DIGITAL TWIN: AN EMERGING TOOL FOR URBAN PLANNING AND DESIGN

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Abstract. The concept of digital twin has acquired attention in urban planning and design for its potential to revolutionize city understanding, planning, and management. This article explores the contributions of digital twin technology to smart city planning and development, aiming to understand its functionalities, benefits, and limitations. An overview of digital twin definition and functionalities is provided, emphasizing their ability to create virtual city replicas and simulate different scenarios. Case studies from London, Zürich, and Athens exemplify digital twin applications, and a comparative analysis reveals diverse objectives, technology deployments, user interaction levels, outcomes, and funding sources. Findings demonstrate digital twins as powerful tools for improved decision-making, resource allocation, and infrastructure management. They also facilitate stakeholder collaboration, community engagement, and evidence-based policy design. However, challenges related to data integration, privacy, and scalability exist. Nonetheless, results underscore the relevance and transformative potential of digital twins in shaping smart cities and fostering sustainable urban environments.

Key words: digital technologies, urban modeling, urban governance, participatory planning, urban management

1. Introduction

In the digital age, the importance of advanced planning tools in smart cities has become increasingly apparent, as cities strive to optimize the rapid growth of urbanization, as well as the urban infrastructure and public services delivery to improve the quality of life for citizens (Sassen, 2015). In parallel, technology has rapidly progressed, reaching unprecedented influence on various aspects of life, including production methods, lifestyles, urban planning and governance (Riggs and Gordon, 2017; Lv *et al.*, 2022). Cities worldwide face a multitude of challenges, including population growth, resource constraints, environmental sustainability, and the need for efficient infrastructure and services (Lehlota *et al.*, 2022). Unfortunately, traditional urban planning approaches often struggle to cope with the complexities and dynamic nature of modern cities (Florescu and Mitrea, 2015). Furthermore, the need for advanced planning tools in cities arises from the necessity to handle the contemporary urban systems and predict the long-term impacts of decisions. The use of advanced technologies such as Big Data, Internet of Things (IoT), Virtual Reality (VR), Artificial Intelligence (AI), as well as geo-spatial and digital modeling approaches notably contributed to the emergence of smart cities (Batty, 2018; Mortaheb and Jankowski, 2022). This approach led to the adoption of new tools to effectively manage urban complexities, contributing, at the same time, at reducing design mistakes and increase productivity (Miettinen and Paavola, 2014).

Upon this background, the concept of digital twins has emerged as a powerful tool with huge potential in the realm of smart cities (Farsi *et al*., 2020). A digital twin refers to a virtual replica or simulation of a physical object, system, or environment that mirrors its real-world counterpart (Batty, 2018). It encompasses a wide range of elements, including buildings, infrastructure, transportation systems, utilities, and even entire urban areas. By capturing and integrating real-time data from sensors, devices, and other sources, digital twins enable a deep understanding and analysis of the physical world. In fact, this technology combines the digital and physical realms, allowing for real-time monitoring, analysis, urban management, and optimization of urban systems (Grieves and Vickers, 2017; Barricelli *et al*., 2019; Al-Sehrawy *et al*., 2023). With the rapid advancement of technology, the digital twin concept has gained interest as a tool to bridge the gap between the physical and digital worlds (Guo *et al*., 2018). According to a study conducted by ABI Research, the number of digital twins is expected to reach 500 by the year 2025, in various cities worldwide.

The core idea behind a digital twin is to create a dynamic and interactive three-dimensional representation of a physical entity, without limiting only to it (Fuller *et al*., 2020; Ferré-Bigorra *et al*., 2022). It serves as a virtual counterpart, providing insights into the behaviour, performance, and characteristics of the corresponding physical object or system through real-time data provided by the sensors (Ketzler *et al*., 2020). This virtual replica is continuously updated with data, ensuring its accuracy and alignment with the real-world counterpart.

In this context, digital twins play a crucial role in the process of urban planning and design of smart cities. By simulating various scenarios and predicting outcomes, digital twins empower city planners to optimize resource allocation, enhance sustainability, and improve overall urban liveability, as well as to encourage data-driven decision-making (Nochta *et al*., 2021). Moreover, city digital twins offer a platform for experimentation and innovation in urban planning. Through the virtual environment, planners can simulate different scenarios and assess their potential impact on the city. This capability allows for the exploration of alternative strategies, the evaluation of different development plans, and the prediction of potential challenges or risks. By conducting these simulations within a city digital twin, costly and time-consuming real-world experiments can be minimized. In other words, the digital twin enables the simulation and modeling of the urban form within a digital environment, entirely linked to its physical counterpart through a faithful representation. Therefore, a digital twin constitutes a dynamic model that evolves in tandem with its physical entity.

However, despite the growing interest and adoption of digital twin technology, there remains a research gap in understanding the outcomes of its implementation in various urban contexts. As this technology is still in its infancy, limited research has been conducted on the use of digital twins in urban planning and development. This article aims to address this gap by presenting a comparative analysis of case studies, shedding light on the practical applications of city digital twins in different urban settings. By exploring these examples, the paper provides valuable insights and contributes to the knowledge base surrounding the effective utilization of digital twins as a planning tool for smart cities. Finally, this paper contributes to the ongoing discourse on leveraging innovative tools and advanced technologies for urban planning and design.

