Application and Development of Digital Twins in Smart Cities

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***Abstract*—This paper synthesizes existing research to explore the synergistic relationship between the advancement of digital twin technology and the evolving landscape of smart cities. It delves into the mechanisms by which digital twins are integrated into smart city frameworks, positioning digital twins as pivotal components in the evolution of these urban environments. Understanding the influence of digital twin technology on smart cities is crucial for fostering the deployment of digital technologies in future urban settings. Moving forward, the seamless integration and application of 5G, cloud computing, the Internet of Things (IoT), blockchain, artificial intelligence, digital twins, and 3R technologies (virtual reality, augmented reality, mixed reality) will be essential for the development and management of smart cities. The investigation into the utilization of digital twin technology within smart cities aims to enhance the efficiency of resource allocation and urban governance.**

Keywords—Digital Twin, Smart City, Digital Twin Application, Smart City developed trends.

I. Introduction

Since the advent of the Internet revolution, data has emerged as a pivotal production factor and societal resource. Against the backdrop of the 'Internet+' era, the rapid evolution of big data, the Internet of Things (IoT), blockchain, the metaverse, and the integration of digitalization into daily life have become central themes. The concept of smart cities (SC) represents a novel development in the information age, aiming to provide residents with intelligent services, promote safer and more eco-friendly urban environments, and elevate the quality of life. This approach seeks to mitigate the challenges posed by the widespread influence of technology. Government decision-makers endorse SC initiatives that strive for sustainable economic growth, enhance the quality of life for both residents and visitors, and effectively tackle these issues [1]. With urbanization on the rise, the urban population is expected to grow; Statista predicts a global urbanization rate of 57% by 2022, with 56% of the population residing in urban areas [2]. Consequently, urban management necessitates smarter and more customized solutions, a fact that has attracted significant interest from researchers in the field of smart urban management. Although the concept of smart cities originated in the 1990s, it is in the past decade that this domain has witnessed an extraordinary surge in growth and diversification, incorporating a multitude of interdisciplinary perspectives [3]. Smart cities are poised to become more digitized and intelligent, integrating various cutting-edge technologies such as IoT, 5G, blockchain, collaborative computing, and simulation. This review aims to examine the existing foundations of smart cities and explore the application of big data in their development.

The paper is structured as follows: the second section delves into the framework and developmental trajectory of smart cities; the third section discusses the implementation of digital twin technology within smart cities; and the concluding fourth section addresses the challenges and issues encountered in the evolution of digital twin cities.

II. The Development of Smart Cities

A. Structure of Smart City

The classification of existing smart city frameworks is diverse, as illustrated in Figure 1, which depicts the typical system architecture of smart cities. The evolution of smart cities emphasizes the integration of digital technologies, distinguishing them from conventional urban structures. Building upon Khalid's (2019) delineation of smart city applications, which originally categorized the structure into perception, network, and application layers [4], this study, in conjunction with the insights from Khalid and Rasha F., proposes an advanced five-layer model for smart city development. This model, as depicted in Fig. 1, encompasses the City Application Layer, Urban Decision-Making System Support Layer, City Data and Control Layer, Communication and Network Layer, and Sensing Terminal Layer, each of which plays a crucial role in the implementation of smart city initiatives.

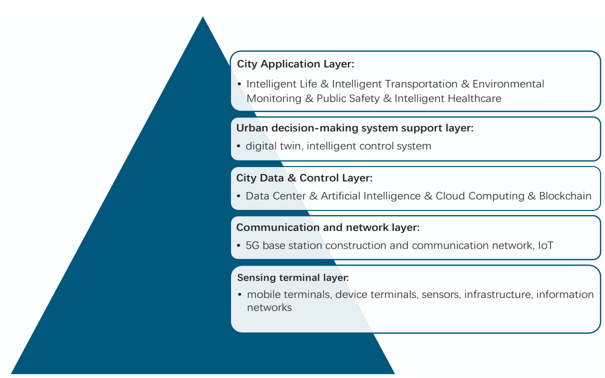

Fig. 1. Instructions of digital twin in smart city application

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B. *The Trend of Smart Cities*

Since 2010, the evolution of smart cities has encompassed the realms of digital cities, smart cities, and digital twin cities. Through the construction of smart cities, both industry and academia have benefited from the exploration of digital management and governance. T. Nochata examines the distinctions between smart cities and traditional cities, as well as the influence of digital twin technology on smart city development and management, using the Cambridge smart city case study as a reference [5]. Additionally, Allam (2021) discusses the future and development characteristics of a meta smart city in the 6G era, emphasizing the role of digital twin and immersive reality applications in smart cities [6]. This paper synthesizes existing research to outline the developmental trajectory of smart cities, as depicted in Fig 2.

