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Digital twin-supported smart city: Status, challenges and future research directions

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ABSTRACT

A city can be considered a carrier of multiple sources of data and information that are updated in real time and experiences continuous operation and development. Therefore, a system that can obtain and manage data/information gathered from different physical objects in a city in real time is needed. Digital twin (DT) technology is a virtual representation of an object or system that spans its lifecycle; it is updated from real-time data and uses simulation, machine learning and reasoning to help with decision-making. However, how to apply these features of the DT to better manage smart cities (SCs) has not yet been systematically summarized and analysed. In this study, 202 papers on DT-supported SCs are reviewed, based on which the drivers and challenges of applying DT-supported SCs and the solutions for the challenges were identified. In addition, this study explored the possible outcomes of applying DT-supported technologies in SCs. This study also contributes to the DT-supported SCs for city management research and practice.

1. Introduction

A digital twin (DT) is a technology that is currently emphasized in academia and industry. The DT concept was first proposed by Michael Grieve in his presentation about “product lifecycle management” in 2002 (Grieves, 2014). However, the DT concept was ignored until the National Aeronautics and Space Administration (NASA) defined it from a practical perspective: a DT is a multiscale, probabilistic and ultra-fidelity simulation that presents the status of the corresponding twin in a timely manner using historical data and real-time data (Glaessgen and Stargel, 2012). Accordingly, a DT is characterized by its capability to integrate physical and virtual data throughout the product lifecycle (Tao et al., 2019). In addition, within the DT environment, a large amount of data can be analysed, communicated and updated between physical and virtual ends in real time. Because DTs leverage the benefits of both the virtual and physical environments to a complete system, the concept of the DT has attracted more interest and has been applied in various application fields to improve the interaction between humans, machine systems and the environment during the production lifecycle (Zheng et al., 2019).

IBM defines smart cities (SCs) as cities that use information and communication technology (ICT) to sense, analyse and integrate the key information of their core systems (IBM, 2014). Consequently, SCs can intelligently respond to a wide variety of needs in terms of livelihood, environmental preservation, safety management and economic activities (Su et al., 2011). Currently, health care, power grids, transportation, buildings and resource utilization have been considered key aspects within the concept of SCs (Camero and Alba, 2019; Su et al., 2011). Various types of tools have been involved in constructing SCs, such as cloud computing, the Internet of Things (IoT), geospatial technologies, blockchain, and artificial intelligence (AI). According to Washburn et al. (2010), SCs integrate smart computing technologies and apply them to critical infrastructure components and services. A DT can be created using the data collected from SC systems to conduct high-performance simulations (Ruohomäki et al., 2018). Different from a generic digital model that represents an object without automatic or with only one-way data exchange, DTs enable bidirectional data exchange between a physical and its virtual object in the SC. A DT system can continuously update itself from multiple data sources and learn from historical data to reflect the physical objects of the SC in near real time. Additionally, DTs can help city developers create a real-time “test model” within a virtual twin to proactively test different scenarios of an SC. Thus, DTs extend the possibilities to explore the behaviour of potential solutions in virtual space. According to White et al. (2021), the

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DT of an SC can be developed based on six-hierarchy data/information in the city from bottom to top: terrain, buildings, infrastructure, mobility, digital layer/SC, and virtual layer/DT.

Furthermore, the increased data available in SC systems and advanced AI and computing technologies allow a DT to be created that can update and change as the physical objects of a city change (Kaur et al., 2020). With the data of different domains generated by SCs, DTs can be used to improve different aspects of SCs, such as urban planning (Schrotter and Hürzeler, 2020), policy decisions (Deng et al., 2021), resource arrangements (Conejos Fuertes et al., 2020), public safety and health (Coorey et al., 2021; Han et al., 2020), energy management (Francisco et al., 2020), and transport system optimization (Bhatti et al., 2021; Kumar et al., 2018). The real-time virtual simulation environment provided by DTs improves the accessibility of stakeholders from diverse domains to collaboratively address a common problem in a city. Recently, some techniques, such as the IoT, cloud computing and AI algorithms, have been coupled with DTs for greater accuracy and prediction analysis. For example, AI-supported DTs can perform data analytics on live city data to predict the current and future performance of city objects. In addition, the data collected by IoT sensors and the predictability and learnability of the AI algorithm allow DTs to learn and monitor simultaneously.

Scholars have recognized the potential benefits of DT adoption in SCs. Some studies have summarized the application of DT technologies. For example, He and Bai (2021) reviewed the application of DTs in sustainable intelligent manufacturing. Jones et al. (2020) outlined the characteristics of DT applications through a systematic literature review. Shahat et al. (2021) explored the potential of DTs in city management. Deng et al. (2021) reviewed studies on DT applications in urban governance. These studies either studied DTs in only a specific aspect or examined the potential of DT applications to city management; however, they failed to identify the challenges and solutions of DT-supported SCs. Compared to the above studies, this study explored the current research status, challenges and solutions of DT-supported SCs from the perspective of the data lifecycle management process, clarifying SC practices enabled by DT technologies to facilitate data collection, storage, modelling, visualization and connectivity.

Existing studies focus on the application of DT technology to a specific aspect, overlooking many other aspects of the SC system. Governments in many countries have recognized the value of DTs for developing SCs. For example, to apply DT technologies properly in SCs, governments in Japan have tried to evaluate the effect of DTs on SCs and have proposed an initiative for innovating AI government in resilient SCs (Obi and Iwasaki, 2021). Deng et al. (2021) also indicated that involving DT technologies allows citizens to participate in city governance processes and monitor policy implementation. Despite the increasing use of DTs in SCs and the governments' emphasis on DT-based SCs, a roadmap for development in this area is lacking. Specifically, many technologies are currently used with DTs, such as the IoT, machine learning and cloud computing; however, how these technologies can interact with the DT to facilitate SC strategies has not been explored comprehensively. Therefore, it is necessary to conduct a systematic literature review to explore how DT-supported applications support SCs. The purpose of this paper is therefore to summarize existing research on DTs in SCs to propose an integrated research framework. In the systematic literature review, a taxonomy of DT applications in SCs will be presented based on the traditional data management process. Then, DT application drivers and outcomes in the specific domain of SCs are identified. Building on these results, an integrated research framework is derived with data management propositions that explain the relationships between data management activities in DT applications and the development of SCs. To guide this study, we address the following research questions (RQs):

RQ1: What are the drivers of and challenges of applying DT technologies in SCs?

RQ2: What are the possible solutions for current challenges in DT-supported SCs?

RQ3: What are the outcomes of applying DT technologies in SCs?

The remainder of this paper is structured as follows. Section 2 presents an overview of the methodology used for the systematic literature review. In Section 3, we present a descriptive analysis of the literature review. Section 4 presents the taxonomy and thematic findings of DT-supported SCs. In Section 5, an integrated research framework is developed based on the findings of this literature review, which identifies the current research status, knowledge gaps in existing studies, and future research topics concerning DT-supported SCs. The last section concludes this paper.

2. Methodology

A systematic review is conducted to achieve the objectives of this research. A literature review can provide up-to-date information on a knowledge domain and identify significant issues in the existing body of knowledge. Additionally, it can develop a knowledge basis for further research (Gray, 2013). In this study, the reviewed literature is relevant to DT applications in SCs. According to Jesson, Matheson and Lacey (2011), a systematic literature review requires a transparent process, a rigorous search, a paper selection protocol, rational analysis, and evidence synthesis. This study includes four primary stages, as shown in Fig. 1. To eliminate possible author bias, databases and keywords were identified based on discussions among the coauthors. Then, the first author screened and analysed a paper independently, which was double-checked by coauthors based on the same criteria. If any disagreement arose, the issue was discussed until agreement was reached. All extracted information is subjected to descriptive statistical analysis to provide an overview of the reviewed papers.

Both deductive and inductive approaches were used to analyse the contents of publications, in which the categories can be determined based on existing theory and collected information (Neuendorf, 2017). A DT is a technology that is used to improve the data/information management between physical objects and their corresponding virtual model, which is a process including data/information collection, storage, modelling, and connectivity (Hinton, 2006). For example, Yousefnezhad et al. (2020) applied a DT to support data/information management between a real building and its virtual model. Additionally, Singh et al. (2021) proposed a data management framework for DT technologies in the aircraft manufacturing sector. These activities of the data management process were confirmed as initial categories through deductive reasoning. In addition, the DT applications used in SCs, including but not limited to smart homes, city services, and safety management, were identified via inductive coding.

