, which reveals that the rapid growth of literature [68] has drawn attention to the need for building sustainable DTs within the context of civil infrastructure.

Fig. 5 presents the evolution of core journals based on the frequency of published papers from 2012 to 2022, which can provide further insights into the dynamics of IDT knowledge. The upward trend in all journals, as shown in Fig. 5, illustrates the growing attention to IDTs in all core journals. Moreover, the growing gap between the “Automation in Construction” journal and other core journals imply that information technologies (IT) applications in IDTs dominate the body of knowledge in this field. In addition to this,

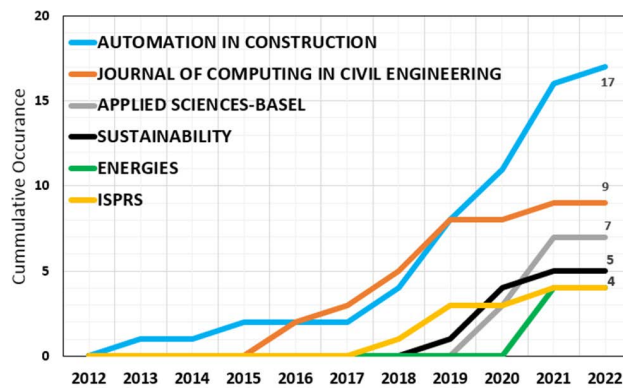


FIGURE 5. The dynamics of core journals within the review date range from 2012 to 2022.

the sustainability-focused journals (“Sustainability” and “Energies”) began to publish the first IDT-related studies in 2018 and 2020, demonstrating the fact that this aspect of the knowledge domain is still in its infancy. Therefore, it can be concluded that there are two major knowledge territories in the highest level of knowledge, the technological side that dominates the literature and the sustainability-related one that is in its early stages. However, the interpretations drawn here only provide an overview of IDT knowledge in a broader context without considering the relationship between research areas. As a result, a more detailed analysis is needed to gain a better understanding of IDT knowledge structure, which is explored in the next section.

**B. KNOWLEDGE DOMAINS**

**1) CO-CITATION NETWORK ANALYSIS**

According to Small [69], the co-citation is defined as “the frequency with which two documents are cited together”. The co-citation analysis is reported as a valid and reliable method for gaining insights into the knowledge structures due to the objectivity of measurements [70]. It is likely that concepts in two documents that are frequently cited together are similar or connected. One can identify closely related knowledge domains by evaluating the frequency of co-cited studies in the same research. In a co-citation network, nodes represent cited documents, and links indicate how frequently two documents are cited together. Depending on their interconnections, individual nodes in the network can be grouped or clustered, and each cluster may represent a distinct knowledge domain [59], [71]. As mentioned in the methodology section, we utilized the Citespace for clustering the body of DT knowledge within the context of infrastructures.

The document co-citation network was visualized in Fig. 6 using a set of assumptions. The review’s date range was divided into ten slices each representing a year from 2013 to 2022 (from dark blue to yellow slices). Labels for clusters were selected using the implementation of text-mining algorithms on titles, keywords, and abstracts of publications. There are three available text-mining algorithms in the Citespace. The log-likelihood ratio (LLR) was selected

