

ORIGINAL RESEARCH ARTICLE

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Dynamic Simulation and Resource Optimization of Urban Solid Waste Lifecycle Based on Digital Twin

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Abstract: The disconnect between urban solid waste management and urban planning represents a critical bottleneck for sustainable urban development. This paper proposes a digital twin-based method for dynamic simulation and resource optimization throughout the entire lifecycle of urban solid waste, establishing a collaborative platform integrating "Smart Urban Planning" and "Waste Resource Recovery" modules. Through 3D visual modeling, multi-dimensional simulation analysis (economic, engineering, and social benefits), and AI-driven dynamic matching of waste types with recycling technologies, the platform enables closed-loop management of construction and demolition waste—from generation and sorting to recycling and application. The system integrates BIM, GIS, IoT, and machine learning technologies to support real-time monitoring, dynamic early warning, and planning optimization, facilitating a shift from reactive governance to proactive optimization. Research demonstrates that the system significantly improves waste recycling rates, reduces carbon emissions and material costs in pilot areas, offering a replicable technical pathway for building "zero-waste cities."

Keywords: Digital Twin; Solid Waste Resource Utilization; Full Life Cycle; Dynamic Simulation; Smart City

Introduction

With accelerated urbanization, China's annual production of urban construction solid waste exceeds 3 billion tons, yet the recycling rate remains below 20%. Landfill disposal leads to severe land occupation and pollution. Moreover, there is insufficient coordination between urban planning and solid waste management, and the traditional "end-of-pipe treatment" model lacks comprehensive oversight. In recent years, digital twin technology has shown significant potential across various urban domains, but its application in

coordinating urban planning and solid waste recycling is still exploratory. Existing platforms have limitations, and solid waste recycling technologies are not deeply integrated with intelligent planning. Therefore, this paper proposes relevant methods to construct an integrated closed-loop system, supporting the green and low-carbon transformation of cities.

1. Synergistic Mechanism of Digital Twins and Solid Waste Resource Utilization

1.1 Digital Twin Technology Framework

Digital twin technology enables real-time perception,



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dynamic simulation, and intelligent decision-making for urban systems by establishing a bidirectional mapping between physical entities and virtual models. The digital twin platform constructed in this paper consists of a three-layer architecture: the perception layer, the model layer, and the application layer. The perception layer collects heterogeneous data—such as solid waste generation at construction sites, equipment operating status, and environmental parameters—in real time through IoT sensors, BIM models, and GIS data. The model layer builds a 3D visualization sandbox using Three.js and WebGL technologies, integrating a physical parameter database for recycled materials and AI algorithm models. The application layer offers functions including planning simulation, recycling pathway optimization, and carbon emission accounting. Leveraging a collaborative edge-cloud computing architecture, the system processes sensor data in real time and employs AI algorithms such as convolutional neural networks to automatically identify damage features like cracks and settlement, achieving dynamic historical traceability and precise localization.

1.2 Dynamic Simulation of Solid Waste Life Cycle

The full lifecycle of solid waste encompasses four stages: "generation, sorting, recycling, and application." This paper proposes a dynamic simulation mechanism that utilizes a collaborative edge-cloud computing architecture to process sensor data in real time, combined with convolutional neural networks (CNNs) to automatically identify solid waste types and impurity content, dynamically matching recycling process parameters. In the field of construction site solid waste recycling technology, an intelligent sorting and recycled building material production system has been developed. Existing crushing equipment has been improved by adding high-frequency vibration decontamination components and particle size monitoring sensors, enhancing crushing efficiency and aggregate quality, thereby promoting the implementation of an on-site conversion model for solid waste. Precise control of aggregate particle size (error ± 2 mm) is achieved through vibration decontamination and speed adjustment, improving the strength stability of recycled concrete^[1].

1.3 Planning-Regeneration Linkage Mechanism

Traditional planning and solid waste management have long been disjointed, leading to a mismatch

between the supply and demand of recycled materials. This paper develops an AI algorithm to dynamically match solid waste generation capacity with planning requirements, optimizing the application pathways of recycled materials based on transportation costs, engineering applicability, and carbon reduction goals. By utilizing BIM models to monitor construction site waste generation in real-time, it generates low-carbon building material application plans. Ultimately, a WebGL-based platform enables the integrated visualization of urban planning and resource cycling. During the planning phase, a digital twin platform simulates solid waste output and recycled material demand under different building layouts, achieving closed-loop optimization characterized by "production guided by demand, planning driven by production." This establishes a full life-cycle management chain of "planning-construction-recycling."

