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Article

Intelligent Construction Technology Integration for Green Transformation of Existing Buildings in Urban Renewal

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Abstract: As China's urbanization process enters a new stage, urban renewal has become a key pathway for promoting sustainable urban development and improving the quality of the built environment. The green transformation of existing buildings, as a core component of urban renewal, faces prominent challenges such as low construction efficiency, high disturbance to occupants, and difficulties in coordinating multiple stakeholders and complex building systems. These issues urgently require the support of intelligent construction technologies and new construction models. This paper focuses on the integration of intelligent construction technology with the green transformation of existing buildings, with the aim of constructing a systematic and operable technical framework. First, core concepts such as intelligent construction, urban renewal, and green transformation are clarified, and the research foundation is established based on sustainable development theory, systems engineering, and life-cycle thinking. Second, by analyzing the current application status of technologies such as building information modeling, the Internet of Things, and big data in urban renewal projects, the paper systematically elaborates a full-chain technical system covering digital surveying, intelligent design, construction management, and energy-saving operation and monitoring. The study highlights how intelligent technologies enhance reconstruction accuracy, reduce resource and energy consumption, shorten construction periods, and optimize building performance. Finally, the proposed technical system provides theoretical support and practical guidance for the green renovation of existing buildings driven by intelligent construction, offering important reference value for promoting green, low-carbon, and high-quality urban development.

Keywords: intelligent construction; urban renewal; green buildings; building retrofit; sustainable development; digital technology

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1. Introduction

With the increasingly severe global climate change and the gradual implementation of the "dual carbon" goals, urban renewal has become an important means to promote sustainable development. The stock of buildings is vast, and their drawbacks, such as high energy consumption and high carbon emission intensity, are becoming increasingly apparent. As the core driving force for the industrialization, digitalization, and greening of the construction industry, intelligent construction technology has brought a new perspective to the green renovation of existing buildings. In local practice, cities are integrating construction robots and large-scale AI model technologies, combining them with urban renewal projects to promote the energy-saving renovation of existing buildings in an integrated manner [1]. From a technological standpoint, the intelligent construction technology system encompasses digital design, intelligent construction, and intelligent operation and maintenance, which can significantly improve the efficiency of renovation. However, it faces challenges such as high costs, and there is an urgent need to establish a systematic technical framework suitable for urban renewal to meet the needs of large-scale renovation.

2. Definition of Core Concepts and Theoretical Foundation

2.1. Definition of Core Concepts

2.1.1. Intelligent Construction

As a construction methodology spanning the entire project lifecycle, intelligent construction is driven by advanced information technologies, including Building Information Modeling (BIM), the Internet of Things (IoT), artificial intelligence (AI), and big data. The essence of this approach is to leverage interconnected data and intelligent decision-making to enhance the digitalization, automation, and collaboration of processes across design, production, construction, operation, and maintenance. Within the domain of urban renewal, intelligent construction enables the simulation of existing building conditions using digital twin technology, facilitates the precise execution of renovation tasks with smart equipment, and optimizes resource allocation through the use of AI algorithms. These capabilities significantly enhance renovation efficiency and quality while minimizing the environmental impact [2].

2.1.2. Urban Renewal

Urban renewal aims to address the challenges faced by the architectural environment of older houses and factories in the city, such as limited accessibility and outdated facilities. Through methods such as comprehensive transformation, reconstruction, or demolition and rebuilding, it systematically integrates spatial optimization, industrial upgrading, and cultural preservation. The primary goal of this initiative is to enhance urban vitality and improve quality of life. Therefore, it advocates for the coordinated approach of "preservation, transformation, and demolition." Special emphasis is placed on preserving the historical character and neighborhood connections of the city [3, 4]. In the process of implementing green transformations for existing buildings using urban renewal technologies, these methods provide valuable support for policy formulation and identifying practical implementation pathways. This approach facilitates the transition from focusing on energy efficiency in individual buildings to creating a sustainable green ecosystem for entire communities.

2.2. Related Theoretical Basis

2.2.1. Sustainable Development Theory

The concept of sustainable development emphasizes the harmonious integration of the economy, society, and ecology. In the process of green upgrading existing buildings, this concept is reflected in the practical goal of "four saving and one environmental protection," which includes energy saving, land saving, water saving, material saving, and environmental protection [5]. Through the application of intelligent construction technology, effective resource recycling has been achieved, environmental interference minimized, and social benefits significantly enhanced.

2.2.2. The Theory of Systems Engineering

Systems engineering theory views complex problems as whole systems, achieving optimal goals through structured analysis and multi-element coordination. Green retrofitting of existing buildings involves multiple factors such as building structure, equipment systems, user needs, and policies and regulations. Intelligent construction technology can build a "data-model-decision" closed-loop system, with BIM integrating all-element information of the building. The Internet of Things is used to monitor the retrofitting process in real time. Big data analysis is employed to optimize construction steps and ensure that the retrofitting plan strikes a balance between technical feasibility, economic rationality, and ecological benefits. It ultimately achieves overall system efficiency optimization.

