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Research on the Construction of Digital Twin-Driven Smart City Renewal Technology Framework and Application Paths

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Abstract

Under the background of accelerating new urbanization process, smart urban renewal has been transformed from "incremental construction" to "stock optimization", and the traditional renewal mode is difficult to meet the demand of sustainable urban development due to data silos and lack of dynamic simulation. Based on digital twin technology, this paper explores the application path of smart urban renewal by constructing its technical framework, aiming to provide a full life cycle digital solution for urban renewal. The study proposes a layered architecture technology framework, covering perception layer, data layer, platform layer, application layer and user layer, integrating key technologies such as Internet of Things, three-dimensional modeling, big data analysis, etc.; designing a four-phase application path including status quo assessment, program design, implementation monitoring and operation and maintenance optimization, and carrying out an empirical analysis by combining the case studies of Qianhai, Shenzhen and Xiong'an New Area. The study shows that digital twin technology can significantly improve the planning science, construction efficiency and operation and maintenance intelligence of urban renewal, providing theoretical and technical support for smart urban renewal practice.

Subject Areas

Civil Engineering

Keywords

Digital Twin, Smart Urban Renewal, Technology Framework, Application Path, Full Life Cycle Management

1. Introduction

1.1. Background

Driven by global economic integration and rapid development of science and technology, the urbanization process is moving forward at an unprecedented speed. According to authoritative statistics, the global urbanization rate has exceeded 55%, and China's urbanization rate has even exceeded 65%, which not only marks the expansion of the city scale, but also means that the city development has gradually entered the key transition period of stock optimization. At this stage, cities are no longer purely pursuing the expansion of area and population growth, but are focusing on the efficient use of existing space, the rational layout of functions, and the iterative upgrading of infrastructure. As a core driving force for sustainable urban development, smart urban renewal is essentially a systematic and holistic optimization and innovation of urban space, functional system and infrastructure with the help of advanced technology to meet the diversified needs of urban development in the new era [1].

However, the traditional urban renewal model has revealed many drawbacks that are hard to ignore in practice. At the planning level, it relies excessively on empirical subjective judgment and lacks accurate quantitative analysis of complex urban systems, leading to a serious disconnect between resource allocation and actual demand, resulting in a large amount of wasted and inefficient use of resources. In terms of data management, due to the scattered storage and different standards of data from various departments and fields in the city, it is impossible to realize effective integration and sharing, which makes it difficult to form a scientific and reasonable decision-making plan due to lagging information acquisition and one-sided analysis in the decision-making process. In addition, the traditional model lacks dynamic simulation capabilities, and when facing complex scenarios such as emergencies, changes in population flow, and industrial restructuring in the urban operation process, it is impossible to predict and simulate the possible impacts in advance, and it is difficult to formulate forward-looking and adaptive coping strategies.

Digital twin technology, as a landmark innovation of the fourth industrial revolution, brings a brand-new solution to the problem of smart city renewal. The technology realizes real-time interaction and deep integration between the physical world and the virtual world by constructing accurate mirrors of physical entities in the virtual space and applying technologies such as Internet of Things, big data and artificial intelligence. With the help of digital twin technology, it can carry out all-around, full-cycle real-time simulation and intelligent decision-making for the urban system, effectively make up for the shortcomings of the traditional mode, and open up a new technical paradigm and development path for smart urban renewal.

1.2. Significance of the Study

At the theoretical level, the cross-study of digital twin and smart city renewal is still in the development stage, and there are many theoretical gaps that need to be filled. This study explores the application principle, technical architecture and mechanism of digital twin technology in smart urban renewal, which helps to improve the technical theoretical system of digital urban governance, provides theoretical support and research direction for the subsequent related research, and promotes the development of theoretical research in the field of urban renewal to a deeper level and a wider field.

From a practical point of view, the results of this research have significant practical application value. By constructing a set of practicable technical frameworks and application path, it can provide a scientific and accurate decision-making basis for urban renewal projects. In the project planning stage, simulation analysis based on digital twin technology can optimize resource allocation, avoid blind investment and repeated construction, and effectively reduce construction costs; in the project implementation and operation stage, real-time virtual simulation and intelligent decision-making functions can help managers identify and solve problems in urban operation in a timely manner, improve the refinement and intelligence level of urban governance, and help realize the "city as a living organism". It helps to realize the goal of fine management of "city as a living organism" and promote the high quality and sustainable development of the city [2].

2. Research Methods and Technical Routes

This research comprehensively applies the literature analysis method, system modeling method and case empirical method to carry out the research work in a multi-dimensional and systematic way. In terms of literature analysis, research results in the field of digital twin and smart city renewal at home and abroad, including academic papers, research reports, policy documents, etc., are widely collected and sorted out, and through in-depth analysis and summarization, the current research status, development trend, and existing problems in the field are comprehensively grasped, and a solid theoretical foundation is constructed.

