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The adoption of urban digital twins

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A B S T R A C T

The urban management industry has recently shown interest in implementing digital twins in cities to improve urban planning, optimize asset management and create secure, sustainable cities. Built on the knowledge gained with the development of smart cities and the implementation of digital twins in other industries, urban digital twins have experienced a significant expansion in just a few years. However, this rapid growth has led to a fragmented situation where the definition of the concept of urban digital twin is not clear and implementations share few similarities. For this reason, the main objective of this paper was to contribute to the conceptualization of the digital twin in urban management. To do so, existing initiatives were mapped in terms of applications, inputs, processing and outputs. Requirements were elicited and the basic structure of a city digital twin was defined. Benefits, open issues and key challenges were also identified. This paper will be useful for stakeholders within the urban management area as it establishes the basis for the future design, development and widespread adoption of urban digital twins.

1. Introduction

The concept of digital twin has been defined recently by VanDerHorn and Mahadevan (2021) as "a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems". This concept first appeared in 2002 at the University of Michigan as a model for product lifecycle management (Grieves & Vickers, 2016). During the presentation, a real space was mirrored in a digital environment as a virtual space with links that transmitted data from the real to the virtual space and information in the reverse direction. However, the name digital twin was not used to refer to Grieves' concept until 2010 in a NASA integrated technology roadmap (Shafto et al., 2010). Even though the first applications of digital twins were in the field of aeronautics, their usage has expanded to other sectors and they have been adapted to several use cases. According to Jones et al. (2020), most digital twins are currently used in manufacturing. Nonetheless, digital twins are also used in applications as varied as product design (Liu et al., 2018; Xiang et al., 2018), structural health monitoring (Jiang et al., 2021; Li et al., 2017; Tharma et al., 2018), recycling (Wang & Wang, 2018) and agriculture (Verdouw et al., 2021), among others. In the construction industry, the development of digital twins did not gain traction until 2018 (Opoku et al., 2021). Since then, digital twins of buildings have been published focusing on the design phase (Kaewunruen & Xu, 2018), and the operation and maintenance phase (Lu, Xie, et al., 2020) with the construction phase lagging behind (Greif et al., 2020).

Digital twins focused on urban management also started to be developed around 2018. However, digital twins are not the first digital tool used in urbanism. The first urban models were developed in the 1950s with the advent of commercial computers. In 1955, the Chicago Transportation Area Study (CATS) (Chicago Area Transportation Study, 1962) became the first urban model. From that point, plenty of urban models were developed to assist in planning and policy making with the focus on the social aspects of the city. The evolution of urban models can be found in historical reviews such as the one by Boyce and Williams (2015) on urban transportation modelling or the more general review on urban models by Batty (2008). Examples of these models include transportation (Ben-Akiva, 1973; Boyce, 1984; Echenique, 1985; Waddell, 2002; Warner, 1962; Wegener, 1994), land-use and urban growth (Allen, 1997; Couclelis, 1985; Lathrop & Hamburg, 1965; Tobler, 1970; White & Engelen, 1997) or economic development (Alonso, 1964; Anas, 1973; Goldner, 1971; Ingram et al., 1972; Lowry, 1964; Wilson, 1970; Wilson et al., 1981).

Urban infrastructure models were typically developed separately as they had a completely different background and used different methods.

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Technical oriented urban models cover systems as varied as road infrastructure (Ding et al., 2018; Nebiker et al., 2012), water supply (Hinthorn & Liou, 1991), sewage (Melo et al., 2020; Zug et al., 2001), and electric power transmission and distribution (Farruggio & Glattfelder, 2001). In some cases, 3D city models have also been developed (Chen, 2011; Takase et al., 2003). Even though digital models were adopted early, city plans did not start to be replaced by 3D city models until the 2000s (Takase et al., 2003). Then these city models were further refined by linking existing digital representations of built assets in the form of Building Information Modelling (BIM) data (Döllner & Hagedorn, 2007). In the 2010s, the smart city concept (i.e., a city where the administration and citizens cooperate with new technologies with the aim of making the city more efficient, intelligent, sustainable, safer, inclusive and democratic) was popularized and cities were sensorized (Arroub et al., 2016). Nevertheless, current approaches usually lack the capability to directly interact with the city.

Urban digital twins have the potential to change this and drive the smart city concept and urban models to the next level. By taking advantage of the data that are gathered in smart cities and automatically introducing them in the city model and its systems, an accurate digital replica capable of autonomously interacting with the city is maintained. City digital twins not only can model, mirror and interact with the physical aspect of the city but can also be centred on the social and economic aspects (Wan et al., 2019). In fact, the continuous and bidirectional data exchange allows the model inside the digital twin to be the most accurate representation possible of the real city and its systems. The interactivity derived from this data exchange has the potential to bring important benefits in urban infrastructure management and operation. To date, several digital twins of cities have been developed. However, each implementation has been different and there is no clear picture of what an urban digital twin is and what systems it models. For example, already developed urban digital twins model systems as varied as urban transportation (Nochta et al., 2021), disaster management (Ford & Wolf, 2020), citizen participation (Dembski et al., 2020), infrastructure management (Pedersen et al., 2021) or urban planning (Schrotter & Hürzeler, 2020). In particular, this is a pressing issue with digital twins on physical urban infrastructure as they model a wide range of systems that have to be integrated in a single tool. As this is a relatively new topic, there is the need to refine and clarify their definitions and concepts, map the current state of development and identify future challenges.

The main objective of this paper was to contribute to the definition of the scope, concept, objectives, applications, and structure of urban digital twins from the technical perspective of urban services provision for the infrastructure management. For this reason, Section 2 describes the methodology used in this research. Section 3 reports the results obtained from following the methodology and discusses them. Section 4 describes benefits, issues, and challenges faced by urban digital twins on physical infrastructure management that were found while conducting this research. Finally, Section 5 presents the conclusions of the paper.

2. Methodology

The methodology (Fig. 1) used in this paper consisted of four main steps: (a) identification of existing urban digital twins by searching and identifying bibliographic sources of city digital twins, (b) analysis of identified urban digital twins by extracting data from the selected bibliographical references and exhaustively reviewing it, (c) proposal of the urban digital twin structure, and (d) identification of benefits, open issues and key challenges from the results of the previous steps.