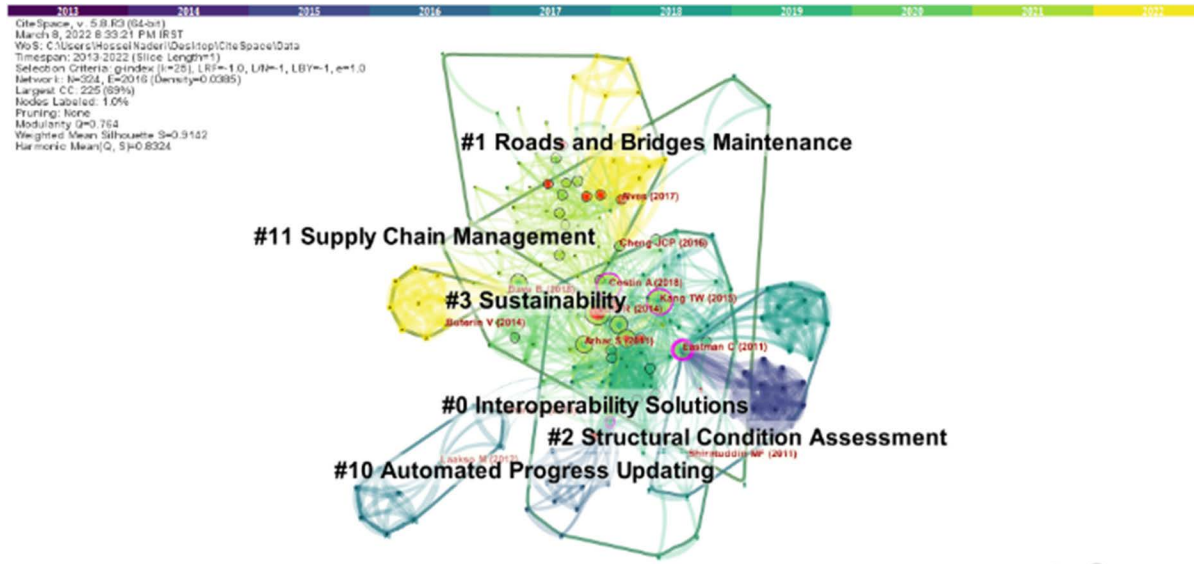


FIGURE 6. Document co-citation network and knowledge clusters in the Citespace software.

for this process since it uses a weighting algorithm to present the core concept of each cluster [72]. As shown in Fig. 6, the main characteristics of the network are listed in the upper left corner, including software version, analysis date, time span of each year slice, default settings for analysis, total number of nodes and edges, largest connected components among all nodes, and other network metrics such as modularity and mean silhouette. A node’s size indicates the number of citations for a particular study, while the purple rings around some nodes indicate the high value of betweenness centrality (see section 4.2.3). Each link between two nodes is represented by a color corresponding to the year in which co-citation occurred. Clusters are numbered in the network based on their sizes, meaning that the most extensive cluster is #0 and the smallest one is #11 (see section 4.2.2). Missing numbers are related to clusters that are not connected to the network and are small enough to be ignored.

Several network parameters, like modularity and mean silhouette value, can provide insight into the overall quality of the network. Modularity and mean silhouette of the network are respectively 0.76 and 0.91. A modularity score above 0.7 (0.764 in this study) indicates that the network is reasonably divided into loosely coupled clusters where borders are clear between discernible clusters [59]. A mean silhouette value above 0.6 (0.91 in this study) demonstrates a heterogeneous network with more intracluster citations [59]. Fig. 6 illustrates and the above-mentioned parameters suggest that the body of IDT knowledge is fragmented. It encompassed six well-structured clusters that can be seen as isolated islands with almost no connection across the body of knowledge. In this situation, researchers are inward-looking and do not cite other documents outside their clusters, leading to silo-based knowledge domains with limited ideas and theories from other domains [73], [74]. This is one of the

TABLE 3. Identified clusters and their associated network metrics.

Cluster ID	Size	Silhouette value	Mean (Year) <sup>a</sup>	Top terms (LLR)
0	64	0.875	2012	Interoperability Solutions
1	53	0.856	2012	Roads and Bridges Maintenance
2	31	0.985	2009	Structural Condition Assessment
3	31	0.924	2012	Sustainability
10	10	1	2009	Automated Progress Updating
11	10	0.997	2004	Supply Chain Management

<sup>a</sup> Average year of citations in the cluster

most critical knowledge gaps that should be addressed in the future.

## 2) CLUSTER ANALYSIS

To answer RQ1, this section, first, introduces main developed knowledge domains within the context of IDTs. Then, knowledge gaps and future development areas (RQ2) are identified based on identified domains. Table 3 presents all six clusters and their associated terms, silhouette values, and size. The most significant cluster is termed “interoperability solutions”, which includes 64 articles. As nodes (papers) with a high degree of centrality are more connected to other nodes, we can use this metric to identify papers representing each cluster’s essence. As such, most studies with a high degree of centrality, including Kang et al. [75] and Irizarry et al. [76] with the highest degrees of 61 and 50, have attempted to integrate BIM and other technologies, like GIS. This indicates that most studies focus on the interoperability solutions in the most significant cluster of IDT knowledge. The published



literature also supports this, which identifies interoperability issues and a lack of standards as the main barrier to DT development regarding civil infrastructures [21]. Therefore, it is apparent that, based on the results of the previous section, IT applications within IDTs have a significant branch of efforts dedicated to interoperability solutions (answer to RQ1). However, the silhouette value associated with this cluster demonstrates that it is almost isolated and requires pushing the frontiers of its knowledge to new areas and disciplines (answer to RQ2).

