Digital Twins in Smart Cities: A Survey

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***Abstract*—This report presents, summarizes, and reinterprets the findings from various papers on the topic of digital twins in smart cities in a structured manner. It also defines the terms Digital Twin, Digital Shadow, Digital Model, Smart City, Digital Twin City, and Urban Digital Twin, and distinguishes between them. Benefits and challenges of the development and usage of Urban Digital Twins are explained, and some exemplary use cases are given. Also, the usage of Urban Digital Twins for more sustainable cities is described in more detail. After the discussion, an outlook with suggestions for improvement in this topic is given.**

***Index Terms*—Digital Twin, Digital Shadow, Digital Model, Smart City, Digital Twin City, Urban Digital Twin**

I. Introduction

As a contribution to the research seminar "Digital Twins and their Use Cases" in the summer semester 2025 at the University of Potsdam, the focus of this report is the usage of the Digital Twins in Smart Cities and for city management. First, some frequently used terms in the context of digital twins in smart cities are defined in section II and distinguished from one another. Next, the characteristics, benefits, and challenges of urban digital twins are presented in section III. This is followed by a selection of use cases and examples of urban digital twins in section IV, and the sustainability advantages of urban digital twins are examined in more detail in section IV-A. Finally, a discussion and an outlook are provided in section V as well as the findings are summarized and conclusions are drawn in section VI.

II. Definitions of frequently used terms

A. Digital Twin, Digital Shadow, and Digital Model

A Digital Twin, Digital Shadow, and Digital Model are virtual models of a physical object or system, with the virtual models being continuously updated with data from sensors and other sources. So in all of these three concepts, there are two parts: A physical object (real world) and a digital object (virtual world) [3].

The differences of the three concepts Digital Model, Shadow, and Twin are visualized in Fig. 1.

While in a Digital Model the data flows in both directions only with human interaction (manually), the data flow in the Digital Shadow Concept is automatic in one direction and manual in the other: The data from the physical object to the digital object is updated automatically, while for the data flow from the digital to the physical object, humans have to contribute (manual data flow) [7].

The two-way interaction between the physical and virtual world characterizes the concept of Digital Twins. Without human interaction, the data in both directions is updated automatically. This allows both real-time monitoring and active control of urban systems. There is dynamic feedback and interaction between the real and the virtual world, i.e. real-world actions can be triggered from the virtual model [3] [7].

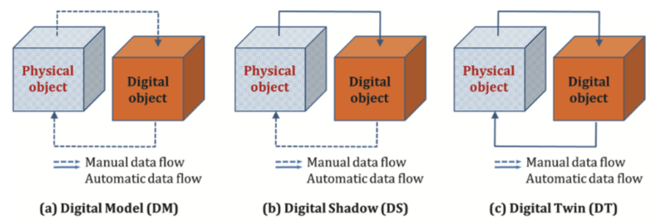

Fig. 1. Digital Model vs. Digital Shadow vs. Digital Twin [7]

B. Digital Twin City and Urban Digital Twin

Digital Twin City (DTC) and Urban Digital Twin (UDT) are both a comprehensive urban implementation of digital twin technology. There is an interactive, bidirectional synchronization between physical infrastructure and virtual simulations to achieve smarter urban areas [3].

For the monitoring part of the digital twin concept (data flow from physical to digital object) there is a real-time data integration from multiple sources such as sensors. There is also a multi-dimensional modeling across various domains. For the data flow from the digital to the physical object, the digital model acts as a decision support and control system for complex urban challenges [3]. Examples of complex urban challenges are efficient energy management, mobility in cities, and consequences of the climate crisis.

Without technologies like Internet of Things (IoT), Artificial Intelligence (AI), Cloud Computing, and Big Data, UDTs wouldn't be possible [9].