2.1. *Identification of existing urban digital twins*

First, existing urban digital twins were identified by performing a wide literature search. Digital twins are just starting to be considered in the urban management sector and only a small number of towns and cities already have operating urban digital twins. As a result of this incipient implementation, research on urban digital twins is limited and recent (most studies were published in the last three years). To collect as much information as possible, articles and conference papers were reviewed. To a certain extent, this redressed the lack of bibliographic sources. In some cases, the information on urban digital twins has not been published in peer-reviewed literature. Usually, information is found on the city council's website or in news items published in the general media. As mentioned by Biljecki et al. (2015) in a 3D city model review, informal sources have unspecific terminology and provide ambiguous, unclear information. Therefore, they are outside the scope of this paper. In addition, a review of grey literature on urban digital twins has recently been published by Ketzler et al. (2020). In this case, all articles and conference papers were extracted from the Scopus database to filter low-quality publications.

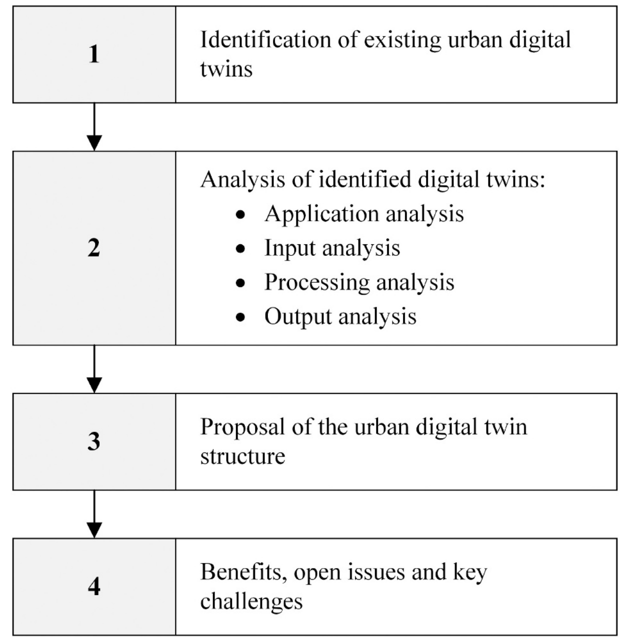

Fig. 1. Methodology used in this paper.

Keywords were selected in accordance with the most common words used in the urban digital twins topic. Journal and conference papers containing identified keywords in the title, abstract or keywords were preselected. The search queries used to identify existing bibliographic sources related to urban digital twins in Scopus were the following:

- TITLE-ABS-KEY ((‘city*’ OR ‘urban’ OR “built environment” OR ‘district’) AND “digital twin”)
- TITLE-ABS-KEY ((‘infrastructure’ OR ‘sewer*’ OR “water supply” OR “road traffic” OR ‘street’ OR ‘road’ OR “public transport” OR “electrical network” OR “street lighting” OR “natural gas network” OR “district heating” OR “wireless network”) AND (“digital twin” OR “digital model” OR “digital management system” OR “virtual management system” OR “autonomous management system”))

Research papers extracted from the search were collected and the corresponding abstracts were analysed for their relevance. All articles that were confirmed to be relevant were archived for the analysis of identified urban digital twins that would be performed later on. As a last step in this review, key data from the abstract were extracted and summarized in a table for subsequent analysis. Key data included the type of reference (journal paper, conference paper or project report), development status (already in operation, prototype or under development), location, and scope of the digital twin (digital twin of a city, district, infrastructure or building).

2.2. Analysis of identified urban digital twins

The second step of this methodology consisted of extracting data from the selected references and studying it. The thorough review involved checking whether the proposed system in each paper matched the definition of digital twin and the focus was on the physical urban infrastructure. In other words, the digital system must have inputs and outputs from/to the real system (Jones et al., 2020) and revolve around the physical aspect of urban infrastructure.

When all the papers that did not fit the scope of the study had been discarded, the data were extracted from the remaining references and organized to analyse them. The main characteristics of the urban digital twins were explored in terms of: (i) application data, (ii) inputs of the digital twin, (iii) data processing and (iv) outputs of the digital twin. For each of the abovementioned categories, a table is created where the main characteristics of the references being analysed are summarized. Characteristics were selected based on the availability of the data in the body of literature and the interdependence with other characteristics of urban digital twins. Application data included basic information on urban digital twins such as users (i.e., citizens, public administration, asset managers/owners or researchers), life-cycle stages (i.e., planning, construction, operation and maintenance, or end-of-life), and modelled systems (e.g., mobility, flooding or atmospheric pollution). The inputs table gathers the types of collected data (e.g., aerial imagery, temperature or electricity consumption), and data sources (e.g., aerial 3D scanner, temperature sensor or energy market database) that provide data from the physical model to the digital twin. The digital twin data processing table keeps track of the two key computational characteristics of urban digital twins, that is the type of computing operations executed by the processing system (e.g., simulation or machine learning) and the distribution of computing resources (edge, cloud or fog computing). Lastly, the table of the digital twin outputs, which is the same as the inputs to the physical model, contained information about the user interface or control panel (e.g., dashboard, map or 3D model) and the actuators required to act on the city (e.g., traffic lights, HVAC system control or issuing a work order).

Once the tables had been completed with the information extracted from all the analysed literature, they were used to easily identify the most frequently modelled systems. Next, the relations between modelled systems and corresponding inputs and outputs and data processing techniques were explored by analysing the tables. In other words, for each modelled system, the required sensors, data sources, data capture systems, computing systems, user interface and actuators were listed.

2.3. Proposal of the urban digital twin structure

From an analysis of the identified digital twins, the minimum required characteristics of an urban digital twin were defined. The basic urban digital twin was assumed to be the one that includes the most frequently modelled systems. In addition, from the modelled systems that make up the digital twin core and the relations found in Section 2.2, the requirements for data acquisition, data processing, data visualization and actuator systems were established. Once the urban digital core had been defined, complementary modules for the urban digital twin core could be proposed. A complementary module is a set of systems (data acquisition, processing, visualization and actuation) that models various systems while sharing part of the infrastructure. Due to complementary modules, the implementation of an urban digital twin can be adapted to the needs of the city management services to maximise their efficiency while taking full advantage of the systems implemented for the digital twin.