The second significant cluster is related to the application of DTs on highways and bridges. As examples of citing studies that covered a considerable amount of nodes, we can note Jiang et al. [77] study focused on developing highway digital twin from map data, DTs for operation and maintenance of tunnels [78], and the generation of as-built models from TBM data [79]. Studies in this cluster are more concerned with applications of IDTs for the O&M phase; however, the use of digital twins for the design and construction phase has remained less developed despite the recommendations of some experienced industry professionals [21] and authors [79] within the context of infrastructures (answer to RQ2). However, this topic has attracted attention in manufacturing context. For example, Wu et al. [81] proposed a DT-based framework for the designing process of complex products, leading to the reduction of common changes and iterations in the design process. This finding is also true in the manufacturing field, as highlighted by Errandonea et al. [82]. Furthermore, the majority of areas in this cluster fall within the yellow spectrum (see cluster #1 in Fig. 6), indicating that it is an emerging area in IDT knowledge (answer to RQ2).

Other core clusters are structural condition assessment and sustainability, both with a similar size but different nature. The structural condition assessment covers structural applications of DT models, such as structural health monitoring [83], [84] and defect monitoring [85]. The sustainability cluster is focused on emerging DT applications, such as vulnerability assessment [86], [87], and sustainability-based lifecycle management [88]. The yellowish range of the color in this cluster supports our findings in the previous section about the nascent nature of sustainability-based knowledge areas. The high value of silhouette metrics in this cluster indicates the scant connection between articles in this domain with others, as another significant existing research gap (answer to RQ2).

Despite the smaller size of the remaining clusters that suggest they should not be considered a domain of IDT knowledge, a few points about them are worth noting. According to silhouette values, “automation progress updating” is isolated from all other clusters, supporting our finding from the second cluster that the use of DTs during the construction phase is rarely explored. However, with the recent developments in DT applications for supply chain management of modular construction [89], [90] (Cluster 11 with the yellow color), it is not rare to see these two clusters integrated in the near future, as predicted by Boje et al. [35] (answer to RQ2).

**TABLE 4. The most influential documents in terms of the betweenness centrality.**

Author (ref.)	Betweenness centrality	Year	Sources	Cluster
Eastman C [91]	0.28	2011	Book (Wiley& Sons)	Structural Condition Assessment
Kang TW [75]	0.14	2015	Automation in Construction	Interoperability Solutions
Irizarry J [76]	0.13	2013	Automation in Construction	Interoperability Solutions

### 3) BETWEENNESS ANALYSIS

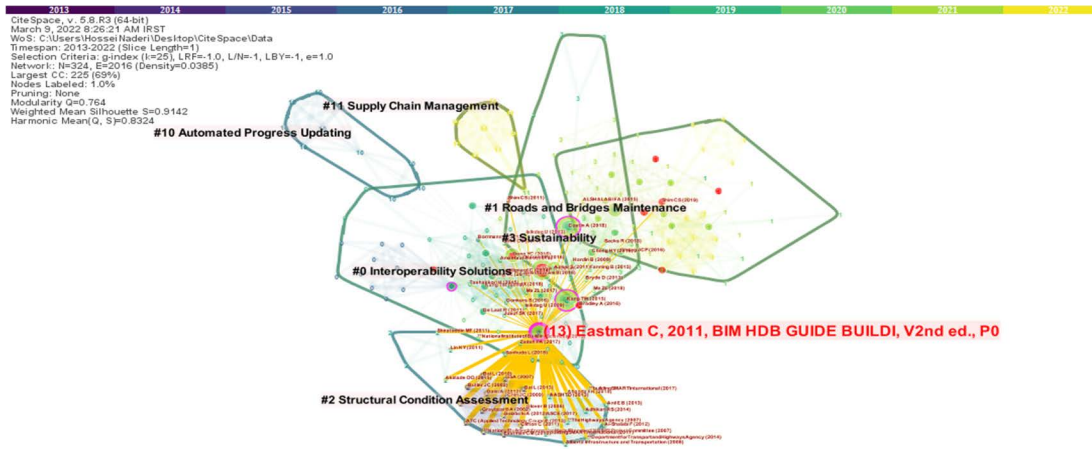
Betweenness centrality, as defined in section 3.4, identifies nodes which serve as bridges between other nodes within a network. This metric becomes crucial when considered in conjunction with the silhouette values of identified clusters (table 3), which indicate the fragmented nature of IDT knowledge. Nodes with a high betweenness centrality serve as gateways through which most knowledge pathways pass [58], thereby reducing silhouette values of clusters and resulting in a more integrated body of knowledge. These influential papers are marked in Fig. 6 with purple rings, and the thickness of purple is proportional to its centrality value [52].