Although the distinction between the two concepts of Digital Twin City and Urban Digital Twin is not strict, according to [10] a DTC represents an integrated vision of the city as a whole and UDTs contain specific applications and systems within a city. So Urban Digital Twin is the more general term, as it can be a Digital Twin of an urban area smaller or bigger than a city. In practice, DTC and UDT can overlap or be used together to achieve the goals of smart city development.

In the following, the term Urban Digital Twin will be used because it is the more general term and includes DTC.

C. Smart City and Sustainability

According to [4] a smart city is defined as the usage of intelligent information- and communication-technology to increase participation and quality of life and to create an economically, ecologically, and socially sustainable community or region.
Cities in general are referred to as "systems of systems" with diverse stakeholders and dynamic interactions. When implementing a UDT, it should represent the complexity of a city and take the smaller systems within a city system into account.
Sustainability in general is defined as the ability to meet the present needs without compromising future generations. There are also specific definitions for sustainability from different perspectives: Environmental sustainability includes protecting the climate, leaving ecosystems intact and protecting biodiversity. Part of that is the consideration of resource usage, e.g. energy, water, and carbon emissions. Economic sustainability is not to extract resources faster than they can regenerate in order to be able to use them in the long term, so that economic activity is possible on a permanent basis. Lastly, social sustainability enables people to live together stably and peacefully in the long term [6] [8].

III. Characteristics of Urban Digital Twins

The authors of reference [5] claim that UDTs have experienced significant growth in the last few years. This rapid expansion led to a fragmented situation where the definition of the concept urban digital twin is not clear anymore, and implementations share few similarities. This statement indicates that every UDT looks and acts differently and that there is a need for standardization.
According to [2] UDTs shift traditional governance from static and reactive to dynamic, data-driven, and predictive.

A. Benefits

There are various benefits of UDTs. In general, UDTs lead to improved urban management and more sustainable cities.
The real-time urban data monitoring and integration give the opportunity for city planning and development in the virtual model and thus are improving urban management. Scenario simulation facilitates more informed decisions and thus provides decision support e.g. about city planning and operation [2] [5] [9]. Furthermore, automated actions based on the urban monitoring pave the way to a smarter city [5].
UDTs enhance citizen engagement and provide higher transparency of urban management and governance [2]. This way, democratic governance is supported, and social sustainability is extended.
Since UDTs integrate management across various domains such as infrastructure, transportation, environment, and security into a single tool, in general, the management efficiency is improved [2] [9]. This has various benefits, such as a better overview of interrelationships between interdisciplinary effects.

B. Challenges

This interdisciplinarity is also one challenge, since harmonizing data from heterogeneous sources may be difficult [9]. Keeping the right accuracy, building consistency, and standardizations between the different data formats is a challenge. What comes along is the difficulty of governance coordination and communication among stakeholders [2]. Since UDTs are all about being interdisciplinary, there is a necessity for co-creation and participatory approaches [9].
Because of the mentioned lack of unified frameworks and protocols, there is a need for standardization [9] [12]. Stakeholders of different domains should come together and work on a way to establish common protocols, frameworks, clear policies, and organizational structures.
One very important challenge UDT-developers have to take into consideration is data privacy and security [2] [9]. UDTs contain much sensitive and private data like high-resolution images and 3D-models of private properties. The owners of each property have the right to decide which data could be published or used and which not. Another case where data privacy should be the priority is governance places and critical infrastructures, such as military bases. The risk of having high-resolution data public could have fatal consequences.
Another challenge could be possible infrastructure limitations in existing infrastructure, e.g. Storage, Computation, and Network [12]. There could also be difficulties of data acquisition and actuation, i.e. collecting real-time data and implementing responsive actions [12].
Since UDTs bring data from heterogeneous sources together, they also come with higher costs than simpler systems [5] [12].
In general there could be challenges in governance, organizational structures, and social issues, e.g. societal acceptance [5] [12].