2.4. Benefits, open issues and key challenges

The fourth and final step of the methodology consisted of summarizing and discussing the benefits, open issues, and key challenges of city digital twins. These conclusions were mainly extracted from the results of the preceding steps. In addition, some conclusions were gathered from the previously selected and reviewed papers.

3. Results and discussion

This section presents and discusses the results of applying the methodology presented in Section 2.

3.1. Review of existing urban digital twins

From the initial literature search 131 references were identified. However, due to unspecific terminology, a considerable number of the preselected papers had to be discarded as they did not present an urban digital twin but a digital model that does not interact with its physical counterpart. In addition, urban models focusing only on the economic or social city aspects were out of the scope of the study and were therefore discarded as well. In other cases, the presented digital twins were

Table 1
Key data extracted from the abstracts.

Ref. no.	Reference	Type of reference	Development status	Location (country)	Scope
1	Bartos and Kerkez (2021)	Research paper	Prototype	–	Infrastructure
2	Marai et al. (2021)	Research paper	Prototype	Tokyo (JP)	Infrastructure
3	Pedersen et al. (2021)	Research paper	In operation	Odense and Nordfyn (DK)	Infrastructure
4	Raes et al. (2021)	Research paper	Under development	Athens (GR), Pilsen (CZ)	City
5	Rudskoy et al. (2021)	Conference proceedings	Under development	–	Infrastructure
6	Simonsson et al. (2021)	Research paper	Prototype	Luleå (SE)	City
7	White et al. (2021)	Research paper	In operation	Dublin Docklands (IE)	District
8	Dembski et al. (2020)	Research paper	In operation	Herrenberg (DE)	City
9	He et al. (2020)	Conference proceedings	Under development	–	Infrastructure
10	Lehner and Dorffner (2020)	Research paper	Under development	Vienna (AT)	City
11	Lu, Parlikad, et al. (2020)	Research paper	Prototype	Cambridge (UK)	Building
12	O'Dwyer et al. (2020)	Research paper	Prototype	Greenwich, London (UK)	District
13	Schrotter and Hürzeler (2020)	Research paper	Under development	Zurich (CH)	City
14	Sofia et al. (2020)	Conference proceedings	In operation	Morocco (MA)	Infrastructure
15	Tomin et al. (2020)	Conference proceedings	Prototype	Irkutsk (RU)	District
16	Carbonaro (2019)	Conference proceedings	Prototype	New York (US)	City
17	Whyte et al. (2019)	Project report	Under development	London (UK)	City
18	Dawkins et al. (2018)	Conference proceedings	Prototype	London (UK)	University campus
19	Ruohomäki et al. (2018)	Conference proceedings	Under development	Helsinki (FIN)	City
20	Bacco et al. (2017)	Research paper	Prototype	Pisa (IT)	City
21	Rauch et al. (2017)	Research paper	Prototype	Melbourne (AU)	District
22	Urich et al. (2013)	Conference proceedings	Prototype	Innsbruck (AT)	Infrastructure

Table 2
Urban digital twin application data.

Ref. no.	User					Life-cycle stage				Modelled systems			
	Citizens	Public administration	Asset owners	Asset managers	Researchers	Planning	Construction	Operation and maintenance	End-of-life	Physical city model	Meteorology	Climatology	Atmospheric pollution
1		X	X	X				X			X		
2		X	X	X		X		X			X		
3		X	X	X		X		X		X	X		
4	X	X				X		X		X			X
5		X				X		X					
6	X	X	X	X				X			X		
7	X	X			X	X		X		X			
8	X	X				X		X		X	X	X	X
9		X	X	X				X					
10	X	X				X				X			
11		X	X	X				X		X			
12		X	X	X				X					
13	X	X			X	X				X		X	X
14		X	X	X				X					
15		X		X		X		X					
16		X				X		X					
17		X	X	X		X	X	X			X		
18	X	X			X	X				X	X		
19	X	X	X	X		X		X		X			X
20	X	X				X		X		X	X		X
21		X						X		X	X		
22		X				X		X		X	X		

unrelated to urban management. After discarding 83 % of the initial sources, it is apparent that the concept of the digital twin (known as a model capable of interacting with the real system it represents by means of a continuous and bidirectional data exchange) is still not fully understood. After the preliminary review, 22 references were selected for further analysis (Table 1). The oldest study dates back to 2013 and the most recent one to 2021. Of the 22 references, there were 13 research articles, 8 conference papers and a project report. As described in the methodology, key data from the abstracts of the preselected papers were extracted and summarized. An analysis of the key data revealed that urban digital twins are still in their infancy, as only 18 % of the references related to systems that are already in operation. The rest of the studies were based on prototypes and projects still under development. Urban digital twins are being developed particularly in Europe (only five of the projects were implemented outside Europe) probably due to the major funding opportunities provided by the Horizon 2020 initiative (European Commission, 2011). Regarding their scope, most of the urban digital twins model and interact with the entire town area.

3.2. Analysis of identified urban digital twins

The following subsections summarize the results obtained with an in-depth analysis of the urban digital twins identified in Section 3.1.

3.2.1. Application analysis

The applications of a digital twin can be inferred from its users, the life-cycle stages when the digital twin is in operation and the system it models (Table 2).

An analysis of the results showed that the target user of urban digital twins varied from city to city. The most common users are public administrations (present in all digital twins) followed by asset managers, asset owners and citizens. In contrast, researchers were the least common users. They were beneficiaries of the urban digital twin in just 3 out of 22 cases. Another interesting fact that can be extracted from the user section of Table 2 is that existing urban digital twins may assist citizens and asset managers (and owners in case of public concessions) but not both groups at the same time (citizens and asset owners or managers only coexist as users in two of the analysed urban digital twins). Currently there are no technological barriers preventing urban digital twins from being useful to both types of users. Therefore, this underlines the importance of political factors in the design process of urban digital twins.