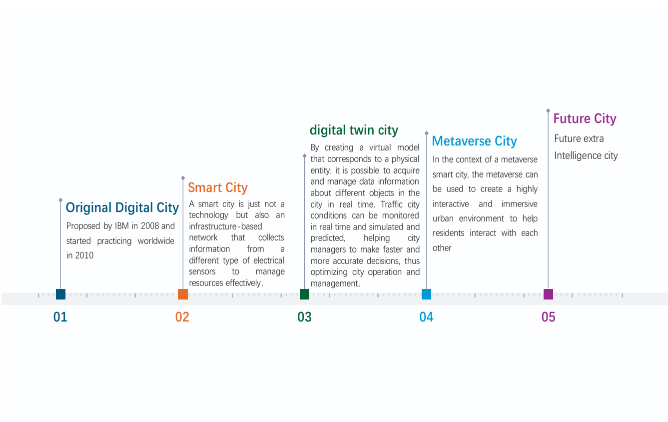

Fig. 2. Smart City developed trend

As shown in Fig 2, digital twin cities represent the advanced and profound evolution of smart cities. Smart cities are built upon the foundation of digital cities, focusing on enhancing urban intelligence and expanding and upgrading city functions through the integration of cutting-edge information technologies like cloud computing and the Internet of Things. Digital twin cities, as a high-level iteration of smart cities, are established by further integrating a suite of information technologies including artificial intelligence, 3D modeling, BIM, and CIM. By reimagining urban planning, optimizing infrastructure control, and fostering a bidirectional interaction and integration between the real and virtual, digital twin cities embody a more sophisticated form of smart city construction. These cities achieve comprehensive digitalization and intelligence through digital technologies, marking a pivotal juncture in the progression of smart cities.

The distinguishing features of digital twin cities include data, interactivity, and integration, which are evident in: (1) efficient information transmission and sharing; (2) dynamic urban environment perception and monitoring; (3) enhanced synergy in urban management and services; and (4)The convergence of digital twin and smart city.

III. The Convergence of the Digital Twin and Smart City

A. *Digital Twin(DT)*

The inception of the digital twin concept can be traced back to 2002, when Michael Grieve introduced it during a presentation on 'Product Lifecycle Management' [7]. Its application in aerospace, particularly by NASA, has been instrumental in defining a digital twin as a multiscale, probabilistic, and ultra-fidelity simulation that accurately reflects the status of its physical counterpart in real-time, utilizing both historical and current data [8]. This approach has become prevalent in the manufacturing sector, where digital twins are integral to product design, manufacturing processes, and lifecycle management, continuously evolving with technological advancements. This integration addresses criticisms that often confuse digital twins with mere digital shadows [9]. Research into digital twin applications within Smart Cities primarily explores their role in the design, operation, and management of urban environments. The foundational principle of digital twins involves translating the physical components of a city into a virtual cyber-space representation, thereby creating a mirrored relationship between the real and virtual cities.

