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SURVEY

An Urban Digital Twin Framework for Reference and Planning

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ABSTRACT Urban management systems evolve from merely overseeing urban growth to comprehending interactions among cities' natural, physical, cyber, and social systems. Urban digital twins leverage emerging technologies and serve as platforms to support city transitions. However, a generic urban digital twin framework with essential building blocks leading to a sustainable urban digital transformation is lacking, as most urban digital twin implementations focus on specific application areas and usages. In addition, as urban digital twins are rather new developments, it is important to clarify their concept, definition, and characteristics, including their joint components and functions. This paper presents findings from a domain analysis based on a systematic literature review on urban digital twins, including investigating the concept, definition, and characteristics of urban digital twins and identifying joint components and functions as building blocks for developing a conceptual framework of urban digital twins for sustainable digital transformation. In total, we identified six main components that could be subdivided into 16 sub-components. Moreover, we identified four main features that could be subdivided into ten sub-features. A conceptual framework for urban digital twins is proposed based on those components and features. Two case studies were conducted to illustrate the framework's applicability. It is an overarching goal that the proposed framework will become a useful reference and decision-making tool for urban planners, designers, constructors, and others.

INDEX TERMS Urban systems, digital twin, sustainable digital transformations.

I. INTRODUCTION

Urban systems present complex and dynamic processes with social, economic, and environmental challenges that involve various services and engagement of stakeholders, such as citizens and policymakers [1], [2]. These challenges encompass concerns, such as energy consumption [3], air pollution [4], inadequate infrastructure [5], traffic congestion [6], water management problems [7], and climate change [8], all of which pose obstacles to urban areas' sustainable development and livability. For instance, one of the most pressing concerns is the escalating impact of climate change. The effects of climate change, such as extreme weather events (e.g., floods, heatwaves, and storms), rising sea levels, and temperature fluctuations, pose significant threats to urban areas and the well-being of their residents. Consequently, the need for rapid and effective responses from authorities has become more crucial than ever. Timely and informed decision-making is paramount in mitigating the impacts of climate change, safeguarding infrastructure, and ensuring the resilience of urban communities. Urban systems must be transformed into smart entities that effectively tackle these challenges to support and realize timely and informed decision-making.

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The transformation from conventional to intelligent cities has emerged as a comprehensive solution, introducing new requirements for urban development that can be facilitated by advanced technologies [9]. Such transitions offer the potential to enhance the efficiency of services, maintain infrastructure, and manage socio-economic processes within urban governance. Ultimately, the development of smart cities promises to improve citizens' quality of life and needs to be developed [10]. The development of smart cities has enabled the collection and accessibility of diverse data from physical, cyber, and social sensing [11], [12]. Analyzing and assessing modern cities' data increasingly demands the integration of multifaceted data sources. As a result, urban management systems are evolving from merely overseeing urban growth to comprehending interactions among natural, physical, cyber, and social systems within cities. One of the promising emerging technologies that can support the transitions is a Digital Twin.

A Digital Twin (DT) can be defined as a digital counterpart of a real-life object that mirrors its state and behavior over its lifetime in a virtual space [13], [14]. The concept of DT has been widely used in various fields, such as manufacturing, aerospace, healthcare, and urban systems, to optimize processes, reduce costs, and improve performance. In the field of urban systems, recently, the DT concept has gained significant attention and serves as a platform for analyzing, simulating, and optimizing complex urban systems [15], [16], and it is called Urban Digital Twins (UDT). A UDT can create a virtual replica of a smart city and simulate factors, such as climatic conditions, the trajectory of the people, and traffic congestion [17]. This can help in inclusive and efficient decisions.

Although there is no universally agreed-upon definition for a UDT, it is commonly understood that a UDT is a virtual representation of an integrated urban system, where the digital built environment acts as the foundation for connecting physical, cyber, and social infrastructure systems [18], [19]. It serves as a platform for data-driven decision-making, employing various models and methods (simulation- and data-driven-based). In recent years, numerous urban studies have employed digital twins to address challenges in areas like transportation [20], infrastructure management [21], disaster management [22], urban planning [23], healthcare [24], and citizen participation [25]. However, since each urban digital twin implementation is geared towards a more or less unique usage, there seems to be no general framework of UDTs with a shared objective of contributing towards urban sustainable digital transformation. Additionally, as this is a relatively new topic, it is necessary to refine and clarify the concept, definition, and characteristics of UDTs and to identify such UDTs' components and functions (features) and then assemble them into an overarching framework design that provides a reference for urban planners, designers, constructors, and others aiming for sustainable smart urban development.

This paper addresses this need based on findings from a domain analysis based on a systematic literature review of existing literature on urban digital twins. More specifically, we strive to deliver the following contributions:

1) A summary of previous findings from the literature on UDTs regarding associated concepts, definitions, and characteristics.
2) Identification of the components and features of UDTs from the literature.
3) Presentation of a framework of UDTs for sustainable digital transformation.
4) Insight into case studies demonstrating how our conceptual framework could be leveraged for modeling and describing urban digital twins tackling challenging societal problems.

The rest of the paper is organized as follows. Previous related work is presented in Section II. The research methodology is described in Section III. The results regarding identifying components to the discussion of case studies applications are summarized in Section IV. Finally, the paper is concluded in Section V.

II. RELATED WORK

Literature reviews on urban digital twins can be divided into two main categories, depending on the use of a methodology based on Systematic Literature Review (SLR). Concerning literature reviews *without* SLR, well-known studies have introduced and presented the concepts of digital twin cities from different perspectives. For example, Deren et al. [26] analyzed the characteristics of smart cities based on digital twin concepts. Deng et al. [27], in turn, investigated the existing digital twin technologies and proposed a pattern of urban digital twins based on the development of smart cities. In another direction, Mylonas et al. [28] reviewed recent studies in the area of digital twins that were applied to the field of smart cities. Their work also attempted to draw parallels with the application of digital twins in Industry 4.0. In their work, Brucherseifer et al. [29] conducted a comprehensive requirements analysis on infrastructure characteristics, crisis management, and resilience measures and proposed a digital twin conceptual framework for critical infrastructure resilience. Finally, Lehtola et al. [30] examined digital twin technologies serving city needs arising from everyday city functions.

With regards to SLR, literature reviews focused on the relationships of urban digital twins with multiple applications and usage scenarios. For example, Shahat et al. [31] investigated the current and prospective potentials and challenges of city digital twins. Ramu et al. [32], in turn, delved into the integration of Federated Learning (FL) and DT for smart city-based applications and their governance. In another direction, Xia et al. [33] analyzed studies covering the integration of Geographical Information Systems (GIS) and Building Information Models (BIM) for sustainable smart city design. Other recent studies focused on the definition of a research agenda for UDTs for infrastructure resilience [34], the identification of the maturity level of city digital twins [35], and the characterization of integrated research frameworks for digital twin-supported smart city [36]. None of the aforementioned literature reviews propose a conceptual framework based on the conducted SLR.

Literature reviews have proposed a conceptual framework based on the conducted SLR. Shaharuddin et al. [37] attempted to seek the prospects of smart city digital twins as a whole and narrow it to indoor disaster management based on the previous research accordingly. Based on that, a conceptual framework and workflow are proposed to create a smart city digital twin for indoor hazards. Ferré-Bigorra et al. [38] proposed a framework for urban digital twins focusing on the technical perspective of urban services provision for infrastructure management. To do so, existing initiatives were mapped in terms of applications, inputs, processing, and outputs of UDT. Although the studies of [37] and [38] proposed conceptual frameworks, none of them provided case studies to ensure the developed framework was applicable. Shaharuddin et al. [37] developed a conceptual framework with three main components: the smart city component, the digital twin component, and the dynamic connection between them. Ferre-Bigorra et al. [38], in turn, developed an urban digital twin framework with five layers: physical, data acquisition, digital modeling, simulation, and service layers. Some of the concepts and components introduced in those studies are revisited in our work, and we also include additional components of our proposed framework. Table 1 provides a summary of related surveys and reviews.

Abouelrous and Zhang [39] proposed a conceptual model for the general design of an urban logistics digital twin. They used a knowledge graph to construct a design for an urban logistics digital twin to be deployed by a Logistics Service Provider in planning their daily operations regarding Vehicle Routing Problems (VRP). They consider a standard VRP with capacity constraints and time windows for planning routing operations as an example. Belfadel et al. [40] elaborated a use case that is based on the proposed conceptual framework for digital twin applications in urban logistics. The use case considers the management of an Urban Consolidation Center that includes three case models: VRP, Traffic, and Demand cases. The task of the VRP solver is to find relevant routes through the network and ideal sequences of pick-up and delivery stops. The goal of the Traffic solver is to obtain an accurate prediction of travel times in the next few minutes or hours. The purpose of the Demand solver is to predict general and seasonal trends on the total daily transport demand, but also demand surges for specific periods of the year. Even though [39] and [40] present case studies in their proposed framework, both of them focus on a specific urban system, which is the urban logistics digital twin. The approach adopted in this paper is more general and provides a unified view for the analysis and comparison of urban digital twins.