2. Methodology

The purpose of this paper is to explore the role of digital twin technology as a planning and design tool for smart cities. Specifically, it aims to examine the benefits and applications of digital twins in various domains of smart city planning, including urban infrastructure management, traffic and mobility planning, resource management, and citizen engagement. To explain the operation of this tool in the field of smart city planning, it is necessary to understand the technologies indispensable for the operation of a Digital Twin. In this sense, the following terminology is explained:

- Internet of Things (IoT) – it refers to an intelligent network of objects equipped with sensors, software and Internet connection which allows for continuous data collection and transittion, remote monitoring and control of devices (Kim *et al.*, 2017; Shafiq *et al.*, 2022).
- Big Data (BD) – it refers to a large volume of data, used to analyze the collected data and extract relevant information about the city (Qi and Tao, 2018).
- Artificial Intelligence (AI) – it refers to an automated processed used to analyze and predict trends based on collected data (Allam and Dhunny, 2019).
- Geographic Information System (GIS) - is a computer system that analyzes and displays geographically referenced information (Li *et al.*, 2020).
- 3D modelling – software to generate three-dimensional models based on semantic and geographical informations, ensuring an accurate and refined representation of urban forms and architectural objects (Döllner and Hagedorn, 2007).

The research question that guides this article is: *How does digital twin technology contribute to the planning and design of smart cities?* To answer this question, a comprehensive review of existing literature on digital twins, smart cities, and urban planning was conducted. This review involved books, academic papers, and relevant publications from reliable sources. The literature review served as a foundation for understanding the key concepts related to digital twins and their applications in smart city planning. The desk research includes various sources such as industry reports and studies, as well as websites of 3D models from where the digital twin examples were retrieved. The following documents were consulted:

(1) ABI Research - Digital Twins, Smart Cities, and Urban Modeling, (https://www.abiresearch.com/market-research/product/1033835-digital-twins-smart-cities-and-urban-model);

(2) ABI Research - Urban Planning and Digital Twins, (https://www.abiresearch.com/market-research/product/7779044-urban-planning-and-digital-twins/).

Throughout the research process, efforts were made to critically evaluate the available literature and case studies, acknowledging any limitations or biases in the sources. The aim was to provide an objective and balanced perspective on the role of digital twin technology in smart city planning and design, considering the potential benefits and challenges associated with its implementation.

Furthermore, the paper includes an analysis of real-world case studies that showcase the outcomes of digital twins' deployment in different urban contexts. These cases were selected based on their relevance to different domains of urban planning and the availability of detailed information regarding their implementation. The selected case studies represent diverse geographical locations and urban contexts, providing a holistic view of the applications and impacts of digital twin technology in real-world settings. Finally, data from the selected case studies were analysed through a comparative approach.

2.1. Comparative analysis

The comparative analysis focused on identifying common patterns, challenges, and success factors associated with the implementation of digital twins in smart city planning. Key parameters considered in the analysis include the objectives of the digital twin development, the technologies employed and the data sources utilized, the user interaction and the achieved outcomes in terms of improved decision-making, resource optimization, overall city performance, as well as the funding sources. Concretely, the comparative analysis comprises of the following elements:

- Case Study Objectives: to identify the primary intention of the digital twin and determine the specific goals of the case study, such as improving urban planning, reducing energy consumption, enhancing public transportation, creating a virtual experiential space or other.
- Technology deployment: to assess the technologies used to build and model the virtual city (such as virtual reality, artificial intelligence, and big data) and evaluate the accuracy, detail, and interoperability of the digital twin, including the integration of data from various sources.
- Level of Interaction with the Digital City: to examine user interaction by assessing the visualization and interaction capabilities with the virtual city and identify tools or devices used for interaction.
- Results and Impact: to evaluate the case study outcomes and analyse the impact on urban policies, the community, and the urban environment.
- Sources of funding for the digital twin (if the information is available).

The three case studies, namely London, Zürich, and Athens, were selected based on specific criteria to provide diverse insights into the implementation and outcomes of digital twin technology in urban planning at the European level. The main selection criteria included:

- Relevance to Urban Planning and Development: each case study demonstrates the application of digital twins in the context of urban planning and development. The selected cities have utilized digital twin technology to address various urban challenges and improve the efficiency and sustainability of their urban systems.
- Geographic Diversity: the case studies represent cities from different regions, offering insights into digital twin implementations in diverse urban contexts. Specifically, London, Zürich, and Athens provide a broader perspective on the potential benefits and challenges associated with digital twin technology in various geographic settings (Fig. 1).
- Availability of data: the selected case studies provide sufficient data and documentation to support a comparative analysis of the applications and impacts of digital twins in urban planning.

Fig. 1. Geographical distribution of case studies.

The comparative analysis is built upon relevant literature and publications related to the three case studies, as well as the available sources showcasing the digital three-dimensional platforms of the three digital twins (London, Zürich, and Athens). Therefore, the following websites were consulted:

(1) Digital Twin of Zürich, Switzerland (https://www.stadt-zuerich.ch/portal/de/index/politik_u_recht/stadtrat/weitere-politikfelder/smartcity/english/projects/zwilling.html);

(2) Digital Twin of London, UK (https://connected-environments.org/portfolio/vilo-platform/)

(3) Digital Twin of Athens, Greece (https://www.digitalurbantwins.com/athens-twin).

3. The emergence of Digital Twin in urban planning and design

The concept of Digital Twin (DT) has been defined in various ways in the literature, but in the context of urban planning domain, it primarily refers to digital representations of the urban form (Batty, 2018; Guo *et al.*, 2018). An urban digital twin is an intelligent virtual representation of a physical system that encompasses existing objects, processes, and services in the physical world, imitating their behaviour (Kuhn, 2017; Qi and Tao, 2018). This digital representation is characterized by unique attributes and properties, providing a detailed understanding of the physical urban forms. Furthermore, the advantage of a digital twin lies upon its capacity to offer updated information based on the real-time data retrieved from the sensors (Kuhn, 2017; Barricelli *et al.*, 2019).

3.1. Definition and functionalities

The concept of "Digital Twin" was introduced in 2002 by John Vickers and subsequently developed with Michael Grieves in the context of product lifecycle management in the manufacturing industry (Grieves and Vickers, 2017; Stark *et al*., 2019). Over time, the concept gained attention across various sectors like aviation, manufacturing, and healthcare (Barricelli *et al*., 2019), due to the necessity of data exchange between real and virtual entities (Grieves and Vickers, 2017; Vohra, 2023). The growth of interest was constantly fuelled by advanced technologies like IoT, big data, and real-time sensors, aligned with the industry 4.0 shift. Continuous communication with geographic information systems (GIS) and sensor networks has enabled the development of applications previously impossible to imagine (Nochta *et al*., 2021; Lei *et al*., 2023).