2.2.3. Life Cycle Theory

Life cycle theory examines the environmental impact of a product throughout its entire life cycle, encompassing design, production, use, and disposal. In the construction industry, this approach emphasizes the integration of green upgrading across the complete process of "diagnosis-design-construction-operation and maintenance-demolition and recycling." Intelligent construction technology employs digital twin platforms to simulate the long-term performance of retrofitted buildings, predicting energy consumption and carbon emission trends [6]. It utilizes intelligent operation and maintenance systems to make real-time adjustments to equipment operating conditions, thereby extending the building's service life. Modular retrofitting techniques are applied to facilitate future material recycling and functional iterative updates, aiming to minimize environmental costs throughout the life cycle and promote the sustained realization of the building's value.

3. The Application Status of Intelligent Construction Technology in Urban Renewal

3.1. Application of Digital Surveying and Information Modeling Technology

The "digital cornerstone" of the green renovation of existing buildings is digital surveying and information modeling technology. In the initial stage of renovation, advanced methods such as 3D laser scanning are used to perform rapid and precise reverse modeling of existing buildings, obtaining high-precision point cloud data and realistic models. This effectively addresses challenges encountered in traditional surveying methods. The data provides a reliable foundation for subsequent information modeling. By applying Building Information Modeling (BIM) technology, a model integrating multidimensional information, such as geometric details and material properties, can be constructed. Designers can utilize the model to simulate and analyze building characteristics, including lighting, ventilation, and energy consumption, thereby optimizing renovation plans. Construction teams can perform collision detection and construction simulation to proactively identify and resolve potential issues, reducing resource waste. The deep integration of digital surveying and BIM technology achieves an accurate mapping of buildings from a "physical entity" to a "digital virtual entity," offering data support for scientific decision-making and refined management in green renovations. This significantly enhances the predictability and efficiency of the renovation process.

3.2. Application of Intelligent Construction Equipment and Technology

In urban renewal projects, the application of intelligent construction equipment and technology is essential due to challenges such as site limitations and strict surrounding impact restrictions. In the green upgrading of existing buildings, robotic technology is increasingly replacing traditional high-risk and high-intensity manual operations. Construction robots can be employed for repetitive tasks such as indoor and outdoor spraying, masonry, and wall plastering, offering high efficiency, consistent quality, and significantly reducing dust and noise pollution, which aligns with green construction standards [7].

For core processes such as structural reinforcement, advanced equipment, including intelligent tensioning and carbon fiber cloth laying robots, ensures precise installation, guaranteeing project quality. Additionally, modular and prefabricated decorative methods are widely implemented [8]. Components such as partitions, suspended ceilings, and kitchens or bathrooms are prefabricated in factories and then transported to the site for rapid assembly, resembling the process of building with blocks. This approach minimizes on-site wet work and construction waste, shortens the project timeline, and reduces disturbance to the original structure and its surrounding environment. 3D printing technology is utilized for the rapid and customized production of non-standard components in renovation projects. In summary, intelligent and industrialized construction methods effectively address the limitations of traditional renovation models, representing a key technical pathway to achieving green, efficient, and safe renovations.

3.3. Application of the Internet of Things and Big Data in Project Management and Control

Big data and Internet of Things (IoT) technologies have created a "smart brain" for green building renovation projects, enabling digital and intelligent supervision throughout the entire process and across all dimensions [6]. By deploying sensor networks on construction sites and building equipment, real-time data on noise, dust, energy consumption, structural stress, and ambient temperature and humidity can be acquired. This information is transmitted to the cloud via IoT gateways, where it is processed and analyzed using big data to facilitate real-time tracking of project progress, safety, quality, and costs.

In terms of safety, the system can automatically alert personnel when entering hazardous areas and assess the stability of scaffolding. Green construction allows for real-time tracking of energy and resource consumption, enabling optimized construction plans that reduce carbon emissions [3].

For quality control, the system can evaluate construction metrics of core processes to ensure compliance with design specifications. Project supervisors can utilize a dashboard interface to clearly monitor overall progress, shifting management from reactive responses to proactive interventions. This approach establishes a data foundation for the green and efficient operation of the renovated building, creating a closed-loop of full-cycle digital management that integrates renovation and operation.