In order to conceptualize UDTs from literature, we integrate and extend frameworks and ideas found in [41], [42], and [43]. Tao et al. [41] proposed a five-dimension architecture DT, including physical entity, virtual entity, interaction between physical and virtual parts, data from physical and virtual aspects, and services for unified management. This structure is also partially found in the study of Josifovska et al. [42], which proposed a framework for digital twins within cyber-physical systems decomposed into physical, virtual, data management, and service platforms. To further elaborate on services and features observed in UDT literature, we depart from the study by Al-Sehrawy et al. [43], who developed a taxonomy of DT uses in urban planning and infrastructure management.

III. MATERIALS AND METHODS

The methodology used in this paper consists of three main phases, shown in Figure 1. The first phase concerns a domain analysis, aiming to identify urban digital twins' concept, definition, and characteristics by exploring existing bibliographic sources of urban digital twins. The second consists of analyzing the identified urban digital twin papers by identifying common digital twin components and features discussed in the studies from the selected bibliographical references. Finally, we introduce a conceptual framework for urban digital twins and discuss it.

A. DOMAIN ANALYSIS

We follow Neighbors [44](pg. vi-vii), who defines domain analysis in the context of software engineering as "the activity of identifying objects and operations of a class of similar systems in a particular problem domain". As one of the components of domain engineering, domain analysis is "the activity of identifying and documenting the commonalities and variabilities in related software systems in a domain, that is, systems in a domain that share common design decisions" [45](pg. 126). For an introduction to domain analysis in the context of software engineering activities, the reader may refer to [46] and [47].

In our study, we carried out a domain analysis based on a literature review to methodologically analyze and synthesize the body of research material already in existence on the common components and functionalities of urban digital twins.

Four academic search engines were used to gather relevant literature: Web of Science,[1] Scopus,[2] IEEE Xplore,[3] and ACM Digital Library.[4] These were chosen because they include high-quality publications in relevant fields for this study, including engineering, computer science, and information technology. The papers were retrieved in April 2023. Only articles in English among accessible articles in conference proceedings and international journals have been included in the analysis. Table 2 shows the search query

[1]https://www.webofscience.com/wos/ (As of April 2023)
[2]https://www.scopus.com/ (As of April 2023)
[3]https://ieeexplore.ieee.org/ (As of April 2023)
[4]https://dl.acm.org/ (As of April 2023)

TABLE 1. Summary of related surveys and reviews.

Ref	Theme of Work	Review	Framework	Cases	General UDTs
[26]	Smart city based on digital twins				✓
[27]	A pattern of urban digital twins based on the development of smart cities		✓		✓
[28]	Digital twins from smart manufacturing to smart cities				✓
[29]	Digital twin conceptual framework for critical infrastructure resilience		✓		
[30]	Digital twins technology serving city needs				✓
[31]	The current and prospective potentials and challenges of digital twin cities	✓			✓
[32]	Integration of FL and DT for smart city-based applications and its governance	✓			✓
[33]	GIS and BIM integration for sustainable smart city design	✓			✓
[34]	Research agenda for UDTs for infrastructure resilience	✓			✓
[35]	Maturity level of city digital twins	✓			✓
[36]	Integrated research framework for digital twin-supported smart city	✓			✓
[37]	Digital twins for indoor disaster in smart city	✓	✓		
[38]	Structure of urban digital twins from the technical perspective for infrastructure management	✓	✓		
[39]	Conceptual model for the general design of an urban logistics digital twins	✓	✓	✓	
[40]	Conceptual framework for digital twin applications in urban logistics	✓	✓	✓	

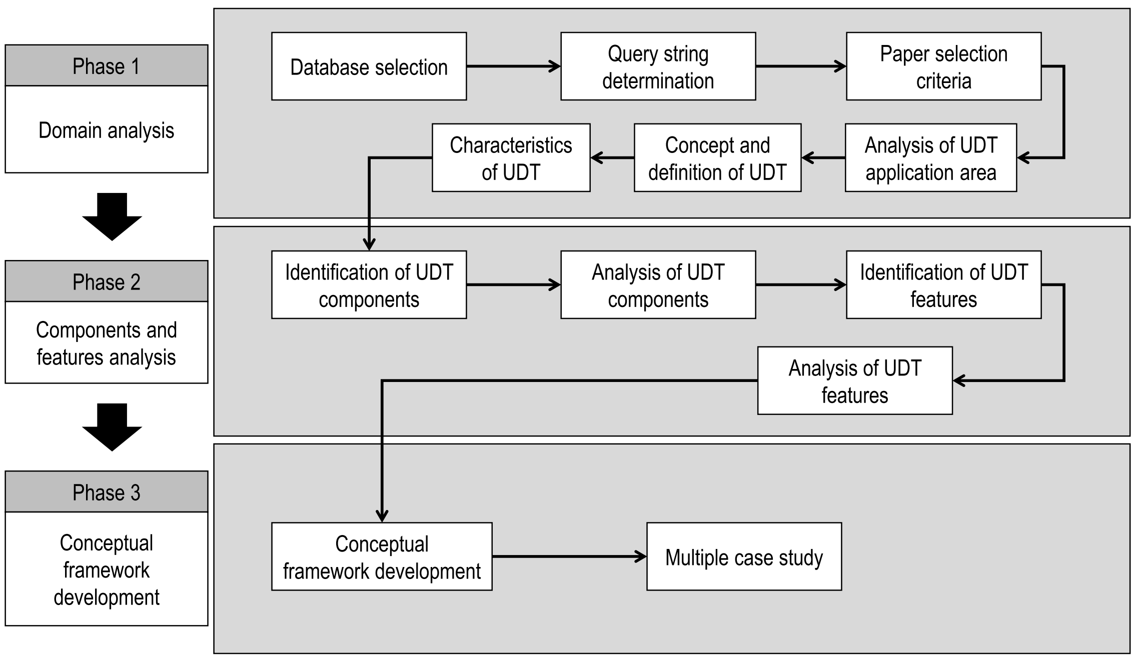


FIGURE 1. Research methodology.

strings used for each search engine. The search query strings were chosen based on discussions among the co-authors to exclude any potential author bias. The initial version of the search strings was relatively simple and only included the keywords "digital twin" and "urban." The search strings were extended through a series of iterations. With each iteration, new keywords were added to take synonyms into account, thus making the search strings more comprehensive. In addition, the query string were also double-checked two librarians who have experience in conducting systematic searches.

After combining the papers obtained from each database using the search strings from Table 2, the total number of collected papers was 301, ranging from 2002 to 2023.

This number decreased to 134 after removing duplicates and survey papers. The first author then independently checked and analyzed each manuscript, which was then double-checked by co-authors using the same standards. Any differences of opinion were discussed until a compromise was reached. Distribution analysis is used for all the gathered data to summarize the evaluated publications.

The next step consisted of reading the abstract and title of each article and assigning (evaluating) them based on rating criteria from 1 to 4, with 4 being the highest relevance, as shown in Table 3. The paper selection process consisted of two steps: (1) selection through examining the title, abstract, and keywords of a paper, and (2) selection through scanning the full text of the paper. Based on the title, abstract, and keywords, any paper rated 1 or 2 was removed without scanning the full text. For any paper rated 3, the full text was scanned to determine whether the paper could be included in the literature review. A total of 38 papers were discarded in this step, leaving 96 potentially relevant papers for the next step in the selection process, which consisted of reading the full text. At last, any paper rated 4 was deemed suitable for the literature review, so it was selected for this study. This approach aimed to identify relevant papers that only mention components and features of a particular conceptual UDT framework in their full text. This step resulted in a final list of 34 relevant papers. The paper selection process is summarized in Figure 2.

The 34 selected papers were listed in a spreadsheet. There, bibliographic information for each article was recorded, including authors, title, year of publication, abstract, DOI, and journal or conference of publication. The selected papers were thoroughly analyzed. Each paper describes or discusses a proposed UDT's conceptual framework and overviews its components and features. Information regarding components and features was registered in a spreadsheet. Finally, the domain analysis has been examined based on the existing literature on using DT in the context of urban systems.

B. COMPONENTS AND FEATURES ANALYSIS

Identified components and features were organized using deductive and inductive methods [48]. Those methods were employed to analyze the content of papers, and the categories were established using gathered information and relevant conceptualizations introduced in recent studies. A five-dimension architecture DT was proposed by Tao et al. [41]. Besides the physical virtual interaction, their proposed model defines data from both physical and virtual aspects and describes services for unified management and on-demand usage. In another study, Al-Sehrawy et al. [43] developed a taxonomy of all identified technical functions or actions executed by DT using a simplified ontology development methodology. Those studies were used as a starting point through the deductive method. On the other hand, a new conceptual framework of components and features for urban digital twins is developed from the relevant literature as a result of this study. The components and features found are analyzed by scanning all papers. This approach follows the inductive method.

C. CONCEPTUAL FRAMEWORK DEVELOPMENT

Duplicates of components and features were merged after scanning each paper and identifying all mentions of components and features of UDT implementation. Based on those components and features, a conceptual framework is developed. The development of the framework is also based on the characteristics of UDTs defined in this paper.

In order to evaluate the applicability of the developed framework in the context of urban areas, two case studies are discussed. It was picked as an example of different urban systems. The first case is the NorDark project, while the second refers to the Twin Fjord and SmartPlan projects (Section IV-E).

IV. RESULTS AND DISCUSSION

This section presents and discusses the results of applying the methodology presented in the previous section. In the first part, we examine the results of identified papers, including the application areas of UDT, the concepts and definitions of UDT, and the characteristics of UDT. In the second part, we discuss the components and features of UDT we found in each paper and categorize them into reference terms defined based on the studies of [42], [41], and [43]. In the third part, we propose a conceptual framework of UDT according to the components and features discussed in the previous part.