Table 4 presents three papers with the highest betweenness centrality. The BIM Handbook [91] is by far the most influential cited document of other studies in terms of the betweenness metric. This suggests that many IDTs are developed based on BIM models and the body of IDT knowledge is built on the bases of BIM technology. This can be further the reason for the high betweenness centrality of second and third ranks, both of which focus on addressing interoperability solutions as one of the main issues of implementing BIM technologies [92]. However, this BIM-centric era in IDT's body of knowledge is not permanent. As can be seen in Fig. 7, the Eastman study serves as a gateway for the cluster of structural condition assessments and interoperability solutions. There is no solid tie between this node and emerging clusters, such as sustainability and supply chain management. Thus, it can be inferred that the scene can be changed once a better path for passing knowledge is found in the network.

### C. KNOWLEDGE TOPICS

A more detailed look through IDT domains discovered in the previous section was felt necessary to highlight research topics that remained less investigated despite their potential (answer to RQ2). To this end, a keyword co-occurrence analysis is an effective method for exploring the main content of articles and the range of research topics within a given knowledge domain [93]. Our study applied this methodology to gain a detailed picture of topics and trends in the IDT knowledge domains. VOSviewer was used to create a keyword co-occurrence network based on all keywords retrieved from our identified studies. Before building the network, a two-step standardization process was implemented as follows: (1) similar terms, such as “Building Information Modeling”,





**FIGURE 7.** The relationships of the most influential co-cited document (in terms of betweenness centrality) with other cited documents.

“BIMs”, and etc. were merged to a single keyword using the thesaurus feature in the VOSviewer [94]; (2) generic terms, such as “study”, “data”, and etc. were omitted. 103 keywords met the threshold to be included in the network by meeting a minimum of 2 keyword occurrences in identified studies. Since the VOSviewer cannot provide network parameters, which is essential for further analysis, the generated network was imported into the Gephi to extract network metrics. Fig. 8 illustrates the keyword co-occurrence network that can be considered the top area of investigation within the body of IDT knowledge. In Fig. 8, the nodes represent keywords, and their sizes are proportional to the frequency they appeared in identified studies. The link between nodes represents the co-occurrence of nodes in a given study and their thickness presents the frequency of this co-occurrence. Various node colors indicate the period of time that a given keyword occurs in the literature, ranging from dark blue to orange.

Table 5 lists the top-twenty most influential keywords in identified studies based on their frequency and node degree (number of edges in a given node). The first interesting observation is that “bim” keyword is by far more used in all identified studies, even more than the digital twin term as the main keyword of our review. This is in line with our finding in the section 4.2.3 about the high betweenness centrality of the BIM Handbook [90], and a few reviews that refer to BIM technology to gain insights into the DT ‘s body of knowledge in the AEC industry [33], [35] (answer to RQ1). Moreover, this indicates the excessive dependence of IDTs on BIM technology that was originally created for the design stage [5]. This excessive dependence is also the reason for subsequent interoperability issues, which studies related to them created the most influential cluster of IDT knowledge in the previous section.

Among the terms shown in table 5, the high frequency of using “bim”, “iot”, “gis”, and “point cloud data” indicates their significance in IDTs in recent years for various infrastructures. For example, Kowon et al. [95] developed

**TABLE 5.** Most influential keywords of co-occurrence network.

row	Terms	Freq.	Degree
1	bim	67	83
2	digital twins	41	66
3	iot	26	54
4	operation and maintenance	23	52
5	ifc	17	43
6	gis	17	33
7	facility management	13	34
8	shm	12	26
9	optimization	10	29
10	point cloud data	10	22
11	bridges	10	23
12	big data	9	30
13	roads	9	30
14	interoperability	8	31
15	artificial intelligence	8	29
16	industry 4.0	8	25
17	energy management	7	20
18	bridge maintenance	7	15
19	sustainability	7	27
20	construction management	7	21