4. Green Transformation of Existing Buildings

4.1. The Key Technology and Process of Green Transformation

The key technology system for the green renovation of existing buildings integrates intelligent inspection, performance simulation, and precision construction techniques. By utilizing technologies such as oblique photography drones, 3D laser scanning, and infrared thermal imaging, it efficiently captures a building's geometric parameters, structural defects, and energy consumption data, which are then used to construct a high-fidelity digital twin model. On a BIM platform, energy-saving renovation simulations are conducted to optimize the selection of envelope insulation materials and the layout of renewable energy systems, such as photovoltaic and geothermal heat pumps, using energy analysis software to predict post-renovation energy savings. During the construction phase, methods such as low-disturbance processes, minimally invasive grooving, and the assembly of modular, prefabricated components are employed to effectively control construction waste and noise pollution. After the renovation is completed, a smart sensor network monitors indoor temperature, humidity, air quality, and energy consumption indicators in real-time. Subsequently, dynamic adjustments are implemented to form a complete feedback loop. This process uses data as the basis for decision-making, ensuring that the renovation plan is highly aligned with the building's current condition and renovation goals.

4.2. Integration of Intelligent Design and Evaluation Tools

The scientific implementation of green renovation solutions relies on the integration of intelligent design and evaluation tools [9, 10]. In terms of design, BIM and GIS technologies are combined to construct a multi-scale information model that supports the analysis of renovation solutions in relation to the surrounding environment, such as sunlight and ventilation. Additionally, AI algorithms, including genetic algorithms and neural networks, are employed to automatically optimize building orientation, thereby enhancing the efficiency of natural lighting and ventilation. For evaluation, Life Cycle Assessment (LCA) and carbon emission calculation models are integrated to quantify the environmental impact of the renovation solution. Furthermore, Virtual Reality (VR) is utilized to simulate spatial comfort after renovation. User interaction feedback is incorporated to refine the design solution, and a cloud collaboration platform is developed to enable real-time data sharing among designers, engineers, and owners. This ensures that evaluation criteria are consistently applied throughout the entire design process, thereby improving overall benefits.

4.3. Intelligent Scheme of Construction Management

Intelligent construction management utilizes digital twins, the Internet of Things (IoT), and artificial intelligence (AI) technologies to ensure precise oversight of the renovation process [10]. It employs Building Information Modeling (BIM) to create a 4D construction progress simulation, integrates drone aerial photography for real-time observation of on-site progress, and provides automatic alerts for deviations.

By deploying intelligent wearable equipment and location markers, it monitors the whereabouts and safety status of personnel and machinery, using AI algorithms to identify high-risk behaviors [1]. During the materials management phase, Radio Frequency Identification (RFID) technology is used to track green building materials throughout the entire process, thereby reducing material loss. For construction quality control, computer vision technology has been implemented to automatically detect parameters such as wall levelness and pipeline assembly accuracy, replacing traditional manual inspections. Environmental monitoring sensors collect real-time data on noise and dust, ensuring the construction process adheres to green construction standards, thereby enhancing the effectiveness of the renovation while improving environmental performance.

4.4. Intelligent Monitoring of Maintenance and Operation

To ensure the long-term benefits of green retrofitting, intelligent monitoring plays a critical role during the maintenance and operational phases [11]. An IoT-driven intelligent operation and maintenance system has been established, utilizing sensors installed within the building to monitor parameters such as temperature, humidity, energy consumption, and structural stress. These sensors collect real-time operational data, which is then used to create a digital twin model that simulates the building's status in real-time.

For energy management, big data analysis is employed to understand user behavior patterns, enabling the optimization of operational strategies for equipment such as air conditioning and lighting to achieve "energy supply on demand." Predictive maintenance is also introduced, using indicators like motor vibration frequency and abnormal current signals to forecast potential faults, thereby minimizing downtime. Furthermore, indoor environmental monitoring, including parameters such as PM2.5 and formaldehyde levels, is integrated with a user feedback mechanism. This allows the system to automatically adjust fresh air volume and air purification devices, ensuring a healthy and comfortable indoor environment [12]. By supporting operational and maintenance decisions with data, this system extends the building's service life, gradually reduces carbon emissions during the operational phase, and ensures the continuous realization of the value of green retrofitting.

5. Integrated Application of Intelligent Construction Technology in Green Transformation

5.1. Intelligent Design and Optimization

In the intelligent design green renovation process, the key lies in leveraging data-driven methods to optimize solutions. Three-dimensional laser scanning and unmanned aerial vehicle (UAV) photography are employed to acquire high-precision point cloud data of the building, which is then used to construct a Building Information Modeling (BIM) information model. This model accurately represents the building's structure, equipment, pipelines, and current energy consumption status. By integrating energy consumption simulation software, dynamic simulations of various renovation schemes are conducted to predict energy-saving effects and the return on investment period. Artificial intelligence algorithms, such as genetic algorithms, are applied for automatic iterative optimization to maximize benefits while ensuring the building's functional and aesthetic requirements are met.

