State of the Art of Urban Digital Twin Platforms

Angelo Martella(✉), Amro Issam Hamed Attia Ramadan, Cristian Martella, Mauro Patano, and Antonella Longo

DataLab, Department of Engineering for Innovation, University of Salento, via per Monteroni, 73100 Lecce, Italy
https://www.unisalento.it

Abstract. Urban Digital Twin platforms are rapidly emerging as a powerful tool for urban planning and development, enabling city planners, architects, and other stakeholders to create virtual versions of real-world cities with extensive data on everything from traffic patterns to energy consumption. This work explores the present and future of Urban Digital Twin platforms, highlighting their potential to support a wide range of users in making informed decisions related to urban development challenges, by simulating the behaviour of cities and their residents using real-world data and advanced modeling approaches. The survey presented in this article examines a selection of state-of-the-art Urban Digital Twin platforms and discusses some of their key features, highlighting the differences in relation with their use cases. Furthermore, this work addresses some of the emerging trends and technologies in the field of Urban Digital Twins. Additionally, it considers how these developments might shape the future of urban planning and development by enabling more accurate predictions about how cities will evolve over time.

Keywords: digital twin · urban digital twin platform · smart city

1 Introduction

Digital twins are actually used in a variety of industries, including manufacturing, healthcare, and transportation, and consist of virtual replicas of physical objects or systems meant to simulate their behaviour in real-world conditions. Digital Twin models are at the basis of AR visualization, 3D Immersive Worlds, and integration with AR/VR Platforms. AR Visualization involves overlaying virtual information onto the physical environment, allowing users to interact with virtual objects and data in a more natural and intuitive way. 3D Immersive Worlds involve simulating urban environments in 3D, providing a highly interactive and engaging way to explore and experience urban spaces. Integration with AR/VR Platforms allows developers to create interactive and realistic simulations that enable users to explore and interact with urban spaces.

A Urban Digital Twin (UDT) represents a specialized digital twin which focuses on modeling and simulating urban environments. UDT platforms are a

L. T. De Paolis et al. (Eds.): XR Salento 2023, LNCS 14218, pp. 299–317, 2023.
https://doi.org/10.1007/978-3-031-43401-3_20

cornerstone in the development of smart cities, as they provide essential tools to allow planners to model and simulate different scenarios before implementing them in the real-world, fostering sustainable, resilient, and livable developments. Given the current scenario, a multitude of DT tools and platforms have been deployed and are tailored to the specific goals and tasks related to real-world use cases they are meant to address. Yet, such platforms exhibit various levels of industrial and technological maturity and may not be designed to address the recent needs for interoperability. Thus, this work focuses on the data acquisition layer of UDT platforms, since this is the core aspect to foster the creation of real Digital Twins of urban elements, at different layers and scopes. The requirements for successful creation of an integration layer made from a combination of all the platforms are investigated. Therefore, in this work some UDT platforms will be analyzed and compared based on their common features and aims. Finally, it is worth noting that at the moment there not exist full-fledged UDT platforms, but only limited approaches that are being maintained and are integrating new features over time. After Sect. 1 that introduces this work, the background is described in Sect. 2. Next, the surveyed platforms are presented in Sect. 3, whilst Sect. 4 discusses the survey criteria, how the platforms are located in the resulting framework and the results of the survey. Finally, in Sect. 5 the conclusions are summarized.

2 Background

Before providing a set of DT definitions, it is necessary to introduce and distinguish the DT concept from other similar ones like digital shadow, and digital model. The terms digital twin, digital shadow, and digital model are closely related, although they present precise and specific characteristics.

2.1 Digital Model

A digital model is a 3D streamlined representation of a physical object or system used for analysis, simulation, and optimization. Although it may not include all of the physical system's components or details, it can still represent a useful tool for different purposes, like testing and improving performance. It is important to highlight that a digital model consists of a mere real-world object representation, without any automatic data stream mechanisms between the real and digital models (as shown in Fig. 1 [19]). Therefore, whether necessary, this synchronization mechanism must be performed manually, regardless the level of accuracy of the model. The digital models have been discussed in several research works [23,32,40].

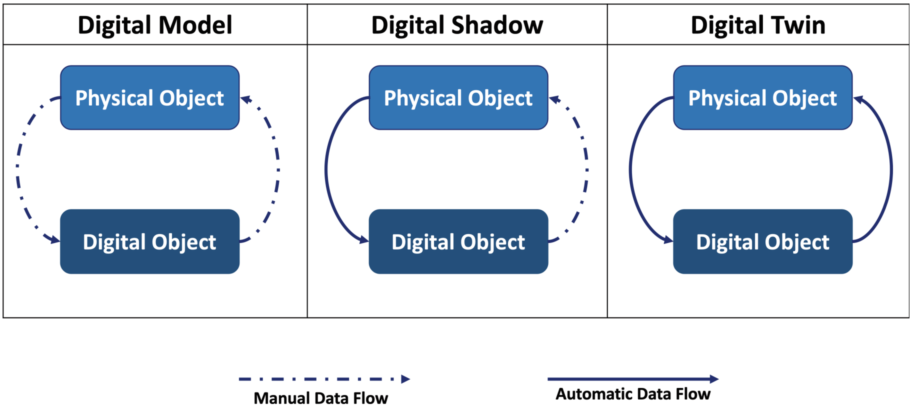

Fig. 1. Digital model, shadow and twin.

