

1. List of Digital Twin for cities definitions analyzed in this work.

Title	Document type	Year	Label	The proposed definition
Path-tracing semantic networks to interpret changes in semantic 3D city models.	Conference proceedings	2022	Urban Digital Twin	An UDT can be thought of as a digital representation of a physical city, including its assets, processes, and services. UDTs provide a central platform for incorporating information from heterogeneous sources, including (real-time) Internet of Things (IoT) sensor readings, remote sensing data, etc. UDTs can therefore be deployed for a wide range of applications, such as urban planning, monitoring and visualization, allowing a risk-free virtual environment to simulate, experiment and evaluate future policies (Nguyen and Kolbe, 2022).
Viability testing of game engine usage for visualization of 3d geospatial data with OGC standards.	Conference proceedings	2022	Urban Digital Twin	An UDT is a 3D model replica of a real-world city integrated with static and dynamic information, providing methods for analyzing and optimizing the built environment. Similar to the DT technologies used in automobile industries to inform manufacturers on how products work and will react in the future, the urban DT are widely used to calculate various urban informatics with which multiple “what if” scenarios can be simulated to understand its future before it gets constructed in the real-world environment (Würstle et al., 2022).
Use Cases for district-scale urban Digital Twins.	Conference proceedings	2022	Urban Digital Twin	Researchers have come to the consensus that UDTs for smart city initiatives should: (i) contain 3D city models; (ii) have semantic or geometrical information; and (iii) have sensor data in real-time; and (iv) implement the most effective design, planning, or system operation and intervention decisions through a variety of analyses and simulations. Importantly, to help those choices, all data should be presented to clients (residents, leaders, specialists) in an all-inclusive resource dashboard within a DT interface that is user-friendly (Alva et al., 2022).
The adoption of urban digital twins.	Research article	2022	Urban Digital Twin	“The city model (physical model) is the first step in the building of the urban digital twin. Sensors and actuators are linked to the model to allow interactivity and convert the physical city model to digital twin. A comprehensive DT can be achieved by the integration of others modelled systems, services, and infrastructures (Ferré-Bigorra et al., 2022).
Digital twin of a city: Review of technology serving city needs.	Review article	2022	Urban Digital Twin and City Digital Twin	A DT represents a real scene in a digital way, and uses several types of data, such as historical data, real-time data, and algorithm models to simulate, verify, predict, and control the entire life cycle of the same real scene. DT becomes, from the information content perspective, an extended, linked 3D city model. Amongst these added properties, at least the following have been mentioned: 1. Lifecycle management of individual city objects and assets. 2. Simulation use of the 3D city model to assess various scenarios; and

3. Linking the city model with real-time (sensor) data sources (Lehtola et al., 2022)

Enabling City Digital Twins through urban living labs.	Conference proceedings	2022	City Digital Twin	The DT is a virtual replica of the real city, which collects data from the infrastructure, processes and services using not only the available systems, but also purposely built connected devices and sensor (Hristov et al., 2022).
Potential of the Geometric Layer in Urban Digital Twins.	Research article	2022	Urban Digital Twin and City Digital Twin	An UDT is the virtual representation of real assets, processes, systems, and subsystems of a city. It uses and integrates heterogeneous data to learn and evolve with the physical city, providing support to monitor the status and predict/anticipate possible future scenarios (Scalas et al., 2022).
Hybrid Aerial Sensor Data as Basis for a Geospatial Digital Twin.	Conference proceeding	2022	Geospatial Digital Twin and Urban Digital Twin	<p>The UDT is much more than just a 3D city model, but often this together with GIS data is the starting point for the urban digital twin. The basis of the UDT is formed by geospatial data in the form of the geospatial DT.</p> <p>DT of a city reflects the real world, with all the streets, squares, trees and houses, but also with all other facilities that make a city what it really is, such as parks, street lighting, public transport or playgrounds. It takes more than static (and therefore always outdated) information, only through the integration of real-time data can a GIS become a DT of a city.</p> <p>The DT hereby acts as a kind of hub into which all relevant and available information is included and analyzed.</p> <p>A geospatial digital twin hereby acts as the base layer of an urban digital twin and provides the spatial context for all other spatial data (Bacher, 2022).</p>
Future City, Digital Twinning and the Urban Realm: A Systematic Literature Review.	Review article	2022	City Digital Twin	A digital city is an interconnected network of city elements that function as a system. For this system to be “alive”, it requires novel applications that establish a real-time connection between the physical and digital environment. Digital twinning is one application that initiates a digital replica of the physical urban realm and generates a real-time flow of information between the physical and digital environments (Saeed et al., 2022).
Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modeling integration.	Review article	2022	Urban Digital Twin and City Digital Twin	A combination of GIS and BIM technologies could provide a core technology for the UDT to support sustainable smart city design (Xia et al., 2022).