IV. Use Cases of Urban Digital Twins

Some of the possible use cases and applications of UDTs are listed below. The list is not intended to be exhaustive.
In Fig. 2 is a representative illustrative example of an Urban Digital Twin.

1. Urban emergency and security systems [3]
The real-time monitoring of UDTs provides the opportunity for real-time crisis monitoring: Since the data is automatically updated and can be processed immediately, rapid responses and situational awareness are possible in emergency situations.

2. Smart energy systems [3] [5] [9]
UDTs can be part of a smart energy system where optimized energy consumption and resource management are in focus. Consumers of large energy sources can, for example, be prioritized at times when renewable energy sources supply a lot of energy, e.g. when the sun shines on photovoltaic systems or when high wind speeds cause wind turbines to run.

3. Urban traffic management [3] [9]
In urban traffic management, UDTs can be used for simulations and monitoring of traffic to find more efficient ways for traffic flow. UDTs could also be permitted to control traffic

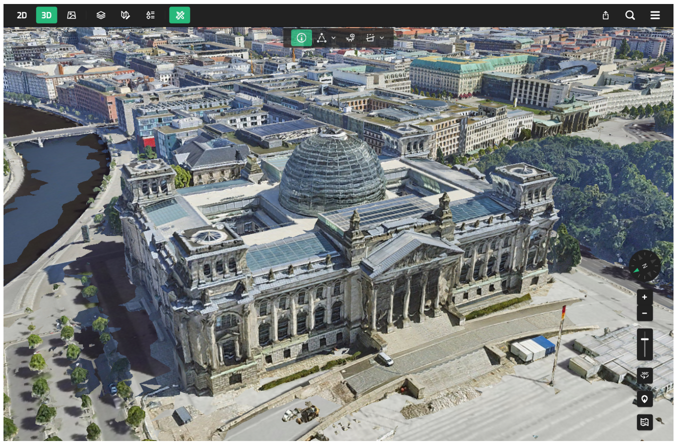

Fig. 2. Illustrative representation of a Urban Digital Twin; Mesh-Model of Berlin [11]

to reduce congestion, e.g. by controlling the number of lanes and the traffic light circuits.

4. Public health monitoring [3]
UDTs could be useful in monitoring the health of the population, e.g. by monitoring pathogens in wastewater. This integrated data could support decisions in population health management.

5. Urban planning and development [3]
Since UDTs combine data from heterogeneous sources which may have never been used together before, simulations and scenario testing are possible by considering multiple perspectives. This gives the opportunity for predictive modeling to guide city design. E.g., new urban districts can be planned taking into account economically, ecologically, and socially sustainable goals.

6. Infrastructure Monitoring [9]
By monitoring infrastructure in cities, e.g. road surfaces, public buildings, and bridges, structural health and maintenance needs could be assessed more easily, and UDTs could again be used as decision support.

7. Environmental Monitoring [5] [9]
Sensors which track different environmental parameters could be connected to UDTs to collect the data of e.g. air quality, temperature, and noise level over time. This could be interesting to know for citizens and to improve life quality in the city.

A. Sustainability

The goal of economical, ecological, and social sustainability was already mentioned in some of the use cases listed above. Since this is a big part of the usage of UDTs, some more specific use cases are listed out of the paper [12]. In general, UDTs support evidence-based decision-making that aligns with sustainable goals.

1. Energy Efficiency and Carbon Reduction
With UDTs, the integration of renewable energy sources gets easier and more efficient compared to fossil energies because smart energy systems become possible. The energy consumption can be optimized and maintenance predicted.

2. Sustainable Mobility
With the help of UDTs, public transport networks, bike lanes, and pedestrian zones could be simulated and optimized. Real-time traffic data can be used to reduce congestion and emissions.

3. Efficient Resource Management
Water, waste, and energy systems can be monitored by UDTs and adjusted dynamically when necessary. The monitoring would give the opportunity for predictive modeling, which supports early detection of inefficiencies or system failures (e.g., leaks, overflows, overuse).