2.2 Digital Shadow

A Digital Shadow (DS) can be considered as a digital model that in addition provides an automated and uni-directional data flow from the physical model to the corresponding digital object (refer to Fig. 1). In this way, the state of the digital model always reflects its physical counterpart's. Vice versa, data synchronization between the digital model and the corresponding physical model is not realized.

2.3 Digital Twin

A virtual replica of a physical object, process, or system is referred to as a digital twin. Unlike the digital shadow, a DT provides a data synchronization mechanism with the corresponding physical one as well (as depicted in Fig. 1). A DT can be considered as a real-time view of its physical counterpart. For this reason, it can also be used to simulate, test, and optimize the physical system's performance.

After introducing these concepts of digital twin, digital shadow, and digital model, a DT definition can be provided. DT is yet to be a mature technology and considering that it is continuously evolving, many definitions exist in literature [11,20,21,34].

According to a recent definition provided in [11], a DT consists of a live digital coupling between the state of a physical asset or process and its virtual representation with a functional output. This definition is the most relevant for the purposes of this paper with respect to the characteristics and functions that a DT management platform must provide.

Similarly to what happens in real life, any asset of the real-world takes part to a specific environment with which the same asset mutually interacts. This prerogative of the real-world can be replicated to the corresponding scenario of DTs, where each DT corresponds to its physical counterpart. As a result, any

DT of this parallel context can be seen as located into a hierarchical structure that is meant to match the organization of the real-world context. The resulting hierarchical organization will be obtained by properly implementing and adding each DT of any physical asset of interest, at different scopes and levels. By mutually interconnecting two DTs, it is possible to realize a pair of real and digital assets with the aim of propagating the changes of state between them. DTs that belong to a specific hierarchical level can interact with upper level virtual assets, forming a complex network that fosters bidirectional interactions, with real-time data exchange. A possible organization of this network may include the following hierarchical levels: component, asset, system, system of systems.

2.4 Urban Digital Twin

In [19], an interesting review of the enabling technologies, challenges and ongoing research for Digital Twins is proposed. The review provides a discussion that is organized into three research areas related to manufacturing, healthcare, and especially smart cities. In this last area, the DTs that make up the basic technological infrastructure take the name of Urban Digital Twins (UDT). These kinds of DTs are sophisticated data models allowing for collaborative processes. Various studies regarding UDTs exist in literature [13,18,33]. A further review of the DT terminology for cities are borrowed from the corresponding similarities and relationships typical of the more well-known context of the 3D city models [24]. This review also includes details about how to implement DTs for cities, along with the application areas and potential challenges for their future development.

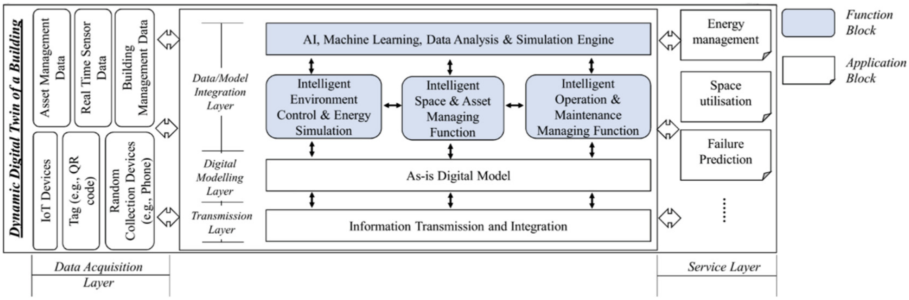

Fig. 2. Architecture of a Digital Twin.

An innovative vision of DT provides to express it as its informative structure, eventually obtained by also integrating the corresponding sub-DTs hierarchy. Indeed, the idea to consider a urban DT as a hierarchical structure of sub-DTs was already introduced in [27], where an architecture of UDTs is proposed at various levels. Considering a city as an asset that integrates different sub-assets (buildings, infrastructure, and people), the corresponding city DT can be obtain by combining and integrating the sub-UDTs related to each sub-asset. In this way, it is possible to organize a hierarchical architecture of UDTs, by replicating the structure of each sub-UDT. Such an architecture can be considered for presenting the logical composition of a generic DT. Specifically, the extract relating to the UDT of a building can be considered for the following discussion and is reported in Fig. 2 [27]. At the moment, the implementation of such an architecture is yet to be fully technologically supported, due to its high complexity. For this reason, it can be considered as a challenging frontier for future research efforts. The proposed architecture encompasses five layers: (1) data acquisition layer, (2) transmission layer, (3) digital modeling layer, (4) data/model integration layer, and (5) service layer. For the needs of this paper, the attention must be focused on the data acquisition layer. A detailed discussion about this layer is proposed in the following.

Data Acquisition Layer. Considering the heterogeneity and large volume of data a DT must deal with, the data acquisition represents the most complex and challenging layer of a DT architecture. Indeed, this layer must provide the necessary support to a wide range of types, formats, sources, and content of data. Considering the hierarchical architecture of DTs, each sub-DT refers to its necessary data/information/models when following up a query from the parent DT. Data collection techniques must include contact-less data collection (radio-frequency identification (RFID), and image-based techniques), distributed sensor systems, wireless communication, and mobile access (e.g., WiFi environment). Observing the image of the DT architecture, the data acquisition layer must implement specific interactions with (1) IoT devices, (2) Asset Management Data, (3) Tag, (4) Real-Time Sensor Data, (5) Random Collection Devices, and (6) Building Management Data. Moreover, the data acquisition layer must support real-time data collection, effective data management, and integration [22,28].