The challenges, solutions and possible research directions in DT-supported SC will be identified as a result of this study, for which the existing theories are limited, using preconceived categories is not application. Content analysis can be used as an effective way to code research contents and generate categories. Therefore, the thematic findings in Section 4 and the current research status are analyzed using the conventional approach that allows the categories to be developed inductively. In this study, a generic coding strategy proposed by Saldaña (2021) is adopted to code the thematic findings and current status, based on which the challenges discussed above can be classified into computing power, system interoperability, information privacy and security, and integrated analysis. Therefore, the discussion about solutions and possible research directions in Section 5.2 will based on the identified four topics.

The open start and end dates of the papers were retrieved in December 2021. Two databases were used for paper retrieval (Web of Science and Scopus) due to their comprehensive coverage of information technologies (ITs), information management, computing science, and SCs. Additionally, these databases are the most comprehensive resources available and include many different academic disciplines (Li and Liu, 2020). However, minor variations exist between the two databases in

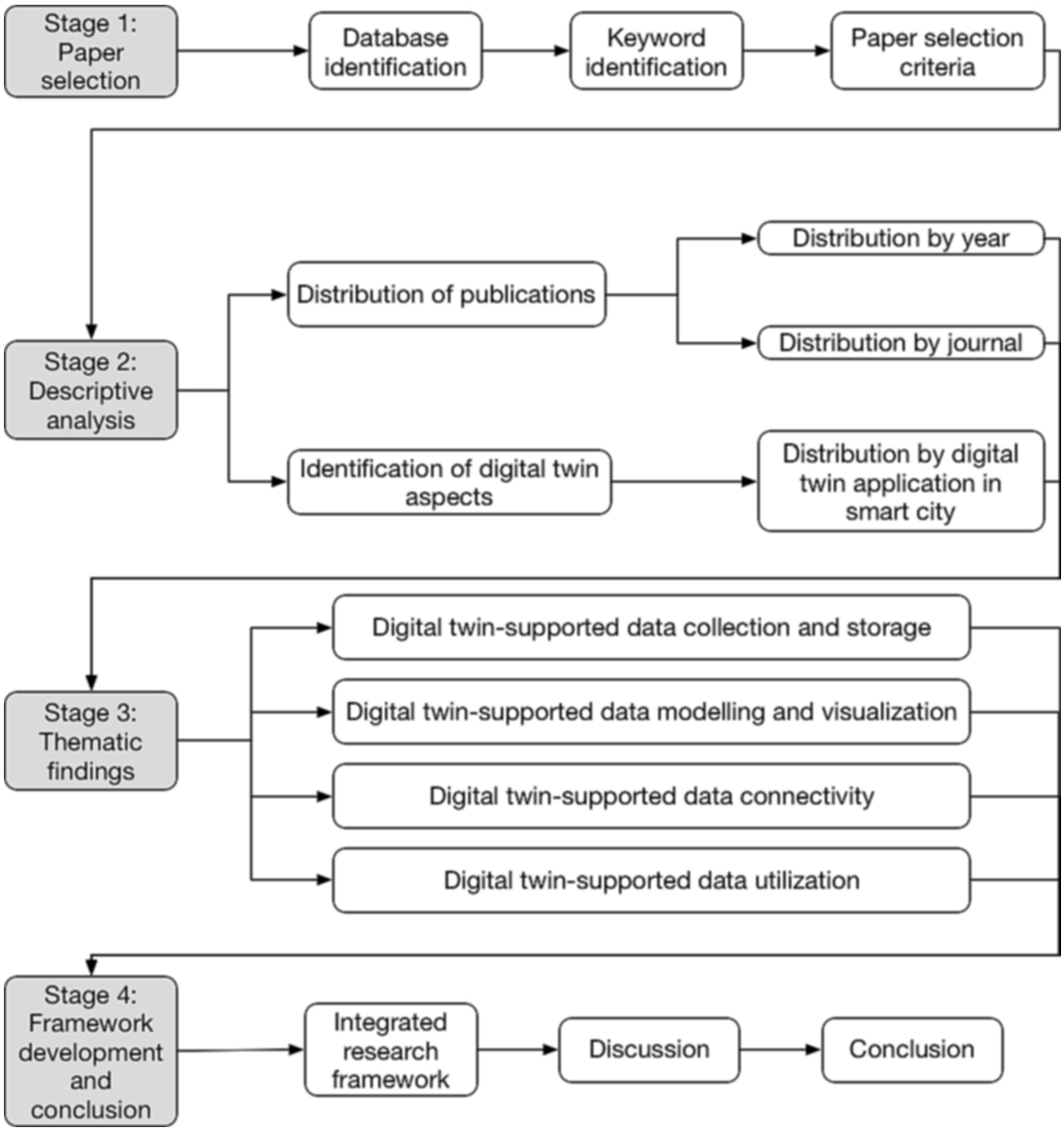

Fig. 1. Method framework of the proposed literature review.

terms of their focus areas. These variations are important because they can reduce the possibility of overlooking useful or important publications for the literature review.

To retrieve literature about DTs in SCs, the following search schemes were applied to verify a paper's title, abstract and keywords in Scopus and the Topic field in Web of Science: "digital twin" OR "digital twinning" OR "digital replica" OR "virtual twin" OR "cyber-physical" AND "smart city" OR "digital city" OR "intelligent city" OR "knowledge city" OR "learning city" OR "virtual city". These keywords and terminologies were selected based on review articles about DTs and SCs (Camero and Alba, 2019; Chen and Huang, 2021; Hou et al., 2021; Lim et al., 2019; VanDerHorn and Mahadevan, 2021).

A total of 206 and 682 results were obtained from Web of Science and Scopus, respectively. First, we selected papers published only in English in peer-reviewed journals. Second, we evaluated each article based on rating criteria (from 1 to 5, with 5 being the highest relevance), as shown in Table 1. The paper selection process consisted of two steps: (1) selection through scanning 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 or 4, in addition to the title, abstract and keywords, the full text was scanned to

Table 1
Literature selection criteria.

Level	Criteria
5	The paper is highly consistent with a DT in an SC based on its title, abstract and/or keywords.
4	Although a few DT technologies and SC concepts are mentioned in the title, abstract and/or keywords of the paper, the use of a DT in an SC is not specified in the abstract.
3	Although the paper focuses on an SC, the title, abstract and/or keywords of the paper do not mention the adoption of DT technologies, and the title, abstract and/or keywords fail to confirm that the paper targets a DT in an SC.
2	The paper is related to DTs but does not concern SC issues.
1	The paper is related to neither DTs nor SCs.

determine whether the paper could be included in the literature review. Conversely, any paper rated 5 was deemed suitable for the literature review, and therefore, it was selected for this study.

We identified 197 papers after excluding duplications. Cross-referencing was then used to reduce the possibility of overlooking any relevant publications. Cross-referencing refers to reviewing the reference list of a paper to identify additional papers (Booth et al., 2016). The same criteria shown in Table 1 were then used in this research, which helped identify-five additional papers on DT-supported SCs. Finally, 202 papers on DTs in SCs were selected and their full text were reviewed carefully for this study.

3. Analysis of digital twin-supported smart city publications

In this section, studies on DT-supported SCs are quantitatively analysed to identify research trends.

3.1. Overall distribution of publications

Table 2 summarizes the distribution of the 202 selected articles about DTs in SCs by journal. The journals that had published more than five articles related to DT-supported SCs were *IEEE Access*, *IEEE Internet of Things Journal*, *Journal of Management in Engineering*, *Sensors*, *Sustainable Cities and Society*, *Applied Sciences*, and *Future Generation Computer Systems*. These journals are often viewed as influential journals in engineering management, technology development, and environmental science; they cover various disciplines; and they indicate wider popularity and recognition of DT-supported SCs in current research and practice. The journals listed in Table 2 are included in the Journal Citation Reports published by Web of Science except for *ACM Transactions on Cyber-Physical Systems (CPS)*, Future Internet and *International Journal of Advanced Science and Technology*. Although, these three journals are not included in Journal Citation Reports, they are premier journals for the publication of high-quality original research papers and survey papers that have scientific and technological understanding of the interactions of information processing, networking and physical processes. Other selected journals are included in the Journal Citation Reports or indexed in the influential index databases such as Emerging Sources Citations Index, Ei Compendex, ACM Digital Library (Association for Computing Machinery Digital Lobrary) and IET Inspec (Information Service in Physics, Electronics Technology and Computer and Control) etc.