A. BIBLIOMETRIC ANALYSIS

Our search yielded a total of 34 relevant papers listed in Table 4. The papers were selected based on their relevance to the topic, as well as their rigor and quality. It was analyzed and synthesized to identify key components and features in the field. The majority of the papers are journal articles (22 out of 34), while the rest are conference papers published between 2020 and 2022. The identified papers cover a diverse range of application areas, most of which focus on urban planning and transportation/mobility, while others have a broader focus that spans multiple application areas. According to [38], the application areas of urban digital twins include public transport, mobility, energy demand, water supply, electricity supply, natural gas supply, and road infrastructure. Based on the content-coding of identified papers, some new areas have been identified in this study, such as urban planning, asset/facility management, disaster/risk management, healthcare, urban logistics, and urban ecological environment.

Figure 3 shows the bibliometric analysis performed in this study. The bibliometric analysis was conducted using two main aspects, i.e., performance analysis and science mapping. Data processing in this part of the study was conducted using VOSviewer and Microsoft Excel [83]. The performance analysis includes examining the contribution of researchers to the investigated domain. As a performance analysis of the selected articles, the distribution of articles over the years,

TABLE 2. Search query string used for the literature study.

No	Database	Search query string
1	Web of Science	(TI=(digital twin*) AND (TI=(urban*) OR TI=(city) OR TI=(cities) OR TI=(municipal*))) AND (AB=(digital twin*) AND (AB=(urban*) OR AB=(city) OR AB=(cities) OR AB=(municipal*)))
2	Scopus	(TITLE (digital AND twin*) AND (TITLE (urban*) OR TITLE (city) OR TITLE (cities) OR TITLE (municipal*))) AND (ABS (digital AND twin*) AND (ABS (urban*) OR ABS (city) OR ABS (cities) OR ABS (municipal*)))
3	IEEE Xplore	((“Document Title”: “digital twin*” AND (“Document Title”:“urban*” OR “Document Title”:“city” OR “Document Title”:“cities” OR “Document Title”:“municipal*”)) AND (“Abstract”:“digital twin*” AND (“Abstract”:“urban*” OR “Abstract”:“city” OR “Abstract”:“cities” OR “Abstract”:“municipal*”)))
4	ACM Digital Library	[Title: “digital twin*”] AND [[Title: “urban*”] OR [Title: “city”] OR [Title: “cities”] OR [Title: “municipal*”]] AND [Abstract: “digital twin*”] AND [[Abstract: “urban*”] OR [Abstract: “city”] OR [Abstract: “cities”] OR [Abstract: “municipal*”]]

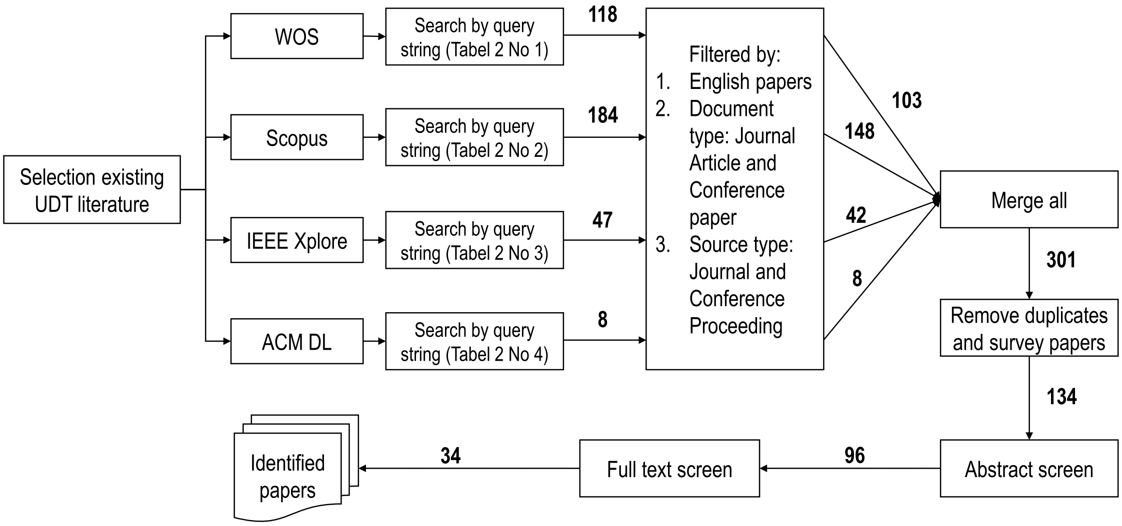


FIGURE 2. Steps in the literature search process.

TABLE 3. Literature selection criteria.

Level	Criteria
4	The paper proposes a conceptual framework of UDTs on a particular urban issue
3	DT technologies and urban system concepts are mentioned in the title, abstract, and/or keywords. Components and features of DTs involved and leveraged in an urban system are not specified in the abstract
2	The paper focuses on an urban system, but the title, abstract, and/or keywords of the paper do not mention the adoption of DT technologies
1	The paper is related to DT but does not concern any urban system issues

and the focused application areas can be observed as shown in Figure 3a and Figure 3b, respectively. Whilst Figure 3a shows that the year 2022 was the most active year in terms of conference papers and journal articles published, Figure 3b shows that the most focused application area in the selected articles is transportation or mobility. In bibliometric analysis, science mapping examines author relationships, including keyword co-occurrence. By displaying the authors’ co-authorship as science mapping, Figure 3c demonstrates the relationships between researchers. We observe a strong collaborative relationship between researchers. The co-authorship analysis focuses on publications, while the keyword co-occurrence analysis focuses on the content of the article itself. The words that appear the most frequently and the linkage among different words show the thematic coverage of the topics in the investigated domain, as shown in Figure 3d. We observe that among others, digital twin is the most frequent word used in the selected articles.

B. DOMAIN ANALYSIS OF URBAN DIGITAL TWINS

An urban digital twin is a virtual representation of the built environment and human activity, such as cities, urban areas and other settlements. Van Den Berghe [62] considers the city as a complex system involving dynamic entities whose behavior is determined by the interaction of many interdependent subsystems, hence it is a system of systems. Although this concept is also called 'digital twin city' or 'city digital twin,' this study used the concept of 'urban digital twin.' An urban digital twin is normally defined by considering the meanings of its three constituent terms:

- "urban," which suggests an engagement in somewhat built-up or dense urban areas;
- "digital," which denotes data storage and analysis in a computer-readable format; and
- "twin," which implies that the digital representation is comparable to or identical to the relevant urban area.

Even though the UDT concept has been widely discussed since 2018, the selected relevant literature has proposed many definitions of UDTs. These definitions significantly differ regarding the scope, technologies, and functionality a DT must have, as listed in Table 5. Schrotter and Hürzeler [50] define UDT with an emphasis on high-fidelity end users by mentioning the enrichment of 3D spatial data. Lu et al. [51] extend this notion by involving a dynamic digital representation and the information feedback from citizens. Ford and Wolf [52] associate the definition of a UDT with its dynamic capability to evaluate how present circumstances and strategies affect future outcomes to enhance decision-making. On the other hand, Austin et al. [54] emphasize real-time monitoring and synchronization of urban activities. In 2022, the attempts to define UDT also considered using multimodal sensor data [71] and their function performances, such as data analytics, machine learning, and simulation models [72].

In addition to the aforementioned explicit definitions, several papers implement UDT by strengthening its development on high-fidelity representation in the form of 3D city models [50], [56], [63], [78]. Adding 3D spatial data and its models expands the current spatial data infrastructure. The emphasis is on 3D spatial data, which serves to connect spatial and other data types. Several other papers link UDT development with 2D Geographical Information Systems [49], [55], [81], [82]. Not only are GIS maps able to analyze geographic data that represent the counterparts of physical assets, but they can also display and analyze spatial relationships between physical assets. A GIS-enabled DT system is built based on the digital twin concept and accurately maps the physical space. It can store, manage, and analyze data describing the distributed urban environment to represent a particular urban system visually. Other papers define UDT as more data-driven operations [53], [58], [64], [67], [73], [75]. Data may be acquired in real-time. Data are processed, leading to simulation- and data-driven-based (based on artificial intelligence methods).

Indeed, each definition would be related to the context and scope of the research, including the proposed definition. There may be scopes that the proposed definition has not touched. In this paper, we combine and complement the definitions from several perspectives in the study literature and propose the following definition: *"An Urban Digital Twin is a dynamic high-fidelity representation of real-life entities of city systems and sub-systems that reflects its states and behavior across its lifecycle and that can be used to securely monitor, analyze, and simulate current and future states using data analytics, data integration, and artificial intelligence aimed at improving the quality of life and well-being of citizens."*

Firstly, this definition involves high-fidelity representation. Both representations of 3D city models containing objects with geometric and semantic information, as well as integrated three-dimensional Building Information Modeling (BIM) and Geographic Information Systems (GIS), provide microscopic and macroscopic geometric databases. Secondly, this definition includes not only city systems but also sub-systems that are more detailed parts of an urban system. Thirdly, we added the secure element to provide security guarantees for monitoring, analysis, and simulation processes. In addition, the existence of data analytics can gain insight into urban operations and assist in formulating strategies. Lastly, intelligent feedback can refer to the intelligent early warning of possible adverse effects and potential dangers of the city through planning, design, and simulation of the urban digital twin.