Urban Digital Twin Platforms. Urban Digital Twin platforms are software tools that enable the creation and management of virtual replicas of urban environments. These platforms typically include a range of features designed to support urban planning and development, including tools for visualizing and analyzing data, as well as simulation capabilities that allow users to test different scenarios and interventions. Referring to the definition of DT provided in [11], it is possible to identify the key features to consider for its design and implementation. These features include the following: (1) Take care of receiving, formatting and processing operational status data, (2) Provide a digital model representing the salient properties, behaviour and functioning of the physical twin during its twinned life cycle, and (3) Provide an interface that allows humans or systems to output and interact with the DTs. In addition to the previous key features, some optional ones should be considered, such as the following: (1) Provide data storage and/or retrieval, (2) Include a toolkit that allows the analysis, simulation and visualization of the physical twin at appropriate levels of fidelity and temporal granularity, and (3) Provide tools to enable data about the physical entity and its environment to be curated.

In literature, various examples of DT platforms exist [10,12,17,25,30,31,40,42] within the most various contexts.

3 Urban Digital Twin Platforms Survey

Given the above challenges (from the above section) and the critical nature of the procedure of creating DT models, many tools have been developed with the objective of creating Digital Twins by both the business world and the academic community to meet the needs of specific applications.

3.1 Survey Settings

Before giving a deep insight of the survey proposed in this paper, it is fundamental to highlight its main goal and characteristics, along with some information about how it was been organized. After a preliminary scouting of the most relevant DT platforms available on the market, the target solutions to consider for the survey have been selected. It is important to underline that the scouting is not meant to be considered as exhaustive, being the offer of DT platforms very large and in continuous ferment. The resulting list of DT platforms was then filtered by considering only the solutions are completely open-source or that at least provide a free trial period. At the best of our knowledge, the filtered list includes the most relevant DT platforms.

The goal of the proposed survey is to perform a comparative analysis of these platforms, by evaluating the main characteristics and features their data acquisition layer offers. The result obtained from the present survey aims at supporting various stakeholders in selecting the most flexible and suitable UDT platform, according to specific purposes and needs. Again, only solutions that are open-source or that offer a free trial period participate in the starting list of the UDT platforms. A more detailed discussion about both the reference criteria and the accomplished comparative analysis for the proposed survey is reported in the following.

Platform Features. The features that are crucial for selecting the UDT platforms to consider for the present survey must include the following.

Urban Simulation Support. It enables the modeling and analysis of urban environments, as well as the effects produced by various urban policies and interventions.

Digital Twin Modeling. Each platform can generate digital twin models of urban environments. These virtual representations of the physical world can be used for a variety of purposes such as urban planning, asset management, and emergency management.

3D Visualization. 3D visualizations of urban environments are fundamental for a UDT platform. Users can view and interact with urban spaces in a more intuitive and immersive manner, thanks to the visualizations this feature makes available.

Geospatial Analysis. A UDT platform makes available its models using geospatial data and analysis. Data on the physical environment, such as building footprints and street layouts, can be eventually integrated. Additional data can be related to population density and land use, which can be used to highlight social and economic factors.

Open-Source and Freely Accessible Platforms. The prerogative of a DT platform to be open-source or to provide a free trial period makes it possible to directly install, configure and evaluate it. This allows developers and users to tailor the platforms to their specific needs and use cases. In this way, it is possible to experience the platform's main features and investigate its capabilities and constraints.

3.2 Platforms Scouting

Before proceeding with the UDT platform evaluation, a scouting in literature has been performed to identify the majority solutions the market offers. Concerning commercial platforms, a valid contribution in this regard can be found in [35]. Regarding non commercial solutions, a more specific scouting in literature has been carried out, identifying these additional UDT platforms: TU Delft project [26], UrbanSIM [43], Digital Twin Cities Center (DTCC) [24], and ArcGIS City Engine [41]. A brief description of each DT platforms resulted from the scouting in literature is provided in the following paragraphs. The appearance order in which the DT platforms are introduced is strictly alphabetical.

Akselos. [8] is a commercial platform for engineering simulation based on finite-element analysis with a reduced basis. The platform can be used to create digital twins of energy infrastructures in order to enhance their design, maintenance, dependability, and lifetime.

Altair. [3] provides a commercial digital twin platform that connects various development disciplines. It optimizes performance by using CAE, IoT, machine learning, and data intelligence.

ArcGIS City Engine. [9] is the only solution that provides a free trial period among the DT platforms resulting from scouting. It is a powerful 3D modeling software for cities that enables users to quickly and easily create 3D models of cities and buildings.

Blockbax. [1] is a commercially available platform that generates a digital twin of any asset in order to generate real-time insights and reduce problems. It is the most efficient and user-friendly method for contextualizing IoT data and creating a dynamic virtual replica of any asset.

Open Cities Planner. [4] is a commercial urban planning and visualization solution that enables users to design and visualize digital cities, nonetheless, it enables the 3D visualization of CAD, BIM, and GIS data.

Digital Twin Builder. [2] is a commercial ScaleOut software that aims at enabling developers to create digital twin models of data sources and deploy them to ScaleOut. It is mainly a toolkit that enables developers to define object-oriented state information and analytics code for tracking telemetry. Its APIs allow developers to create digital twin models that incorporate application-specific algorithms and state data describing either physical or virtual objects.

Digital Twin Cities Center. [15] is an open-source solution that provides a city planning and management software platform that enables the creation of DT model for city's infrastructures and services. The platform can simulate different scenarios and can forecast the effects of changes on the corresponding city's environment.