DTs using BIM and IoT sensors for the anomaly detection of bridges, and in another case, Howell et al. [96] integrated BIM, IoT, and GIS technologies for smart water solutions. Further, a deep learning-based approach is used for the segmentation of industrial components in the process of digital twinning within the context of industrial assets [97]. When we put these detailed findings alongside the most significant cluster in section 4.2.2 (“interoperability solutions”), we can conclude that the DT inner-system architectures and their integration approach are among the most significant concerns in the body of IDT knowledge. Although this research gap has drawn attention in the manufacturing industry [98], no significant attention has been paid to exploring different DT architectures in infrastructure projects and their potential pros and cons. This perspective is further reinforced when we

can find “ifc”, “semantic web”, and “ontology” keywords close to “interoperability” keywords, inviting researchers to investigate this area in more detail and compare the productivity of various interoperability techniques for different DT architectures (answer to RQ2).

The presence of “operation and maintenance”, “facility management”, and “bridge management” among the most frequent keywords supports our interpretation in previous sections that the vast majority of projects in this area so far concentrate on the O&M phase. Specifically, the connection of these terms to “big data” and “artificial intelligence” indicates the application of these tools for IDTs in the O&M phase. For example, Yu et al. [99] developed a DT model using big data techniques to predict pavement performance. Gao et al. [100] also proposed a DT framework for the automation of scheduling of storage yards in ports. Other connected keywords, such as “service life prediction”, “shm” (structural health monitoring), “asset management”, “decision making”, “damage detection”, and “anomaly detection”, are all related to the IDT applications in the O&M phase. Despite these efforts, the user interface of IDTs and frontend solutions for a user-friendly experience has remained unexplored, and there is no related word in this network either. This research gap becomes more significant when it comes to applying DTs in the O&M phase. Since the O&M phase is the longest stage of project lifecycle and a wide range of stakeholders need a stable user interface for utilizing IDTs (answer to RQ2).

Most network algorithms depict networks in force-directed layouts, in which, highly-connected nodes are absorbed into the central area, and less-connected nodes are shown isolated or on the edge of the network [101]. Despite the potential of DTs in sustainable applications [102], sustainability-based research topics, such as “energy efficiency”, “vulnerability assessment”, “resilience”, and “carbon emission”, have remained on the edge of the network, which confirms the lack of adequate attention to sustainable applications of DTs. However, the color of these nodes indicates they are newly investigated topics, and there is a chance for further research in the future in this direction. In addition, social and economic aspects of sustainable infrastructures, which play a pivotal role in a sustainable infrastructure [103], have remained undeveloped in this domain and require more attention (answer to RQ2).

Data security [104] has been identified as the primary issue in the adoption of DTs in industry 4.0 [105] and the infrastructure [21]. Blockchain and edge computing technologies were highlighted as promising solutions for this issue. However, “blockchain” and “edge computing” topics are new topics on the edge of the network and need more attention. In addition, although the potential of some methodologies such as lean construction is investigated in the context of DTs [5], as illustrated in Fig. 8, there is no particular study exploring lean construction and other methodologies like integrated project delivery in the body of IDT knowledge (answer to RQ2).

## V. SYNTHESIS OF FINDINGS

In this section, our findings from the previous section are synthesized in order to answer RQ3: (1) propose a knowledge map that organizes findings in three levels of detail across their maturity levels; and (2) elucidate our three-level knowledge map as a hierarchical practical roadmap for future IDT development intended to serve decision-makers, researchers, and practitioners.

### A. IDT KNOWLEDGE MAP

As can be seen in Fig. 9, the knowledge map is developed based on two principles: (1) the deeper we go, the more details become clear about the IDT knowledge; (2) the knowledge map is designed to provide information about the level of investigation in a particular topic. This means that knowledge domains, and topics on the left side are more investigated by researchers, and those on the right side represent more emerging domains and topics. This provides not only an in-depth picture of IDT knowledge structure, but also gives an understanding of emerging knowledge areas.