Based on the viewpoints of the definitions that have been discussed and the results of evaluating identified papers, the following essential characteristics of UDT can be addressed:

- **Two-Way Communication**: it should establish Internet of Things (IoT) technology, such as sensors and actuators, to enable continuous real-time data collection, accurate replication of the physical entities at any given time, and feedback transmission to the physical urban entities.
- **High-Fidelity Representation**: it should present a precise visual representation of physical entities, such as digitalizing the urban elements into 2D/3D models containing objects with geometric and semantic information; as a result, high fidelity should be balanced during the twining process.
- **Accurate-Consistent-Accessible Information**: it should provide structured storage data foundation, data management, data integration, urban modeling, and knowledge domain pertaining to the physical urban entities.
- **Intelligent Simulation**: it should include effective computation, analysis, and simulation with the ability to predict potential future conditions of the urban system to facilitate decision-making.

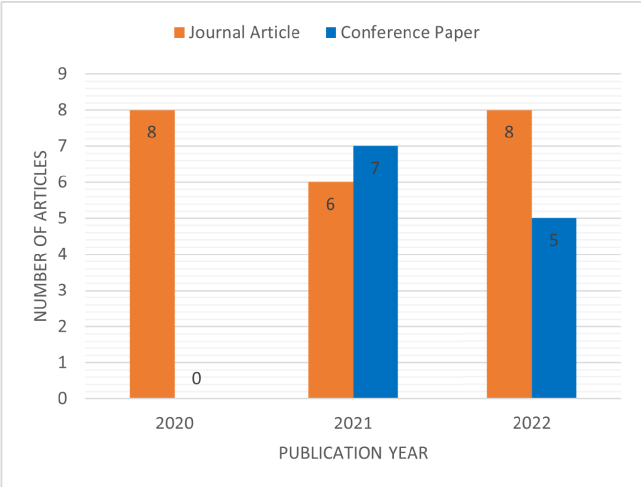
TABLE 4. Identified relevant papers.

No	Authors	Year	Publication type	Application area
1	[49]	2020	Journal	Urban planning
2	[50]	2020	Journal	Urban planning
3	[51]	2020	Journal	Asset/facility management
4	[52]	2020	Journal	Disaster/risk management
5	[53]	2020	Journal	Healthcare
6	[54]	2020	Journal	Urban planning
7	[55]	2020	Journal	Disaster/risk management
8	[56]	2020	Journal	Urban planning
9	[57]	2021	Conference	Transportation/mobility
10	[58]	2021	Journal	Asset/facility management
11	[59]	2021	Journal	Transportation/mobility
12	[60]	2021	Journal	Transportation/mobility
13	[61]	2021	Journal	Building management
14	[62]	2021	Conference	Transportation/mobility
15	[63]	2021	Journal	Urban planning
16	[64]	2021	Conference	Transportation/mobility
17	[65]	2021	Conference	Energy/power system
18	[66]	2021	Conference	Energy/power system
19	[67]	2021	Conference	Urban logistics
20	[68]	2021	Conference	Building management
21	[69]	2021	Journal	Urban drainage system
22	[70]	2022	Journal	Asset/facility management
23	[71]	2022	Journal	Transportation/mobility
24	[72]	2022	Conference	Urban planning
25	[73]	2022	Journal	Building management
26	[74]	2022	Journal	Urban drainage system
27	[75]	2022	Journal	Transportation/mobility
28	[76]	2022	Journal	Transportation/mobility
29	[77]	2022	Journal	Urban planning
30	[78]	2022	Journal	Transportation/mobility
31	[79]	2022	Conference	Disaster/risk management
32	[80]	2022	Conference	Energy/power system
33	[81]	2022	Conference	Urban planning
34	[82]	2022	Conference	Urban ecological environment

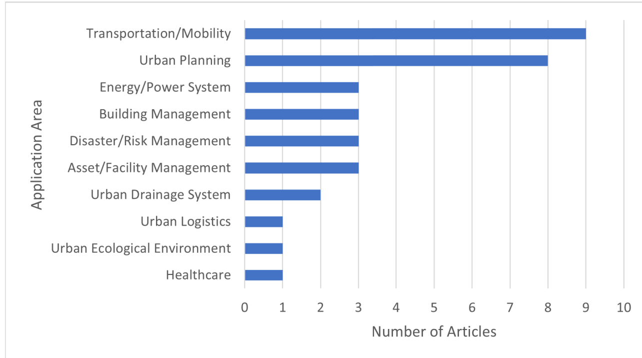
TABLE 5. UDT definitions.

Author	Definition
[50]	A consistent enrichment of the 3D spatial data inventory and, in addition to the modeling and description of the data, lifecycle management of the individual components as well as the entire data inventory.
[51]	A dynamic digital replica of physical assets, processes, and systems through involving Internet of Things(IoT) devices and information feedback from citizens.
[52]	A system of ICT sensors that develop data sets integrated into digital twin models that provide a dynamic ability to assess the future impacts of current conditions and strategies in ways that improve decision-making to achieve desired future results.
[54]	A cyber component that mirrors the physical urban system through real-time monitoring and synchronization of urban activities.
[71]	A digital model of a city consists of physical assets and multimodal sensor data.
[72]	A virtual representation of a city's physical assets, using data, data analytics, machine learning, and simulation models that can be updated and changed as their physical equivalents change.

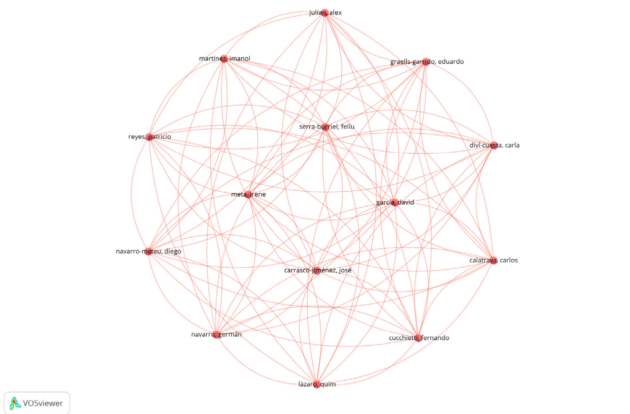
- **Secure mechanisms**: it should impose security/privacy requirements designed to protect the twin's contents and the communication channels connecting it to its physical counterpart.



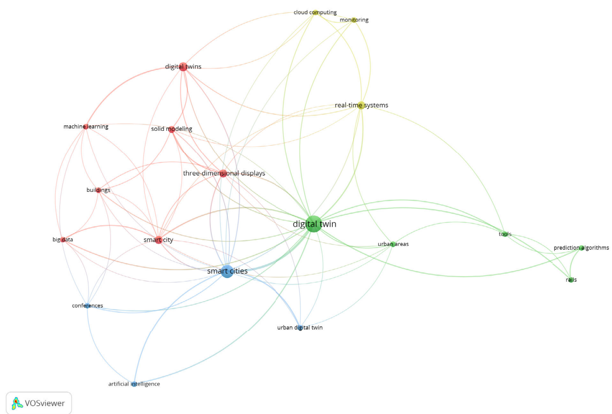
(a) Distribution of selected articles over time for different publication types.



(b) Focused application areas.



(c) Co-authorship among authors.



(d) Co-occurrence of keywords.

FIGURE 3. Bibliometric analysis of selected articles.

- **Human Infrastructure Technology Interaction**: it should consider integrating participatory tactics involving human interactions, such as citizens and policymakers concerned with the effectiveness and sustainability of the growth and progress of the urban environment for improved quality of life.

C. COMPONENTS AND FEATURES OF URBAN DIGITAL TWINS

1) FRAMEWORK COMPONENTS

In this study, the conceptual framework is defined and structured according to the components and entities necessary to support the implementation of UDTs with the aforementioned characteristics. Table 6 lists and defines six framework components, modified from a structure proposed by Tao et al. [41].

Based on UDT literature, we further define an initial set of entity components, as depicted in Figure 4.

a: PHYSICAL ENTITY (PE)

- **Physical objects**: Physically observable components that may be natural, human-made, or mixed. The behavior and attributes of physical objects are observed by physical nodes.
- **Physical nodes**: Physical components that communicate with the UDT to support observation, data acquisition, and/or actuation of physical objects. Examples include IoT and other networked devices that exchange data and information with other systems as seen in e.g., [59], [63], and [79].

b: DATA (DD)

- **Data management resources**: Repositories, methods, and procedures to support organization, storage, protection, and maintenance of data throughout its lifecycle, including data collection, data storage, and data governance [64], [71], [82].

TABLE 6. UDT framework components.