Based on the previous theoretical research, the system modeling method is adopted, and based on the principles of scientific, practical, and extensibility of technical architecture design, the layered technical framework is proposed from the dimensions of data layer, platform layer, and application layer in close conjunction with the actual needs and business processes of urban renewal business. The framework aims to integrate urban multi-source data, realize efficient data processing and analysis, and provide strong technical support for smart urban renewal applications.

In order to verify the feasibility and effectiveness of the constructed technical framework and application path, this study selects representative typical cases such as Shenzhen Qianhai and Xiong'an New Area for in-depth research. Through field research, data collection, case analysis and other methods, the research results are applied to actual cases, and the difference in effect before and after application is compared and analyzed [3].

3. Theoretical Foundation and Research Status

3.1. Core Concept Definition

Digital Twin (Digital Twin) was first proposed by the U.S. Department of Defense in 2003, which refers to the digital modeling of physical entities through sensors, data collection equipment and algorithmic models to form a virtual mirror that can be interacted with in real time. In the field of smart city, digital twin technology integrates all elements of urban data to build a city-level virtual space, realizing real-time monitoring, simulation, prediction and optimization of the city's operational status. Smart city renewal is a process of systematic transformation and upgrading of the physical space, social economy and ecological environment of the city supported by digital and intelligent means, emphasizing the synergy of multiple subjects and full life cycle management [4].

3.2. Development Status of Digital Twin Technology

Digital twin technology has experienced an evolutionary process from single device modeling to complex system integration. Currently, its key technology system covers IoT sensing technology, 3D modeling (BIM/GIS), big data analysis, artificial intelligence algorithms and 5G communication. At the hardware level, the popularity of high-precision sensors and edge computing devices improves the data collection efficiency; at the software level, the optimization of Unity, Unreal Engine and other 3D engines significantly enhances the visualization and interactivity of the twin model. In addition, the integration of digital twins with CIM (City Information Model) has become a new trend, promoting the development of city-level digital twins in the direction of refinement and dynamization.

3.3. Progress of Smart City Renewal Research

The traditional smart urban renewal model relies on manual research and empirical judgment, and there are three major pain points: first, data collection is scattered, making it difficult to form an all-area perception capability; second, there is a lack of dynamic simulation tools to predict the long-term impacts of the renewal program; and third, the inefficiency of multi-body synergy leads to the slow advancement of the project. In recent years, the application of digital twin technology in smart city renewal has gradually increased. Singapore's "Virtual Singapore" project realizes multi-program comparison and risk warning of urban planning by constructing city-level digital twins; Shanghai's Hongqiao Business District uses digital twin technology to optimize traffic organization, which improves traffic efficiency by 15%. However, the existing research mostly focuses on single-scene applications, and lacks the exploration of systematic technical frameworks and universal application paths [5].

4. Construction of Digital Twin-Driven Smart Urban Renewal Technical Framework

4.1. Framework Design Principles

The technical framework proposed in this study follows three major design principles: 1) systematic principle, covering the whole process of urban renewal planning, construction, operation and maintenance; 2) synergistic principle, integrating the data and business needs of multiple subjects such as the government, enterprises, and the public; and 3) scalability principle, adopting a modularized design to support new technologies (e.g., AI macromodel, 6G communication) and seamlessly accessing new technologies. (e.g., AI big model, 6G communication) seamless access.

4.2. Layered Architecture of Technical Framework

The digital twin-driven smart city update technical framework adopts a five-layer architectural design (Figure 1).

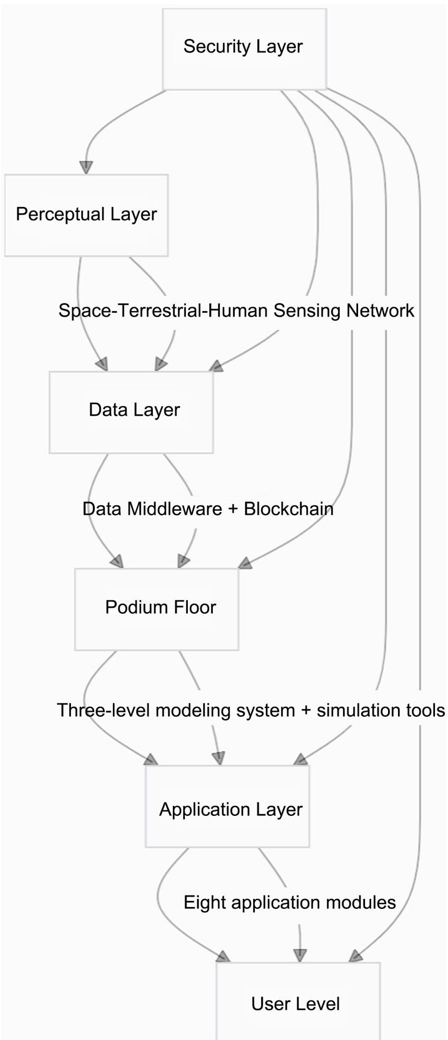

Figure 1. Layered architecture of digital twin-driven smart urban renewal technology framework.