Regarding the life-cycle stage, urban digital twins are mainly used as a tool to help in the operations and maintenance stage. In some cases, urban digital twins are also involved in city planning. The operation and maintenance stage is predominant as urban assets (e.g., roads or utility infrastructures) have to be in good condition for a long life span. However, assistance in the planning stage also appears in about two thirds of the analysed studies as cities continuously evolve, creating the need for constant urban planning. Digital twins to help in the construction phase are already being developed and implemented (Greif et al., 2020) but they only include a single building or infrastructure. Therefore, they are outside the scope of this study.

A city or an urban area includes or is affected by a wide, varied array of systems such as road infrastructure, water supply, electricity supply or public transport, among others. Hence, an urban digital twin models a high number of systems. In this study, 19 modelled systems have been identified (Table 2) and are briefly described next. The physical city model generally includes a 3D map of the city with the textures of façades, roofs and streets. The meteorological and climate models predict the weather and evolution of the microclimate in the city, whereas the atmospheric pollution model predicts the dispersion of aerial contaminants. The noise pollution model analyses noise levels and their evolution around the city. The flooding model predicts the impact of potential flooding while the sewage infrastructure and road infrastructure models contain all the infrastructure assets and predict the behaviour of sewage and road infrastructures. The wireless network coverage model simulates the wireless signal around the city. The electrical network infrastructure model controls the state and operation of the assets that comprise the electrical grid. The electricity, natural gas, heat and water supply models control the electricity, natural gas, heat and water usage in the city. The electricity generation model predicts electricity generation while the renewable energy sources model analyses the renewable energy potential of the entire city. The mobility model analyses and predicts the movement of vehicles and pedestrians whereas the public transport model shows the state of the public transport system and its

Modelled systems														
Noise pollution	Flooding	Sewage	Road infrastructure	Wireless network coverage	Electrical network infrastructure	Electricity supply	Natural gas supply	Heat supply	Water supply	Energy demand	Electricity generation	Renewable energy resources	Mobility	Public transport
	X	X												
			X											
	X	X							X					
X													X	
			X										X	X
					X			X		X	X			
	X		X										X	X
			X										X	
					X									
						X	X			X	X	X		
X			X	X		X			X			X		
			X											
					X					X	X			
													X	X
	X	X												
														X
X	X									X		X	X	
X													X	
	X	X							X					
	X	X							X					

usage level.

In terms of frequency, a physical model of the city is the most common, followed by meteorology, flooding prediction and mobility. Other commonly modelled systems are road infrastructure, atmospheric pollution, sewage, noise pollution, water supply, energy demand and public transport. For example, in the city of London, multiple systems such as the sewage network, electricity supply, energy demand and renewable energy resources have been modelled in two projects carried out by Whyte et al. (2019) and O'Dwyer et al. (2020). The physical 3D model is generally used as the foundation of urban digital twins because of its ease of use and creation compared to other modelled systems. Another interesting relation is the fact that digital twins with 3D city models usually have citizens as users. This confirms the usefulness of 3D models when data are presented to non-expert users. At the same time, flooding prediction is widely adopted as, parting from the physical model, few additional data are necessary to model it. Meteorologic models appear frequently as weather information is usually available as open data from meteorological services. Apart from these basic systems and depending on the general application of the digital twin, some systems can be modelled together. For example, urban digital twins that are developed to control energy demand tend to simultaneously model electricity supply, electricity generation and renewable energy resources. In addition, the target users of energy-related urban digital twins are generally the public administration and asset owners/managers. This can be attributed to the fact that energy generation and distribution does not have a direct impact on citizens.

3.2.2. *Digital twin input analysis*

Digital twin input analysis was performed in relation to collected data and data sources (Table 3). As expected, the most commonly collected data were those needed to model the most frequently modelled systems. These were terrestrial and aerial imagery for the 3D model of the city, temperature and humidity sensors for the meteorological models, pollution sensors for the atmospheric pollution models, and water level sensors for flooding and sewage modelling. Equipment operating parameters were also common (appearing in over one third of the analysed studies).

Sensors were the most frequent inputs of urban digital twins and were the components that varied the most between urban digital twin projects. This is due to the fact that sensor selection is closely linked to the application of digital twins and applications are different in each urban digital twin implementation. For example, in the digital twin of Herrenberg (Germany) developed by Dembski et al. (2020), atmospheric pollution sensors were deployed to monitor and predict urban atmospheric pollution, Sofia et al. (2020) used strain gauges to monitor a bridge and Whyte et al. (2019) employed water-level sensors for the monitoring and control of the Thames Tideway Tunnel in London. Apart from the type of sensors that are selected, sampling rate and sensor distribution density are two parameters that are also important in data collection in urban sensor networks (Muller et al., 2013). With a higher sampling rate and distribution density, the digital twin will represent the real physical system more accurately. In addition, sensors should be properly distributed, considering the city and the use of the data (Mattoni et al., 2015). However, the computational and energy resources needed to process the data also increase. Hence, a middle ground has to be found where the digital twin is accurate enough and the costs are not excessive. It should be noted that minimum sampling rates and sensor distribution densities depend on the modelled system. For example, the 3D digital model of a city does not require a high sampling rate as the city landscape evolves slowly. In contrast, the majority of urban systems such as road traffic need real-time monitoring. Thus, data are sampled yearly (or longer) in digital twins that model static systems while in the rest of the cases, the sampling rate is within the range of hours, minutes or even lower.

In addition to sensors, urban digital twins are supplied with information from databases. These databases can be sourced from the public administration (such as the cadastre) or third parties (e.g., an energy market database). In third-party databases, validation of the data fed to the digital twin is vital for its correct operation (Lee et al., 2021). As in sensors, the most commonly used databases are those that provide information on the most common models: the meteorological service database that helps build the meteorological model, the asset database that serves as a register of the assets in a network or system, and the cadastre and geodata database that contribute to the creation of the 3D city model.

Sensors and databases tend to be implemented in groups that share the system model in which they are required. This is the case of water level sensors, meteorological databases (and/or atmospheric sensors),

Table 3
Urban digital twin input data.