Table 2
Number of papers by journals.

No.	Journal title	Number of papers	Ranking in Journal Citation Reports
1	IEEE Access	16	Q2
2	IEEE Internet of Things Journal	8	Q1
3	Journal of Management in Engineering	8	Q1
4	Sustainable Cities and Society	8	Q1
5	Sensors (Switzerland)	7	Q2
6	Applied Sciences	5	Q2
7	Future Generation Computer Systems	5	Q1
8	ISPRS International Journal of Geo-Information	4	Q2
9	ACM Transactions on Cyber-Physical Systems (CPS)	4	N/A
10	Sustainability (Switzerland)	4	Q2
11	IEEE Transactions on Network Science and Engineering	3	Q1
12	IEEE Transactions on Intelligent Transportation Systems	2	Q1
13	IEEE Internet Computing	2	Q2
14	Pattern Recognition Letters	2	Q2
15	IEEE Network	2	Q1
16	Future Internet	2	N/A
17	International Journal of Advanced Science and Technology	2	N/A
18	Electronics (Switzerland)	2	Q3
19	Journal of Network and Computer Applications	2	Q1
20	Other journals	114	N/A

3.2. Distribution of publications by year

Fig. 2 shows the distribution of relevant publications by year. Although the concept of the DT was first proposed by Michael Grieve in 2002, it was not applied in the field of SCs until 2013. Lei et al. (2013) used a cyber-physical system (CPS) to build an intelligent laboratory. Hu et al. (2013) proposed a mobile CPS that uses mobile devices to facilitate mobile sensing applications between humans and the surrounding physical environment. Based on the number of publications to date, this field of research remains popular. In addition, despite abnormalities in 2018, Fig. 2 shows a steady increase in the number of studies on DT-supported SCs from 2013 to 2021, which implies that scholars have recognized the potential of DTs for SC development. It is thus expected that research interest in DT-supported SCs will continue to rise and become more diversified.

3.3. Distribution of publications by application areas of smart cities

According to Su et al. (2011), the application aspects of SCs include wireless cities, smart homes, smart public services, smart social management, smart transportation, smart medical treatment, smart urban management, green cities and smart tourism. Based on content coding of existing studies, some new aspects have been identified in this study. Table 3 provides a summary of application aspects in SCs. The five most prominent aspects in existing research on this topic are transportation/mobility, energy/power systems, sustainability, urban planning and smart infrastructure. Currently DT-supported transportation systems are regarded as Cyber-Social Systems due to the presence of connectivity and complex interaction between human and technological infrastructure, and the main developments are now focused on sustainable mobility (Roy et al., 2021; Tripathy et al., 2020). DTs applied in energy management system aim to evaluate different scenarios of energy efficiency intervention for conducting smarter energy management, and optimizing the trade-off with renewable energy production (Agostinelli et al., 2021; Tagliabue et al., 2021). In the environmental aspect, DTs are combined with sensors and data collectors, and are mainly used for the evaluation of carbon emissions and the planning of waste management

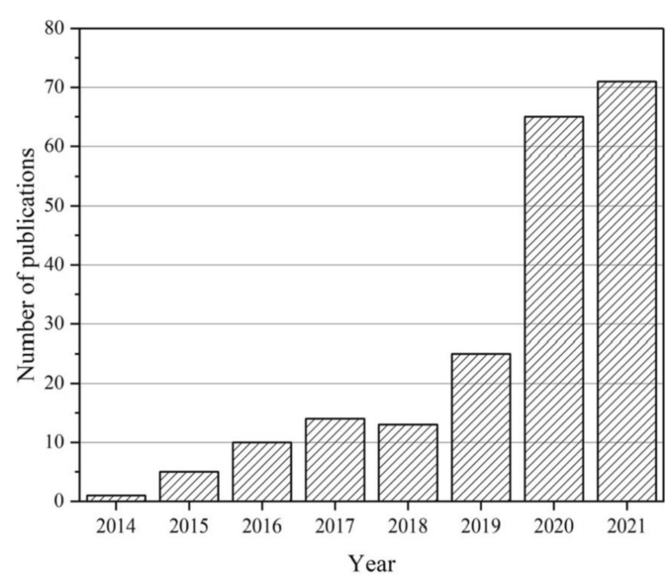

Fig. 2. Distribution of publications by year.

Table 3
Application aspects of DT-supported SCs.

No.	Application aspect of DT-supported SCs	Definition and example	No. of publications
1	Transportation/ mobility	A DT represents a digital version of a transportation physical object or process, e.g., optimization of traffic and pedestrian flows, public transport, and traffic lights, etc.	41
2	Energy/power system	A DT represents a digital replica of energy systems, which establishes a network of interrelated physical and virtual entities to automate the energy/power system, e.g., smart grid management, system dynamic monitoring and demand forecast, etc.	24
3	Environmental and resource management	Combining DTs with geospatial and urban management systems to facilitate sustainable SC development, e.g., carbon emissions, waste reduction, and renewable sources management, etc.	15
4	Urban planning	A DT represents a set of virtual data constructs that fully describes potential or actual physical objects in the city for urban planning decision-making, e.g., building landscape, road planning, urban facility management.	15
5	Public infrastructure management	A DT-supported SC based on visual and nonvisual data from multidisciplinary sources is expected to analyse various what-if scenarios in public infrastructure management, e.g., railway infrastructure, and telecommunication systems, etc.	15
6	City service	DTs help cities do a better job in providing various services, e.g., emergency services, government affairs service systems, and public safety, etc.	14
7	Smart health care	By creating a DT of a hospital, operational strategies, capacities, staffing, and care models can be observed to determine what actions to take, e.g., blood tests, treatment plan outcome prediction, etc.	7
8	Smart building	A DT represents a continuous virtual replica of a physical system to simulate a smart home, e.g., assistive/service robots and human users, etc.	3
9	Smart education/ campus	A DT represents a virtual replica of various educational environment and process scenarios to optimize education, e.g., intelligent campus, virtual gaming technology-based education, etc.	3
10	Smart economy	A DT represents a virtual replica of economic indicators with real-time data that takes into account different points of view regarding economic issues, e.g., the circular economy and trade networks.	2

tasks (Bala Krishna et al., 2020; Park and Yang, 2020). DT-supported representation of 3D spatial data set and models can provide analysis of different scenarios to achieve better decision-making in urban planning, but the release of 3D spatial data under Open Government Data are now required for the creation of different collaborative platform (Schrotter and Hürzeler, 2020; Souza and Bueno, 2022). Pesantez et al. (2022) applied DT to assess COVID-19 impacts on water infrastructure which can be seen as an example of DT-supported public infrastructure management.

In addition, DTs have been applied to other aspects of SCs, such as city service, smart health care, smart homes, smart education/campus and economics. For example, Japanese government involves DTs in the digital government infrastructure for aging society issues. DTs are being applied to model diseases such as Alzheimer's and multiple sclerosis to make better decisions on treatment options. DTs integrated with building sensors making use of the data produced by the building can simulate and assess temperature systems, lighting, and other energy use for optimization. By using a DT, students can easily learn highly engaging tasks which can be too dangerous, complex, or expensive for the classroom.

Table 3 also provides a summary of DT-related publications in different SC aspects. Based on these results, a contour map is developed, as shown in Fig. 3, to represent the distribution and concentration of studies based on time scale and knowledge management. Publications referring to each SC aspect are described by the contour in different colours. The contour map changes colour from cool to warm to reflect low to high research intensity on a given topic.

As shown in Fig. 3, DT-supported SCs have been studied for many years. Fig. 3 shows a red area for transportation/mobility in 2020. Accordingly, transportation/mobility is the most researched area. In addition, some warm-toned areas appeared in other aspects of SCs, including energy/power systems, environmental and resource management, and public infrastructure management, indicating that DT technology is frequently applied to these aspects. Fig. 3 also shows that DTs have not yet been widely used in smart education (9) and the smart economy (10). Overall, research on DTs has received extensive attention in recent years.

4. Thematic findings of digital twin-supported smart cities

Because a DT system is used to process data within virtual-physical objects efficiently, this study categorizes technologies that support a DT in SCs based on the data lifecycle management process of collection, storage, representation, connectivity and utilization (Hubert Ofner et al., 2013). Table 4 provides a summary of DT-supported SC-related publications in different data management processes, as well as the technology applied in each data/information management process.