Predix. [5] is a commercial tool provided by General Electric for creating and managing digital twins and their associated analytic models, making it easier for businesses to leverage the benefits of digital twins.

IoT Production Monitoring. [14] is a commercial IoT Digital Twin Implementation provided by Oracle that permits a data analyst to create a model based on external observation of a machine and to develop multiple models based on the user's requirements. Oracle IoT Digital Twin Simulator enables users to create simulated devices for their environment without the need to connect or configure hardware.

Seebo [6] is commercial platform delivered as Software-as-a-Service (SaaS) for Industry 4.0 that provides prepackaged solutions for Condition Monitoring, Predictive Maintenance, Digital Twin, and Smart Manufacturing. The Seebo Platform incorporates Digital Twin technology, which has been in use for some time to simulate conditions and predict outcomes. The Digital Twin methodology entails the creation of a virtual copy of a physical product or process, which can be used to monitor and optimize performance.

TU Delft Project. [7] is an open-source platform developed by The Delft University of Technology in the Netherlands that provides detailed 3D models of buildings and infrastructures in a country level scope, based on real-world data. The platform can be used to generate detailed simulations and visualizations of urban areas, providing a free and easy-to-use tool to aid in urban planning and decision-making tasks.

UrbanSIM. [39] is an open-source and AI-powered platform for sustainable urban planning and development that reduces the time, effort, and cost of planning urban development and infrastructure projects while increasing confidence that desired outcomes will be achieved. It is mainly used in the real-estate sector.

The resulting list of DT platforms obtained from the scouting was then filtered in order to meet the survey criteria previously introduced. These criteria are related to (1) the prerogative of a platform to be open (not commercial), and (2) the prerogative of a platform to foster the development of a city DT. By considering these requirements, the following considerations for identifying the survey target platforms can be done: (1) Akselos, Altair, Blockbax, Digital Twin Builder, IoT Production Monitoring, Open cities planner, Predix, and Seebo must be excluded being commercial solutions. (2) UrbanSIM is not accounted for in the present survey based on the second prerogative. Therefore, the remaining UDT platforms to consider for the subsequent evaluation are: ArcGIS CityEngine, DTCC and TU Delft Project.

3.3 Platforms Discussion

For each of the UDT platforms resulting from the scouting, a more detailed discussion and a comparative analysis are provided in the following, with a particular focus on the corresponding data acquisition layer.

ArcGIS City Engine. ArcGIS City Engine is a powerful 3D modeling software for cities that enables users to quickly and easily create 3D models of cities and buildings. The platform proposes features that can be addressed to users with different technical skills, including architects, urban planners, and GIS professionals.

ArcGIS City Engine supports the import of various data formats from a variety of sources, such as GIS data, CAD files, and aerial imagery. Furthermore, the platform includes a library of pre-built 3D models and textures in order to make available a quick and simple city creation.

The platform provides specific functionalities for designing urban features, such as streets, and sidewalks, along with powerful visualization and analysis tools. ArcGIS City Engine enables simulations for various scenarios and can highlight and analyse the impact of supposed changes within urban context. Moreover, the platform can be fully integrated to other ArcGIS products, such as ArcGIS Online.

The platform is capable of producing 3D models related to entire cities, but also to smaller areas such as neighborhoods or individual buildings, by using a simple procedure. In addition, this procedure offers the possibility to easily change the look and feel of their models by using different textures, lighting, and other visual effects.

The software supports terrain creation and editing tools, such as hills and valleys, and can export the resulting model into a variety of formats, including 3D PDF, OBJ, Collada (DEA), DXF as well as VOB for Vue.

The platform allows to refer to a scripting language in order to implement specific custom tasks. This is one of the most interesting features for automating repetitive tasks and creating custom workflows that can enable collaboration and sharing operations between users.

ArcGIS City Engine is a proprietary, closed-source, non-free system marketed by ESRI, however, the platform offers a free trial that gives users the chance to test the platform and understand its characteristics. It is strongly integrated with other software products, mainly of the GIS type, from ESRI to create interactive and immersive 3D environments to be used in other platforms such as ArcGIS Urban Suite. It uses Autodesk FBX to interact with game engines and VFX tools. It exports to Alembic or even Pixar's Renderman. 3D object layers are exported as scene layer package (SLPK) files. To the extent of our knowledge, it is a solid modeler oriented toward urban architecture. For this reason, it offers integration modules towards the main commercial 3D modeling software: Puma is a plug-in for Rhino and Grasshopper, Palladio is a plug-in for SideFX Houdini, Serlio is a plug-in for Autodesk Maya, Vitruvius is a plug-in for Unreal Engine.

Digital Twin Cities Center. The Digital Twin Cities Center (DTCC) engine is a city planning and management software platform that makes possible to create the DT model of a city's infrastructure and services. The platform can simulate different scenarios and can forecast the effects of changes on the corresponding city's environment.

The engine behind the DTCC platform can assist decision-makers in making data-driven decisions aimed to improve the city's sustainability, resilience, and livability. Indeed, the DTCC platform can support the gathering of real-time data from a variety of sources, including sensors, IoT devices, and social media. These data are then used to track the city's performance and identify areas for improvement.

The engine of the DTCC can contribute to emergency response and disaster management by providing to the decision-makers a centralized dashboard for monitoring the city's operations and performance.

The platform is highly customizable and can be tailored to support each city's specific needs and is compatible with a wide range of existing city management systems.