The digital twin is a novel concept, with increasing academic use, especially in the field of urban planning and design (Ketzler *et al*., 2020). The Urban Digital Twin concept gained prominence between 2018-2023, bringing significant benefits to understanding and optimizing complex urban systems (Batty, 2018; Al-Sehrawy *et al*., 2023). Despite high learning, experimentation and implementation costs, digital twin technology advances swiftly, supporting smart city development (Shahat *et al*., 2021). Thus, the concept goes beyond a simple three-dimensional model of a city, incorporating semantic data, real-time sensor-generated data, physical models, and simulations (Miller *et al*., 2018; Ketzler *et al*., 2020; Kuru, 2023). In fact, the City Digital Twin was built on the existing smart city platforms, allowing for the exploration of innovative solutions to revolutionize urban planning and, design, within a controlled environment that mimics the real city (Rathore *et al*., 2016; Ruohomaki *et al*., 2018; Major *et al*., 2021; Wan *et al*., 2023).

According to the available literature, definitions of digital twin vary from a virtual model simulating behavior to a digital mirror of the real world (Qi and Tao, 2018; Guo *et al*., 2018). Kuhn emphasizes the process of comprehensive data exchange to reflect the characteristics and behavior of the real world, while others highlight the dynamic representation of the physical system (Kuhn, 2017; Madni *et al*., 2019). These varied definitions illustrate the diverse perspectives and approaches towards digital twins, offering different understandings of the concept and its uses.

In the urban planning domain, digital twins refer to digital representations of urban forms or digital replicas (Batty, 2018; Fuller *et al*., 2020), though this "replica" notion is rather misleading (Tomko and Winter, 2019; Ketzler *et al*., 2020). Instead, digital twins evolve, serving as living, intelligent counterparts of the physical entity (Barricelli *et al*., 2019). Therefore, the main potential of City Digital Twins is based on their capacity to create dynamic and interactive virtual replicas of cities and enable simulations of various scenarios for future development (Wan *et al*., 2023; Almusaed and Yitmen, 2023).

By leveraging advanced technologies present in smart cities, the City Digital Twin opens new possibilities for addressing urban challenges and creating more efficient, sustainable, and resilient cities (Rathore *et al*., 2016; Samih, 2019). From a technical perspective, a City Digital Twin consists of multiple layers of data that provide information about the terrain, buildings, urban fabric, infrastructure, mobility, and other aspects related to the functioning of cities (Saeed *et al.*, 2022). For example, the data retrieved from sensors can include information about infrastructure conditions, energy consumption, air quality, traffic levels, and much more (Lehlota *et al.*, 2022). Furthermore, big data can be employed to analyse the collected data and extract relevant insights for modeling the urban form. Such data may comprise demographic information, urban service usage patterns, preferences, and other pertinent details that can help identify patterns and trends within the urban landscape.

To ensure the effective operation of Digital Twins, it is essential that they are equipped with network devices, enabling uninterrupted connectivity and the seamless exchange of large amounts of data (Engin *et al.,* 2020; Lei *et al*., 2023). Moreover, Digital Twin technology relies on proficient data analysis and decoding techniques, as well as learning algorithms that continuously process data from various sources, including elements within the physical urban context (Barricelli *et al*., 2019). In other words, the main components of a Digital Twin include data collection through sensors and IoT devices, data integration and analysis, and visualization techniques (Saeed *et al.*, 2022; Vohra, 2023).

However, the development of a City Digital Twin is far from an easy task. Besides the permanent connection to network services, IoT and Big Data, the efficient functionality of a Digital Twin requires various conditions to be met.
Firstly, constant communication with Geographic Information Systems (GIS) and sensor networks is essential for data feeding into the digital twins (Dembski *et al*., 2020; Nochta *et al*., 2021; Lei *et al*., 2023). This communication enables the continuous flow of data, ensuring that the digital twin reflects real-time changes in the physical urban environment. Another crucial aspect is the integration of three-dimensional (3D) urban models based on geometric and semantic information (Dawkins *et al*., 2018). For this reason, technology progress already found solutions such as the platform Azure Digital Twins, which offers a framework for the design, development, and deployment of digital twins for various industries, enabling real-world applications (Nath *et al*., 2021). This platform provides a solid foundation for constructing accurate and detailed digital replicas of the urban environment.

Secondly, the user engagement and interaction with the City Digital Twin is fundamental to its success. To interact with a digital twin, technology such as Google Beacon can be incorporated, allowing access to data through mobile devices and providing a connection to the three-dimensional representation of the virtual cities, enhancing its usability and accessibility (Dawkins *et al*., 2018).

Finally, the development of a City Digital Twin can include an additional layer of data comprising synthetic populations and communities, known as societal twins or social twins (Birks *et al*., 2020). These virtual representations of human communities within the digital twin provide valuable insights into human behaviour, infrastructure use and urban interactions. The concept of societal twins allows for a more comprehensive understanding of the city's dynamics and facilitates the planning and design of services tailored to the needs of the population (Lehlota *et al*., 2022).

Therefore, the successful development of a City Digital Twin requires the fulfilment of various conditions such as continuous communication with GIS and sensor, integration of 3D urban models, technologies for user interaction, and the integration of societal twins to capture the complexity of the urban context.