Based on the elaborative feature (first principle), the IDT knowledge map includes three levels of detail. The first level is an overview of active knowledge areas from an upper-level perspective, called knowledge territories. This level covers two knowledge territories, namely technology territories, and emerging sustainability territories, based on findings in section 4.1. No detailed information is provided at this level; instead, this level focuses on identifying future research potentials from the perspective of upper-decision-makers (detailed in section 5.2).

The second level is related to knowledge domains based on our generated knowledge clusters in section 4.2. These domains are placed based on their maturity level. The “interoperability solutions” placed on the left side of the knowledge map as a significant knowledge domain primarily focus on the adoption of IDTs. The rest of the knowledge domains, which all are related to IDT applications, are placed considering whether they are emerging domains or not.

The third level is dedicated to knowledge topics identified using our preceding findings from the co-occurrence network. Identified knowledge topics in section 4.3 are organized based on the level of details into five sub-level, namely infrastructure types, IDT life-cycle, IDT applications, IDT components, and interoperability technologies. The “infrastructure types” introduces civil systems that are utilized for DT application with the explanation that the left ones are more investigated by authors, and the right ones are emerging areas. This enables us to address gaps and opportunities to take full capabilities of DTs in all kinds of civil infrastructures.

Most studies focus their IDTs on a particular lifecycle of infrastructure, which is explored in the next knowledge topic sub-level. Further, knowledge topics related to the applications of IDTs are organized into three groups based on their contents, namely IDT applications in O&M, IDT