Using the DTCC platform, citizens and stakeholders can be involved in the planning and management process. Specifically, citizens can provide feedback and suggestions for city improvements by referring to the platform's user-friendly interface.

The DTCC platform allows to improve the communication and collaboration between decision-makers, stakeholders, and citizens. At the same time, the DTCC platform can support the design and development of urban projects. Proceeding in this way, decision-makers can use the platform to visualize and test various design scenarios before applying changes to the real-world, saving time and money. In [29], the authors propose the virtual copies creation of physical systems, specifically digital twins in cities. They highlight on using digital twins for a variety of purposes, including multi-physics simulations, what-if scenarios, and life-cycle analysis. The authors address the problem of creating 3D models of any urban environment at Level of Detail 1 (LoD1) in the form of both surface and volume meshes. The mesh is generated using publicly available datasets from

Sweden's Mapping, Cadastral, and Land Registration. In general, the authors hope to provide a solution for creating 3D models of urban environments that can be used for a variety of purposes, such as simulations and analysis. The DTCC platform can be particularly suitable in creating LoD1 models from publicly available datasets.

A final aspect to highlight corresponds to the creation of 3D models of historical cities, as well as to simulate the effects of historical events on urban environments.

The basis for building a digital twin of a city is the generation of a 3D city model, often represented as a mesh. The system developed by DTCC is based on an algorithm and its implementation for automatic, efficient and robust mesh generation for large-scale city modeling and simulation. The mesh generation algorithm uses a limited number of parameters initially loaded from a JSON format file and two geographic data files, in particular 2D cadastral maps (building footprints) and 3D point clouds obtained from LIDAR-type aerial surveying. The algorithm generates LoD1.2 city models in the form of triangular surface meshes, suitable for visualization, and high-quality tetrahedral volume meshes, suitable for simulation. In particular, DTCC Builder is capable of generating large-scale conformal tetrahedral volume meshes of cities suitable for finite element simulation (FEM). The long-term goal is to build a system capable of generating a three-dimensional meshed digital twin of city volume in (near) real-time in LoD2.x.

The DTCC system is completely open-source and is developed in a modular way using both Python and C++ in a Unix environment.

TU Delft Project. The Delft University of Technology in the Netherlands developed a platform that provides detailed 3D models of buildings and infrastructures in a country level scope, based on real-world data. Target end users are urban planners, architects, and other city development professionals.

The platform includes buildings information such as function, type of infrastructure (i.e. road, bridge, building, and so forth), location, geometry, and height. The primary source of such information is the Dutch national address and building database, which is constantly kept up to date with new data.

The project encompasses a number of packages that are tailored to address specific use cases [7,36], spanning from 3D representation of cities in country-wide scenarios, with 3D BAG [37], to solar irradiance simulations with Solar3Dcity [38].

The platform can be accessed via a web interface or an API and it is available with an open license. Thus, it has been used in a variety of applications, including flood risk assessment and building energy performance assessments.

Regular updates enrich the platform with new features and capabilities, allowing it to be an important tool for urban planning and development in the Netherlands, with the potential to be used and applied in other countries as well. The Dutch Kadaster and the 3D Geoinformation research group at TU Delft are actively collaborating [16] to create and disseminate 3D city models of the entire Netherlands. The workflow includes automated reconstruction from existing countrywide data, maintenance of 3D data in a unified database, quality control, and making the data available in an open 3D standard. The 3D model is made up of three data products: 3D Basisbestand Volledig, 3D Basisbestand Gebouwen, and building height statistics 3D Hoogtestatistieken Gebouwen.

The model is regularly updated based on new versions of BAG and BGT data, as well as up-to-date height data obtained from aerial images. The data is aligned on a grid for accuracy and stored with mm precision. The 3D data is reconstructed using another open-source model, City3D, and the 3D BAG service, which generates several reference heights per building. The data is disseminated using CityJSON, CityGML, GeoPackage, Wavefront OBJ, PostgreSQL, WMS, WFS exchange formats. The platform also tackles the challenges related to the reconstruction of underground parts of buildings, as well as the workflow from reconstruction to 3D data dissemination.

The ultimate goal is to provide applications with standardized, future-proof 3D topographic data. The Kadaster is working on a workflow to generate and distribute a 3D topographic dataset covering the entire Netherlands. The workflow is scheduled to be re-run every year with new input data. Based on feedback, the Kadaster intends to improve the workflow and research new applications that require 3D data. They also intend to investigate how to make the best use of updated point clouds, as well as integrate and align 3D city models from other governments. Future work will concentrate on generating a single aggregated quality value per building, as well as developing a 3D viewer and a download service.

3D BAG is built by combining two open datasets:

- The Building and Address Register is the most detailed and openly available data set on buildings and addresses in the Netherlands. It contains information about each address in a building, such as its current use, date of construction, or registration status. The data set is regularly updated as new buildings are registered, constructed or demolished.
- The National Height Model of the Netherlands is the openly available elevation dataset of the Netherlands. It is captured by aerial laser scanning (LIDAR), with an average dot density of 8 dots per square meter for the current version.

Three levels of detail are available: LoD1.2, LoD1.3 and LoD2.2. In addition to the 3D models, 2D projections of the roof surfaces are provided with the relative height references.

4 Survey Discussion

In this section, an overview of the criteria used to evaluate Urban Digital Twin platforms is provided, along with a description of how the surveyed platforms are located in the resulting framework, portraying the results of the survey.