Exploring digital twin adaptation to the urban environment: comparison with CIM to avoid silo-based approaches.	Research article	2022	Digital Twin at the City Scale	A DT requires the creation (or re-use) of a digital model which represents all the constituents of its physical twin and contains information related to its entire life cycle. Different forms of data gravitate bidirectionally between physical and virtual entities. These data are delivered in real time by sensors to the virtual twin to be processed to establish knowledge bases, providing one of the added values associated with DT. It must be able to perform various analyses, simulations, and predictions to achieve some decision making and optimization (Adeline et al., 2022).
DUET: A Framework for Building Interoperable and Trusted Digital Twins of Smart Cities.	Research article	2022	City Digital Twin and Urban Digital Twin	A DT is a computer replica of an operational, real-world counterpart. A DT can provide insights into the dynamics of a physical element being mirrored, its current and future states, including how they are impacted by internal drivers and external forces. True or advanced DTs, as some like to point out, are reportedly those that have an Artificial Intelligence (AI) component, which allows them not only to improve decision making but to start making better decisions themselves (Raes et al., 2021).
Digital Twin for Urban Planning in the Green Deal Era: A State of the Art and Future Perspectives.	Research article	2022	City/Urban Digital Twin	a city/urban DT is a realistic digital representation of the system of anthropic-infrastructure elements and, less often, of the physical naturalistic system that presents some invariable characteristics: scalability, predictability (simulation algorithms), integration (IoT sensors, data update and local knowledge), cooperation and accessibility (downloading/uploading data) (Caprari, 2022).
A Geospatial Platform to Manage Large-Scale Individual Mobility for an Urban Digital Twin Platform.	Research article	2022	Urban Digital Twin	A UDT is a digital model of a city and consists of physical assets and multimodal sensor data. Using real data in urban planning can lead to better decision-making that is efficient in terms of cost and operation and allows better management of problems related to urbanization. A UDT platform should provide geospatial data that can be stored, managed, analyzed, and visualized in three dimensions by reproducing various viewpoints (Lee et al., 2022).
3D city model as a first step towards digital twin of Sofia City.	Research article	2021	City Digital Twin	City DT aims at developing a platform for designing, testing, applying, and servicing the entire lifecycle of the urban environment. The core of the platform is a semantically enriched 3D model of the city. Simulation, analytical and visualization tools will be developed on top of it enabling the basic idea of the digital twin – design, test and build first digitally (Dimitrov and Petrova-Antonova, 2021).

A Socio-Technical Perspective on Urban Analytics: The Case of City-Scale Digital Twins.	Research Article	2021	City Digital Twins	City-Scale DTs (CDTs) are digital representations, or “virtual replicas” of cities that can be used as simulation and management environments to develop scenarios in response to policy problems. In other words, CDTs are realistic digital representations of cities (including their assets, processes, and systems) that aid decision-making aimed at delivering city-level outcomes (urban planning, management, and associated services) and provide improved insights for decision-making (Nochta et al., 2021).
Cyber-Physical Systems Improving Building Energy Management: Digital Twin and Artificial Intelligence.	Research article	2021	City Digital Twin	City DTs as a digital replica of a physical asset, collecting information from sensors, drones, or other sensitive IoT devices, applying advanced analytics, machine learning (ML), and AI obtaining real-time processed data about the lifecycle process of physical assets. DT ecosystems are related to three main entities: a physical object, its virtual replica, and the connection between them in terms of collecting and connecting real-time information. Such a digital ecosystem can effectively contribute to the lifecycle management of both vertical and horizontal systems, to store, manage and process big data about the urban environment in a three-dimensional data model as a structured information system connected to the physical (Agostinelli et al., 2021).
Digital Twins for Cities – A State of the Art Review.	Review paper	2020	Digital Twin for cities and city-scale DT	A DT of a city is based on a data model (e.g., CityGML) and enables both data analysis, i.e., calculations operating directly on data provided by the data model with mathematical models (e.g., continuum models or agent-based models) and solving the models (simulation) to generate new data that may form the basis for extended data analysis (Ketzler et al., 2020).
Digital Twin of City: Concept Overview digital twin of a city.	Conference proceedings	2020	Digital Twin of a City and City Digital Twin	The DT of a city is a system of interconnected digital twins, representing certain aspects of the functioning and development of the urban environment. These DTs support fine-tuning and synchronization with the real state of urban infrastructure through data from various sources in real-time. The DT of the city is an extremely complex, integrated solution, the development of which can and should be implemented in stages, through evolutionary development and integration of specific solutions aimed at solving the most urgent (“point”) problems (Ivanov et al., 2020).
The digital twin of the City of Zurich for Urban planning.	Research article	2020	Digital Twin of the City	The DT means a consistent enrichment of the 3D spatial data inventory and, in addition to the modelling and description of the data (metadata), a lifecycle management of the individual components as well as the entire data inventory. The 3D spatial data are the basis for linking