Perception Layer: Deploying the IoT sensor network, including meteorological monitoring devices, traffic flow sensors, and environmental quality detectors, etc., to realize real-time collection of urban physical space data. Edge computing nodes perform preliminary processing of raw data to reduce data transmission pressure.

Data layer: Integrate heterogeneous data from multiple sources through the data governance platform, including GIS geographic information data, BIM building model data, real-time monitoring data, and socio-economic statistics. Blockchain technology is used to ensure data security and credible sharing, and build an urban renewal database.

Platform layer: Based on 3D modeling engine (e.g. CityEngine) and physical simulation engine (e.g. Ansys), the platform builds digital twin model, and combines AI algorithms (e.g. deep learning, reinforcement learning) to realize dynamic optimization of the model. The platform supports multi-scale modeling, ranging from building monoliths to city districts, to meet the needs of different scenarios.

Application layer: Develop scenario-based application modules, including urban renewal planning simulation system, construction progress monitoring platform, urban operation and maintenance management center, etc. Through AR/VR technology, it realizes the integration and interaction between virtual models and real scenes, and improves the intuition of decision-making.

User Layer: Provide multi-access interfaces for government departments, enterprise units and the public, and support visual interaction between Web, mobile and big screen. It realizes hierarchical data sharing through the permission management system to ensure information security.

Security layer: establishes a "cloud-management-end" all-round security protection system and adopts Zero Trust Architecture to ensure data security.

4.3. Key Technology Module

Multi-scale Modeling Technology: Adopt LOD (Level of Detail) model grading strategy to model the core areas of the city (e.g., commercial centers) with high precision, and adopt lightweight models for the suburbs and other areas, so as to reduce the computation cost while guaranteeing the precision.

Real-time data interaction mechanism: Based on 5G/6G communication technology, a two-way data channel is established between the physical city and the virtual twin. Through timestamp synchronization and data verification algorithms, the consistency of virtual and real data is ensured.

Intelligent Prediction Algorithm: Construct a prediction model of the impact of urban renewal, integrating the algorithm of time series analysis (LSTM) and spatial analysis (Graph Neural Network) to predict the impact of the renewal plan on traffic flow, population distribution, energy consumption and other indicators.

5. Application Path Design and Implementation Strategy

5.1. General Framework of Application Path

The digital twin-driven smart urban renewal application path is divided into four phases [6] (Figure 2).