2. Synergistic Mechanism of Digital Twin and Solid Waste Resource Utilization with Full Life-Cycle Dynamic Simulation

2.1 Digital Twin Technology Framework and Municipal Solid Waste Management

Digital twin technology, by establishing a bidirectional mapping between physical entities and virtual models, provides new perspectives and tools for urban solid waste management. This paper constructs a digital twin platform tailored to the needs of urban solid waste management, designing a three-layer architecture comprising the perception layer, model layer, and application layer. The perception layer utilizes IoT sensors, BIM models, and GIS data to collect heterogeneous data in real time, including solid waste generation at construction sites, equipment operating status, and environmental parameters, ensuring data comprehensiveness and real-time performance. The model layer, based on Three.js and WebGL technologies, builds a 3D visualization sandbox, integrating a physical parameter database for recycled materials and AI algorithm models to achieve dynamic simulation and analysis of the entire solid waste lifecycle. The application layer offers functions such as planning simulation, optimization of recycling pathways, and carbon emission accounting, supporting decision-makers in conducting scientific and rational planning and management. In terms of

implementation, the platform leverages a collaborative architecture of edge computing and cloud computing to process massive sensor data in real time. Combined with AI algorithms like convolutional neural networks (CNN), it automatically identifies solid waste types and impurity content, providing an accurate basis for subsequent recycling process matching. Furthermore, through the integration of BIM models and GIS data, the platform visually displays the spatial distribution and changing trends of solid waste generation points, offering decision support for planners.

2.2 Dynamic Simulation Mechanism for Solid Waste Life Cycle

The full life cycle of solid waste encompasses four key stages: "generation, sorting, recycling, and application," each involving complex data interactions and process flows. The dynamic simulation mechanism proposed in this paper achieves real-time monitoring and dynamic optimization of the entire solid waste life cycle through a digital twin platform. During the generation stage, the platform uses IoT sensors to monitor solid waste generation at construction sites in real time, combining historical data and machine learning algorithms to predict future waste generation trends, thereby providing data support for subsequent sorting and recycling. In the sorting stage, the platform employs CNN algorithms to automatically identify waste types and impurity content, dynamically matching optimal sorting process parameters to improve sorting efficiency and accuracy. By incorporating high-frequency vibration decontamination components and particle size monitoring sensors, existing crushing equipment is enhanced to boost crushing efficiency and aggregate quality, laying the foundation for subsequent recycling. During the recycling stage, the platform dynamically matches recycling process parameters based on the type and quality of sorted solid waste, generating optimal recycling solutions. Through improvements in crushing equipment and the addition of decontamination and monitoring components, the platform ensures the quality of recycled aggregates meets the application requirements for road engineering, municipal facilities, and building structures^[2]. The platform establishes a recycled aggregate application system, verifies performance indicators, and provides scientific basis for the promotion and use of recycled building materials. In the application stage, the platform uses

BIM models to monitor waste generation and the demand for recycled materials in real time, dynamically adjusting application strategies to ensure effective utilization. The platform also supports carbon emission accounting, quantifying the environmental benefits of recycled material applications and offering data support for urban green and low-carbon development.

2.3 Planning-Regeneration Linkage Mechanism and Multi-Objective Optimization

Traditional urban planning and solid waste management often lack effective coordination, leading to frequent issues such as resource misallocation, high transportation costs, and mismatched application scenarios for recycled materials. The AI algorithm developed in this study enables intelligent integration of planning and recycling by dynamically matching solid waste generation capacity with planning demands. Specifically, the algorithm constructs a multi-objective optimization model based on transportation costs, engineering applicability, and carbon reduction goals to dynamically generate optimal pathways for the application of recycled materials. During the planning phase, the platform utilizes a digital twin model to simulate solid waste generation and recycled material demand under different building layouts, offering planners multiple planning scenarios and recommendations for recycled material use. Planners can select the optimal solution based on actual needs and constraints for implementation. During the implementation phase, the platform employs BIM models to monitor real-time changes in construction waste generation and recycled material demand, dynamically adjusting the application strategy for recycled materials to ensure efficient utilization and optimal resource allocation. Additionally, the platform supports carbon emission accounting, quantifying the environmental benefits of using recycled materials and providing data support for urban green and low-carbon development. Through the planning-recycling linkage mechanism and multi-objective optimization, the digital twin platform established in this study achieves full-process visibility, measurability, and controllability of solid waste from generation to reuse, offering technical support for urban green and low-carbon transformation. In the future, with the continuous advancement of AI and IoT technologies, digital twin platforms will play an increasingly vital role in urban solid waste management, driving urban construction toward a smarter, low-carbon, and more resilient new era.