3.2. Potential and limitations of digital twins

Digital twins offer opportunities for rapid analysis, real-time decision-making, and visualization of development scenarios, contributing to the efficiency and effectiveness of urban systems (Ketzler *et al*., 2020; Shahat *et al*., 2021). Urban digital twins act as simulation and management environments for scenario development and facilitate decision-making in urban planning and management by providing a detailed perspective of the urban systems (Tzachor *et al*., 2022). Thus, digital twins enable scenario testing, identification of potential problems, and system optimization without generating any negative consequences for the physical environment of the city. Moreover, City Digital Twins are essential tools in the urban planning domain, enabling the testing of various policy options, evaluating the potential impact of urban interventions, facilitating collaboration among different domains and stakeholders, and involving citizens in planning and decision-making processes (Charitonidou, 2022; Ye *et al*. 2022). Therefore, the integration of the City Digital Twins into urban planning and design can facilitate the achievement of sustainable development goals (Tzachor *et al*., 2022).

According to the existing literature, Digital Twins have great potential and bring numerous benefits in urban planning and design. City Digital Twins prove to be an efficient tool for different stages in the urban planning and design process, from the analysis phase to the conception phase, as well as the refinement of the urban model. Due to the three-dimensional modeling and the predictive and dynamic data that feeds the Digital Twin, it has become a powerful tool in the urban planning domain, overtaking the performance of the traditional planning and design tools (Fuller *et al*., 2020; Nochta *et al*., 2021; Lei *et al*., 2023). Their ability to analyse real-time data enables precise real-time diagnostics and facilitates evidence-based planning and decision-making (Tomko *et al*., 2019; Farsi *et al*., 2020; Charitonidou, 2022; Al-Sehrawy *et al*., 2023). Furthermore, Digital Twins can optimize urban planning and design at various spatial scales (Dembski *et al*., 2020).

Moreover, Digital Twins enable efficient urban management (Dawkins *et al*., 2018; Engin *et al*., 2020; Al-Sehrawy *et al*., 2023). Due to their capacity to collect and analyse real-time data, Digital Twins have great potential to monitor and give constant feedback on the evolution of the urban form. In essence, Digital Twins act as central platforms for storing and sharing relevant city data, enabling standardization and data sharing among different city departments, thereby enhancing the efficiency of the zoning activities and the urban management processes (Ferré-Bigorra *et al*., 2022).

Another potential of digital twins in the realm of urban planning is related to smart design and visualization. Thus, Digital Twins support smart design by providing powerful visualization tools, enabling dynamic and personalized experiences for users in virtual urban environments (Zhang *et al*., 2015; Kuru, 2023). This functionality can be applied to various domains such as tourism and cultural heritage, transportation, and mobility, as well as public safety (Kuru, 2023). Moreover, Digital Twins have the advantage of illustrating policies and future development plans, also functioning as a tool to collect citizens' feedback and facilitate co-creation approaches and participatory planning (Lei *et al*., 2023).

In what concerns urban transportation and mobility, Digital Twins play a crucial role in traffic management and mobility planning, integrating data collection systems and sensors into urban infrastructure, optimizing intelligent mobility, and measuring traffic performance (Farsi *et al*., 2020; Fuller *et al.,* 2020; Xu *et al*., 2023). For instance, Digital twins enable more efficient and real-time control over traffic conditions and road infrastructure, optimizing traffic signals and providing various systems for traffic prediction and performance evaluation (Xu *et al*., 2023).

Last but not least, Digital twins contribute to enhancing sustainability, resilience, and liveability in cities by enabling data-driven insights, predictive modelling, and simulations (Saeed *et a*l., 2022; Wan *et al*., 2023).

Although digital twin technology brings significant benefits to the field of urban planning, it also comes with some challenges and limitations associated with its use in the urban context. One of the major limitations is the level of abstraction within a digital twin, which may overlook many elements of the real urban system, such as traffic flows, space utilization intensity, or human emotions (Batty, 2018; Tomko and Winter, 2019). Other frequent challenges faced in the implementation of Digital Twins include data integration, privacy concerns, and scalability (Barricelli *et al*., 2019; Wan *et al*., 2023; Lei *et al*., 2023). Several studies highlight the need for standardized frameworks, interoperability, and collaboration among stakeholders to overcome these challenges and ensure the successful deployment of City Digital Twins (Major *et al*., 2021; Wan *et al*., 2023).

Furthermore, the process of creating a Digital Twin requires a significant amount of continuous data. For instance, obtaining and consistently updating the necessary data can be challenging and costly (Fuller *et al*., 2020). Development costs, including software and hardware components, as well as physical and cloud interconnectivity, can also be obstacles in implementing Digital Twins (Barricelli *et al*., 2019). Therefore, ensuring financial resources is crucial for the Digital Twins' operation (Lei *et al*., 2023).

3.3. Applicability of Digital Twin concept

Digital Twin represents an advanced type of urban form, as it encompasses a comprehensive and interactive approach in developing virtual models of smart cities. Compared to other digital representations of the urban form, Digital Twin provides a more detailed and dynamic representation of the urban environment, integrating various elements such as BIM, as well as functionalities that allow user interaction with the digital interface (Nguyen and Adhikari, 2023).

According to definitions in the literature, Digital Twin can be perceived as a virtual model of a physical entity, maintaining a close and bidirectional connection with its real-world counterpart. It consists of a combination of models, simulations, and algorithms that describe the characteristics, behaviour, and functionalities of a physical entity. It aims to create virtual models of cities to obtain a more efficient understanding and management of the urban environment. For this reason, Digital Twin goes beyond traditional virtual representations by encompassing real-time data, semantic information, and simulations.

The applicability of the Digital Twin is illustrated by the raising number of cities worldwide that adopt this technology in the urban planning and design domain. From Norway to Finland, the Netherlands to Germany, Great Britain to the United States, Switzerland, Greece and Belgium, Digital Twins have demonstrated their value in transforming urban environments. For example, in Norway, a data-driven digital twin of the smart city of Ålesund has been used to showcase its ability to optimize urban systems and inform decision-making (Major *et al*., 2021). Meanwhile, Helsinki in Finland has embraced dynamic digital twins for enabling real-time insights and supporting informed urban development (Hämäläinen, 2021). Similarly, the city of Herrenberg in Germany serves as an example for how digital twins contribute to citizen engagement in smart cities, promoting sustainability and liveability (Dembski *et al*., 2020).