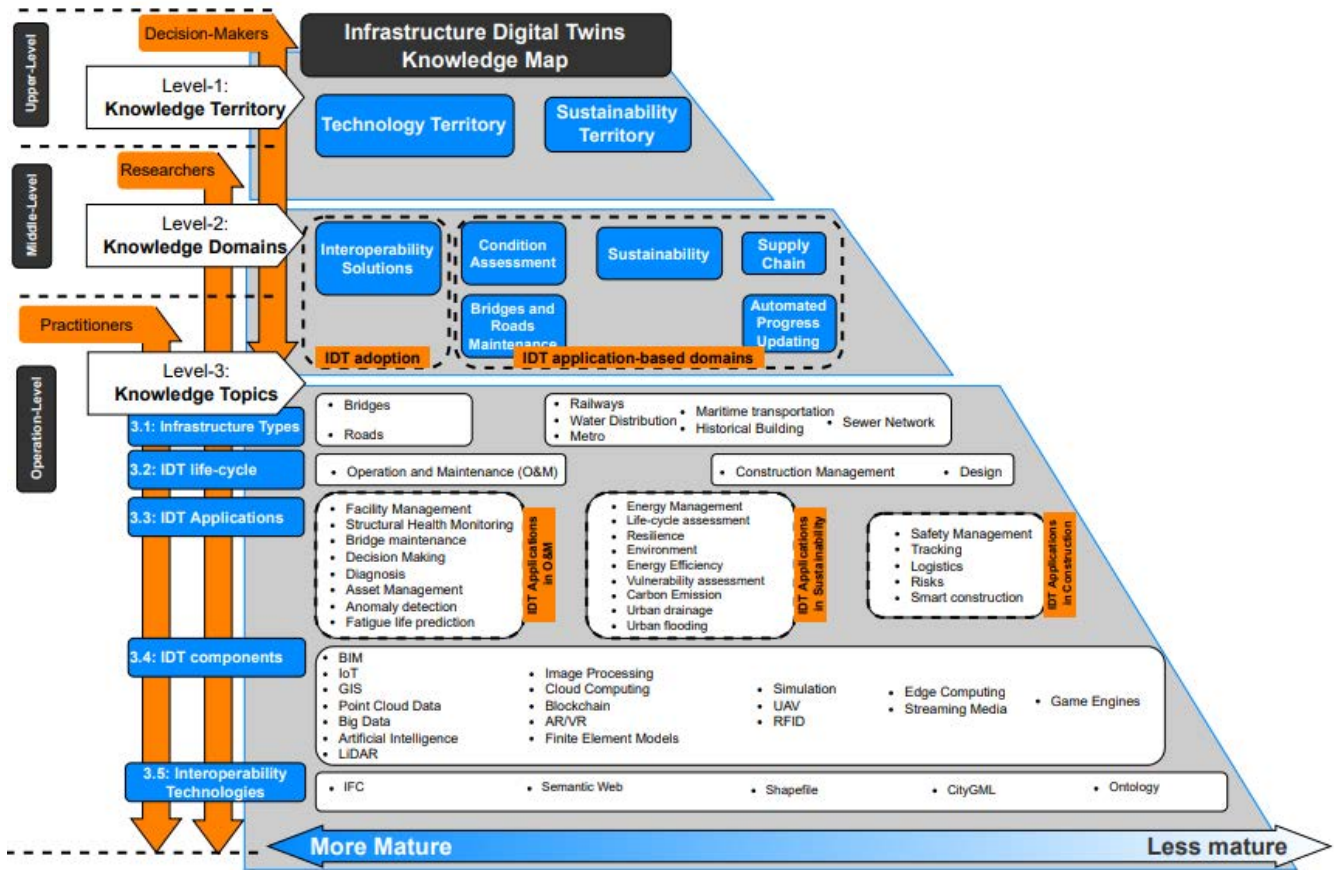


FIGURE 9. The knowledge map of infrastructure digital twins (IDTs).

in charge of public and private research funding agencies should promote collaboration among researchers from different infrastructures. Given that technical issues dominate knowledge territories, and infrastructure projects typically have a long lifecycle, decision-makers should ensure that IDTs can be used for the full lifespan of infrastructure, regardless of changes in management and technologies. Therefore, a maintenance plan is recommended for IDTs in upper-level management.

2) MIDDLE-LEVEL RECOMMENDATIONS

Given the highly fragmented nature of IDT literature, authors recommend that interdisciplinary research among different knowledge domains should be conducted. For example, the application of DTs for supply chain management in the construction stage of roads or bridges not only can change paper-based and labor-intensive traditional supply chain management but also make knowledge domains more consolidated, enabling new IDT applications. Researchers also need to go beyond proposing sustainable-DT frameworks and evaluate the practical application of DTs for assessing sustainability of infrastructures. Furthermore, no knowledge domain has covered the design stage of infrastructure lifecycle. Considering the significance of the design stage in the whole life-cycle of infrastructures, it is recommended that

researchers look into the feasibility and applications of DTs in the design stage of infrastructure. For example, a novel IDT-based design framework can be proposed to investigate potentials of DTs for the Voice-of-Customer (VoC), which can prevent the considerable amount of changes in the design stage and its negative consequences [106].

3) OPERATION-LEVEL RECOMMENDATIONS

The IDT component (see sub-level 3.4 in Fig. 9) presents a considerable number of technologies influencing the DT and its potential. However, less study is available with regard to identifying different characteristics of DT architectures in infrastructures. As a future study, researchers can delve into the inner structure of current IDTs, associated technologies, and interoperability solutions in order to determine which IDT architecture fits well with the open issues of various infrastructures.

Considering the broad range of IDT applications (see sub-level 3.3 in Fig. 9) along with the extended infrastructure lifecycles, we felt that an appropriate front-end solution is needed for a variety of infrastructure stakeholder groups to interact with those applications. However, less emphasis is observed with regard to designing a DT front-end architecture based on different infrastructures with their specific characteristics. As a recommendation, a framework or pro-



prototype of context-aware DTs [107] within different infrastructures can examine the potential benefits of this front-end solution.

Although applications of IDTs in O&M have drawn considerable attention (see sub-level 3.3 in Fig. 9), fewer study has focused on the cost-benefit and performance analyses of DTs in different infrastructures, which should be considered in future works. Furthermore, despite some efforts devoted to exploring DT applications in sustainable infrastructures (see sub-level 3.3 in Fig. 9), less attention has been paid to applications of DTs in the circular economy (CE) and Material Flow Analysis (MFA) within the context of infrastructures.

As highlighted by Errandonea et al. [82], the large civil infrastructures are subject to misalignment of data when it comes to monitoring them. This issue seems more critical when we combine it with our findings in section 4.3, proving the significance of IDT applications in the O&M stage. As a result, researchers and practitioners should investigate different preprocessing algorithms and solutions within the context of different infrastructure projects in their future works. Another recommendation for back-end improvement of IDTs can be classified in potentials of blockchain technology in IDTs. The integration of crypto-economic incentive systems [108] with IDTs can provide practitioners with the opportunity to exchange value in a secure manner between different DTs.

