Research on Dynamic Simulation of VR-Enabled Urban Renewal Planning and Multi-Agent Interest Coordination

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Abstract: With China's urbanization entering a new stage, urban renewal has become a key topic for promoting the city's sustainable development. The traditional planning model has several problems, including low public participation and difficulty in coordinating interests, which make it challenging to cope with the complexity and dynamic changes in the updating process. This research focuses on the urban renewal planning empowered by virtual reality (VR), aiming to build a comprehensive solution that integrates dynamic simulation and multi-stakeholder interest coordination. Firstly, this paper defines core concepts such as urban renewal and VR dynamic simulation, and supported by public participation theory and collaborative governance theory, systematically elaborates on the mechanism by which VR technology achieves virtual-real mapping of spatial scenes through CIM modeling and dynamic data loading, and its path for optimizing planning schemes in multi-scenario deduction and participatory design. In addition, this paper provides a comprehensive analysis of the game characteristics from multiple stakeholders, including the government, market, and residents, proposes effective strategies, and further optimizes the governance mechanism. Research findings show that the deep integration of VR technology can effectively enhance the scientific nature and inclusiveness of planning, providing a theoretical foundation and practical paradigms for developing a perceptible, negotiable, and adjustable intelligent urban renewal governance system.

1. Introduction

Traditional urban renewal models have faced challenges, including inefficient interest coordination and low public participation, during the process of accelerated urbanization. In this context, the rapid development of technologies like virtual reality (VR) and digital twins has brought innovative solutions to urban renewal. By constructing virtual simulation models, urban planners can instantaneously simulate the spatial layouts, environmental impacts, and socio-economic dynamics of different scenarios. Relying on the City Information Model (CIM) platform, urban information can be dynamically mapped to physical spaces and optimized for resource allocation and management [1]. The real-time data loading and dynamic simulation of digital twin cities provide scientific support for our goals of reducing urban carbon emissions and monitoring energy consumption, enabling us to make more informed decisions. At the same time, virtual reality technology can also create an immersive experience, allowing more people to participate in the urban renewal plan. In China, the "14th Five-Year Plan" has explicitly promoted digital transformation and the intensive development of cities. Local policies are exploring new land use mechanisms and dynamic monitoring technologies to coordinate multiple interests. The deep integration of virtual reality and digital twin technology enables us to dynamically simulate various planning schemes, which is convenient for comprehensive management of the entire project cycle. However, their application in coordinating the interests of all parties needs more systematic research.

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2. Core Concepts and Theoretical Basis

2.1 Definition of Core Concepts

2.1.1 Urban Renewal

Urban renewal is a systematic project, primarily aimed at areas in the city with outdated functions, aging facilities, or poor environmental conditions. We will use many methods, such as demolition and reconstruction, upgrading, or protection and activation, to optimize space, upgrade industries, and make the city full of vitality again. At the same time, we should also consider the economic, social, and environmental benefits. Unlike previous demolition and construction projects, the current urban renewal places greater emphasis on involving the public and collaborating with various groups. We will utilize refined planning to inject new vitality into existing urban areas, enabling the city to continue growing [2].

2.1.2 Virtual Reality (VR)

Virtual reality (VR) technology is a simulation system that integrates computer graphics, sensing technology, and immersive human-computer interaction. With the help of devices like head-mounted displays, VR technology can create an interactive, three-dimensional virtual environment. It allows users to experience an "as if they were there" feeling in urban renewal practices. VR technology can transform planning blueprints into visual, walkable digital scenes that support multidimensional spatial simulations, such as streetscapes, architectural details, and public facility layouts. It also supports real-time interactive adjustments. VR technology provides intuitive technical support for planning decisions, public participation, and plan evaluation, thereby reducing discrepancies in information transmission [3-4].

2.1.3 Dynamic Simulation

Dynamic simulation is a methodology that leverages system dynamics and discrete-event modeling to quantitatively analyze and visualize the spatio-temporal evolution of critical factors in urban renewal—including population migration, transportation shifts, economic returns, and environmental impacts. This method uses simulation models that include policy factors and market rules to predict how an urban area will evolve in the short term and over time under different planning scenarios. It also gives related information after renovations, like community vitality scores and how different types of businesses develop over time. The principal advantage of dynamic simulation is its capacity to offer a "what-if" analysis for planning decisions, thereby enabling the identification of potential risks and facilitating the optimization of resource allocation.