The Netherlands stands as a successful example for the adoption of advanced technologies in the urban planning domain. Several Dutch cities have developed a robust urban Digital Twin ecosystem, incorporating advanced technologies to enhance urban planning and design practices (de Matos *et al*., 2022). Also, the city of Zürich in Switzerland has leveraged digital twin technology to improve decision-making processes and urban development strategies (Schrotter and Hürzeler, 2020). Similarly, Great Britain has utilized digital twins for operational management and engagement, showcasing the potential of IoT and Mixed Realities in effective urban planning (Dawkins *et al*., 2018; Lu *et al*., 2020). Across the Atlantic, the Digital Twin of Boston has demonstrated the benefits of this technology in analysing urban mobility and optimizing transportation systems (Tuchen *et al*., 2022).

These examples highlight the versatility and effectiveness of digital twins in various urban contexts. Moreover, these practical examples demonstrate their applicability to the urban planning domain, empowering cities to make data-driven decisions and improve their overall efficiency. Digital twins offer a comprehensive and interactive approach to urban planning, allowing for a more detailed and dynamic representation of the urban environment.

4. Implementation of Digital Twins in Europe

The concept of Digital Twins has gained significance worldwide, and Europe has been at the forefront of promoting and supporting the implementation of Digital Twins across different domains. One prominent area is manufacturing, where Digital Twins enable real-time monitoring of production processes, predictive maintenance, and optimization of resource utilization. In the energy sector, Digital Twins help optimize energy systems, enhance grid management, and support the integration of renewable energy sources. Smart cities also benefit from Digital Twins, enabling urban simulations, smart management of infrastructure, and efficient resource allocation, including land use control.

In the past years, the European Union (EU) has recognized the potential of Digital Twins in transforming industries and enhancing sustainability. As part of its digital strategy, the EU has launched initiatives to foster the development of Digital Twins in the urban planning domain. For instance, DUET (Digital Urban European Twins) project utilizes cloud computing, sensor-generated data, and analytical systems in the form of digital twins to support decision-making in the public sector in a more democratic and efficient manner (Raes *et al.*, 2022). It allows decision-makers to collaboratively create innovative solutions for complex urban challenges by analysing detailed data through a common and user-friendly interface. The project's applicability is demonstrated by the three pilots in European cities and regions: Flanders (Belgium), Pilsen (Czech Republic), and Athens (Greece).

Thus, Europe is at the forefront of implementing Digital Twins in the urban planning domain. In accordance with the technological advancements, Europe is expected to leverage Digital Twins for sustainable development, innovation, and improved decision-making in the years to come. As the adoption of Digital Twins becomes more widespread, the accumulated data and insights will enable data-driven urban planning and design, improved operational efficiency, and the development of innovative services and business models.

For this reason, three case studies, namely London (Great Britain), Zürich (Switzerland), and Athens (Greece), have been selected to provide diverse insights into the implementation and outcomes of digital twins in urban planning at the European level.

4.1. London, United Kingdom

In the United Kingdom, several examples of Digital Twin implementation showcase its diversity and potential in urban planning, design, and management (Batty and Hudson-Smith, 2005). One such example is the three-dimensional model called Virtual London (ViLo), which includes Queen Elizabeth Park in East London. ViLo consists of a city 3D model connected to real-time sensor-generated data, continuously updating the model. In this case, the Digital Twin enables more precise analysis and more efficient urban planning (Dawkins *et al.*, 2018).

The ViLo model, developed by The Bartlett Centre for Advanced Spatial Analysis (CASA) at UCL in collaboration with the Future Cities Catapult (FCC), is an interactive urban data visualization platform. It allows for the visualization of real-time and offline spatial-temporal data sets in a digital, three-dimensional representation of the urban environment. The platform utilizes OpenStreetMap data and the MapBox API to create the digital environment, providing a high-resolution digital terrain model that visualizes the precise locations of buildings, trees, and other urban facilities. ViLo also supports the visualization of custom spatial-temporal data sets in various file formats and allows for the integration of custom 3D models (Hudson-Smith, 2021).

ViLo serves as a digital representation of the city, including various elements such as buildings, bridges, and vegetation, all represented in a virtual 3D environment. By utilizing the Digital Twin technology, ViLo provides an up-to-date and constantly evolving database. The integration of real-time sensor data allows for improved understanding and awareness of the urban environment, enabling simulations and scenario discussions within decision-making bodies (Nochta *et al*., 2021).

According to The Bartlett Centre for Advanced Spatial Analysis, ViLo places specific emphasis on the visualization of mobility data sets. Through the use of Transport for London's procedures, the platform can retrieve and display real-time information about bike sharing docks, bike availability, bus and tube networks, bus stops, tube stations, and the real-time position of buses and trains. The platform also integrates real-time weather information, three-dimensional visualization of Flickr photos related to different points of interest, as well as a walking route planner using the MapBox functionalities.

An innovative aspect of the ViLo project is the capacity to conduct real-time urban analysis within the digital environment. According to CASA and FCC, the ViLo platform enables two-and three-dimensional visibility analysis, including the area and perimeter of visible surfaces, maximum, minimum, and average distances, as well as metrics such as compactness, convexity, and concavity.

While initially focused on visualizing the Queen Elizabeth Olympic Park, Bartlett Centre for Advanced Spatial Analysis upgraded the ViLo models, which has the flexibility to be used for visualizing any urban area worldwide. The platform serves as a powerful tool for observing dynamic urban processes in real-time, benefiting from technological progress.