5.2. Digital Management of Construction Process

Digital construction management enhances transparency and precision throughout the entire renovation process by utilizing digital twins and the Internet of Things (IoT). During the project initiation phase, BIM models are employed to perform 4D construction simulations, allowing for adjustments to construction sequences and resource allocations to avoid procedural conflicts. In the construction phase, core components, facilities, and materials are tagged with RFID or equipped with GPS devices. Their real-time location, status, and usage information are monitored through an IoT platform, enabling efficient and lean management. On-site, high-definition surveillance cameras and drones are used in conjunction with computer vision technology to automatically identify safety hazards and construction defects, issuing timely alerts. Managers can utilize mobile devices to compare the BIM model with on-site progress, enabling immediate corrections to any deviations. For example, in a historical building renovation project, the digital control system facilitated seamless coordination in the production, transportation, and lifting of prefabricated components. This approach reduced the project duration by 20% and significantly minimized disruptions to surrounding traffic and the environment, demonstrating the effectiveness of digital management.

5.3. The Application of Green Construction Technology

The application of green construction technology minimizes the adverse environmental impacts of the renovation process. During the demolition phase, low-noise and low-dust techniques, such as intelligent hydraulic crushing and wire sawing, are employed to reduce noise and dust. After intelligent sorting, construction waste is processed, with concrete and bricks converted into recycled aggregates for use as site backfill or subgrade construction [10]. Throughout the construction period, the widespread use of reusable prefabricated formwork and scaffolding significantly reduces wood consumption. Additionally, an environmental monitoring sensor network tracks on-site noise and wastewater discharge in real-time, activating spray dust suppression facilities and sound-insulating barriers to ensure compliance with environmental regulations. The introduction of clean energy equipment, such as solar-powered construction lighting and electric construction machinery, effectively reduces carbon emissions.

5.4. Intelligent Monitoring and Energy Conservation

Intelligent monitoring and energy conservation are essential for maintaining the continuous delivery of green benefits. By deploying a sensor network within the building that monitors temperature, humidity, CO2 concentration, illuminance, and various energy-consuming equipment (such as air conditioning, lighting, and elevators), a comprehensive perception system is established. All data is aggregated onto a smart operations and maintenance (O&M) platform and integrated with the BIM model to create a visualized digital twin. The platform utilizes big data analytics to examine user behavior patterns and equipment operational efficiency, employing AI algorithms to automatically develop optimal energy-saving control strategies. Based on the temperature difference between indoor and outdoor environments, as well as personnel activity levels, the system intelligently adjusts the operational parameters of the air conditioning system. Depending on the intensity of natural light, it automatically regulates the switching and brightness of LED lamps. This approach enables predictive maintenance, provides early warnings for equipment failures, and prevents energy waste.

Practical applications have shown that this system can reduce operational energy consumption in buildings by 20%-40%, significantly improve indoor environmental comfort, and create a healthy, efficient, and productive work and living space for users.

5.5. Summary of Achievements

The green renovation of existing buildings has achieved significant results through the integrated application of intelligent construction technology. From an environmental perspective, precise design and intelligent construction have enabled renovated buildings to achieve an average energy-saving rate exceeding 30%. Carbon emissions have been notably reduced, and the recycling rate of construction waste has increased substantially. From an economic standpoint, although the initial technological investment is considerable, optimized design shortens construction periods and reduces operating costs [13]. The payback period is approximately 5 to 8 years, offering substantial long-term economic benefits. From a social perspective, the renovation projects improve safety and comfort, preserve historical heritage, and contribute to the revitalization of entire communities.

6. Conclusion

This study integrates intelligent construction technology with green renovation objectives to develop a comprehensive technical system encompassing the entire process, from design to construction, operation, and maintenance. Guided by principles such as sustainable development and systems engineering, this system establishes a robust foundation for green renovation. Through the use of intelligent design and assessment tools, renovation schemes are optimized for performance, and their environmental impacts are pre-assessed. During the construction phase, the integration of intelligent equipment with green construction techniques enhances renovation efficiency while minimizing the environmental burden of the construction process. Additionally, the implementation of Internet of Things (IoT) and big data technologies creates an intelligent management and monitoring platform that supports the project lifecycle, ensuring long-term stability. Practical applications demonstrate that the combined use of intelligent construction technology significantly improves the energy efficiency and environmental sustainability of existing building renovations.

Moreover, this approach facilitates refined process management, enabling resource conservation and cost control while delivering substantial economic, social, and environmental benefits. Looking ahead, as technology continues to evolve and cross-domain integration deepens, this technical system is anticipated to be applied across a broader range of scenarios, driving the development of green, intelligent, and livable cities.

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