Reference number	Collected data																					
	Imagery	Aerial imagery	Point cloud	Atmospheric temperature	Humidity	Atmospheric pressure	Wind direction and velocity	Ambient light	Atmospheric pollution	Noise level	Water level	Deformation	Vibrations/Acceleration	Building or construction information	Equipment operating parameters	Electricity consumption	Natural gas consumption	Water consumption	Energy prices	Citizens' warnings/opinions	Citizens' location	Video surveillance
1											X			X	X							
2	X			X	X	X																X
3				X	X	X	X				X				X			X				
4	X	X	X	X	X	X	X		X	X										X		X
5										X												X
6				X	X	X	X								X							
7		X	X				X							X						X		X
8	X	X	X	X	X	X	X		X					X						X	X	
9															X	X						
10	X	X	X											X								
11		X	X	X	X																	
12																X	X		X			
13	X	X	X																			
14	X		X	X			X					X	X									
15															X	X						
16														X	X							
17											X			X	X							
18			X	X	X	X		X						X								
19		X	X																			
20			X	X	X	X	X	X	X											X	X	
21				X	X	X					X				X			X				
22				X	X	X					X							X				

Reference number	Data sources																													
	Terrestrial 3D scanner	Aerial 3D scanner	Temperature sensor	Humidity sensor	Barometer	Anemometer	Ambient light sensor	Meteorological service database	Atmospheric pollution sensor	Microphone	Water-level sensor	Strain gauge	Accelerometer	BIM	Equipment operating parameters	Electricity meter	Natural gas meter	Water meter	Energy market database	Geodata database	Cadastre or similar	Asset database	EPC database	Surveillance cameras	Citizens (manually introduced data)	Citizens' smartphones sensors	Images taken by citizens	Citizens' location	Public transport database	Other third-party database
1								X			X				X					X		X								
2			X	X	X															X				X						
3								X			X				X			X		X		X								X
4	X	X	X	X	X	X		X	X	X										X	X			X	X		X	X	X	
5										X										X				X					X	X
6								X							X				X	X										
7		X				X								X						X	X	X		X	X				X	X
8	X	X	X	X				X	X					X											X	X	X	X		
9															X	X			X											X
10	X	X																		X	X	X								
11	X	X	X	X																		X								
12			X					X								X	X		X			X								
13	X	X																			X	X								X
14	X		X			X						X	X																	
15															X	X			X			X								X
16								X						X	X					X	X	X							X	X
17								X			X			X	X							X								
18	X		X	X	X		X							X																
19	X	X																			X	X	X							
20		X	X	X	X	X	X		X																X	X	X	X		
21								X			X				X			X		X		X								
22								X			X				X					X	X	X								

equipment operating parameters and the geodata database. Another example of this is terrestrial and aerial imagery with point cloud sensors. Sensors and databases were also found to be grouped when the coexistence of both has a positive impact on the acquired data. For example, in the digital twins developed by Dembski et al. (2020) and Raes et al. (2021), temperature and humidity sensors work together with a meteorological service database to provide precise measurements at points of interest while they offer data for the rest of the urban area. Another example is the combination of aerial and terrestrial 3D scans (Dembski et al., 2020; Lehner & Dorffner, 2020; Lu, Parlikad, et al., 2020; Raes et al., 2021; Ruohomäki et al., 2018; Schrotter & Hürzeler, 2020) that allow the mapping of roofs and façades with better results.

3.2.3. Digital twin processing analysis

Data inputs are processed to determine the outputs that will act over the physical system. Data processing is divided into two categories: the computing operations required to run the digital twin and the distribution of the computing resources, which is the same as the location of the processing units with respect to the sensing units (Table 4).

The computing operations that are generally used on urban digital twins are numerical simulations (in 14 out of 22 papers), logic operations (13 out of 22), and machine learning (4 out of 22). In four digital twins, calculations were only performed for data visualization purposes. Numerical simulations were the most common because several modelled systems require the execution of a simulation to predict the behaviour of the system. An example of numerical simulations in the sample of studied papers is the urban digital twin of Herrenberg (Dembski et al., 2020) where an airflow simulation performed with a computational fluid dynamics application predicts the dispersion of pollution in the town. Logic operations were mainly used to detect and warn about limit values or send work orders, as in the digital twin developed and implemented in the West Cambridge campus (Lu, Parlikad, et al., 2020). Machine learning algorithms are employed in the Thames Tideway Tunnel (Whyte et al., 2019) to predict flooding based on historical data. A clustering technique is used in the district of Greenwich to classify energy demand patterns (O'Dwyer et al., 2020).

Data processing is limited by the device execution capabilities and the data transmission network linking the sensors to the computing device. Centralized execution in the cloud (cloud computing) allows for big computation resources but transmission rates are limited. Latency can be too high for certain applications (e.g., assisting autonomous driving). A decentralized solution (edge computing) has limited computation resources but data transmission is no longer a problem. Edge computing is more resilient than cloud computing as a node can fail but the digital twin can continue working. In addition, edge computing is easily scalable. Fog computing (a hybrid approach consisting of multiple computing devices in charge of computing data from a group of sensors) has mixed properties. Cloud computing is the predominant computing distribution. It was implemented in all but two of the analysed urban digital twins. The reason for this is the fact that even with bandwidth-consuming tasks such as video surveillance transmission, current models have a reduced number of sensors. A digital twin with a limited number of sensors does not generate excessive amounts of data. Thus, this avoids problems when the data are transferred to a central server. In addition, a centralized solution is easier to maintain (Vashisht & Gupta, 2015).

3.2.4. Digital twin output analysis

Digital twins interact with the physical world through user interfaces and actuators (Table 5). User interfaces allow control and visualization of the digital twin and its condition. Common digital twin user interfaces are dashboards, schematic diagrams, maps, 3D models, virtual reality and augmented reality. Digital twins interact with the physical city through actuators. They can act directly on the city, controlling infrastructure systems, or indirectly by requesting and assisting an agent to carry out a task (e.g., the maintenance team is asked to repair a pothole). Actuators can be divided into eight classes: traffic lights, digital traffic signs, valve/gate control, HVAC system control, equipment and machinery control, electrical demand response, work order and long-term planning assistance.