This example of Digital Twin illustrates how this technology can support early stages of policy decision-making, by identifying inconsistencies and potential conflicts between sectoral policies, promoting interdisciplinary thinking in urban policy design, and enhancing the efficiency and effectiveness of modeling exercises (Marcucci *et al*., 2020; Nochta *et al*., 2021).

In conclusion, the Digital Twin model of London represents a significant application of the technology in the urban context. By connecting real-time data to a dynamic 3D representation, ViLo delivers an accurate representation of the urban environment, enabling more precise analysis, efficient planning, and informed decision-making. This example demonstrates the potential of Digital Twins in improving evidence-based urban planning and design, while fostering sustainable development.

4.2. Zürich, Switzerland

The city of Zürich in Switzerland is facing pressing challenges due to population growth, including densification and competing land use as the number of residents and jobs increases. To address these challenges, a digital transformation of the planning and decision-making process was needed, claiming for upgraded tools, which should be more visual, understandable, and intelligible (Schrotter and Hürzeler, 2020).

A key component of the digital transformation in Zürich is the Digital Twin, which serves as an essential database and platform for the entire city. By using 3D spatial data and models, various elements of the city, such as buildings, bridges, vegetation, transportation systems, energy consumption, environmental factors, and social dynamics are digitally represented and continuously updated as needed. The virtual platform provides a user-friendly and interactive way to explore the city's geospatial data.

In order for the city to be able to develop a digital twin, Zürich city administration implemented a project in collaboration with 25 service departments, managed by the GIS City of Zürich (GIS Stadt Zürich). The project involved the creation of a high-resolution 3D model, which includes a terrain model, an urban block model, and a roof model. The data used to construct these models were obtained from LiDAR images, the city cadastral survey, as well as semiautomatic photogrammetry. Additionally, the digital twin incorporates other layers of open government data, such as street spaces, public utilities, and selected public buildings and facilities, to enhance its functionality. Since 2018, the city upgraded the model with "Zürich 4D" application, developed by the Office for Urban Planning, which enables users to visualize the city's structural development over time.

This digital representation of Zürich offers valuable tools for understanding the urban form and advantages for managing urban development in Zürich. As such, the Digital Twin of Zürich is used for promoting public awareness, which is ensured by publishing 3D spatial data within the "Open Government Data" initiative. This allows for application development and facilitates the creation of collaboration platforms among different stakeholders (Schrotter and Hürzeler, 2020). By visualizing and analysing digital prototypes and demonstrating interactions with the built environment, digital scenarios can be created and discussed within decision-making bodies.

Advanced technologies such as IoT devices, sensors, and data analytics continuously update the digital twin, ensuring its accuracy and reliability. Due to this continuous updating process, the digital twin also facilitates the simulation of urban climate-related questions through building temperature analysis, providing results linked to existing 3D spatial data (Schrotter and Hürzeler, 2020). Therefore, the 3D spatial data and models become the reference point for various data inquiries and need to be periodically updated to meet different requirements for illustrating the dynamic processed within the urban form.

According to Schrotter and Hürzeler (2022), the development of the digital twin of Zürich was a collaborative effort involving various stakeholders, including municipal authorities, urban planners, architects, and technology experts.

According to Stadt Zürich, the main objective was to improve the decision-making process within urban development projects, enhance resource allocation, and create a sustainable and liveable city. In this context, the functionalities of Zürich digital twin include the visualization of urban planning scenarios, concrete civil engineering and construction projects or detailed building projects (BIM models) in detail. Thus, the virtual replica of Zürich allows for simulations and testing of scenarios, enabling decision-makers to evaluate the impact of proposed changes before implementation. More importantly, this simulation process avoids any unfortunate consequences in the physical environment. Furthermore, Zürich Digital Twin provides a feasible solution for citizens' involvement in urban planning and design activities. By making the digital twin accessible to the public, citizens can actively participate and provide feedback, propose ideas, promoting a sense of ownership and inclusion (Lei *et al*., 2023).

The example of Zürich Digital Twin showcases an innovative approach to transform urban planning and design, by providing accurate and real-time information about the functioning of the city. Moreover, the digital twin model facilitates the optimization of resource allocation by providing information about infrastructure usage, energy consumption patterns, climate monitoring and traffic flow. By analysing this data, urban planners can identify areas in need of improvement, implement specific interventions, and enhance overall efficiency of the city management.

4.3. Athens, Greece

Athens represents one of the three pilot cases of DUET project (Digital Urban European Twins). As part of this journey, Athens is developing a Digital Twin to revolutionize urban planning and management. By engaging in this project, the city of Athens acknowledges the significance of making decisions based on data and intends to harness the potential of the Digital Twin in comprehending the complex urban environment. By developing a digital twin, Athens aims to understand city relationships, engage citizens in co-creating digital services, enhance decision-making processes, and improve the effectiveness of policy design and implementation (Raes *et al.*, 2022).

One of the primary policy goals in Athens is to address the pressing issue of air quality, which is a significant concern in Greece due to intense traffic flows. For this reason, Athens is seeking an inter-departmental approach (transport, health, and environmental departments) to address the challenge of air pollution.

For this reason, the Digital Twin in Athens was developed to integrate and make easily accessible all the city's digital sources of information and datasets. Thus, the Digital Twin enables exploration and experimentation, leading to data-driven insights for decision-making processes (Raes *et al.,* 2022). There are several use cases of Athens Digital Twin, tackled in DUET project, such as transport and mobility, pollution and city planning. Through the implementation of the Digital Twin, city officials and citizens can gain a deeper understanding of how traffic issues impact daily life and the environment, adopt measures that combine environmental and traffic data to promote green city mobility, suggest strategies for pollution reduction and urban environment protection, and actively participate in co-creating a greener way of life.

According to the DUET webpage, one such example is the application of Digital Twin technology to Athens' Klauthmonos Square for the purpose of planning the placement of benches and developing public space policies. By analysing the location of trees and the density of shade from both trees and buildings in the square, optimized monitoring of shadow coverage and the utilization of shady areas can be achieved.