4.1 Survey Criteria

Evaluation Criteria. The UDT platforms featured in this work are described according to a set of characteristics related to their input, output, and the simulations they perform. Further information is provided about the level of detail of represented objects and the supported data formats. An additional important feature to consider for evaluating a UDT platform regards the integration with AR/VR platforms. Considering that this paper aims to be a first analysis, this aspect can be faced and discussed within its already planned future evolution. Before discussing the survey results, it is fundamental to anticipate that none of the UDT platforms included in the survey is capable of supporting data streams from sensors and of implementing a bi-directional data flow between a physical asset and the corresponding digital replica. Thus, these are not to be intended as full-fledged DTs, but rather as tools to enable and foster the future development of DT platforms. Each of the features considered for the survey is discussed in the following paragraphs.

Users. UDT platforms are generally tailored to help users in performing their activities. Considering that the user base of a UDT platform can be wide and varied, the prerogative of a platform to be supportive of more or fewer user categories is a decisive and important factor for its evaluation. The categories of users that have been considered in this context are: policymakers, researchers, developers, city planners, architects, and infrastructure planners.

Input. The most common input data a UDT platform must support are aerial photography, LIDAR point clouds, and cadastral data. In this way, it is possible to reconstruct accurate 3D models of buildings, infrastructures, and other city assets of interest.

Output. For evaluating each UDT platform, the output we have considered includes 3D City Model, Solar irradiance, Solar shadow, Citizen interaction, Future city development, Digital infrastructure for IoT services, and Energy demand. These outputs are the reference results obtained within the common use cases that have been developed in most research efforts.

Object Representation. Concerning the object representation, several aspects were taken into account, starting with the level of detail (LoD) [26] of the model, the representation of natural elements like trees, the representation of building elements such as openings, roofs, doors, and windows, and finally, the representation of infrastructure elements like road networks.

Simulations. The platforms must enable the users to perform various simulations, leveraging high-performance computing and AI predictive tools to deploy realistic and accurate what-if analyses. For the purposes of this work, the aspects that are considered relevant are supporting models for geotechnical and future development, solar irradiance and shadowing, rain and sea level rise, wind, air quality, and noise models.

Supported Data Formats. As discussed in Sect. 2.4, interoperability between DT platforms can be achieved through open and standard data formats. Being compliant with these requirements, JSON, CityGML, IFC and shape files have been considered for performing the platform evaluation.

4.2 Platforms Comparison

As reported in Table 1, all platforms are suitable for a wide range of users, including policymakers, researchers, developers, city planners, architects, and infrastructure planners. Regarding the inputs, ArcGIS CityEngine and TU Delft Project do not support aerial photography.

In this context, all the platforms considered can ingest LIDAR-generated point clouds. Additionally, DTCC and ArcGIS CityEngine also support cadastral data as input.

Shifting the attention to the output side, the focus is on the type of models and simulations that the platforms can create. In this scenario, it was found that all provide a 3D city model.

DTCC and TU Delft Project support the simulation of solar irradiance and solar shadow, whereas ArcGIS CityEngine does not explicitly mention it. Moreover, DTCC supports digital infrastructure for IoT services and encourages citizen interaction with the platform. These characteristics have not been found in the other platforms. Furthermore, DTCC provides tools to assess and model the energy demand of cities and perform geotechnical and future development of cities, while ArcGIS CityEngine can perform rain and sea rise-related simulations.
To the extent of our knowledge air quality and noise, simulations could be done by Tu Delft with the help of additional tools and platforms.
Regarding the detail level of entities represented in each platform's virtual environment, it was found that DTCC represents objects at LoD 1, whereas ArcGIS CityEngine is designed to provide more advanced LoD 3 objects. Additionally, TU Delft Project can manage LoD 1 and LoD 2 entities for different objects.

Trees and other natural elements are well targeted by DTCC and TU Delft Project, which mention tree representation using terrain mesh and LIDAR, whereas ArcGIS CityEngine does not mention explicitly any kind of representation in this regard.
Doors and windows are represented only by TU Delft Project as a 3D polyline. Road network is represented by two platforms, DTCC and TU Delft Project as a terrain mesh.

As for the formats supported by the platforms, the goal is to assess the most common types that can be leveraged to achieve interoperability between different platforms and systems, such as JSON, CityGML, IFC, and Shapefile.

In particular, it was found that Shapefile and CityGML are supported by all considered platforms. TU Delft Project supports all of the file formats, making it a strong option to be considered when it comes to creating 3D models of cities.

Table 1. Comparison between the platforms considered in this work.

		UDT PLATFORMS		
FEATURES		DTCC	ArcGIS CityEngine	TU DELFT Project
Users	Policy makers	✓	✓	✓
	Researchers	✓	✓	✓
	Developers	✓	✓	✓
	City Planners	✓	✓	✓
	Architects	✓	✓	✓
	Infrastructure planners	✓	✓	
Input	Aerial Photography	✓		
	Point clouds (Lidar)	✓	✓	✓
	Cadastral data	✓	✓	
Output	3D City Model	✓	✓	✓
	Solar irradiance	✓		✓
	Solar shadow	✓		✓
	Citizen interaction	✓		
	Future city development			
	Digital infrastructure for IoT services	✓		
	Energy demand	✓		
Object representation	LoD level	LoD 1	LoD 3	LoD 1-2
	Trees	Terrain mesh		3d with Lidar
	Doors/Windows			polyline 3d
	Road network	Terrain mesh		Terrain mesh
Simulations	Wind			
	Air quality			
	Geotechnical/future development	✓		
	Solar shading/irradiance	✓		✓
	Noise			
	Rain/sea level rise		✓	
Supported data formats	JSON			✓
	CityGML	✓	✓	✓
	IFC			✓
	Shapefile	✓	✓	✓

4.3 Final Considerations

Various approaches can be taken into consideration to achieve compatibility and interoperability between the platforms analyzed in this survey. For instance, APIs can be used to enable data sharing and exchange between platforms. Data can also be transformed or converted into a common format that is supported by all platforms.