3. Application Verification and Effectiveness Analysis

3.1 Overview of the Pilot Area

A social housing construction project in Xi'an was selected as a pilot, with a total floor area of approximately 120,000 square meters, generating about 12,000 tons of construction solid waste. A digital twin platform was deployed to monitor real-time waste generation at the site, dynamically match recycling processes, and generate low-carbon building material application plans. Based on data from the Xi'an pilot, the system is projected to reduce annual landfill waste by 500 tons per site and lower building material costs by 20%–30% after implementation.

3.2 Implementation Results

Through systematic operation, the resource utilization rate of solid waste in the pilot area increased from less than 20% to 68%, reducing annual landfill volume per construction site by approximately 500 tons and lowering the cost of recycled building materials by 20%-30%. In road engineering sections where the replacement rate of recycled aggregates reached 70%, pavement performance indicators met national standards. The main structural strength and stability of buildings using recycled C40 concrete remained satisfactory, with carbon emissions reduced by approximately 35% compared to conventional concrete. By promoting solid waste recycling and the application of low-carbon building materials, the project effectively reduced carbon dioxide emissions and facilitated the transition of urban construction from a "high-energy-consumption extensive model" to a "low-carbon circular model" ^[3].

3.3 Dynamic Simulation and Early Warning Capabilities

The system dynamically tracks and precisely locates solid waste generation points through three-dimensional mapping of defect data. By simulating structural responses of recycled building materials under various seismic scenarios, it predicts the cumulative effects of aftershocks on damaged structures, providing a scientific basis for regional disaster prevention planning. Additionally, the technology forecasts the progressive impact of aftershocks on compromised structures through seismic simulations, offering data-driven support for resource allocation. The system also

enables urban resilience assessment by modeling the effects of disasters such as floods and heat islands on resource circulation systems, thereby enhancing the city's overall risk resilience.

4. Innovations and Technical Features of Urban Solid Waste Full Lifecycle Management Based on Digital Twin

4.1 Innovation Points

(1) Technology Integration and Innovation: The project deeply integrates cutting-edge technologies from multiple fields such as BIM, QGIS, IoT, and machine learning, breaking down traditional technical barriers to achieve collaborative application in post-earthquake building assessment scenarios. BIM technology visually displays geometric deformations of building structures, QGIS assists analysis from a geospatial perspective, IoT is responsible for real-time data collection, and machine learning algorithms process data and identify damages, collectively visualizing and digitizing post-disaster building damage conditions. This cross-domain technology integration not only provides targeted repair guidance for construction personnel but also databases the information for designers to accumulate knowledge and optimize subsequent design plans, establishing a new paradigm for technological application in post-disaster assessment.

(2) Model Innovation: Against the backdrop of the "dual carbon" goals and the development of "zero-waste cities," urban planning faces dual challenges of resource waste and environmental pollution. Traditional urban planning lacks dynamic simulation and recycling systems, while construction solid waste accounts for 30%-40% of municipal solid waste, with a recycling rate of less than 20%. This project integrates digital twin technology with the recycling and reuse of construction solid waste to establish an integrated "planning-recycling-application" system. It aims to address issues such as extensive urban planning decisions and pollution from construction solid waste, thereby promoting green and low-carbon urban development ^[4]. The innovation of the project lies in its closed-loop design of "planning simulation-recycling management," shifting urban sustainable development from "reactive governance" to "proactive optimization."

4.2 Features

Extend digital twin technology from macro-level planning to micro-level building material production

processes, establishing a "virtual planning–physical regeneration–data feedback" closed loop. This approach breaks through the traditional "end-of-pipe treatment" model for solid waste by using digital twins to pre-plan application scenarios for recycled materials, achieving synergistic coordination across the entire chain of "planning source–regeneration process–engineering application." The system responds to the "dual carbon" goals and the development needs of "zero-waste cities," deeply integrating the concepts of "smart cities and green building materials" to provide Chinese solutions for the sustainable development of global smart cities.

Conclusion

The deep integration of municipal solid waste management and urban planning is a critical pathway for achieving sustainable urban development. The digital twin collaborative platform developed in this study elevates solid waste resource utilization from "end-of-pipe treatment" to "source planning" through dynamic simulation and pathway optimization, achieving a win-win scenario for resource circulation and urban development. Against the backdrop of China's "dual carbon" strategy and new urbanization initiatives, this research provides a replicable and scalable technological framework for "zero-waste cities," demonstrating the broad application prospects of digital twin technology in urban green transformation. In the future, with the

continuous advancement of AI and IoT technologies, digital twins will become more deeply embedded in urban governance systems, propelling urban construction toward a new era characterized by greater intelligence, low-carbon practices, and resilience.

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