In what concerns transportation and mobility, another application of digital twin in Athens is the simulation of a pedestrian road extension, specifically the extension of the Great Walk pedestrian path to Kallimarmaro Stadium. By simulating the impact on traffic flows, city planners can evaluate the feasibility of the extension and promote its implementation if the projected result shows low traffic impact. Furthermore, in order to explore the creation of a green route in the congested centre of Athens, the closure of Stadiou Street is tested and evaluated using Digital Twin technology. By assessing the impact on nearby traffic load, planners can determine whether the green routing plan is viable. Alternatively, partial closures or limited-time closures of Stadiou Street can also be examined.

Another relevant area for the air quality objective is related to green spaces. For this reason, Athens Digital Twin collects citizens' feedback on green routing initiatives, particularly the transformation of Stadiou Street into a pedestrian route. Through asking feedback on alternative modes of transportation such as walking, cycling, or using public transport, a decision-making process can be simulated that incorporates citizens' input, leading to optimized urban planning and eco-friendly solutions.

Additionally, the Athens Dashboard provides valuable insights into traffic load on Stadiou Street. By comparing sensor data from different time periods, such as average working weeks and average vacation weeks, decision-makers can gain valuable information on traffic distribution throughout the day. This information can be utilized for various purposes, including traffic arrangement, such as traffic light automation, street lighting planning, road cleaning, and the implementation of bus lanes.

In conclusion, the Digital Twin implementation in Athens represents an ambitious endeavour to leverage technology and data for sustainable development and pollution reduction. Overall, these use cases demonstrate the diverse applications of Digital Twin technology in Athens, supporting optimized urban planning, informed decision-making, and the development of sustainable and efficient city systems. Finally, the Digital Twin technology provides an innovative solution to address urban challenges, improve quality of life, and create a greener, more liveable city (Raes *et al.,* 2022).

4.4. Comparative analysis of urban digital twins

The comparative analysis of digital twins in London, Zürich and Athens is based on five key criteria: (1) case study objectives; (2) technology deployment; (3) level of interaction with the Digital City;

(4) results and impact and (5) sources of funding for the digital twin.

First of all, in what concerns the objectives of the digital twins, the examples from London, Zürich, and Athens have distinct focuses. London's digital twin primarily aims to improve urban planning and decision-making processes. Its objectives include enhancing transportation efficiency, reducing energy consumption, and improving infrastructure management. The focus is on optimizing resource allocation and supporting sustainable development. In the case of Zürich, the digital twin is designed to create a virtual experiential space for stakeholders to explore and understand the city's urban environment. The goal is to foster collaboration among stakeholders and enable evidence-based decision-making. Athens' digital twin focuses on data-driven decision-making, citizen engagement, and urban policy effectiveness. It addresses urban challenges such as traffic congestion, air pollution, and sustainable mobility. The objectives include understanding city relationships, co-creating digital services with citizens, and improving policy design and implementation efficiency.

While all examples share the overall goal of improving urban planning, they differ in their specific objectives. London's digital twin emphasizes transportation efficiency and energy reduction, while Zürich's digital twin prioritizes creating a virtual experiential space for citizens, and Athens' digital twin focuses on data-driven decision-making and citizen engagement for addressing urban challenges such as air pollution.

Regarding the technology deployment and the particular technologies that have been used for each Digital Twin, there are again, several important differences. London's digital twin utilizes a variety of technologies, including virtual reality, artificial intelligence, and big data analytics. The model integrates data from multiple sources, such as sensors, satellite imagery, and social media feeds. The level of detail and accuracy of the digital city model is high, allowing for comprehensive analysis and simulations. In what concerns the Digital Twin of Zürich, it also incorporates various technologies, including 3D modeling, geospatial data, and simulation tools. It integrates data from different sources, such as municipal databases, environmental sensors, and citizen feedback. The digital city model is detailed and accurate, providing a comprehensive representation of the urban environment. Lastly, Athens' digital twin incorporates technologies such as data integration, analytics, and simulation tools. It merges diverse digital sources to create a comprehensive and accessible platform for exploration and simulation. While specific details about the technology stack are not mentioned, the aim is to utilize advanced data processing and modeling techniques.

Overall, all three cities recognize the importance of technology deployment in building their digital twins. London, Zürich, and Athens utilize different combinations of technologies to create accurate and detailed digital city models, integrating data from various sources. Altogether, they serve as valuable tools for understanding urban environments, supporting decision-making processes, and addressing urban challenges.

In terms of the level of interaction with the digital city, London, Zürich, and Athens each offer different capabilities for users to engage with their respective digital twins. London's digital twin provides users with a range of visualization tools and interactive interfaces. These tools allow policymakers, urban planners, and citizens to actively explore the virtual city and interact with its components. Users can visualize different scenarios, test interventions, and assess the potential impact of various policies on the city's infrastructure. The interactive nature of London's digital twin empowers stakeholders to make informed decisions based on comprehensive and dynamic simulations. Zürich's digital twin offers detailed visualization tools and user-friendly interfaces for users to engage with the virtual city. These tools provide a highly interactive experience, enabling stakeholders to explore Zürich from different perspectives and gain a comprehensive understanding of the urban environment. Users can simulate urban interventions, such as changes in energy consumption, transportation systems, and urban design, and assess their potential outcomes. While specific details about the level of interaction are not explicitly mentioned for Athens' digital twin, it can be inferred that it provides visualization and interaction capabilities to support data exploration, scenario testing, and citizen engagement.

Overall, the three digital twins offer varying degrees of interaction with the virtual city. The greater the level of interaction, the more advanced and useful the digital twin becomes. With increased interaction, users can actively engage with the virtual city, explore its various components, and manipulate variables to understand the potential outcomes of different scenarios.