Integration of bibliometric analysis and social network analysis helps this study to provide an accurate picture of IDT body of knowledge without relying on inherent subjectivity of qualitative analyses. This methodology allows us to capture relationship and gaps behind knowledge maps in different detail levels. This multi-level perspective helped us to synthetically provide the IDT knowledge-map, which also serve as a roadmap for decision makers, researchers, and practitioners of IDT in order to improve IDT adoption in civil infrastructure.

## VI. CONCLUSION

This study aims to facilitate IDT implementation by providing a holistic and accurate picture of DT development within the context of infrastructures for different stakeholders. Despite some qualitative efforts, this study applied a systematic review using bibliometric analysis and social network analysis on 139 relevant studies from 2012 to 2022. This approach, as a quantitative method, not only is less error-prone to subjective judgments but also can capture relationships and trends among different research areas, enabling us to identify hidden issues in different levels of detail. Using this method, first, the DT's knowledge territories in infrastructures are identified from an eye's bird view perspective to answer RQ1. Second, the most significant research themes of IDTs are classified through a co-citation analysis. In this level of detail, Network theories combined with a co-citation network of research themes enabled us to answer to RQ2 and extract kinds of gaps that

cannot be obtained using qualitative methods. Third, the co-occurrence network of keywords among identified studies revealed where (see sub-level 3.1 in Fig. 9), why (see sub-level 3.3), and what (see sub-level 3.4) enabling technologies have been employed so far, as in-depth answers to RQ1 and RQ2.

Findings in previous sections are synthesized to create a three-layered knowledge map of IDTs to answer RQ3. Each layer provides a clear understanding of mature and emerging areas, as well as indicates what needs to be done by decision-makers, researchers, and practitioners. The first layer, as the upper-level layer, synthesized findings of knowledge territories and recommend some fundamental directions to decision-makers for further development of IDT knowledge. The second layer, as the middle-level layer, employed findings of the research theme and co-citation network to recommend decision-makers and researchers some solutions for the consolidation of existing fragmented knowledge. In the operation-level layer, knowledge topics and their sub-levels (see Fig. 9) are utilized to provide practitioners and researchers with practical future direction in both the back-end and front-end of IDTs. We believe that our three-layered knowledge map and future directions contribute to the body of knowledge, since it not only provides a common understanding of IDT knowledge to decision-makers, researchers, and practitioners, but also serves as the basis for further development of IDT knowledge.

Despite the contributions of this study as discussed before; all research studies have limitations, and the present attempt is no exception to this rule. Main limitation of this study is that despite the wide domain of DT application, this study focused its scope on civil infrastructures. This should be noted that, civil IDTs serve as a system in bigger systems, like smart city digital twins. Furthermore, there are some infrastructures in the same system level, including energy and digital infrastructure, that are out of the study's scope in spite of their inevitable impact on civil infrastructures. Moreover, there are many smaller DT systems under the umbrella of civil infrastructure that can serve as part of civil IDT system. To address this limitation, authors recommend future studies with a system-of-systems perspective to provide a holistic picture of entire DT knowledge and its relationship with upper- and lower-level systems. Additionally, the review process only considered studies in English, and used a particular set of keywords for searching. Besides, the screening process of core studies can be considered subjective in nature, although the process was performed three separate times to minimize the error. In addition, all analyses are based on the data retrieved from WoS database. Therefore, the findings may not fully reflect the entire available IDT-related studies in the literature.

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**HOSSEIN NADERI** received the B.S. degree in civil engineering from the Semnan University, in 2016, the M.S. degree in construction engineering and management from Pars University, Tehran, in 2019. He is currently pursuing the Ph.D. degree with the Myers-Lawson School of Construction, Virginia Tech. He is a Graduate Research Assistant with Virginia Tech. His main research interests include digital twins, machine-learning, blockchain technology, construction automation, and construction informatic.



**ALIREZA SHOJAEI** received the B.Sc. degree in civil engineering and the master's degree (Hons.) in construction management from the University of Reading, U.K., and the M.Sc. degree in management and Ph.D. degree from the University of Florida. He is an Assistant Professor of building construction with the Myers-Lawson School of Construction, Virginia Tech. His research interests include digital engineering, construction automation, digital twin and smart cities, construction informatics, computer-based modeling and simulation, artificial intelligence, and project management and economics. He is invested in the challenge of revolutionizing the architecture, engineering, and construction industry toward a more resilient built environment, specifically through digital innovations.

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