4.1. Digital twin-supported data collection and storage

A DT can be considered a computer program that uses real-world data/information to create simulations that can predict how a product or process will perform (Tao et al., 2019). Therefore, a DT application requires data from a physical object or process to create a virtual digital model (Jones et al., 2020). The data/information required by the DT can be related to production, operation, maintenance and business (Su et al., 2011).

Various sensors are used to collect data from the physical object or its surrounding environment to create and update the digital models of a DT system. In DT-supported smart transportation systems, GPSs are the most commonly used sensors for collecting passenger and vehicle data (Imoize et al., 2021; Karim and Rawat, 2021; Roy et al., 2021). However, GPS systems can collect data related to latitudes, longitudes, altitudes, and the moving speed of objects only; they cannot collect data on accelerations, angular rates, and magnetic fields. To address these limitations, Wu et al. (2020) integrated an inertial measurement unit (IMU) with a GPS. In addition, Gilanifar et al. (2019) indicated that traffic forecasting systems supported by GPSs have relied on historical traffic data and failed to consider real-time electricity network data. Thus, they used a Bayesian spatiotemporal process to collect data from a multi-networked environment.

In recent years, wireless sensors have been incorporated into wearable devices to collect data related to people's physical condition, which

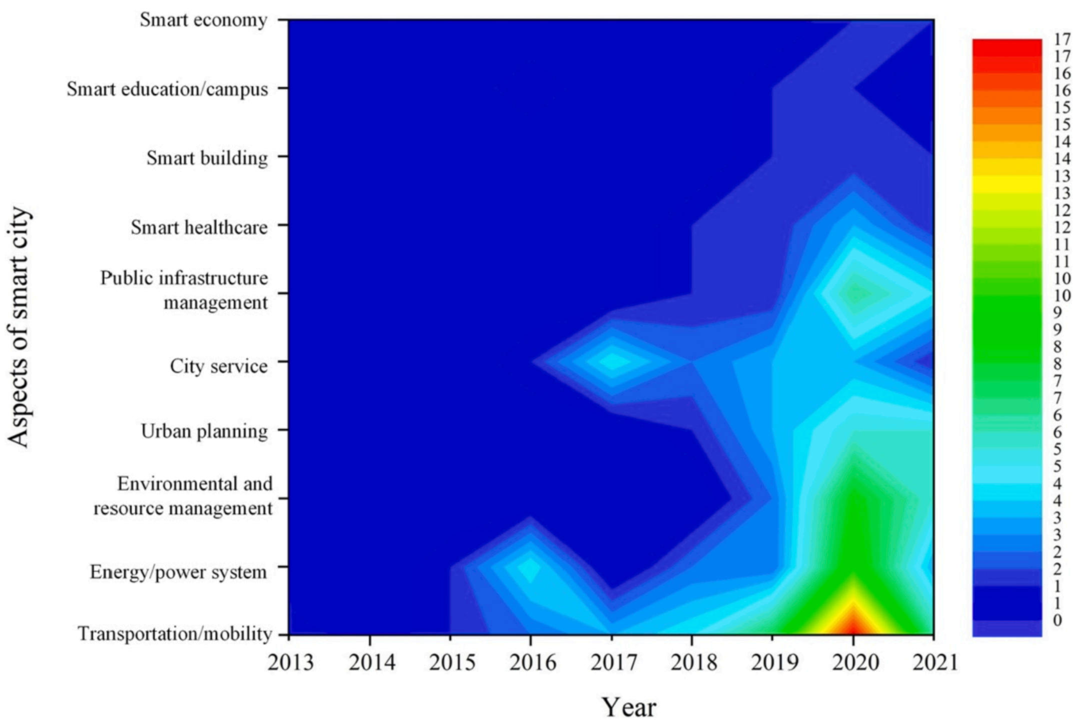

Fig. 3. Distribution and concentration of studies on DT-supported SCs.

renders health monitoring more intelligent (Rodgers et al., 2015). To explore the relationship between human health and geographic distribution, existing studies integrate data from wearable devices into a GIS. For example, Rodgers et al. (2015) used a wearable device to collect data about the stress state of elderly people and analysed the data collected by a GIS to discover the stress hotpot of elderly people. BIM technologies are also used to facilitate data collection in DT-supported SCs. For example, Lei et al. (2020) integrated BIM in a CPS to develop an intelligent disaster prevention and mitigation structural system. In this system, BIM is integrated with IoT technology to construct a cloud architecture of CPS to achieve real-time and accurate intelligent monitoring. In addition, Zaballos et al. (2020b) incorporated BIM and IoT-based wireless sensor networks into a DT to collect environmental data and detect users' emotional perceptions of their smart campus to provide insights into the comfort level on campus. Breunig et al. (2020) reported that the topology as a portion of the mathematical domain can be used to model the relationships between spatial entities and to analyse the data collected by BIM and GIS technology in terms of data structures, which is important for DT-supported SCs.

Although various tools can support data collection for DTs in SCs, there are still many problems to be solved. Existing studies indicate that most sensors can process only one access request. If different systems send data to the sensor simultaneously, conflicts may occur. To solve this problem, Zheng et al. (2021) used edge computing to analyse and process data close to the physical side. Wang et al. (2019) applied fog computing technologies and extended the Hungarian algorithm to mitigate service collisions when sensors receive multiple service commands simultaneously. Consequently, the possibility of data conflicts on the sensor side is reduced. In addition, Simić et al. (2020) integrated AI tools into smart sensors to collect data from distributed smart systems. In addition to multitasking conflicts when collecting data, some studies have emphasized security and privacy issues during data collection in DT-supported SCs (Caviglione and Coccoli, 2020; Karim and Rawat, 2021; Wu and Luo, 2020).

4.2. *Digital twin-supported data modelling and visualization*

Originally, a DT was a digital representation of physical objects, such as processes, persons, buildings and systems, that was used to improve manufacturing production. With the development of ICT, various tools have been applied to digitally represent different components of an SC and serve as the basis for creating DTs (Farsi et al., 2020). Real-time expression of data from physical objects in the form of 3D is critical for DT technology (Breunig et al., 2020; Qi et al., 2021). BIM is a technology that can represent geometric and nongeometric information in an integrated model (Wang and Meng, 2021). However, BIM can manage static information only and cannot automatically update the models with real-time information without help from other tools. White et al. (2021) integrated a BIM model, big data and an IoT sensor to create a DT-supported SC, in which BIM was used to present the collected information in 3D format. In addition, this BIM-based 3D SC model can reflect proposed changes and allows the public to virtually walk around a city to identify problems with city components, based on which citizens can interact and report feedback on planned changes in the city. Shahat et al. (2021) also reported that the BIM model can be used as a mirrored digital counterpart of the DT because it can be a more intelligent process of 3D modelling that integrates and manages all information on the physical object. Coupry et al. (2021) extended BIM to a DT building model by adding dynamic data exchange capability to enable predictive anomaly detection during the O&M process and further extended Industry Foundation Classes (IFC) to facilitate the integration of BIM and DT for O&M activities. In addition to applying IFC standards for data integration, ontology is often used to solve issues of interoperability because it enables modelling data in a unified form and introduces the possibility of data expansion (Augustine, 2020). In addition, Miller et al. (2021) indicated that generic DT technologies usually lack the spatial context in the built environment, but adding BIM and GIS to DT technologies can be seen as a reliable solution to these issues. Similar to the IFC adopted by BIM applications, GIS applications adopt city geography markup language (CityGML) to achieve the interoperability. The integration of BIM and GIS can realize the data fusion between building level and city level, in which the geometric and

Table 4
DT-supported SC-related research in different data management processes.