According to the results shown in Table 5, most of the analysed digital twins have more than one user interface, as the interface is tailored to the needs of different users. For example, citizens prefer easy-to-use interfaces without excessive information while the public administration or the digital twin operators require complex user interfaces that show more data. Maps are the most common user interface of urban digital twins, followed by 3D models. Both of them have the property of being easy to interpret and provide different information just by changing layers. 3D models are generally aimed at citizens and maps are used by both types of users (in most cases maps provide the same information as a 3D model). Schematic diagrams and dashboards are common in digital twins of infrastructure as they can be simplified easily in 2D schemes. Virtual and augmented reality is only used in the study of Dembski et al. (2020) as a means of encouraging and involving inhabitants in city planning.

Actuators vary a lot depending on the application of the digital twin and the modelled systems. All but one of the analysed digital twins include indirect actuators. A total of 68 % of the identified digital twins assist in long-term planning. An equal percentage of digital twins include work orders. Indirect actuators are extensively used because of their low implementation cost. Direct actuators vary depending on the modelled systems. For example, digital twins of sewage and water supply control valves, gates and other related equipment while energy digital twins have HVAC controls, other machinery controls and electrical demand response systems.

3.3. *Proposal of the urban digital twin structure*

An integrated analysis of the abovementioned variables (Tables 2, 3, 4 and 5) allowed identification of the minimum characteristics a digital twin should have. From this analysis, it became clear that urban digital twin characteristics are highly dependent on their use (i.e., users, lifecycle stage and application) and share few similarities, which complicates the description of a basic city digital twin acting as the foundation from which other modules can be added for expanded functionalities and uses. What city digital twins have in common is a digital model of the physical city. This city model becomes the first step in the creation of the urban digital twin as it helps to build the digital twin around it. Sensors and actuators are added to the model to give it interactive capabilities and convert it into a digital twin. Then, a comprehensive urban digital twin can be created by integrating other infrastructures, services and systems (and their models, data sources and actuators). Although 2D models are used in some city digital twins, such as the ones presented by Marai et al. (2021), Pedersen et al. (2021) or Rudskoy et al. (2021), certain uses such as city planning and flooding prevention greatly benefit from a 3D model. Examples of such cases are found in the papers of White et al. (2021) and Ruohomäki et al. (2018). Furthermore, 3D models have the advantage of being easier to interpret by the general public. Consequently, the 3D digital model of the city is defined as the foundation of the urban digital twin. However, the city model digital twin has limited uses as it is an updated visual replica with limited interactive capabilities that does not integrate the operation of city systems and services. The digital twin of the 3D city model can then be used to model other systems on top of it and expand its use cases.

Then, from Tables 2, 3, 4 and 5 in Section 3.2, modelled systems that appear to frequently share components, data sources or processes are grouped in modules. In this way, a module offers the possibility to model several systems without needing a specific full set of components, data sources and processes for each system. Hence, modules could facilitate and reduce costs in the future implementation of urban digital twins. In addition, a single urban digital twin structure can help standardize these systems. Considering the infrastructure they share, their similarities and the frequency of implementation, four main modules have been devised:

- Mobility management: includes road infrastructure, private mobility, public transport and noise pollution modelling.
- Water management: includes water supply, sewage and flood prevention modelling.
- Energy management: includes electric power transmission and the distribution network, electricity generation inside the city and energy demand modelling.

Table 4
Urban digital twin processing data.

Ref. no.	Computing operations							Computing distribution	
	Processing only for visualization	Logic	Optimization (solver)	Simulation	Clustering	Machine learning	Neural network	Edge	Cloud
1				X					X
2		X				X		X	
3		X		X					X
4		X		X					X
5		X		X					X
6		X		X					X
7				X					X
8				X					X
9		X		X					X
10	X								X
11		X							X
12			X	X	X	X			X
13	X								X
14		X				X	X		X
15		X		X					X
16		X							X
17		X		X		X			X
18	X							X	
19				X					X
20	X								X
21		X		X					X
22		X	X	X					X

Table 5
Urban digital twin output data.

Ref. no.	User interface						Actuator							
	Dashboard	Schematic diagram	Map	3D model	Virtual reality	Augmented reality	Traffic lights	Digital traffic signs	Valve/ gate control	HVAC system control	Control of equipment and machinery	Electrical demand response	Work order	Assist in long-term planning
1		X							X		X		X	
2			X										X	X
3	X		X						X		X		X	X
4			X	X									X	X
5			X				X	X					X	X
6	X	X	X							X	X		X	
7			X	X									X	X
8				X	X	X								X
9		X									X		X	
10			X	X										X
11		X		X						X			X	
12		X								X		X		
13			X	X										X
14				X									X	
15	X	X									X	X	X	X
16			X										X	X
17		X							X				X	X
18				X										X
19			X	X										X
20			X											X
21			X	X					X		X		X	
22			X	X					X		X		X	X

- Atmospheric monitoring and prediction: includes atmospheric pollution, meteorology and climatology modelling.

Remaining systems are modelled individually for two reasons: systems do not appear frequently and are only implemented when the city has a particular need (e.g., renewable energy resources) or the modelled system does not share components (sensors, actuators and/or processing systems) with the rest of the digital twin.

The digital twin city model, the proposed modules and the remaining individual systems are then divided into four layers according to their function (data acquisition layer, data modelling layer, simulation layer and service/actuation layer). In addition to the four internal digital twin layers, a physical layer comprising the physical systems or services that are represented by the digital twin module is also defined. Depending on the physical systems represented in a module, the components included in each layer vary accordingly. In order to accurately represent the physical layer, the data acquisition layer is responsible for the automatic data capture and transmission to the digital modelling layer where the digital replica of the real system is continuously updated. Then the simulation layer processes the data included in the model and sends the results to the service/actuation layer, where the digital twin interacts with the real system through direct actuation (and also indirectly by providing data to users). The proposed urban digital twin structure is presented in Fig. 2.