Component	Definition	References
Physical Entity	Identifiable and observable parts of the physical environment, natural and/or human-made. It may be divided into physical nodes that sense and communicate attributes of physical objects in the UDT context.	[41], [42], [84]
Data	Collection of resources and rules for acquiring, managing, processing, and storing data. Includes data acquired from physical nodes as well as data generated internally in the UDT environment.	[41], [42]
Virtual Entity	Digital representations of physical objects and their attributes.	[41], [42]
Users	Human or digital users interacting with the UDT for management and configuration or service consumption (clients). Users link virtual and physical entities through manual or automated actuation of physical objects and/or nodes.	[84], [85]
Services	Functionalities and operations provided by the UDT to accommodate user needs.	[43]
Connection	Communication among entities and components to make services accessible to users.	[41]

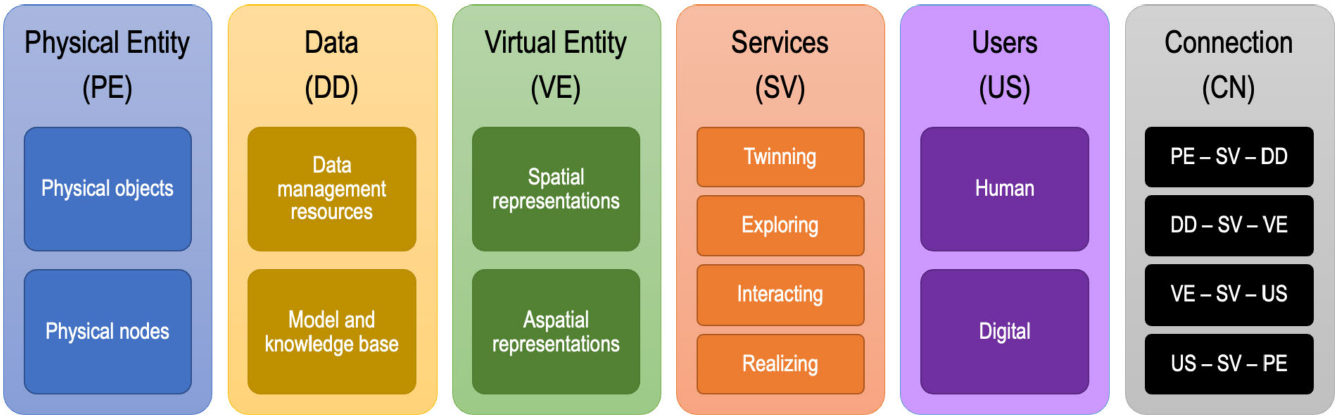


FIGURE 4. UDT framework components.

- **Model and knowledge base**: Information, models, and domain knowledge about physical objects, their attributes, and behaviors necessary to provide UDT services to users [54], [58], [62], [69], [72], [74], [77].

c: VIRTUAL ENTITY (VE)

- **Spatial representations**: a high-fidelity virtual representation of the physical entity that integrates multiple variables, scales, and abilities to reproduce its geometries, physical properties, behaviors, and rules in the virtual world. Includes 2D, 3D, and 4D (spatiotemporal) representations [50], [56], [63], [76].
- **Aspatial representations**: a representation of data using numerical values or visual elements, such as graphs, charts, diagrams, or images that is easier for humans to understand and interpret [53], [65].

d: SERVICES (SV)

- **Twinning**: Handling replication of physical entities in the real world in the form of virtual entities in the cyber world at a point in time [51], [68], [72], [80].
- **Exploring**: Handling the creation of new knowledge and providing insights for users about physical entities [43], [60], [66], [81].
- **Interacting**: Handling the interpretation and exchange of information to support user operations [43], [70], [77].
- **Realizing**: Handling utilization of the collected and analyzed data to intervene back into the real world to achieve a desirable state [62], [73].

e: USERS (US)

- **Human**: Human users include individuals and groups in civil society who inform and utilize the design of the urban environment [55], [59], [63], [70].
  - **Citizens**: Individuals and groups in civil society who inform and utilize the design of the urban environment [55], [59], [63], [70].
  - **Public authorities**: Government officials, such as policy-makers [67], [77], administrators and managers [51], [52], planners and architects [49], [61], and other actors responsible for developing and managing the urban environment.
  - **Private companies**: Commercial organizations engaged in planning, development, and management of systems in the urban environment [50], [58].

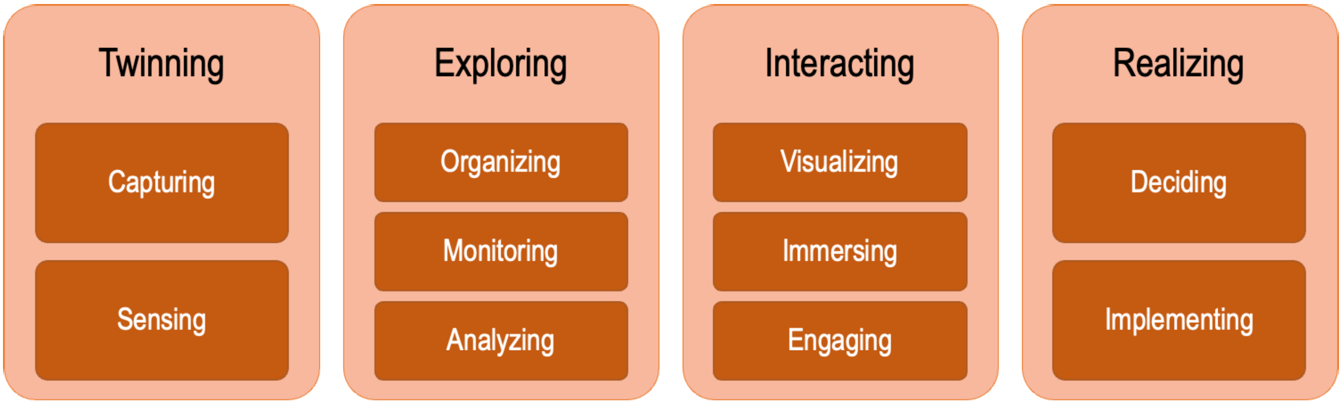


FIGURE 5. UDT framework features.

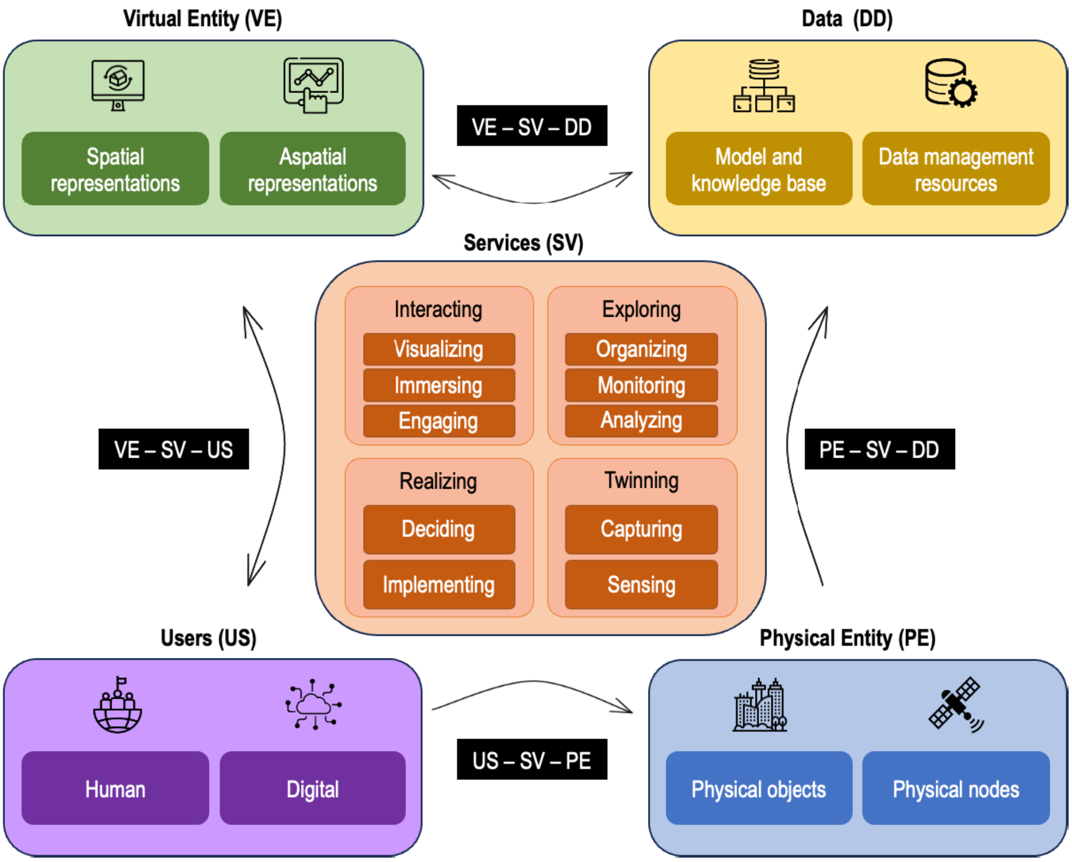


FIGURE 6. Proposed conceptual framework for Urban Digital Twins.

 - **Researchers and developers**: Actors providing expertise, guidance, and support in the development, implementation, and operation of systems both in the physical entity as well as the urban digital twin. Includes academic researchers [51], [69], along with other R&D consultants and experts [56].
- **Digital**: Digital users may be client applications as well as other devices that consume UDT services and support the actuation of physical objects. Human and digital users may operate simultaneously in the UDT environment [55], [59], [63], [70].

f: CONNECTIONS (CN)

The following relationships represent key connections in the UDT conceptual framework.

- **PE - SV - DD**: Data about physical objects is acquired from physical nodes through twinning services.

- **DD - SV - VE**: Data externally acquired or internally generated is used to generate new knowledge, information, and data via exploration services.
- **VE - SV - US**: Users interact with the virtual entity to access other services necessary to support user operations.
- **US - SV - PE**: Users implement changes to physical entities based on decision support from the UDT.