No.	Data management process	Applied technology	References
1	Data collection and storage	Sensor	(Akre and Rajan, 2020; Austin et al., 2020; Bhuiyan et al., 2017; Breunig et al., 2020; Caviglione and Coccoli, 2020; Chen et al., 2021; Cicirelli et al., 2017; Ferdowsi et al., 2019; Gilanifar et al., 2019; Gotovtsev, 2020; Karim and Rawat, 2021; Kim, 2018; Laamarti et al., 2020; Lay-Ekuakille et al., 2017; Lee et al., 2020b; Lei et al., 2020; Minerva et al., 2021; Minerva et al., 2020; Mishra et al., 2019; Molinara et al., 2021; Moustafa et al., 2018; Mydlarz et al., 2017; Park et al., 2019; Park et al., 2018; Rolim et al., 2016; Roy et al., 2021; Simić et al., 2020; Sliwa et al., 2020; Thomas and Cook, 2016; Wang et al., 2016; Wang et al., 2019; Wu et al., 2020; Xiao et al., 2017; Xue et al., 2020; Younis and Moayeri, 2017; Yun and Lee, 2019; Zaballos et al., 2020a; Zheng et al., 2021)
		Remote sensing	(Lu et al., 2020; Major et al., 2021; Marai et al., 2020; Shirowzhan et al., 2020; White et al., 2021; Yang et al., 2021; Zaballos et al., 2020b)
		Building Information Modelling (BIM)	(Breunig et al., 2020; Deng et al., 2021; Hasan et al., 2021; Lei et al., 2020; Lin and Cheung, 2020; Liu et al., 2020; Parn and Edwards, 2019; Shahat et al., 2021; Zaballos et al., 2020a)
		Global Positioning System (GPS)	(Brock et al., 2021; Clark et al., 2020; Deng et al., 2021; Habibnezhad et al., 2020; Marai et al., 2020; Minerva et al., 2021; Shirowzhan et al., 2020; Wu et al., 2020)
		Geographic Information System (GIS)	(Breunig et al., 2020; Bujari et al., 2021; Hämäläinen, 2021; Park and Yang, 2020; Schrotter and Hürzeler, 2020; Shahat et al., 2021; Shirowzhan et al., 2020; Villanueva et al., 2020; Wang et al., 2021; Zhu and Wu, 2021)
2	Data modelling and visualization	BIM	(Breunig et al., 2020; Deng et al., 2021; Hasan et al., 2021; Lei et al., 2020; Lin and Cheung, 2020; Liu et al., 2020; Ozturk, 2021; Parn and Edwards, 2019; Sepasgozar, 2021; Shahat et al., 2021; Shirowzhan et al., 2020; White et al., 2021; Zaballos et al., 2020a, b; Zhu and Wu, 2021)
		CIM (City Information Modelling)	(Kemp, 2020; Lehner and Dorffner, 2020; Lu et al., 2020; Scalas et al., 2022; Souza and Bueno, 2022; Stojanovski et al., 2020)
		AR	(Charissis et al., 2021; Hasan et al., 2021; Kim, 2018; Kuts et al., 2020; Minerva et al., 2020; Park et al., 2018; Shahat et al., 2021; Tan et al., 2020; Yun and Lee, 2019)
		VR	(Charissis et al., 2021; Dembski et al., 2020; Du et al., 2020; Ham and Kim, 2020; Kuts et al., 2020; Minerva et al., 2020; Shahat et al., 2021; Yun and Lee, 2019)
3	Data connectivity	Data standard format	(Al-Sehrawy et al., 2021; Badawi et al., 2021; Götz et al., 2020; Laamarti et al., 2020; Lu et al., 2020; Palomar et al., 2016; Pang et al., 2021; Ruohomäki et al., 2018; Shahat et al., 2021)
		5G	(Allam and Jones, 2021; Deng et al., 2021; Hu et al., 2021; Kumar et al., 2018; Sutrala et al., 2021; White et al., 2021)
		Edge computing	(Alfakih et al., 2020; Casadei et al., 2020; Cicirelli et al., 2017; Ferdowsi et al., 2019; Kadhum et al., 2019; Kim, 2018; Kumar et al., 2018; Lay-Ekuakille et al., 2017; Marai et al., 2020; Rahman et al., 2019; Simić et al., 2020; Tan et al., 2020; Tran et al., 2021; Wang et al., 2018; Zheng et al., 2021)
		Blockchain	(Esposito et al., 2021; Hu et al., 2020; Kanak et al., 2019; Karim and Rawat, 2021; Parn and Edwards, 2019; Rahman et al., 2019; Rejeb et al., 2021; Singh et al., 2020; Yun and Lee, 2019)
		IoT	(Akre and Rajan, 2020; Al-Ali et al., 2020; Alam et al., 2015; Bala Krishna et al., 2020; Cho and Kim, 2016; Cicirelli et al., 2017; Diaz et al., 2020; Elshenawy et al., 2018; Giacobbe et al., 2020; Gotovtsev, 2020; Hanif et al., 2018; Jimada-Ojuolape and Teh, 2020; Jin et al., 2014; Kumar et al., 2020; Kumar et al., 2018; Lei et al., 2020; Liang et al., 2019; Lin et al., 2017; Lin and Cheung, 2020; Ma et al., 2020; Marai et al., 2020; Marques et al., 2020; Minerva et al., 2021; Minerva et al., 2020; Mishra et al., 2019; Mishra and Ray, 2020; Moschella et al., 2021; Ning and Liu, 2015; Pan et al., 2019; Park et al., 2019; Park et al., 2018; Plaza et al., 2018; Raes et al., 2021; Rahman et al., 2019; Sahil and Sood, 2020; Salim and Haque, 2015; Santana et al., 2018; Shahat et al., 2021; Singh et al., 2020; Sliwa et al., 2020; Sun et al., 2016; Sutrala et al., 2021; Tan et al., 2020; Tripathy et al., 2020; Wang et al., 2018; Wazid et al., 2019; White et al., 2021; Yun and Lee, 2019; Zaballos et al., 2020a)
4	Data utilization	Data processing	(Austin et al., 2020; Chang et al., 2020; Chindanonda et al., 2020; Ferdowsi et al., 2019; Fernández et al., 2020; Francisco et al., 2020; Kadhum et al., 2019; Ma et al., 2020; Poulkov, 2019; Roy et al., 2021; Shahat et al., 2021)
		Data analysis	

(continued on next page)

Table 4 (*continued*)

No.	Data management process	Applied technology	References
			(Al-Ali et al., 2020; Al-Sehrawy et al., 2021; Alam et al., 2015; Amin and Choi, 2020; Du et al., 2020; Fan et al., 2020; Francisco et al., 2020; Hämäläinen, 2021; Kadhum et al., 2019; Lei et al., 2013; Pang et al., 2021; Pesantez et al., 2022; Qi et al., 2021)
		Big data	(Al-Ali et al., 2020; Amin and Choi, 2020; Breunig et al., 2020; Bujari et al., 2021; Caviglione and Coccoli, 2020; Gao et al., 2020; Shirowzhan et al., 2020; Simić et al., 2020; Sun et al., 2016; Wazid et al., 2019; Yun and Lee, 2019)

semantic mapping between IFC and CityGML is required (Xia et al., 2022).

In addition to BIM, Augmented Reality (AR) is used to optimize the 3D representation of the physical object by "augmenting" the information associated with the physical object itself (Minerva et al., 2020). Thus, AR keeps physical objects more in line with expectations due to the augmentation of the associated information. For example, Tan et al. (2020) applied AR to acquire energy performance-related information and optimize the 3D placement of unmanned aerial vehicles, thereby reducing energy consumption. Park et al. (2018) applied AR to visually represent information about visibility, through which an optimal guide for quick response to disaster can be generated. Different from AR, Virtual Reality (VR) creates a complete virtual environment in which people interact with objects (Sherman and Craig, 2003). VR can also represent the expected behaviour of physical entities (Dembski et al., 2020). In addition to the representation of physical objects, VR technologies have been used to represent abstract information. For example, Du et al. (2020) proposed a personalized information system as a solution for potential cognitive overload issues, in which VR was applied to represent human cognition-related information. However, if AR and VR are used to represent data/information in a DT environment, the system must have a continuous data/information flow between the physical and virtual objects and allow AR and VR to display physical data/information in real time.

The data/information that must be represented in DT-supported SCs is detailed. How to coordinate and represent this unstructured data/information is both important and challenging for DT-supported SCs (Fuller et al., 2020). Ham and Kim (2020) proposed a novel participatory sensing-to-DT city framework, in which the unstructured crowd-sourced visual data/information of physically vulnerable objects is represented and integrated with a 3D virtual city model, allowing decision-makers to anticipate extreme weather events accurately and thus facilitate data-driven infrastructure disaster management.

4.3. Digital twin-supported data connectivity

Data connectivity is critical in the context of DT cities (Farsi et al., 2020). Existing studies have reported that interoperability between systems of different domains is critical for DT-supported data connectivity because data/information in a city is often distributed across different industrial platforms (Liang et al., 2019; Mora et al., 2017; Qi et al., 2021). For example, Liu et al. (2019) proposed a cross-domain data mining approach to mitigate the incompatibility between vehicle positioning and passenger transaction data. Additionally, to improve interoperability between health devices and medical systems to facilitate health and well-being in SCs, Laamarti et al. (2020) developed a standardized DT framework based on the ISO/IEE 11073. In addition, Badawi et al. (2021) pointed out that data/information should be shared between systems of different domains within one city and across cities. However, interoperability issues can lead to difficulties when developing a unified model that is interoperable across cities. When this unified model is created, it can be used as a basis for DT-supported SC modelling. Thus, Badawi et al. (2021) developed a unified model based on leading international standards (ISO 37120) to enable data and information sharing across cities. Based on this unified model, SCs can learn from each other.