2.1.4 Multi-Agent Interest Coordination

Multi-agent interest coordination refers to the process of utilizing system construction, communication channels, and negotiation procedures to reconcile the needs and rights of various stakeholders, including the government, developers, residents, merchants, and other relevant parties, during urban renewal. The key problem is to address information asymmetry, which refers to the imbalance in the distribution of information. The pursuit of public interests by government departments often conflicts with the pursuit of economic returns by developers; indigenous people maintain the imprint of their lives, which is contrary to the needs of regional modernization and development. Therefore, the coordination system should integrate the expression of interests, build a governance model of "co-construction, co-governance and sharing," and ensure the fairness and operability of the plan.

2.2 Theoretical Foundation

2.2.1 Public Participation Theory

As for public participation theory, its development can be traced back to the trend of democratization in the field of urban planning [5]. Its core is to emphasize the leading role of residents as users of urban space, and to advocate an institutionalized approach to all stages of planning and decision-making. The key content of this theory includes the participation ladder model (i.e., a gradual participation mechanism from information transmission to residents) and participatory planning tools. In the practice of urban renewal, public participation is beneficial in improving the fit between the planning scheme and local characteristics, as well as in enhancing residents' sense of identity with the renovation project.

2.2.2 Collaborative Governance Theory

Collaborative governance theory is committed to building a governance network of equal cooperation among government, market, and society, to achieve public goals through resource sharing and joint responsibility. Its key elements include establishing a trust mechanism, building an information-sharing platform, and formulating common decision-making rules [6]. In the urban renewal project, the collaborative governance model is embodied in the cooperative mechanism of "government guidance, enterprise operation, and community supervision". We utilize a VR dynamic simulation platform to integrate data from various departments, thereby achieving the collaborative promotion of cross-departmental plans and balancing the developer's return on investment with the public interest of the community. This theory provides a framework for aligning the diverse interests of multiple stakeholders.

3. The Application Path of VR in Dynamic Simulation of Urban Renewal

3.1 The Mechanism for Mapping Virtual and Real Elements in a Spatial Scene

3.1.1 Digital Modeling of Physical Space Based on CIM

The cornerstone of constructing a VR scene is the digital modeling of the CIM physical space, whose core lies in building a digital twin that corresponds to the city, covering all elements, multiple dimensions, and is computable. This process utilizes diverse technical methods such as oblique photography, laser scanning, BIM (Building Information Modeling), and GIS (Geographic Information System) to accurately collect and integrate static physical data of the city, including terrain, landforms, buildings, roads, and more, thereby forming a unified and structured urban 3D information model. Compared with traditional 3D models, the CIM not only involves geometric morphological information but also carries rich attribute information, such as building materials, structures, property rights, and municipal facility capacity, thereby constructing a "living" data foundation.

In a VR environment, this CIM model is imported and transformed into an immersive, interactive virtual space. This move completely overturns the conventional planning model based on 2D drawings and abstract renderings, providing a credible and comprehensive digital test field for subsequent dynamic simulations, scenario analysis, and decision-making, and becoming a key prerequisite for achieving virtual-to-real mapping and interaction [7].

3.1.2 Dynamic Data Loading and Environmental Response Simulation

Dynamic data loading and environmental response simulation are core components built upon the static CIM model, endowing the virtual scene with "dynamic" and "intelligent" characteristics. This mechanism uses real-time or near-real-time data from Internet of Things (IoT) sensors, traffic monitoring systems, weather stations, and energy meters to import dynamic information, such as pedestrian and vehicle flow, energy consumption, lighting levels, temperature, and wind speed, into the virtual 3D city model. In the virtual environment, it is possible to reproduce the fluctuations in traffic flow within various areas over 24 hours, display traffic congestion at key intersections in real-time, and test planning solutions (such as adjusting signal light timing or adding dedicated bus lanes) to visually observe the effects of improved or worsened traffic flow. By integrating building energy consumption models, it simulates the impact of new construction on the local microclimate. With the capability for dynamic simulation, we can predictively evaluate the chain reactions triggered by planning interventions before their implementation, avoid potential risks, optimize the comprehensive operational efficiency of the urban system, and make informed decisions.

3.2 Iterative Optimization of Planning Scheme

Multi-scenario simulation is a VR-driven approach that facilitates the iterative refinement of planning proposals. It enables planners, within a virtual environment, to rapidly generate and visualize diverse concepts for a renewal area—such as high-density building clusters, low-density ecological communities, or mixed-use districts—while assigning distinct parameters to each. Leveraging embedded simulation algorithms, the system can automatically or semi-automatically project the prospective impacts of each concept over several decades, evaluating outcomes across economic, social, and environmental dimensions [8]. This intuitive and comprehensive comparison substantially bolsters the soundness and predictive capacity of decision-making, driving the planning proposal through successive iterations to arrive at the optimal solution.