Detailed information on the framework components covered in each paper can be seen in Tables 7 and 8. All of the papers cover the *Physical objects* and *Physical nodes* aspects in the context of UDTs. This indicates the importance of existing objects and connected devices in collecting data and enabling real-time communication with the UDT to support observation, data acquisition, and/or actuation. Regarding the Data component, most papers address the *Data management resources* aspect of UDTs. They play an important role in the Data component. *Data management resources* can improve reliability and consistency in data processing and storage. On the other hand, the *Model and knowledge base* aspect can help represent the physical system accurately and enable effective simulation of different scenarios and analysis of their impact. These aspects might be foundational for creating accurate and comprehensive UDTs, and almost all papers consider this *Model and knowledge base* aspect.

The papers that cover the *Spatial representations* aspect (e.g., 2D/3D model) of physical entities dominate the papers that cover the *Aspatial representations* aspect (e.g., graphical or numerical representations). This shows that some studies focus on creating visual representations in the UDT. It can help stakeholders or users understand complex data and information. The *Spatial representations* aspect can also be used for real-time monitoring, enabling stakeholders to detect and respond to changes quickly. Moreover, 3D models can be used for property valuation, as they can capture the vertical dimension of buildings and the surrounding environment. This can provide a more accurate and comprehensive view of the property value.

All papers cover the *Twinning* and *Interacting* aspects. It shows that these two aspects are important and must exist within the framework of a UDT. These aspects could be indicated as key aspects for successful UDT implementation. It differs from the *Exploring* and *Realizing* aspects; not all papers cover them. For instance, Luo et al. [70] only build physical entity replicas and display them to the Users, without any *Exploring* aspect. On the other hand, several papers do not discuss the *Realizing* aspect because the Virtual Entity component is presented only as information for the Users.

The Users component is divided into two categories: *Human* and *Digital*. Some papers involve both, but some of them only cover one of them. Many papers recognize the significance of involving *Human* and *Digital* in the development and utilization of UDTs. This highlights the need for participatory approaches and user-centered design to ensure the relevance and usability of digital twin solutions. Nevertheless, a few papers do not cover both aspects; it might be that the system was built only for private consumption or is still in research development.

It can be seen that all papers cover the following aspects: *PE-SV-DD*, *DD-SV-VE*, and *VE-SV-US*. This suggests that these aspects are fundamental and widely recognized as important in the field. Besides, these connections are the main connections for how a UDT is constructed and become the minimum workflow that must exist to build a UDT. It starts with every data originating from PE sent to DD, then together with SV implemented to VE to be presented to US. While for *US-SV-PE*, not all of the papers implement them. It depends on the scope of work in each paper.

2) FRAMEWORK FEATURES

In this paper, a feature is defined as an activity that is supposed to be performed by a framework component, and it is called a framework feature. The features are derived from the service components. We propose the framework features depicted in Figure 5. Based on the four main services, we have found and broken down into ten features with the following details:

a: TWINNING

To duplicate physical entities in the real world in the form of virtual entities in the cyber world at a point in time.

- **Capturing**: to collect data in a spatial format within the virtual world, which is the geolocation of physical entities [43], [49].
- **Sensing**: to collect data related to the measurement of physical entities [43], [55], [75].

b: EXPLORING

To create new knowledge and provide insights for stakeholders about physical entities.

- **Organizing**: To store, browse, retrieve [51], update [49], convert [55], secure [57], [79], and integrate [53] information about physical entities.
- **Monitoring**: To state the status and performance of physical entities [43], [52], [73].
- **Analyzing**: To uncover new information about properties and behaviors of physical entities through computing [43], [53], [60], mining [43], [64], simulating [43], [65], and predicting [43], [66], [81].

c: INTERACTING

To participate in knowledge-building, problem-solving, and decision-making processes using visual representations of collected and analyzed data.

- **Visualizing**: To form and vision a realistic representation or model of current or predicted physical entities [43], [82].
- **Immersing**: To apply interested users in real-like experiences using immersive technologies, such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) [43], [50], [55].
- **Engaging**: To involve citizens and large groups of people, including decision-making processes [43], [56].

TABLE 7. Detail framework components of UDT based on identified literature (part 1).

Ref	Physical Entity (PE)		Data (DD)		Virtual Entity (VE)	
	Physical objects	Physical nodes	Data management resources	Model and knowledge base	Spatial representations	Aspatial representations
[49]	✓	✓	✓	✓	✓	
[50]	✓	✓	✓	✓	✓	
[51]	✓	✓	✓	✓	✓	
[52]	✓	✓	✓	✓		✓
[53]	✓	✓	✓			✓
[54]	✓	✓	✓	✓	✓	
[55]	✓	✓	✓	✓	✓	
[56]	✓	✓	✓	✓	✓	
[57]	✓	✓	✓		✓	
[58]	✓	✓	✓	✓		✓
[59]	✓	✓	✓			✓
[60]	✓	✓	✓	✓		✓
[61]	✓	✓	✓	✓	✓	
[62]	✓	✓	✓	✓	✓	
[63]	✓	✓		✓	✓	
[64]	✓	✓	✓			✓
[65]	✓	✓	✓	✓		✓
[66]	✓	✓	✓	✓	✓	
[67]	✓	✓	✓	✓		✓
[68]	✓	✓	✓	✓	✓	
[69]	✓	✓		✓		✓
[70]	✓	✓	✓	✓	✓	
[71]	✓	✓	✓	✓	✓	
[72]	✓	✓	✓	✓	✓	
[73]	✓	✓	✓	✓		✓
[74]	✓	✓	✓	✓	✓	✓
[75]	✓	✓	✓	✓		✓
[76]	✓	✓		✓	✓	
[77]	✓	✓	✓	✓	✓	
[78]	✓	✓	✓	✓	✓	
[79]	✓	✓	✓	✓	✓	
[80]	✓	✓		✓	✓	
[81]	✓	✓	✓	✓	✓	
[82]	✓	✓	✓	✓	✓	

TABLE 8. Detail framework components of UDT based on identified literature (part 2).

Ref	Services (SV)				Users (US)		Connection (CN)			
	Twinning	Exploring	Interacting	Realizing	Human	Digital	PE - SV - DD	DD - SV - VE	VE -SV - US	US - SV - PE
[49]	✓	✓	✓	✓		✓	✓	✓	✓	
[50]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[51]	✓	✓	✓	✓		✓	✓	✓	✓	
[52]	✓	✓	✓	✓		✓	✓	✓	✓	✓
[53]	✓	✓	✓	✓	✓		✓	✓	✓	
[54]	✓	✓	✓	✓		✓	✓	✓	✓	
[55]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[56]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[57]	✓	✓	✓			✓	✓	✓	✓	
[58]	✓	✓	✓	✓		✓	✓	✓	✓	✓
[59]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[60]	✓	✓	✓	✓			✓	✓	✓	✓
[61]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[62]	✓	✓	✓	✓		✓	✓	✓	✓	✓
[63]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[64]	✓	✓	✓				✓	✓	✓	
[65]	✓	✓	✓	✓			✓	✓	✓	
[66]	✓	✓	✓				✓	✓	✓	
[67]	✓	✓	✓	✓		✓	✓	✓	✓	
[68]	✓	✓	✓	✓		✓	✓	✓	✓	
[69]	✓	✓	✓	✓		✓	✓	✓	✓	
[70]	✓		✓	✓	✓		✓	✓	✓	✓
[71]	✓	✓	✓				✓	✓	✓	
[72]	✓	✓	✓	✓		✓	✓	✓	✓	✓
[73]	✓	✓	✓	✓		✓	✓	✓	✓	✓
[74]	✓	✓	✓			✓	✓	✓	✓	
[75]	✓	✓	✓			✓	✓	✓	✓	
[76]	✓	✓	✓				✓	✓	✓	
[77]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[78]	✓	✓	✓	✓		✓	✓	✓	✓	✓
[79]	✓	✓	✓	✓		✓	✓	✓	✓	✓
[80]	✓	✓	✓	✓		✓	✓	✓	✓	✓
[81]	✓	✓	✓	✓		✓	✓	✓	✓	✓
[82]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

TABLE 9. Framework features of UDT based on identified literature.

Ref	Twinning			Exploring			Interacting		Realizing	
	Capturing	Sensing	Organizing	Monitoring	Analyzing	Visualizing	Immersing	Engaging	Deciding	Implementing
[49]	✓	✓	✓		✓	✓			✓	
[50]		✓	✓		✓	✓	✓	✓		✓
[51]	✓	✓	✓	✓	✓	✓		✓	✓	
[52]		✓		✓	✓	✓				✓
[53]		✓	✓	✓	✓	✓			✓	
[54]		✓		✓	✓	✓			✓	
[55]	✓	✓	✓	✓	✓	✓	✓			✓
[56]		✓	✓		✓	✓	✓	✓		✓
[57]		✓	✓	✓	✓	✓	✓			
[58]		✓	✓	✓	✓	✓				✓
[59]		✓	✓	✓	✓	✓				✓
[60]		✓	✓		✓	✓				✓
[61]		✓	✓		✓	✓				✓
[62]		✓	✓		✓	✓			✓	✓
[63]	✓	✓	✓		✓	✓		✓		✓
[64]		✓	✓		✓	✓				
[65]		✓	✓	✓	✓	✓			✓	
[66]		✓	✓	✓	✓	✓				
[67]		✓		✓	✓	✓			✓	
[68]	✓	✓		✓	✓	✓			✓	
[69]		✓	✓	✓	✓	✓			✓	
[70]	✓	✓				✓	✓	✓		✓
[71]	✓	✓	✓		✓	✓				
[72]	✓	✓		✓	✓	✓		✓		✓
[73]		✓	✓	✓	✓	✓		✓	✓	✓
[74]		✓	✓	✓	✓	✓				
[75]		✓	✓		✓	✓				
[76]		✓	✓		✓	✓				
[77]		✓	✓	✓	✓	✓		✓		✓
[78]		✓	✓		✓	✓				✓
[79]	✓	✓			✓	✓	✓			✓
[80]		✓	✓	✓		✓				✓
[81]		✓	✓	✓	✓	✓				✓
[82]		✓			✓	✓				✓

d: REALIZING

To leverage the collected and analyzed data to intervene back into the real world to achieve a desirable state.