Due to the large amount of data and information that must be shared in a DT-supported SC, the efficiency of data and information sharing has become particularly important (Deng et al., 2021). Some technologies have been applied in a DT environment to improve the efficiency of data and information sharing. Allam and Jones (2021) indicated that 5G technologies can enhance the efficiency of data and information sharing in DT-supported SCs. However, applying 5G technologies in SCs is much more expensive and complex to implement because it requires many more base stations than 4G technologies. Additionally, the limited interoperability of DT systems of SCs with 5G technology has become an obstacle to using 5G technology to accelerate data and information sharing; 6G technology is expected to improve this issue. Existing research also applies different computing strategies to improve the efficiency of knowledge sharing in the DT systems of SCs. For example, Qi et al. (2021) and Tran et al. (2021) applied edge-cloud computing to analyse and determine the data and information that must be shared, thereby reducing the computational load of information sharing.

In recent years, security and privacy issues in data and information sharing in the DT systems of SCs have been emphasized by many studies. Blockchain is considered to be the most effective and most commonly used technology to ensure the privacy and security of data and information (Hu et al., 2020; Karim and Rawat, 2021; Parn and Edwards, 2019; Rahman et al., 2019; Singh et al., 2020). In the privacy risk reduction model developed by Karim and Rawat (2021), blockchain technology enables users to share specific data, which protects private data in the Internet of Vehicles (IoV) and mobile edge networks. Singh et al. (2020) indicated that blockchain can be combined with Software-Defined Networking (SDN) to take advantage of blockchain providing a distributed environment for specific information while using the protocols established for data sharing in the specific network. The information in this system is shared based on unified protocols and within a particular environment. Thus, information privacy and security are ensured. Rahman et al. (2019) applied AI technology to process and extract significant information before it was saved to blockchain and cloud repositories, which enhanced blockchain performance for secure SC services.

4.4. Digital twin-supported data utilization

Collected data/information can be used in various fields within DT-supported SCs, such as transportation, environment, energy, health care, safety and education (Farsi et al., 2020). Information is used as the basis for analysis and simulation to support decision-making or to forecast and optimize the physical counterpart's performance (Shahat et al., 2021). In health care, the biosensor-based DT model established by Lee et al. (2020) can be used to monitor the health information of elderly individuals to identify risk hotspots in cities in real time and analyse and recommend safer alternative routes. For safety, Sahil and Sood (2020) incorporated IoT and fog-cloud computing into the proposed DT framework to analyse trapped persons and their surrounding environment in a fire scene to determine how a rescue should be performed. According to Agostinelli et al. (2021), combining DTs with dynamic analysis algorithms enables the assessment of different scenarios of energy usage. Hence, optimized decision-making for energy management can be achieved. Tagliabue et al. (2021) also indicated that the sensorized asset monitoring energy behaviour supported by DTs optimizes the trade-off with renewable energy production.

Existing studies indicate that using data and information in a DT environment to support SCs still faces various problems and challenges. DT-supported SCs require real-time analysis of city-scale information and provide accurate feedback, which places high demands on a computer's computational capabilities (Shahat et al., 2021). Some studies have used edge computing and fog computing technology to relieve pressure related to data/information processing within DT systems (Casadei et al., 2020; Wang et al., 2018; Wang et al., 2019). In SCs, it is necessary to conduct centralized analysis of data/information from different knowledge domains to make integrated decisions. Lu et al. (2020) reported that interoperability is the most critical issue when dealing with information from different domain systems. In addition, recognizing which information is required from heterogeneous and massive data sources is another challenge of DT-supported SCs. Austin et al. (2020) pointed out the benefits of combining machine learning technologies with semantic modelling to better manage large-sized and heterogeneous data. Systems in a SC involve a large amount of user information; it is thus becoming necessary to secure user privacy before this information is integrated for further mining, analysis, and application (Roy et al., 2021). Fernández et al. (2020) investigated users' privacy by modelling and semantically representing user consent, preferences, and data usage policies.

The deployment of multitude of sensors and agents spanning many application domains including healthcare, environment, transportation, and buildings will generate large amounts of multi-source heterogeneous data. Thus, some techniques related to big data are applied to DT-supported SCs. For example, cloud-based platforms can be used in a cloud-driven IoT-based big data environment to store the data generated by sensor devices, which can be regarded as a big data warehouse (Wazid et al., 2019). White et al. (2021) indicated that BIM can transform big data into the form of building plans and add it to DTs to support simulation for better decision making. Although data is the basis for the development of DT-supported SC, the processing of big data is challenging. Many AI tools have been applied to process big data in DT-supported SC, such as data mining, machine learning and computer vision. For example, Chen et al. (2021) combined differential evolutionary algorithm with big data analytics applied as data mining tool to improve data privacy and security management in SC. Simić et al. (2020) analyzed the computer vision techniques supported by the combination of multi-spectral cameras and AI-based data processing for public safety systems. Austin et al. (2020) applied machine learning to support semantic knowledge representation and reasoning for analysis of energy usage in buildings.

5. Integrated research framework of digital twin-supported smart cities

Based on the thematic findings in Section 4, an integrated research framework is proposed in Section 5 to provide state of the art of DT-supported SCs (see Fig. 5). Future research directions are also proposed in the framework. The proposed research framework shows how DT technologies are applied in SCs, the challenges of their application and possible solutions, including future research directions to address the challenges. In this integrated research framework, each row represents the aspects supported by digital twin technologies, namely, data collection and storage, data modelling and visualization, data connectivity, and data utilization. These aspects are identified based on the data lifecycle management process, as digital twin technology can be seen as real-time and bidirectional data communication between physical and virtual ends. The first two columns of the integrated research framework are the current research status, including research outcomes and challenges in DT-supported SCs identified from the analysis in Section 4, while the last column shows the related solutions and possible research directions based on the research outcomes and challenges.

The integrated research framework not only covers data/information management in the context of the DT-supported SC discussed above but also defines the relationship between them. It further clarifies possible solutions as research directions. For example, incorporating BIM and GIS into the DT environment to improve the collection of spatial-related data and can facilitate the predictive capability of the SC system. Additionally, applying AI techniques to extract needed information before data processing can relieve information processing pressure. Therefore, the integrated framework can also provide a reference for city planners, building O&M workers, power suppliers, construction companies or governments to customize their own DT-supported SC systems. Specifically, they can adopt data management aspects from the integrated research framework that are relevant to them.

Based on the thematic findings in Section 4, the following subsection present the current research status and critical challenges of DT-supported SC (Section 5.1). In Section 5.2, possible solutions and research directions are discussed in depth. The development of discussion in following subsections is illustrated in Fig. 4.

5.1. Current status of digital twin-supported smart city research

The discussion in Section 4 highlights the current research status of DT applications in SCs in terms of the data management process. The issues that should be solved or considered are also identified. Recently, with the development of technologies such as the IoT, cloud computing and AI, the development of SCs has gradually evolved from static

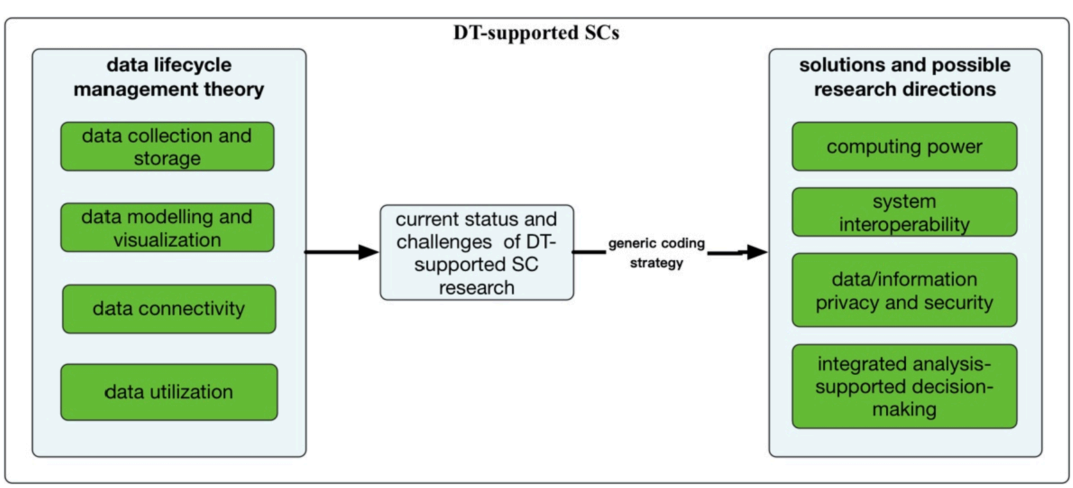

Fig. 4. Mapping solutions and research directions against data management processes.