				further spatial data or other data (Schrotter and Hürzeler, 2020).
Digital geoTwin Vienna: Towards a Digital Twin City as Geodata Hub.	Research article	2020	Digital Twin City and Digital GeoTwin	a Digital geoTwin is a virtual, semantic 3D replica of all elements and objects of the city. Digital twins are an upcoming concept of digitizing elements, processes and systems of physical entities in order to create living digital simulation models as collaborative platform for many disciplines (Lehner and Dorffner, 2020).
Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg.	Research article	2020	Urban Digital Twin	An UDT is not the exact copy of reality, but a sophisticated abstraction of ibidem. This results from a classical dilemma in the field of modeling, as models always have a certain level of abstraction. An UDT can be best characterized as a container for models, data, and simulations. Beyond these challenges, it has great potential to support scenario development processes and testing of these at all scales (Dembski et al., 2020).
A systematic review of a digital twin city: A new pattern of urban governance toward smart cities.	Research paper	2021	Digital Twin City	The DT refers to the state of mutual symbiosis between digital entities and physical entities. DT technology is a technology that integrates data, models, and physical entities. DT refer to the mapping collection of entities in the digital world. A DTC collects digital twins of the entities of a city through digital twin technologies (Deng et al., 2021).
Digital Twins of cities and evasive futures.	Book chapter	2020	City Digital Twin	CDTs are emerging from the fusion of geographic information systems (GIS) and building information modeling (BIM) data of buildings to form digital replicas at a regional scale. The city digital twin has resulted from a technological convergence, which results from a “stacking” of technologies (Cureton and Dunn, 2021).
Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus.	Research Article	2019	City Digital Twins	In the AEC/FM sector, a DT of a city, for instance, would be built on a hierarchical architecture and include a network of sub-DTs (e.g., building DTs). For the purposes of this study, a DT refers to “a dynamic digital replica of physical assets, processes and systems through involving internet of things (IoT) devices and information feedback from citizens”. Dynamic city DTs integrate their sub-DTs and intelligent functions (e.g., AI, machine learning, and data analytics, among others) to create digital models (e.g., simulations) that are able to learn and update from multiple sources and to represent and predict the current and future condition of their physical counterparts correspondingly and timely (Lu et al., 2019).
Smart city digital twin.	Conference proceedings	2017	Smart City Digital Twin	The digital replica of the city is progressively informed by the real city through real-time spatiotemporal data from infrastructure and human systems. The DT city, cognizant of the city’s infrastructure performance, human

dynamics, their interdependencies and interoperability, and their fluctuations in time and space, is progressively able to anticipate changes of state in the systems and predict possible future behaviors. The predictive conduct of the DTC relies on the real-time and aggregated historical performance of the human-infrastructure systems. Additionally, irrespective of the current state of the city, a DTC can simulate what-if scenarios in the system and anticipate emergent behavior. This helps analysts understand how cities equipped with smart technologies will likely perform under various economic, environmental, and social conditions, and identify the drivers of possible disruptions. Such understanding is critical in assessing whether or not smart growth strategies are effective, minimizing the gap between the smart utopia and smart reality (Mohammadi and Taylor, 2017).

2. References

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