This survey highlighted the state-of-the-art features provided by the considered UDT platforms. It was found that currently, DTCC is the most mature platform, addressing the largest number user and stakeholder categories and supporting the largest set of input and output types. Yet, it does not provide advanced object representation support as other platforms, e.g. ArcGIS CityEngine and TU Delft Project, do.

Concerning the supported data formats, TU Delft Project is the strongest option, given its support to all the file formats accounted. Nevertheless, it is worth mentioning that the capabilities of all the platforms can be further expanded with additional plugins or through their regular updates.

5 Conclusion and Future Work

Urban Digital Twin platforms have the potential to break through urban planning and management by providing a comprehensive and integrated view of cities. In this paper, after introducing an architecture for UDTs and providing a survey of some UDT development solutions, a comparative analysis restricted to the open-source or free trial UDT platforms is performed. This analysis aims at evaluating for each platform the corresponding features, benefits, and potential applications by focusing on its data acquisition layer.

UDT platforms can support a wide range of users, including policymakers, researchers, developers, city planners, architects, and infrastructure planners, enabling them to perform simulations and make informed decisions in order to address urban development challenges, such as sustainability, resilience, and livability.

Future developments in UDT platforms will play a critical role in addressing the above challenges. Being not sufficiently mature, current UDT platforms are expected to evolve in two distinct directions in the future. The first is towards more advanced modeling methodologies, such as agent-based modeling and machine learning, which can deliver more accurate and realistic simulations of cities and their residents. The second direction is towards improved integration with other technologies, such as Internet of Things devices and cloud computing, which can enhance the capabilities of UDT platforms and distribute the computational requirements across the entire edge-cloud continuum spectrum.

Acknowledgements. This work is partially supported by ICSC-Italian Center on Supercomputing and Italian Research Center on High Performance Computing, Big Data and Quantum Computing, funded by European Union - NextGenerationEU, by CETMA DIHSME and Brindisi Smart City Port.

References

1. Digital Twin – blockbax.com. https://blockbax.com/digital-twin/. Accessed 18 May 2023
2. Digital Twin Builder – scaleoutsoftware.com. https://www.scaleoutsoftware.com/products/digital-twin-builder/. Accessed 18 May 2023
3. One Total Twin - Digital Twin Technology|Altair – altair.com. https://altair.com/one-total-twin. Accessed 18 May 2023
4. OpenCities Planner: Digital Twin Software | Bentley Systems – bentley.com. https://www.bentley.com/software/opencities-planner/#:~:text=What%20is%20Opencities%20Planner%3F%201%20Easily%20Share%20Information,Get%20Started%20Quickly%20with%20this%20Easy-to-use%20Application%20. Accessed 18 May 2023

5. What is Predix Platform?|Predix Edge 2.8.1 Documentation|GE Digital – ge.com. https://www.ge.com/digital/documentation/edge-software/c_what_is_predix_platform.html. Accessed 18 May 2023
6. Seebo industry 4.0 solutions (2022). https://www.solidworks.com/media/seebo-industry-40-solutions. Accessed 18 May 2023
7. 3d geoinformation at tu delft. https://3d.bk.tudelft.nl/. Accessed 18 May 2023
8. Akselos - The Fastest Engineering Simulation Technology – akselos.com. https://akselos.com/. Accessed 18 May 2023
9. arcgis.com. https://desktop.arcgis.com/es/cityengine/. Accessed 18 May 2023
10. Browning, J., et al.: Foundations for a fission battery digital twin. Nuclear Technol. **208**, 1089–1101 (2022). https://doi.org/10.1080/00295450.2021.2011574
11. Catapult, H.: Untangling the requirements of a digital twin. Univ. Sheff. Adv. Manuf. Res. Cent. (AMRC), p. p7 (2021), cited by: 1
12. Clemen, T., et al.: Multi-agent systems and digital twins for smarter cities. In: Proceedings of the 2021 ACM SIGSIM Conference on Principles of Advanced Discrete Simulation, pp. 45–55 (2021)
13. Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., Yamu, C.: Urban digital twins for smart cities and citizens: the case study of Herrenberg, Germany. Sustainability **12**(6), 2307 (2020)
14. Developing Applications with Oracle Internet of Things Cloud Service – docs.oracle.com. https://docs.oracle.com/en/cloud/paas/iot-cloud/iotgs/oracle-iot-digital-twin-implementation.html. Accessed 18 May 2023
15. Dtcc. https://github.com/dtcc-platform/dtcc-core. Accessed 18 May 2023
16. Dukai, B., et al.: Generating, storing, updating and disseminating a countrywide 3D model. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLIV-4/W1-2020, 27–32, September 2020. https://doi.org/10.5194/isprs-archives-xliv-4-w1-2020-27-2020
17. Fan, C., Zhang, C., Yahja, A., Mostafavi, A.: Disaster city digital twin: a vision for integrating artificial and human intelligence for disaster management. Int. J. Inf. Manage. **56**, 102049 (2021). https://doi.org/10.1016/j.ijinfomgt.2019.102049
18. Ferré-Bigorra, J., Casals, M., Gangolells, M.: The adoption of urban digital twins. Cities **131**, 103905 (2022)
19. Fuller, A., Fan, Z., Day, C., Barlow, C.: Digital twin: enabling technologies, challenges and open research. IEEE Access **8**, 108952–108971 (2020). https://doi.org/10.1109/access.2020.2998358
20. Gelernter, D.: Mirror worlds: Or the day software puts the universe in a shoebox... How it will happen and what it will mean. Oxford University Press (1993)
21. Grieves, M., Vickers, J.: Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems. Transdisciplinary perspectives on complex systems: New findings and approaches, pp. 85–113 (2017)
22. Hu, Z.Z., Tian, P.L., Li, S.W., Zhang, J.P.: Bim-based integrated delivery technologies for intelligent mep management in the operation and maintenance phase. Adv. Eng. Softw. **115**, 1–16 (1 2018). https://doi.org/10.1016/j.advengsoft.2017.08.007
23. Huang, X., Huang, P., Huang, T.: Multi-objective optimization of digital management for renewable energies in smart cities. Journal Européen des Systèmes Automatisés **53**(6), 893–902 (2020). https://doi.org/10.18280/jesa.530615
24. Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., Logg, A.: Digital twins for cities: a state of the art review. Built Environ. **46**(4), 547–573 (2020). https://doi.org/10.2148/benv.46.4.547