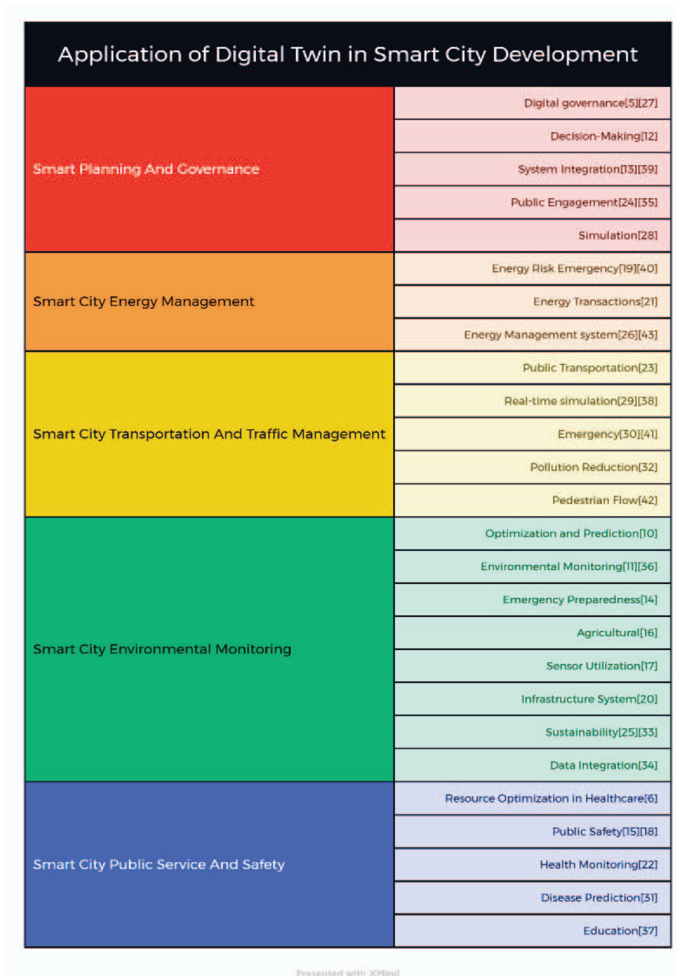

Fig. 3. digital twin in smart city application

Figure 3 depicts the application of digital twin technology in smart cities, enhancing urban planning and governance efficiency through optimized resource allocation and information integration. Significant advancements have been made in energy management, transportation, environmental monitoring, and public safety. The Smart City concept integrates key urban infrastructure components such as environmental, emergency, traffic, and power management. Digital Twin (DT) technology supports the development and maintenance of virtual models of real-world entities and processes. This approach leverages the capability to autonomously gather and process data streams from distributed IoT sensors efficiently.

Digital Twin technology facilitates the prediction of alterations in urban infrastructure conditions and offers optimal solutions by analyzing data on the dynamics, dependencies, and temporal and spatial variations of people and traffic. Additionally, Digital Twins enable the exploration of "what-if" scenarios, aiding in understanding how a city equipped with smart technologies will operate under particular economic, environmental, and social conditions, and in detecting potential malfunctions of influencing factors [9]. Current urban smart architecture is deficient in harmonized standards, whereas the Digital Twin technology framework has reached a more advanced stage of development. For instance, Rasha F (2022) introduced a Five-layer architecture framework encompassing the Physical Layer, Data Sensing Layer, Data Transmission Layer, Virtual Layer, and Application Layer. This paper utilizes the Urban Intelligence (UI) modeling structure proposed by Giordano (2022), which is a UI architecture designed to represent all urban systems and subsystems, including urban infrastructure and the interactions of urban users [10].

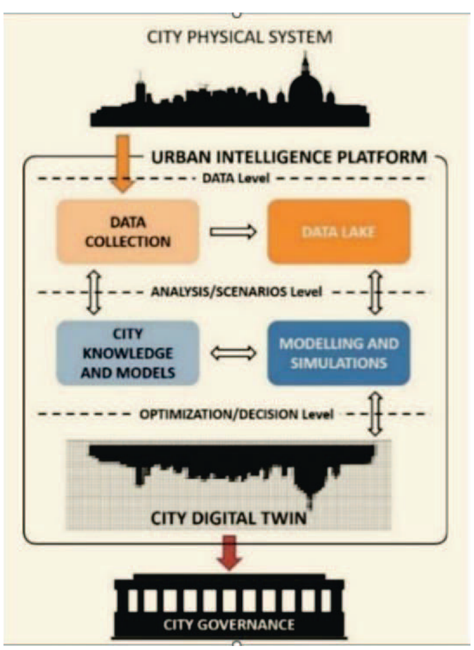

Fig. 4. The UI platform architecture

Figure 4 depicts the user interface platform, which comprises five interconnected modules: 'city knowledge and models', 'data collection', 'data lake', 'modelling and simulations', and 'city digital twin'. These modules leverage key enabling technologies including IoT networks, data science and modelling, high-performance computing, and advanced numerical optimization [11].

B. Applications of Digital Twin Technology

- Digital characterization, simulation and reduction of physical space: The authors posit that digital twin technology enables the recording and monitoring of urban physical entities, as well as the digital representation of city's physical spatial elements, processes, and actions through modeling simulation and 3R technologies (augmented reality, virtual reality, and mixed reality). This advancement is expected to enhance the efficiency and precision of urban management, facilitating a deeper understanding of city structure and function among planners, and optimizing the allocation of planning and funding resources.
- collaborative effort: Leveraging the synergistic integration of big data, cloud computing, the Internet of Things, digital twin technology, and visualization, a scientific and intelligent system for multi-departmental coordination is established, effectively consolidating data and resources across various entities[12][13].
- Environmental Monitoring and Energy Management. City administrators can enhance urban environmental sustainability and energy efficiency through the deployment of smart grids and advanced energy management systems. Swift and adaptable responses to emergencies and security challenges serve to showcase the city's governance capabilities. The ability to promptly address situations is crucial, as is the capacity to respond swiftly to evolving circumstances[14][15].
- Scenario landing for new business: Digital twin technology can facilitate the expansion of smart city functions and service upgrades and support the development and implementation of new types of business scenarios, such as smart transportation and smart energy management. Digital twins provide a pilotable environment for many once hypothetical businesses, such as smart transportation, smart healthcare, and immersive virtual reality games, accompanied by advances in visualization technology (3Rs) and blockchain technology[16][17].

IV. Smart City Challenges and Issues

A. Technical Issues

The integration of novel technologies in smart cities far exceeds that of conventional urban settings. Key challenges that must be resolved encompass the maturity and compatibility of these technologies, along with societal acceptance. Pertinent issues also involve data-related complexities, including data sharing, visibility, validity,