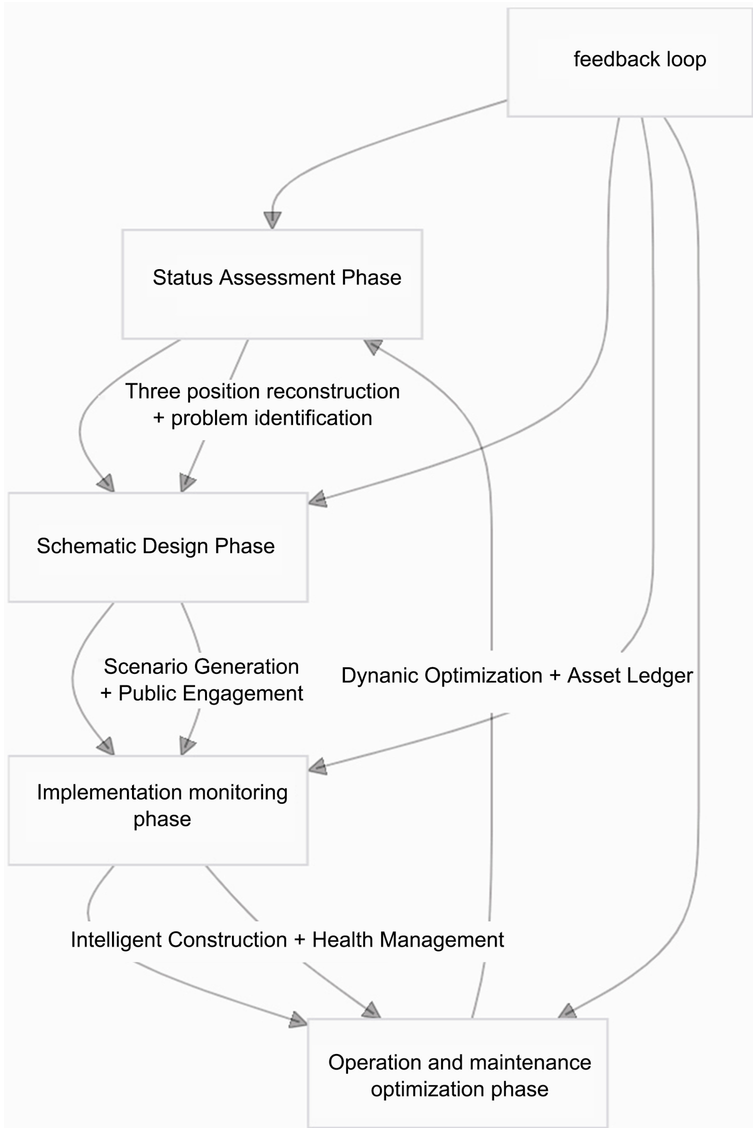

Figure 2. Application path of digital twin-driven smart urban renewal.

Current Situation Assessment Phase: Integrate data on urban space, facilities, and population through the digital twin model, and identify the renewal needs and problems (e.g., safety hazards of old buildings, insufficient public service facilities).

Scenario design phase: Simulate multiple scenarios based on the digital twin model to evaluate the economic benefits, environmental impact and social acceptance of different renewal scenarios to assist in decision-making and optimization.

Implementation monitoring phase: track construction progress in real time using the digital twin platform, monitor construction safety and quality through IoT devices, and provide early warning of potential risks (e.g., collision of underground pipelines).

Operation and Maintenance Optimization Phase: Connect the updated urban facility data to the twin model, and optimize urban services such as energy scheduling and traffic management through real-time monitoring and simulation analysis.

5.2. Paths for Key Application Areas

Infrastructure Renewal: Taking underground comprehensive pipeline corridors as an example, the digital twin model integrates pipeline layout, geological structure and real-time monitoring data to predict the aging trend of pipelines and formulate accurate maintenance plans. After applying this path in Shenzhen Qianhai Integrated Pipeline Corridor Project, the response time of pipeline failure was shortened by 40%, and the operation and maintenance cost was reduced by 25%.

Optimization of public space: Based on the thermal simulation of human flow in digital twin model, we analyze the use efficiency of public space such as parks and squares. Through simulation of different renovation plans (e.g., adding rest facilities, optimizing green layout), the accessibility of the space and the satisfaction of residents can be improved.

Building Energy Efficiency Enhancement: Building digital twins are constructed to simulate the energy-saving effects of different energy-saving retrofit programs (e.g., external wall insulation, photovoltaic system addition) by combining energy consumption monitoring data and climate models. An office building in Xiongan New Area realized an 18% reduction in annual energy consumption through this path.

5.3. Implementation Guarantee Strategies

Policy Mechanisms: Promote the incorporation of digital twin technology into urban renewal standards and norms, and establish cross-departmental data sharing and collaborative management mechanisms. For example, Shenzhen has issued a white paper on digital twin city construction, clarifying the scope of data openness and security requirements.

Technical standards: Develop digital twin model format standards (e.g., IFC, CityGML), data interface specifications and security protection guidelines to promote interoperability between different platforms.

Talent Cultivation: Jointly offer interdisciplinary courses on digital twins and smart cities with universities and enterprises to cultivate composite talents with both technology development and urban planning capabilities.

6. Challenges and Countermeasures

6.1. Challenges

Data Privacy and Security: City-level data involves a large amount of personal information and sensitive data, and there is a risk of data leakage and malicious attacks [7].

Model accuracy and cost balance: High-precision digital twin models require high hardware computing power and algorithm complexity, leading to rising construction and operation and maintenance costs [7].

Multi-subject synergistic problems: the government, enterprises and the public have differences in data authority and interests, and the imperfect synergistic mechanism affects the efficiency of project promotion [7].

6.2. Countermeasure Suggestions

Technical level: Adopt federal learning, homomorphic encryption and other technologies to realize "available and invisible" data, and research and develop lightweight modeling algorithms to reduce computation costs.

Management level: establish a collaborative governance mechanism led by the government, participated in by enterprises and supervised by the public, clarify the rights and responsibilities of data sharing, and improve the benefit distribution and dispute resolution mechanism.

7. Conclusion and Outlook

This study constructs a digital twin-driven smart city renewal technology framework, designs a full-process application path, and verifies its effectiveness through cases. The study shows that digital twin technology can significantly improve the science, efficiency and intelligence of urban renewal. In the future, the study can further explore the deep integration of digital twin with meta-universe and AI big model, and expand its application scenarios in the fields of urban emergency management and low-carbon development; at the same time, it is necessary to strengthen the standardization construction and international cooperation of digital twin technology, so as to promote the development of smart city renewal to a higher level [8].

Conflicts of Interest

The authors declare no conflicts of interest.

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