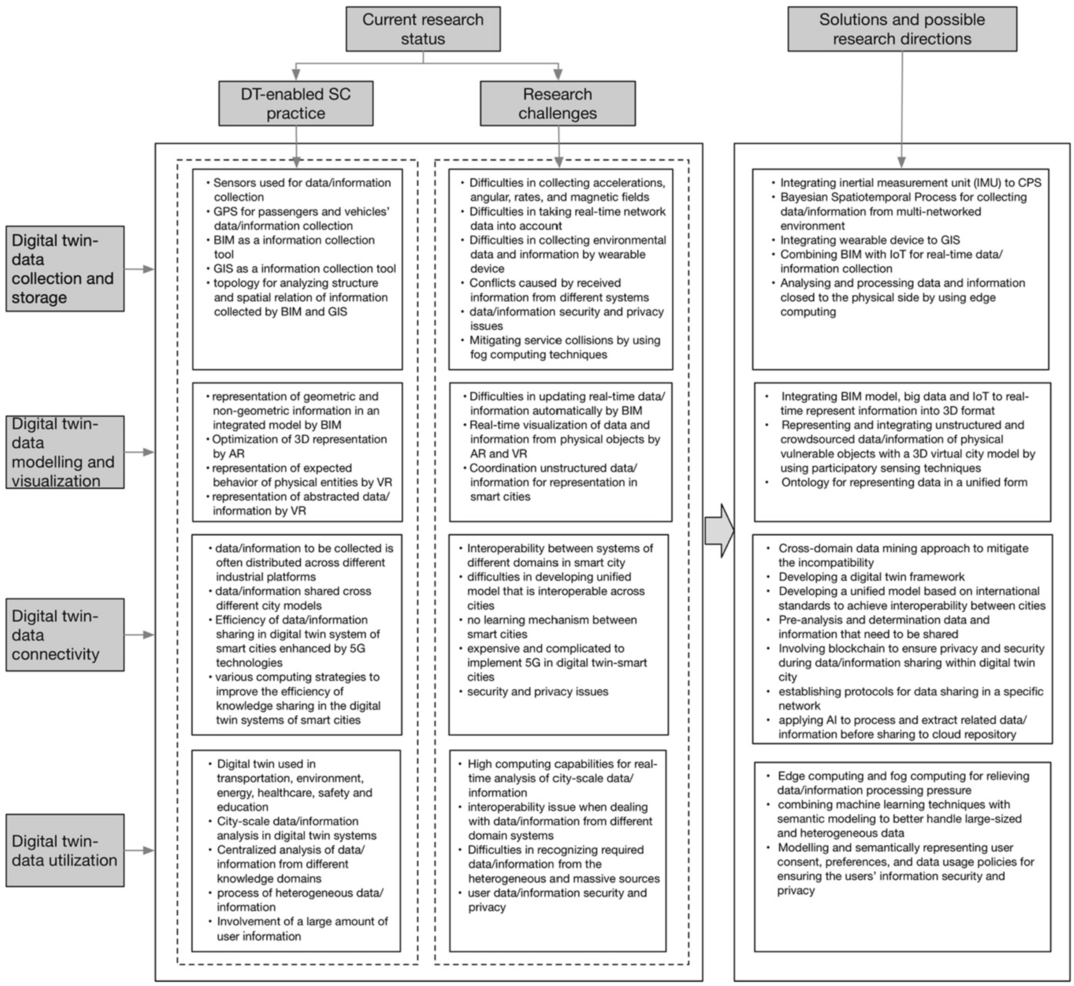

Fig. 5. Integrated research framework of DT-supported SCs.

visualization towards DTs (Yan et al., 2019). Three primary characteristics of DTs have been identified: connection between virtual and physical objects; update and change in time as physical objects change; and prediction of objects' behaviours. The application of DT technologies at the city level can efficiently digitize and virtualize various elements in the city, the real-time visualization of city status, and the coordination and intelligence of decision-making. Thus, a complex system of one-to-one correspondence, mutual mapping and collaborative interaction between the physical city in the physical dimension and the virtual city in the information dimension can be established. SCs based on DT technology promote urban planning, construction, and services during city management.

A DT-supported SC has four primary capabilities of precise mapping; virtual and real interaction; scientific analysis; and intelligent intervention. Accurate mapping enables the digitalization of various facilities and elements in the city by arranging sensors at various locations in the city and fully perceiving and dynamically detecting the city's operating status. Accordingly, information transmission and mapping between the virtual city and the physical city can be achieved. With DT technologies, data and information can be collected in the physical city, and the urban planning, construction, and various activities of people observed can be searched and represented in the virtual city. Thus, SC model development can be considered a collaboration between virtual and physical data and information. In addition, virtual ends created in physical cities with the help of tools, such as cloud computing and edge computing, can facilitate scientific and effective analysis of the behaviour of components in cities, thereby aiding decision-making in city management. Additionally, based on the analysis and simulation of the elements in cities, potential problems in cities can be proactively identified, and intelligent interventions can be performed. Accordingly, the proactive management of cities can be achieved. Albeit the benefits brought by DT to SC, there are significant challenges, which are detailed in below:

The first challenges is related to data collection and storage. Most existing sensors can only collect static data and information. How to collect dynamic data, such as accelerations and angular rates, needs to be further studied. In addition, sensor-based data collection at city level cannot handle the access requirements of multiple data sources. Since data are collected from different systems in different domains, data security and privacy issues have also become one of challenges of data collection. Some studies have started to explore the relationship between people and the environment by integrating physical data collected by wearable devices with data collected by city sensors. However, the exchange of data/information in different domains poses a challenge to related applications.

DT-supported SCs often lack spatial and geographic context, which lead to the second challenge of data modelling and visualization. GIS and BIM are two information modelling systems that are used mainly in geographical characteristics description and building lifecycle management in the built environments. However, it is impossible to achieve the management of real-time data and information by using them without the help from other tools. Existing studies have tried to link them to the data collected by city sensors to achieve the transformation from static to dynamic data management. As a result, the integrated modelling between geography, buildings and cities has been established.

Similar to BIM and GIS, AR and VR are being used to represent physical entities in the form of 3D, but they cannot deal with the real-time data flow between the physical and virtual entities. Whether it is BIM, GIS, AR or VR, they can only handle data and information in a specific domain. Therefore, how to integrate them to manage data in the unstructured data environment becomes the challenge of DT-supported SC. In addition, the issues of data privacy and security have not received extensive attention in research on DT-supported data modelling and visualization.

The third challenge of DT-supported SCs is about data connectivity. The main issue affecting data connectivity is interoperability, which leads to the difficulty of exchanging data between SCs. The current solution is to establish data standards, however, the systems involved in SCs are complex and from different domains. According to the principle of BIM data standard such as Construction Operations Building Information Exchange (COBie) and IFC, existing studies have proposed the idea of establishing a unified city model standard. However, it is difficult to establish a data standard at the city level.

The fourth challenge lies in recognizing which kind of data/information is required by which specific task, i.e., how to utilize data collected. Based on the thematic findings, few studies focus on data utilization in DT-supported SCs, the critical challenge of it is the inefficiency of computing power for processing city-level and unstructured data. The challenges are summarized in Fig. 5.

5.2. Solutions and future research directions

Given the increasing number of related studies in recent years, DT-supported SCs are being considered and have development potential. DTs have been applied to various aspects of SCs. Most related research has focused on improving transportation, energy systems, the environment, urban planning and services in SCs. Neglected applications, such as health care, home, education and economics, should be considered in future research.