3.3 Problems and Challenges

3.3.1 The Contradiction between Simulation Accuracy and Computing Power Requirements

A persistent trade-off between simulation fidelity and computational demands fundamentally constrains the efficacy of VR dynamic simulation. Achieving immersive experiences and dependable simulation outcomes necessitates models of high geometric accuracy, intricate material textures, and computationally intensive physics. For instance, building energy consumption simulations require precise geometric data, while large-scale crowd evacuation modeling demands sophisticated AI-driven behavioral algorithms for each agent. These high-fidelity simulations impose immense processing loads, challenging the limits of a system's GPU rendering performance, CPU speed, and memory bandwidth. Urban renewal projects, which operate on a significant scale, compound these challenges. Implementing city-wide, high-fidelity, real-time simulation is currently only feasible with prohibitively expensive high-performance workstations and clustered server infrastructures. The high cost and limited accessibility of this hardware necessitate a practical compromise, compelling practitioners to strike a balance between model accuracy and rendering performance in real-world applications.

3.3.2 Technology Bottlenecks

Achieving seamless, real-time synchronization between virtual models and their physical counterparts is a critical objective for deploying digital twin and VR technologies in smart city management. Nevertheless, several technical barriers hinder this goal across three primary dimensions. The first is the inherent delay in data acquisition and transmission. Data from the physical environment, collected by a vast network of IoT sensors, must undergo processing steps including network transit, data cleansing, and integration before it can update the virtual model. This pipeline makes a "real-time" state extremely challenging. The second challenge lies in the complexity of model adaptation and update. When a physical entity undergoes even minor modifications, the virtual model often struggles to automatically and precisely capture and mirror these changes, necessitating significant manual intervention. It leads to a progressive divergence between the "digital twin" and the "physical entity." The third issue is the uncertainty associated with bidirectional control. The ideal of a virtual-to-physical mapping is twofold: the virtual world must accurately reflect the real one, and the virtual system must be able to exert control over physical equipment. This feedback loop involves intricate control algorithms and formidable security barriers, where any fault or latency can trigger operational disruptions or safety hazards. Thus, ensuring an efficient, accurate, and secure synchronization of data, models, and control flows between the virtual and physical realms represents the paramount challenge and key bottleneck for technological advancements.

4. Innovation of Multi-agent Interest Coordination Mechanism

4.1 Game Analysis of Stakeholders

4.1.1 Differences in Government, Market and Residents' Demands

Regarding urban renewal, the process of multi-party participation and negotiation can lead to significant differences in expectations among the government, market, and residents, potentially triggering latent conflicts. As representatives of public interest, the government's goal is to enhance urban operational efficiency, preserve historical and cultural characteristics, and ensure social order stability, striving to achieve optimal overall benefits. However, it is often constrained by fiscal pressure and performance evaluation.

Market entities, represented by developers and investors, prioritize capital appreciation, focusing on building density, commercial returns, and project cycles. They prefer high-density, high-return renovation methods while neglecting social costs.

The needs of the resident group are diverse, as original residents place greater emphasis on improving living conditions and the reasonableness of resettlement compensation. In contrast, newly moved-in residents are more concerned with public services and the convenience of daily life.

In summary, they are embroiled in a struggle over planning objectives, benefit distribution, and risk sharing, making it difficult to effectively reconcile through traditional management models. Therefore, there is an urgent need to establish a mechanism that can clearly articulate the demands of all parties and balance and coordinate them.

4.1.2 The Fragmentation of Property Rights and the Conflict of Income Distribution

A primary source of conflict of interest in urban renewal is the fragmented ownership of properties within the zones. Historic neighborhoods often face intricate property types, ambiguous ownership boundaries, and unclear shared ownership proportions. This results in a multitude of stakeholders, each with their own set of demands. There are significant differences in preference among these groups regarding renewal plans, and the distribution of land appreciation value is a major point of contention. Developers, who shoulder the financial and market risks, believe they are entitled to the profits. The government, in contrast, prioritizes land transfer fees and taxes for public funding. Meanwhile, residents argue that land appreciation is generated by their original property rights and their contributions to the community, and thus, they deserve a greater share of the proceeds.

The fragmented ownership substantially increases the costs of negotiation, often leads to holdout ("nail household") and collective disputes, and obstructs the successful execution of redevelopment projects.

4.2 Design of Collaborative Decision-making Platform

4.2.1 Use Blockchain to Achieve Transparency in Benefit Distribution

The decentralized, tamper-resistant, and traceable nature of blockchain technology offers a novel approach to addressing the issue of low transparency in benefit allocation within urban renewal projects. We have developed a blockchain platform based on smart contracts to store on-chain data, including government planning metrics, developer investment details, resident property rights information, and compensation standards. It ensures all parties have equal access to information regarding the rules and execution of benefit distribution. Smart contracts are pre-programmed with a "land value-added revenue distribution formula." Once the project reaches certain milestones, such as completing the cost accounting, the system automatically transfers the related revenue to the government's treasury, the developer's account, and the residents' digital wallets according to preset ratios. It reduces the chance of human interference.