- **Deciding**: To design and select actions concerning the future state of physical entities [43], [62], [69].
- **Implementing**: To employ decisions about physical entities through human and/or digital actuation [43], [78], [80].

Detailed information on the framework features covered in each paper can be seen in Table 9. All papers covering the *Sensing* aspect highlight the importance of collecting real-time data for understanding and managing urban environments, which suggests its recognition as a fundamental component in UDT development. The lower coverage of the *Capturing* aspect indicates that this aspect is relatively less explored or less emphasized in the context of urban digital twins due to data collection, integration, and processing challenges, which might require more effort and resources. The varying coverage of the *Capturing* and *Sensing* aspects reflects the multidimensional nature of UDTs and their diverse applications. The *Sensing* aspect is widely recognized as a fundamental pillar for real-time data collection. Despite being crucial for spatial fidelity, the *Capturing* aspect might receive less attention due to potential data acquisition and integration complexities.

Most papers cover the *Organizing* and *Analyzing* aspects. The emphasis on the *Organizing* aspect suggests that many researchers are concerned with solid (stable, reliable, and trustworthy) data organization and computation processes. Without solid organizing and computing capabilities, other advanced functionalities would not be feasible. The substantial coverage of the *Monitoring* aspect underscores its significance for maintaining the usefulness and relevance of UDTs over time and it could be due to its alignment with the ongoing maintenance and management needs of cities, making it a compelling use case for UDTs.

The fact that all relevant papers cover the *Visualizing* aspect suggests that it is a foundational aspect of UDTs. It involves creating accurate and detailed representations of physical entities within a city. More likely, it can range from 2D maps to detailed 3D models that provide a comprehensive view of the urban environment. On the other hand, only a few cover the *Immersing* and *Engaging* aspects. It might indicate the evolving nature of research priorities. Initially, the focus has been on developing accurate visualizations, as they form the foundation for the other aspects. As the technology matures and understanding grows, researchers are exploring the potential of immersive experiences, citizen engagement, and security measures in the context of UDTs.

Although most papers cover the *Implementing* aspect compared to the *Deciding* aspect, both aspects are crucial for successfully implementing UDTs. The literature's emphasis may lean towards the *Implementing* aspect. Nevertheless, the significance of the *Deciding* aspect is essential for building adaptive, responsive, and efficient urban systems that can effectively address the challenges of modern cities. As the field continues to evolve, a balanced consideration of both aspects will likely lead to more comprehensive and impactful urban digital twin implementations.

D. CONCEPTUAL FRAMEWORK OF URBAN DIGITAL TWINS

The conceptual framework of this paper should provide a basis for implementing digital twins, including twinning, exploring, interacting, and realizing existing and desirable future urban systems. More specifically, the framework must address the cyber-physical control cycle of smart cities that seamlessly integrates sensing and monitoring, smart analyses, and smart control of urban operations; the framework must support the implementation of essential characteristics of UDTs discussed in the previous section; and the framework must support the life cycle of urban objects. Based on the discussion of components and features in the previous section, we propose a conceptual framework of UDT, as visualized in Figure 6.

The framework starts with measuring the Physical Entity (PE): the physical object system's state by the physical node's function and acquiring relevant data sources. These data (DD) are then managed, integrated, modeled, and some of them could be new knowledge to be translated into a virtual entity (VE) as a virtual representation with support from services (SV). The VE includes all information relevant to users (US). Depending on a specific purpose of usage, a virtual view may filter irrelevant information and present it so that it can be processed optimally by specific users. It could be visualized as a spatial (2D/3D) model or aspatial (numerical/graphical) view. Besides visualizing the object system's state, several services might be implemented, such as monitoring and analyzing based on specific computations. Some other services related to the interaction between US and VE could be performed, such as using immersive technology that applies to users in real-like experiences using VR, AR, and MR; and user engagement. The use of that technology involves users adjusting some values in the VE environment. Moreover, the SV also addresses the existence of cyber security, which is crucial to protect PE, DD, and VE against unauthorized access, manipulation, or theft of data. In addition, the realizing function, especially the deciding aspect, which compares a virtual view of the object system with a specific control norm, could be executed. It selects appropriate interventions based on its decision support model. The selected intervention is then communicated directly or via remote actuator systems with the effector function in the PE. On the other hand, the implementing aspect involves supporting human decision-making throughout the implementation of interventions in the real world by US.

E. APPLICATIONS OF URBAN DIGITAL TWINS

To illustrate the conceptual framework presented in this paper, we explore two UDT cases used to support lighting design and mobility design.

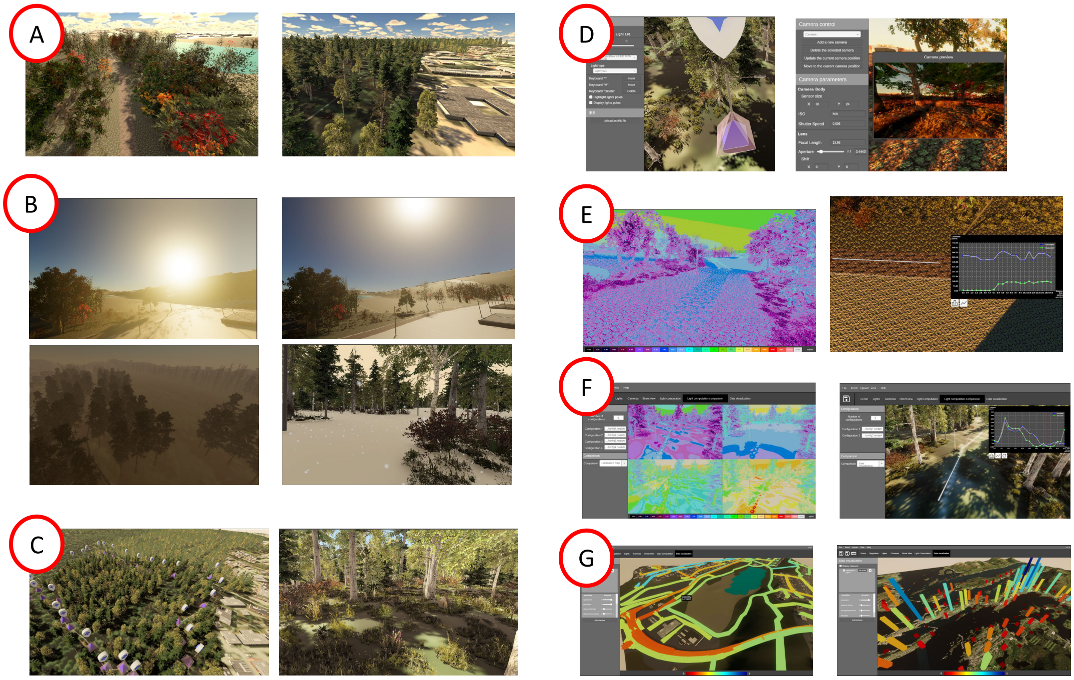


FIGURE 7. NorDark-DT. A: 3D scene navigation; B: Environmental condition definition; C: Vegetation condition definition; D: Light infrastructure and wildlife camera trap view; E: Luminance analysis; F: Light infrastructure comparison; and G: Data visualization.