25. Kunzer, B., Berges, M., Dubrawski, A.: The digital twin landscape at the crossroads of predictive maintenance, machine learning and physics based modeling (6 2022)
26. Lehner, H., Dorffner, L.: Digital geotwin vienna: Towards a digital twin city as geodata hub (2020)
27. Lu, Q., et al.: Developing a dynamic digital twin at building and city levels: a case study of the west Cambridge campus. J. Manage. Eng. **36**, October 2019. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000763
28. Mohammad, S., Fattah, M., Sung, N.M., Ahn, I.Y., Ryu, M., Yun, J.: Building IoT services for aging in place using standard-based IoT platforms and heterogeneous IoT products (2017). https://doi.org/10.3390/s17102311. https://www.mdpi.com/journal/sensors
29. Naserentin, V., Somanath, S., Eleftheriou, O., Logg, A.: Combining open source and commercial tools in digital twin for cities generation. IFAC-PapersOnLine **55**(11), 185–189 (2022). https://doi.org/10.1016/j.ifacol.2022.08.070
30. Pang, J., Huang, Y., Xie, Z., Li, J., Cai, Z.: Collaborative city digital twin for the covid-19 pandemic: a federated learning solution. Tsinghua Sci. Technol. **26**(5), 759–771 (2021). https://doi.org/10.26599/tst.2021.9010026
31. Riaz, K., McAfee, M., Gharbia, S.S.: Management of climate resilience: exploring the potential of digital twin technology, 3d city modelling, and early warning systems. Sensors **23**(5), 2659 (2023). https://doi.org/10.3390/s23052659
32. Ruiz-Zafra, A., Pigueiras, J., Millan-Alcaide, A., Larios, V.M., Maciel, R.: A digital object-based infrastructure for smart governance of heterogeneous internet of things systems. In: 2020 IEEE International Smart Cities Conference (ISC2). IEEE, September 2020. https://doi.org/10.1109/isc251055.2020.9239077
33. Schrotter, G., Hürzeler, C.: The digital twin of the city of Zurich for urban planning. PFG-J. Photogrammetry Remote Sens. Geoinform. Sci. **88**(1), 99–112 (2020)
34. Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., Wang, L.: Modeling, simulation, information technology & processing roadmap. National Aeronautics Space Adm. **32**(2012), 1–38 (2012)
35. Teng, S.Y., Touš, M., Leong, W.D., How, B.S., Lam, H.L., Másva, V.: Recent advances on industrial data-driven energy savings: digital twins and infrastructures. Renewable Sustainable Energy Rev. **135**, 110208 (2021). https://doi.org/10.1016/J.RSER.2020.110208
36. Tudelft3d project repository. https://github.com/tudelft3d. Accessed 18 May 2023
37. Tudelft3d/bag3d: Software for generating a 3d version of the bag dataset and more. https://github.com/tudelft3d/bag3d. Accessed 18 May 2023
38. Tudelft3d/solar3dcity: An experimental utility to estimate the yearly solar irradiation of roof surfaces in citygml. https://github.com/tudelft3d/Solar3Dcity. Accessed 18 May 2023
39. urbansim.com. https://www.urbansim.com/about. Accessed 08 May 2023
40. White, G., Zink, A., Codecá, L., Clarke, S.: A digital twin smart city for citizen feedback. Cities **110**, 103064 (2021). https://doi.org/10.1016/j.cities.2020.103064
41. Xiong, H., Wang, Z., Wu, G., Pan, Y.: Design and implementation of digital twin-assisted simulation method for autonomous vehicle in car-following scenario. J. Sens. **2022** (2022)

42. Xue, F., Lu, W., Chen, Z., Webster, C.J.: From LiDAR point cloud towards digital twin city: clustering city objects based on gestalt principles. ISPRS J. Photogrammetry Remote Sens. **167**, 418–431 (2020). https://doi.org/10.1016/j.isprsjprs.2020.07.020
43. Ye, X., Du, J., Han, Y., Newman, G., Retchless, D., Zou, L., Ham, Y., Cai, Z.: Developing human-centered urban digital twins for community infrastructure resilience: a research agenda. J. Plan. Lit. **38**(2), 187–199 (2023)