Blockchain's distributed ledger technology can record the flow of every sum of money in detail, allowing us to comprehensively supervise the entire process, from land transfer to development and compensation. It enhances the trust among all participants, reduces the contradictions caused by unequal information, and provides strong technical support for coordinating the interests of all parties.

4.2.2 Experiment with a Virtual Sand Table

By integrating urban geographic information, building information modeling (BIM), Internet of Things (IoT) data, and VR visualization technology, the digital twin platform creates a virtual sand table that is updated synchronously with the real city, providing an immersive experimental space for our multi-party cooperation. On this platform, government departments can input various policy settings, and developers can submit different architectural layouts and commercial portfolio plans. Residents can enter the virtual space through VR equipment, experience the changes of space elements such as sunshine, ventilation, and greening, and express their design preferences at any time. The platform's built-in simulation engine rapidly calculates the economic benefits (e.g., return on investment), social impacts (e.g., population density, traffic flow), and environmental indicators (e.g., carbon emissions). The digital twin platform transforms abstract planning indicators into perceptible scenarios, reducing communication barriers.

4.3 Optimization of Governance Mechanism

4.3.1 Dynamic Contract

Because the urban renewal project is a lengthy and complex undertaking that involves significant changes, it is necessary to establish a flexible contract mechanism to facilitate effective management. The key to this mechanism is to include the "adjustment clause" at the very beginning of the contract signing, clearly specifying when the adjustment can be initiated (such as market interest rate fluctuations, policy and regulatory updates, and major accidents), and explaining how to renegotiate to protect everyone's interests. If the population structure of this area has changed significantly, for example, with an increase in the number of older adults, we can discuss expanding facilities for older adults. The dynamic contract utilizes blockchain's smart contract to complete the operation automatically. It employs a preset algorithm to initiate the adjustment program, thereby reducing the delay and subjective influence caused by manual negotiation. Third-party evaluation agencies are introduced to quantify the impact of changes, provide an objective basis for interest adjustments, and ensure that contract modifications can not only adapt to changes in the external environment but also promote the long-term, stable development of the project.

4.3.2 Supervision and Accountability System Based on Data Sharing

In the field of urban renewal, supervisory and accountability mechanisms often face challenges such as information barriers, unclear responsibility demarcations, and slow responses. Therefore, it is necessary to utilize data interconnectivity to create an innovative, end-to-end, and multi-faceted supervisory and accountability framework. The digital twin platform of this framework, serving as the data core, gathers information on government department approvals, corporate construction records, resident feedback, and third-party monitoring data to construct a comprehensive data resource library. By using artificial intelligence to analyze data in real-time, it can automatically identify violations and potential risks, and then send alerts to the relevant authorities, responsible individuals, and the public. All operational steps are stored on the blockchain as proof, ensuring clear evidence for holding people accountable.

5. Conclusion

This study focuses on how VR can support the dynamic simulation of planning schemes and the balance of multiple interests in urban renewal, and draws the following conclusions.

First, by constructing high-precision, interactive digital twin urban environments, VR creates unprecedented dynamic simulation capabilities for urban renewal planning. It utilizes the CIM-virtual-real mapping mechanism to dynamically simulate key factors such as energy consumption and traffic flow, enabling multi-scenario, low-cost simulation and continuous improvement of planning schemes, which significantly enhances the scientific and forward-looking nature of planning. The immersive experience of VR effectively lowers the professional threshold for public participation, allowing residents to engage in participatory design based on intuitive perception, and incorporating diverse needs in the early stages of scheme formation, laying the foundation for subsequent interest coordination.

Second, it is necessary to explore the integration of the empowering effects of VR technology and an innovative governance system to effectively address the complex challenges of interests among multiple stakeholders. Against the backdrop of the complex interplay among stakeholders, including the government, the market, and the public, this study aims to develop a collaborative decision-making system that integrates VR digital sandboxes and blockchain technology, utilizing visual interaction to foster consensus. In addition, institutional arrangements should shift from a fixed protocol framework to a flexible, dynamic contract, adapting to the evolving interest landscape. This approach should utilize data interoperability to establish a comprehensive supervision and accountability mechanism, ensuring the unity of fairness and efficiency.

In conclusion, VR is not only a means to enhance the accuracy of planning simulations but also the core driving force in reshaping the urban renewal governance system. In urban renewal practices, it is recommended to create a closed-loop system of "planning, simulation, consultation, and management" supported by intelligent collaboration and data, to achieve the goal of coordinated development that improves urban spatial quality while promoting social fairness and justice.

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