Based on the challenges identified in section 5.1, we have identified corresponding solutions which can be classified into four aspects as follows:

5.2.1. Computing power

To address the first challenge, high-performance computers are required to process city-scale information. DT technology requires real-time data collection, mapping and status reflection of physical entities, which in turn require higher computing performance. Cloud computing, fog computing, and edge computing can be used to alleviate pressure on the local computing of data but do not fundamentally solve the issue of inadequate computing performance. For example, Agostinelli et al. (2021) applied edge computing to facilitate the data processing efficiency in energy performance analysis of 16 eight-floor buildings with 216 apartment units in Rome. However, at the city level, computing power is still a major challenge for DT-supported SCs. Future studies should address this problem proactively from the beginning of data/information collection. For example, when collecting data/information, applying data mining technology to filter out the data required by DT-supported SC systems will markedly reduce the pressure on computing in the analysis and application stages.

To address the second challenge, in which the application of BIM technology is also challenged by information overload and redundancy in DT-supported data modelling and visualization, the concept of employer information requirements has been proposed (Ashworth et al., 2019; Wang and Meng, 2019). Similarly, DT-supported SC systems can identify the required data and information proactively to reduce the unnecessary data processed by the system. To identify the data/information required by an SC from a city-scale data/information pool, future research can employ machine learning and semantic modelling-related tools in DT systems (Austin et al., 2020). The use of machine learning and semantic modelling can also improve the accuracy and reliability of the data/information (Bloch and Sacks, 2018).

For the data connectivity of DT-supported SCs (Third challenge), city-scale data/information also require high transmission speed. Existing research reports that 5G technology can speed up data transmission (Barik et al., 2021). However, city-scale data transmission through 5G technology is expensive. Therefore, future research could explore an effective way to transmit data in smart cities.

5.2.2. System interoperability

Data collection and connectivity in DT-supported SC are hindered by the issue of interoperability (the first challenge), as the sensors and systems in DT-supported SCs are distributed across different knowledge domains. The structure and format of data/information collected by sensors are different. In addition, there is the possibility of data/information being captured repeatedly. Accordingly, the interoperability of data/information between systems has become the primary problem that must be solved when applying DT technologies to collect data/information in SCs (the first challenge). Based on previous experience, the solution to data/information interoperability is to establish data structure standards and classify the collected data/information. The SC system proposed by Ålesund city in Norway combines GIS data, predictive demographics and IoT data from traffic telemetry, meteorology, telecommunication, and power based on application programming interface and predefined file formats (Major et al., 2021). However, it is heavy workload to pre-define the corresponding data structure for the data/information from different domains at the city scale (the second challenge and the third challenge). According to Rahman and Hussain (2021), the method of automatically clustering the collected data/information using technologies such as machine learning is more efficient for solving interoperability problems. Therefore, future research can apply machine learning-based automatic clusters to improve the interoperability of systems in the SC while avoiding conflicts when sensors receive data/information. In addition, if sensors receive data from different systems simultaneously, conflicts between smart city systems will arise (the third challenge). Zheng et al. (2021) pointed out that edge computing can analyse data close to the physical side of DT, while Wang et al. (2019) showed that fog computing combined with the Hungarian algorithm can mitigate collisions when sensors receive multiple service commands simultaneously. Accordingly, future research could apply edge computing and fog computing with related algorithms to address the conflicts that arise when sensors receive data from different systems simultaneously.

Interoperability also impacts the data modelling and visualization of DT-supported SC systems, which is the second challenge identified. For example, data from GIS and BIM systems are important for DT-supported SCs, but the exchange of data and information between the different domain systems is inefficient. According to Binding and Tudhope (2016), combining linked data and ontology can achieve data interoperability between different knowledge domains. Therefore, future research should investigate cross-domain data/information exchange using common semantic mechanisms and linked data technologies between different knowledge ontologies. There is a requirement for mutual learning between SCs (the third challenge); therefore, establishing data exchange standards at the city level can be a future research direction. Based on city-level data exchange standards, DT technology can be used as a bridge for data/information transmission between cities. Hence, a mutual learning mechanism between cities can be developed.

5.2.3. Data/information privacy and security

The connectivity of data/information between different domain systems and improvements in data/information interoperability will inevitably lead to problems of data/information privacy and security (the third challenge). In practice, this issue is addressed by customizing the permission of users in the SC systems. For example, in the DT system of a railway bridge located in city of Crewe in the United Kingdom, the users have different levels of access permissions through an individual account to accommodate the data security and privacy issues (Gürdür Broo et al., 2022). Currently, blockchain technology is used to solve data/information security and privacy issues (Bhushan et al., 2021). Additionally, modelling and semantically representing user consent, preferences and data usage policies can mitigate data/information security and privacy issues in data modelling and visualization (the second challenge). Future research should explore the balance between data/ information availability, accuracy, security and privacy.

5.2.4. Integrated analysis-supported decision-making

The purpose of utilizing data/information in an SC based on a DT is to make better decisions. However, few studies combine a DT with analysis methods to make integrated decisions (the fourth challenge). Future research can integrate a DT's ability to obtain real-time data and the scientific nature of integrated analysis methods, such as case-based reasoning, rule-based reasoning and multiple-criteria decision analysis, to make better decisions (Zhu et al., 2020). On the other hand, the distributed nature of SC systems identified as the third challenge in DT-supported SCs leads to the difficulty to make decision with the consideration of integrated multi-domain data. Therefore, the connectivity of data between systems of different domains needs to be further explored for the achievement of integrated decision-making (Austin et al., 2020). In addition, decision-making in current DT-supported SCs failed to involve human knowledge (the fourth challenge). In the city of Zurich in Switzerland, parts of this city are transformed into a virtual world on the basis of DT to encourage the young people to participate the urban planning procedures, but it is just on a trial basis (Schrotter and Hürzeler, 2020). Cognitive DT integrates human knowledge to DT technologies (Ramu et al., 2022). Future research can explore how to apply cognitive DT to connect human knowledge for better decision-makings.

6. Conclusions

The development and activities of SCs are always data/information-intensive. Various IT tools or systems have been applied to facilitate data and information management in SCs. Compared to existing IT tools or systems, DT is a revolutionary IT application. A total of 202 papers on DT-supported SCs published between 2014 and 2021 are reviewed in this study. Based on the literature review, this study identified current applications and challenges, which are followed by possible solutions to the challenges of DT-supported SCs. An integrated research framework is developed to show current and future research trends of DT-supported SCs in terms of data/information collection, storage, information connectivity, and utilization.

A DT has distinctive features, such as real-time connectivity between the physical component and its digital counterpart, homogenization of data and decoupling of the data/information from its physical artefact. Additionally, by integrating sensors on a physical product, AI technologies and predictive analytics, DT cities can adjust automatically to allow elements of physical cities to be up-to-date and work as well as possible. With the support of a DT, various city development plans can be simulated, and possible problems in city operation can be discovered in advance, providing support for decision-making during city development. Additionally, DTs can help avoid potential risks. All of these results demonstrate the strong potential of a DT for SCs and the necessity of transforming generic IT-based SCs into DT-supported SCs. This study demonstrates the capability of DT technologies for promoting SCs in terms of data lifecycle management process including data collection, storage, modelling, visualization, connectivity and utilization. Although, DTs have been applied in various aspects of SCs including transportation, energy system, environment city service and health care etc, DT-supported SCs still face many challenges. These challenges can be classified into four aspects namely computing power, system interoperability, data/information privacy and security, and integrated analysis-supported decision-making. Corresponding solutions and possible research directions were identified. DT-supported SCs are emerging and are still developing. For example, most current DT systems in SCs can manipulate data/information in their corresponding domain only, and data/information cannot be exchanged between different domain DT systems. For this reason, further improvement is needed to enable digital-twin SCs to achieve their full potential.

The identification of the current research status, challenges and potential of DT-supported SCs is the major contribution of this study. Every study has limitations, and this study uses a literature review as its only method. Thus, a lack of empirical support is the primary limitation of this study. For this reason, follow-up research is required to collect empirical data and provide empirical evidence. Follow-up research can modify the integrated research framework in this study based on empirical evidence. Research should investigate to what extent DTs are used for data/information management in SCs. It is also important for follow-up research to identify what is required or expected for DT-supported SC systems. Originally, DTs were applied primarily in manufacturing. Cities are generally recognized as concepts containing various industries. It is hoped that this research can draw more attention to DT applications to facilitate data lifecycle management in SC development.

CRediT authorship contribution statement

Hao Wang: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization. **Xiaowei Chen:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Fu Jia:** Conceptualization, Writing – review & editing, Visualization, Supervision, Project administration. **Xiaojuan Cheng:** Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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