4. Resilience to Climate Change and Sustainable Urban Planning
UDTs can be used for simulations of extreme weather events and their urban impact, which would enable disaster preparedness. Concrete examples for the UDT usage are flood modeling or heat island mapping.
Testing and simulating climate adaptation strategies (e.g., solar systems, green roofs, reflective materials) before a large-scale rollout could be a beneficial usage of UDTs. In Fig. 3 is an exemplary use case of a UDT shown: A visualization of the solar potential on a Level-of-Detail 2 (LoD2) building layer of Berlin. The solar potential shows how much energy a photovoltaic system on each surface would produce. The profitability calculator of virtualcitysystems GmbH then shows how beneficial a solar system installation would be.
In city development, it would be meaningful to evaluate the long-term sustainability impact of development decisions by predicting consequences.

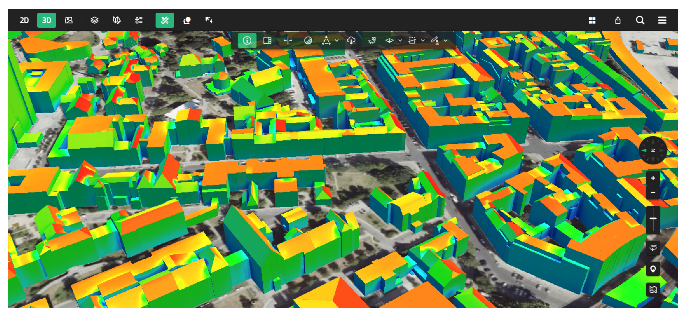

Fig. 3. Solarpotential of LOD2 buildings in Berlin [11]

5. Improved transparency, enabling citizens to engage in planning for sustainability
UDTs can visualize the consequences of decisions before implementation. This improves transparency for citizens and also improves policy quality and accountability. People could, this way, gain a greater understanding of sustainability and the impact they can make.

V. Discussion and Outlook

The term digital twin is used a lot in the topic of virtual representations of urban areas, even if, by definition, in some cases it is only a digital model or shadow. Some of the use cases that were mentioned are also possible with digital models or shadows, i.e. without automatic bidirectional data flow. In general, the digital models of urban areas seem to be used mostly for monitoring and simulations. Especially, simulations can be done more easily by human interaction and without automation.

For the outlook, some perspectives and suggestions for a future with Urban Digital Twins were collected.

According to [3] Digital Twins are not just a tool, but a new paradigm for urban governance and sustainable development. So it would be an infrastructure investment to enhance computational and network capabilities to support UDTs.

According to [2] there is a need for interdisciplinary approaches due to the interdisciplinarity of UDTs. Branches that should collaborate are, for example, urban science, data science, and public policy. Interdisciplinary Research would be equally meaningful [5], e.g. collaboration between technologists, urban planners, and social scientists. An expansion into global comparative studies could be very interesting [2].

The need for the development of standards and interoperability protocols was already mentioned. This would include establishing common protocols, frameworks, clear policies, and organizational structures to get more unified UDTs [2] [9].

To improve data management, robust data governance practices to ensure quality and consistency should be implemented.

Another aspect to consider is the scalability: Developing solutions that can adapt to varying city sizes and complexities would be proactive [9].

To focus on ethics and sustainability would increase the potential of UDTs. Part of that could be to address privacy, equity, and inclusivity [2] [9].

Lastly, early investing in human resources and training to develop necessary skills for the development and usage of UDTs would have a great long-lasting impact [12].

VI. Conclusion

This paper was about the urban implementation of digital twin technology. The main characteristic of digital twins is the two-way interaction between the physical and virtual worlds. The goal of a smart city is to increase participation and quality of life, and to create an economically, ecologically, and socially sustainable community or region. Urban Digital Twins have various benefits but also challenges. The use cases range from monitoring for rapid responses and simulations to urban management and planning.

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