In what concerns the results and impact of the digital twin technologies, all three cases have demonstrated positive outcomes and impacts on urban policies, the community, and the urban environment. The digital twin in London has had a significant impact on urban policies and decision-making. It has facilitated more informed and evidence-based decision-making processes, leading to improved urban planning strategies, enhanced transportation systems, and optimized resource allocation. The digital twin has also fostered community engagement by involving citizens in the planning and development processes. In the case of Zürich, the digital twin has led to improved urban planning processes and informed decision-making. It has facilitated collaboration among stakeholders by providing a common platform for data sharing and visualization. The digital twin has also contributed to the optimization of energy consumption, the development of sustainable infrastructure, and the enhancement of the city's resilience to climate change. Unfortunately, the outcomes and impact of Athens' digital twin are not specified in the available sources. However, it is anticipated that the digital twin will contribute to informed decision-making and improved urban planning strategies.

Finally, the sources of funding for the digital twins vary from one case to another. For instance, the funding for London's digital twin comes from a combination of public and private sources. The Greater London Authority, research institutions, and technology companies collaborate to secure funding and resources for the development and maintenance of the digital twin. The Digital Twin of Zürich is funded by a combination of public funds, research grants, and collaborations with industry partners. In what concerns the Digital Twin of Athens, the project receives funding from a combination of EU funding programs (such as Horizon 2020) and government budgets.

Overall, the three digital twin projects in London, Zürich, and Athens leverage a combination of public and private funding sources to support their development and implementation. This diverse funding approach ensures financial sustainability and allows for collaboration with different stakeholders in advancing and upscaling the digital twin initiatives.

4.4. Results and discussion

The comparative analysis of the urban digital twins in London, Zürich, and Athens reveals some interesting insights into their objectives, technology deployments, level of interaction, results, impact, and sources of funding. According to the comparative analysis results, digital twins have the potential to improve urban planning, decision-making, and community engagement, ultimately contributing to more sustainable and liveable cities in all cases.

The results indicate that digital twins can significantly improve urban policies. By utilizing advanced technologies like 3D modeling, big data analytics, and simulation tools, digital twins provide a comprehensive and detailed representation of the urban environment. This enables exploration of different scenarios, testing of interventions, and evaluation of policy impacts on various elements of the urban form, from optimized energy consumption, mobility planning and traffic management, without producing any consequences in the physical environment.

The interactive nature of digital twins, with visualization tools and user-friendly interfaces, empowers different categories of stakeholders to actively participate in the process of urban planning and design. They foster collaboration, citizen engagement, and promote a sense of ownership in shaping the future of cities.

Despite being in the early stages, the funding sources for digital twins reflect their recognition in addressing urban challenges and improving urban planning strategies. It is expected that in the coming years numerous sources of funding will be available for cities to develop digital twins as tools for urban planning and design. This statement is reinforced not only by the investment efforts channelled towards the research and development of urban digital twins (as seen in the DUET example), but also by the European commitments towards the digital transition of cities. Furthermore, London and Zürich examples illustrate that collaboration between the public authorities, research institutions, and technology companies can secure the necessary financial resources for digital twins.

In what concerns the technology, digital twins utilize advanced technologies to build and model the virtual cities. According to the three case studies, these technologies include virtual reality, artificial intelligence, big data analytics, 3D modeling, geospatial data, and simulation tools. Moreover, the examples showcase that the level of interaction with the digital cities is highly important.

The results of the comparative analysis indicate the relevance of digital twins in the urban planning and design domain, despite their current infancy level. As demonstrated by the case studies in London, Zürich, and Athens, digital twins have the potential to significantly improve decision-making processes, enhance urban policies, and engage the community in urban planning and design. These outcomes are expected to upscale in the following years, due to the digital transition, becoming a common practice for the urban planning domain.

5. Conclusions

The rapid advancement of technology has paved the way for innovative approaches to urban planning and design. Among these, digital twin technology has emerged as a promising tool with the potential to revolutionize the way cities are planned, developed, and managed. This article explored the concept of digital twins and its application in the context of urban planning and design, paving the way for further understanding of the digital twin concept.

Digital twins, in essence, are virtual replicas of physical cities, encompassing their ecosystem, from infrastructure and buildings to the entire urban context. They leverage cutting-edge technologies such as IoT, big data analytics, artificial intelligence, and simulation tools to create accurate and interactive models of urban environments. According to the literature review, Digital Twins serve as powerful decision support tools, enabling stakeholders to gain a comprehensive understanding of cities, explore different scenarios, and test various interventions in a virtual environment.

To evaluate the impact of digital twins on urban planning and design, three case studies were analysed: London, Zürich, and Athens. Each case study provided valuable insights into the objectives, technology deployment, level of interaction, results, and sources of funding for the respective digital twins. The three examples illustrate how digital twin technology can be useful in upgrading urban planning and design. By leveraging advanced technologies, digital twins provide accurate representations of cities, enabling comprehensive analysis, simulations, and scenario testing. They facilitate stakeholder engagement, inter-departmental collaboration, and evidence-based decision-making.

Overall, digital twins hold great potential for shaping smart cities and creating sustainable, liveable urban environments. Furthermore, the comparative analysis emphasized the relevance of digital twins in the urban planning domain, despite their current infancy level. Digital twins have the potential to significantly improve decision-making processes, enhance urban policies, and optimize resource allocation. The interactive nature of digital twins empowers stakeholders to actively participate in the planning process, fostering collaboration and community involvement.

In conclusion, digital twin technology represents an emerging tool for urban planning and design. As the technology continues to advance and more cities adopt digital twins, their impact on urban planning and development is expected to grow significantly in the upcoming years. Digital twins hold great promise for shaping smart cities, but they are not without limitations. Despite their huge potential, Digital Twin technology still has some concerns regarding data collection, continuous upgrading and maintenance, data privacy, funding sources, as well as implementation challenges related to specialised human resources. Therefore, further research is needed to unlock the full potential of digital twins and drive the transformation of cities towards a smarter and sustainable future.

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