4. Benefits, open issues and key challenges

From the analysis of the selected references, it has been found that urban digital twins can benefit the various agents involved in a city (citizens, public administration, asset managers, asset owners and researchers) when they are properly implemented. To begin with, urban digital twins allow the public administration to make more informed decisions about city planning and operation, which results in improved urban management and a more sustainable city (Hämäläinen, 2021). Better city management not only benefits the public administration but the entire society. In addition, digital twins can model multiple systems and process information from a wide range of datasets at the same time, allowing city planning and control in a single tool. Having everything unified also facilitates the use of data by basic (e.g., citizens or tourists) and expert (e.g., asset managers or researchers) users. Facilitating data use for citizens also has the side benefit of increasing their participation and engagement in urban planning (White et al., 2021).

A unified city digital twin can be a more efficient urban management tool than traditional methods. Cities are continuously evolving and their models have to be updated regularly to be useful. This is unsustainable and a unified multifunctional 3D city model is an alternative. At the same time, a unified tool such as the urban digital twin allows the data to be further exploited as relations and trends between systems can be identified more easily. Finally, urban digital twins act as strategic planning sandboxes where public and private efforts can be tested and coordinated.

Even though the implementation of digital twins in the urban environment is considered beneficial for the city, its citizens and its administrators, it does not come free of drawbacks. To begin with, the development and implementation of digital twins has a higher cost than simpler control and monitoring systems. In addition, due to the technical complexity of a digital twin, skilled workers are needed to design, install and maintain it. Batty (2018) has also expressed concern about the viability of an urban digital twin because of the challenge of integrating economic and social functions in the city. Apart from the need to integrate heterogeneous data, city digital twin datasets are large and complex. To process these large datasets in real time, servers with high computing capacity are required (Shahat et al., 2021). However, computational resources are expensive and limited. As an alternative, simplified models can be used at the expense of precision. Beside the approximate results, simulations carried out in the digital twin are also impacted by the quality of the data they are fed (that is, lack of data accuracy, errors in datasets, bad sensor distribution, etc.). As previous studies have pointed out (Kim et al., 2019), data quality is a problem when participatory sensing and crowdsourced data are used, as human errors are more frequent and sensors used by citizens (generally smartphone sensors) are not usually calibrated and can give inaccurate or imprecise readings. In addition, measurement locations are not homogeneously distributed and places more densely populated (or with a higher number of engaged citizens) are favoured over the rest. Data input is one of the issues that has been worked on the most, as inaccurate data directly affect the digital twin outputs and prevent the digital twin from providing useful assistance in decision making or the prediction of future scenarios (Nochta et al., 2021). City digital twins also face issues regarding the output of information from the digital twin to the physical model. As of now, most literature on city digital twins describe systems that act on the physical model by assisting authorities in urban planning. However, more actuators and response systems have to be developed so the digital twin can act directly on the physical counterpart and have an impact in real time.

There is a need to develop widely accepted standards to simplify the development and implementation of city models and gain the benefits of time, cost and error reduction (Shahat et al., 2021). In addition, a commercial city digital twin solution has not been developed yet. Currently, this lack of standards and interoperability is a significant limitation as only a small number of urban digital twins can share data with other cities or organizations. As a result of the aforementioned issues and challenges, urban digital twins present in the literature are not comprehensive enough to model all the infrastructures and systems in a city. This is apparent with the fact that the most comprehensive urban digital twin analysed in this study (Schrotter & Hürzeler, 2020) only models 9 out of 19 systems and the second one (Ruohomäki et al., 2018) models only 7 systems. It is expected that with their progressive evolution, future digital twins will be able to include most of the processes and functions of the city. At the same time, interoperability would facilitate the completion of country-wide digital twins such as that proposed in the National Digital Twin Programme (Centre for Digital Built Britain, 2018).

Cybersecurity is another main concern as cyber-attacks on urban digital twins can be critical. If an urban digital twin is compromised, it could leak sensitive data. Furthermore, the attacker could gain control of the system, which could have severe consequences on vital urban infrastructures such as traffic management systems, electric power transmission grids or water supply networks (J. Lee et al., 2019). In addition, citizens may be concerned about the use of data by the public administration. Finally, there is the legal question of who is accountable if the digital twin makes a wrong decision. Similar questions are being discussed in other fields such as autonomous driving.

5. Conclusions

This paper analysed 131 journal papers and conference proceedings in the urban management and modelling field and thoroughly studied 22 of them related to the development, implementation and operation of urban digital twins. The subsequent analysis allowed characterization of existing approaches and definition of the concept and minimum requirements an urban digital twin should meet. In addition, the gathered data also allowed identification of the main benefits provided by urban digital twins, the open issues and key challenges that they face.

From the results of this paper, it is clear the urban management sector is just starting to implement digital twins, as less than 20 % of the studied articles focused on projects that were already in operation and all references except one were published in the last 5 years. In addition, Europe is emerging as the main centre of development of urban digital twins, with over 60 % of the existing initiatives. As a result of being in an early adoption stage, existing literature is limited and city digital twin terminology is often confused. This is apparent in the misuse of the term urban digital twin to refer simply to a 3D digital model of a city. This confusion is partly fuelled by the fact that the digital 3D model of the city is used as the base upon which comprehensive urban digital twins are built. Promoters of urban digital twins are local public administrations. Consequently, the main user of these digital twins are public administrations themselves. However, asset owners, asset managers and citizens also appear frequently as users although the user pair asset owners/managers and citizens is not common, probably due to decisions taken during the process of designing the urban digital twin. Public administrations usually use city digital twins as a tool to assist in operation and