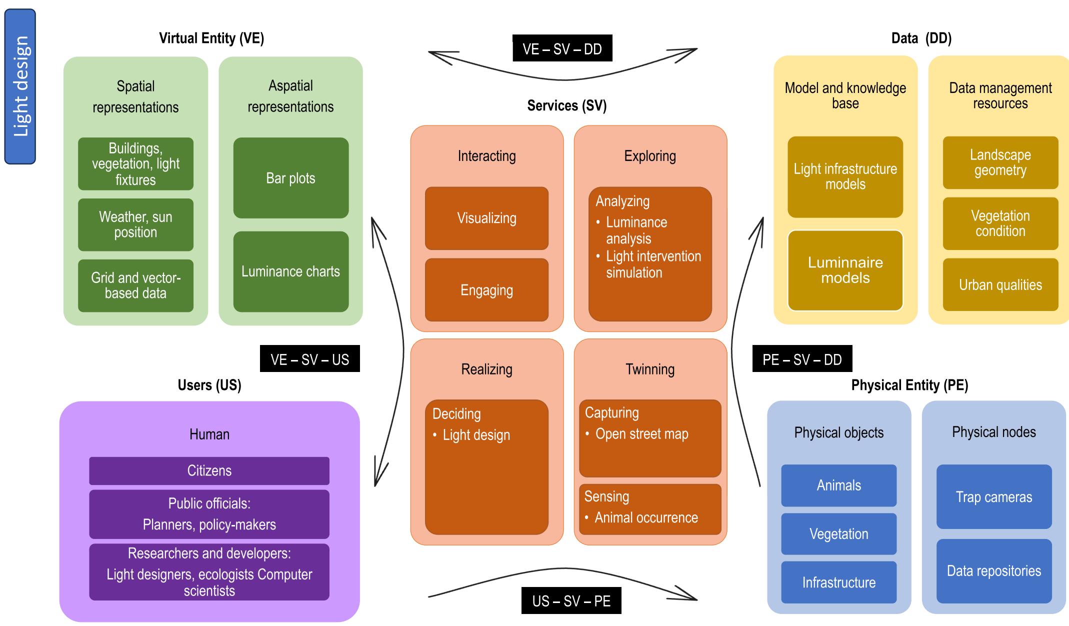


FIGURE 8. Light design case related to the NorDark project.

a: LIGHTING INTERVENTION DESIGN

As part of the NorDark project,[5] a digital twin has been created to support lighting intervention design for urban green areas. The project aims to establish new tools and knowledge on lighting design that not only account for aesthetic aspects but also human perception and comfort. The interventions have been designed also taking into account a more-than-human perspective to consider risks to animals, such as e.g., birds, bats, and other species. The UDT has been used to plan and simulate different lighting conditions and interventions as well as to analyze and understand collected data in the field based on visualizations in target sites in Sweden, and Norway.

Figure 7 provides an overview of some functionalities available in the digital twin. The digital twin supports 3D

[5]https://nordark.org (As of Oct. 2023)

FIGURE 9. **Digital twin for mobility design. A: 3D scene navigation; B: Demography specification; C: Road network design; D: Traffic simulation; E: Walkability parameter definition; F: Walkability 2D/3D visualization.**

navigation through pre-defined scenes, the definition of environmental and vegetation conditions, the definition of a light intervention, and the planning of animal sampling procedures based on trap cameras, comparison of different light intervention alternatives based on light calculations, and data aggregation and visualization tools.

Figure 8 presents the conceptual design of the light intervention case using the proposed UDT conceptualization. The physical objects include for example natural (vegetation and animals) and built environment (light infrastructure). The physical entity also encompasses external data repositories on environment conditions (e.g., sun position), urban areas (e.g., tree distribution, water body geometry, and location), climate information (e.g., rain, snow), light pole location, luminaire specifications, and images from trap camera. The data entity includes, for example, light infrastructure models, JSON files with light pole distribution and luminance calculations, luminaire models (IES file specification). The data entity also manages data about physical objects (e.g., landscape geometry, vegetation condition attributes, urban qualities). The virtual entity includes 3D models of buildings, vegetation types, and light fixtures; simulation of climate conditions, simulation of sun location, visual structures for grid- and vector-based data visualization. It also contains visualization representations (bar plots and luminance charts). Possible users of the UDT include citizens, public officials (e.g., policy-makers and urban planners), and researchers and developers (e.g., light designers, ecologists, and computer scientists). Some of the available services are illustrated in Figure 7. The service component includes, for example, interacting (e.g., 3D navigation and comparison of luminance maps), exploring (luminance calculation, light intervention simulation), realizing (deciding based on light design), and twinning (capturing data from open street maps and sensing animals through trap cameras) features.

b: MOBILITY INFRASTRUCTURE DESIGN

In the Smart Plan [86] and Twin Fjord[6] projects, UDTs to support municipal land-use and transportation planning have been developed. The UDTs support mobility system design and simulation [87] and walkability system analysis [88] The twins aim to support planning practitioners,

[6]https://www.twinfjord.no/ (As of Dec. 2023)

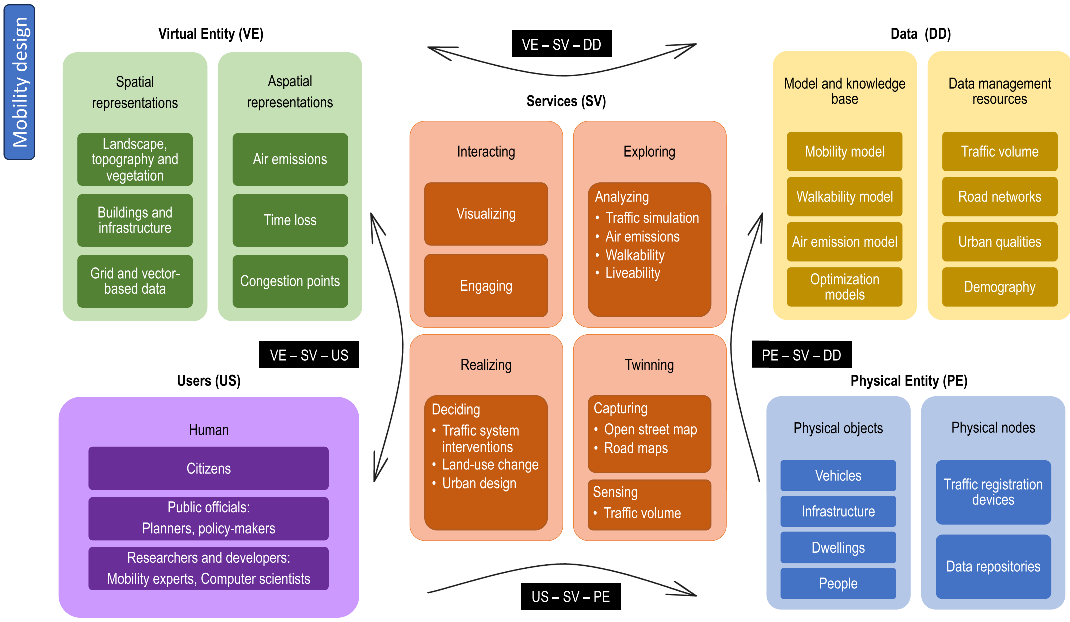


FIGURE 10. **Mobility design case related to the Smart Plan and Twin Fjord cases.**

policy-makers, developers, residents, and other key stakeholders in co-creatively shaping safe and sustainable mobility systems [88], [89].

Figure 9 provides an overview of some functionalities of the UDT for mobility design. The UDT supports analysis and visualization of alternative mobility infrastructures to design and evaluate both motorized and pedestrian mobility [88], [89]. Among the functionalities, the UDT includes 3D navigation within the transport region, adjustment of parameters such as residential demography, distribution and density, travel behavior, workplace distribution and density, and pedestrian preferences. The UDT supports a range of assessments, such as air emissions, location, and extent of traffic congestion within the system, along with pedestrian friendliness.

Figure 10 presents the conceptual design of the mobility intervention using the proposed UDT conceptualization. The physical entity includes physical objects such as vehicles, road infrastructure, dwellings, and people. Physical nodes refer to data repositories containing information on, for example, road networks and demographic data. Also, traffic information is sensed based on mobile data information. The data entity encompasses models, such as mobility, walkability, air emission, and optimization models. Raw data on traffic, roads, urban qualities, and demography is also part of this entity. The virtual entity includes spatial (e.g., landscape, topography, vegetation, buildings, and grid- and vector-based data) and aspatial (e.g., air emissions, time loss, and congestion points) representations. Users include citizens, public officials, and research developers. Services include visualizing and engaging features, exploring (e.g., traffic simulation, walkability, and livability computation), realizing (e.g., traffic system intervention, land-use change implementation, and urban design), and twinning (e.g., capturing data from open street maps and sensing traffic volume based on mobile data).

F. LIMITATIONS

The proposed conceptual framework is developed based on components and features found in the selected relevant literature. Determining the keywords included in search query strings plays an important role in the process of collecting literature. With the different keywords, different results will be obtained. The collected papers are limited to the keywords we include in the search query strings. A total number of 301 papers were collected, ranging from 2002 to 2023, and 34 papers were selected. Hence, the framework is limited to the components and features of the 34 selected relevant papers.

This paper provides a conceptual framework for implementing digital twins in urban systems, including data and services. It is beyond the scope of this paper to develop a detailed reference architecture that can be used to model and realize UDT-based information systems. We also do not discuss particular tools or technologies for realizing the UDT, but we categorize the different roles and relationships of components and features on a conceptual level.

V. CONCLUSION

In this paper, we conducted a domain analysis based on a systematic literature review of the existing body of knowledge on urban digital twins and proposed a comprehensive conceptual framework for a digital twin in urban systems. Out of 134 journal and conference papers in the urban system field, 34 relevant studies were selected and thoroughly analyzed. Information regarding components and features from each paper was documented. We identified six main components: physical entities, data, virtual entities, services, users, and connections. The main components were then derived into 16 sub-components. Moreover, based on the four components of services, we then derived ten features. Based on those components and features, a conceptual framework was developed. The framework provides a conceptual basis for implementing digital twins in urban systems, including monitoring, analyzing, communicating, and supporting decision-making processes. More specifically, the framework addresses the cyber-physical control cycle of smart cities that seamlessly integrates sensing and monitoring, smart analyses, and smart control of urban operations; the framework supports the implementation of essential characteristics of UDTs and the life cycle of urban objects.

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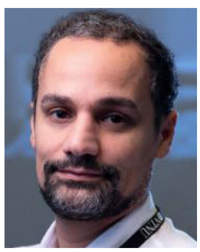

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