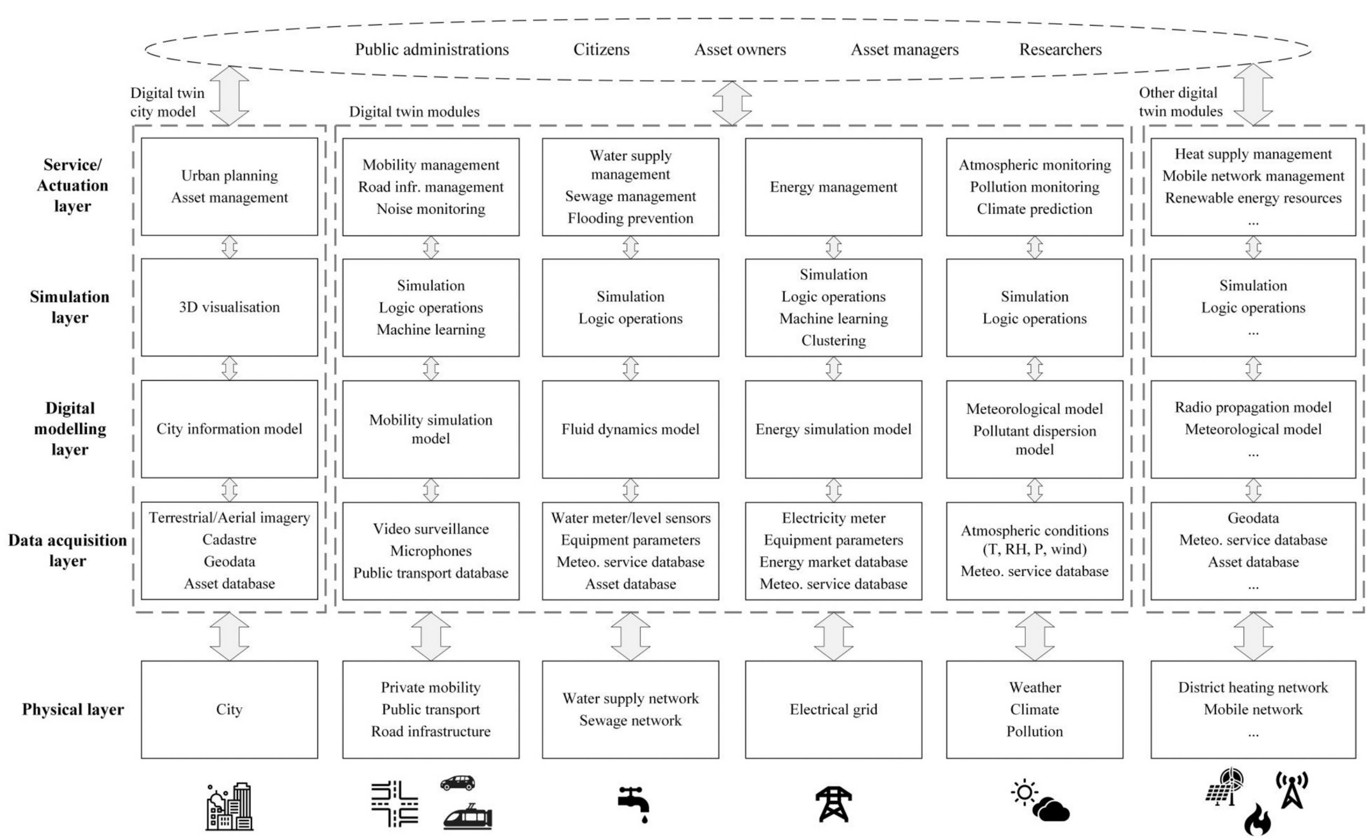

Fig. 2. Proposed urban digital twin structure.

maintenance (19 out of 22 urban digital twins assist in this stage). To a lesser degree (15 out of 22 cases), urban planning also benefits from the implementation of digital twins. An examination of the modelled systems, apart from the 3D city model, showed that the most frequently modelled systems are meteorology, flood prediction and mobility, probably because the required data are easily available. Data are mostly collected from sensors and databases (owned by the public administration or a third party). Types of data depend highly on the systems being modelled by the digital twin. Data processing is almost always executed on a cloud server, as centralized systems are preferred because they ease the development and deployment of the digital twin. Nonetheless, in the future, once urban digital twins become more comprehensive and model most city infrastructure and services (and consequently more sensors are added), it is expected that some cities will switch to the edge computing approach to reduce bandwidth requirements. Regarding outputs, in general urban digital twins currently act indirectly over the physical model rather than directly, either through visualization tools (maps for infrastructure-focused digital twins and 3D models for the rest) or other indirect actuators. City digital twins indirect actuators are common as they are easy and inexpensive to implement. These include work orders and provision of assistance in long-term planning. In contrast, direct actuators are highly dependent on the modelled systems.

Even though urban digital twins are still in their infancy, they are capable of bringing improvements to urban management. First, a digital twin of the city allows integration of city planning and management in a single tool. This eliminates the need for a myriad of management systems. Secondly, urban digital twins enable faster response times as they can actuate autonomously. Thirdly, the management of the city can become more efficient as a result of knowing the exact state of the city in real time. However, digital twins in the urban environment have some issues that are not resolved yet, the most important being the lack of interoperability, which reduces their usefulness and data exploitation possibilities. Apart from interoperability issues, urban digital twins suffer from other technical problems, the most relevant being data quality issues and the lack of computing resources to analyse in real time all the data a city can generate. Furthermore, funds allocated for the implementation and operation of urban digital twins are limited, which results in the need to find a compromise between cost and functionality. In addition, concerns about how secure they are against cyber-attacks have been found in the literature.

This research proposes an urban digital twin structure composed of a 3D city model (that interacts with the city through sensors and actuators) and optional modules that expand the functionality of the urban digital twin. The modules allow for a flexible system capable of being adapted to the needs of different cities while reducing costs by not installing unnecessary or redundant components. In addition, the predefined modular structure also has the potential to offer faster design times. On a more general level, this paper helps clarify the concept of urban digital twin and differentiate it from other digital city models or replicas. Last but not least, the basic urban digital twin also paves the way for standardization in the field of digital twins in urban management.

Future research lines should focus on providing solutions to the aforementioned issues. Studies should be devoted to developing standards and protocols so that urban digital twins can share data with other cities or administrations. Future efforts should also be invested in solving scalability issues, such as reducing computing requirements with simplified models or decreasing data transmission by implementing edge computing systems. By solving these problems, comprehensive urban digital twins that model most infrastructure and services could become the default city management tool. Finally, socio-political analysis of urban digital twins should also be performed to study and comprehend their socio-political nature, determine the socio-political implications of using these systems and identify key issues and challenges that might hamper their widespread adoption.

CRediT authorship contribution statement

Jaume Ferré-Bigorra: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Miquel Casals:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Marta Gangolells:** Methodology, Resources, Writing – review & editing, Supervision.

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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