

Research on Collaborative Efficiency Optimization and Low-Carbon Development Path of Mountain Urban Environmental Construction Based on Digital Twin

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Abstract:

This paper applies digital twin technology to collaborative management of mountain urban environmental construction. A virtual twin model is constructed to realize real-time mapping of physical environment and share data across design, construction and operation phases. With a case study on an environmental renovation project in Chongqing's mountainous area, efficiency indicators are compared between digital twin mode and traditional mode. The result proves digital twin greatly improves collaborative efficiency. Optimization suggestions including unified data standards, multi-party collaborative platform construction, deeper integration of BIM and digital twin and vocational training are put forward, offering new digital ideas for mountain urban construction collaboration.

Keywords:

Digital Twin, Mountain City, Environmental Construction, Collaborative Efficiency

1. Introduction

Constrained by rugged terrain, large elevation difference and scarce construction land, mountain cities face complicated difficulties in planning, construction and operation. Under conventional construction mode, poor information communication among planners, constructors and operators forms isolated information islands, leading to low collaboration efficiency, prolonged schedule, cost overrun and poor quality control. For mountain road projects, terrain limits often cause delayed design revision and disconnected information between construction and operation, hindering rapid responses to environmental changes.

Digital twin realizes virtual modeling and real-time mapping of physical entities via digitalization and optimizes physical projects through virtual-real interaction. In mountain urban construction, full-lifecycle digital twin models covering design,

construction and operation enable seamless data sharing and effectively boost collaborative efficiency.

2. Application of Digital Twin in Urban Construction

Digital twin digitally reproduces urban buildings, roads, bridges and pipelines to support real-time data interaction and status simulation. It helps optimize urban planning by simulating environmental impacts of alternative schemes [1]. Nevertheless, existing digital twin applications mostly focus on single infrastructure, lacking researches on full-lifecycle coordination for complex multi-stakeholder mountain construction projects.

As a widely-used digital tool, BIM builds 3D models with geometric and attribute information for collaborative design and management. BIM discovers design conflicts in early stage to shorten construction period and realizes data inheritance from construction to operation, yet it is limited within single-project lifecycle. Digital twin expands BIM by combining with IoT and big data to achieve continuous real-time physical mapping and cross-project collaborative management.

Collaborative management aims at information sharing to avoid schedule delay and extra cost caused by information asymmetry. Establishing shared platforms, unified data standards and agile management plus digital technologies have been verified effective in improving coordination performance.

3. Particularities of Mountain Urban Environmental Construction

Different from plain cities, mountain construction is restricted by undulating topography, complex geology and fragile ecology. Design must adapt to natural conditions; construction prevents landslide and elevation-related risks; later operation copes with terrain-induced environmental troubles. Traditional management fails to evaluate terrain influence in preliminary design, resulting in frequent design adjustment, troublesome site coordination and inadequate facility maintenance. Digital twin integrates terrain, geological and architectural data on one unified digital platform to break information barriers.

4. Digital Twin Collaborative Management Framework

The framework consists of three core layers: Data Layer: Integrate GIS terrain data, BIM data, IoT sensor data and project management data with unified data standards and interfaces. Model Layer: Generate precise 3D virtual twin models to map mountain terrain, roads, pipelines and buildings based on aggregated multi-source data. Application Layer: Provide collaborative design, construction simulation, schedule supervision, quality inspection and environmental early-warning for all construction phases for online interaction of all participants.

4.1. Data Collection

Two types of data are collected: practical data from projects adopting digital twin and historical data of similar local projects under traditional mode [2]. Traditional data are collected from project documents and field investigation; digital twin data are automatically recorded by the twin platform. Data sources include construction reports, cost records and acceptance files.

4.2. Collaborative Efficiency Evaluation Indicators

Four evaluation dimensions are defined: Project Cycle: Total construction duration from initiation to final acceptance (Month). Cost Control: Cost overrun rate = Actual cost / Budget cost. Construction Quality: Qualification rate of key acceptance nodes (%). Communication Efficiency: Average confirmation days of design modification.

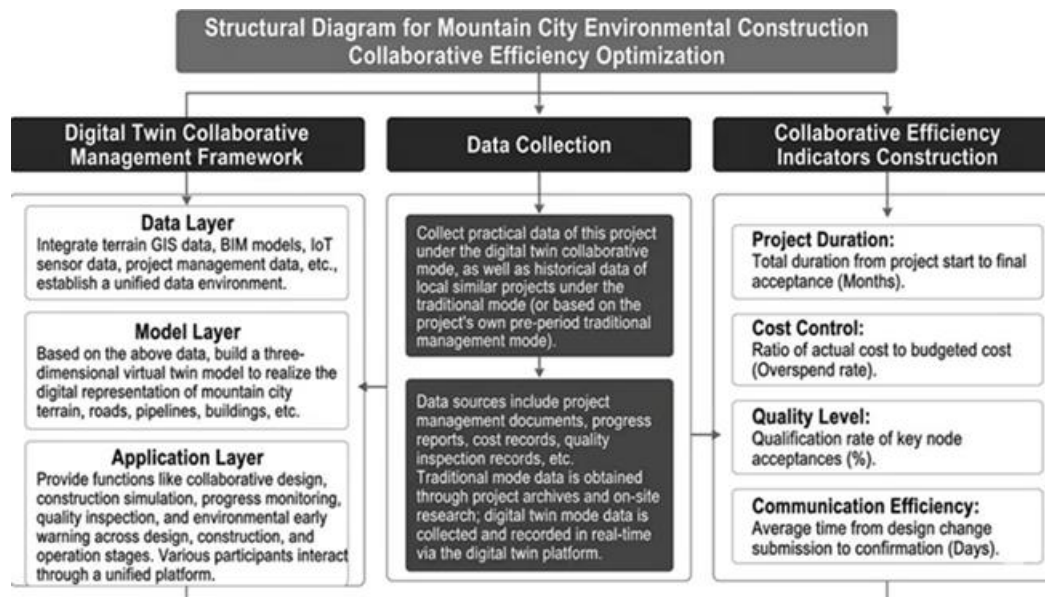


Figure 1. Structural Diagram for Mountain City Environmental Construction Collaborative Efficiency Optimization.

5. Case Study

5.1. Project Overview

The case is an old-town comprehensive renovation project in Chongqing mountain area, including 2km arterial road widening, sidewalk upgrade, green space reconstruction and underground pipeline renewal. Featured by large terrain drop and dense surrounding buildings, the original planned construction cycle is 24 months.

5.2. Deficiencies of Traditional Collaboration Mode

Participants exchange information via paper drawings and emails without unified sharing platform. Separated discipline design triggers frequent later revisions; lack of integral BIM simulation leads to unexpected on-site conflicts and high coordination cost; operation departments cannot obtain complete construction data for later maintenance. Traditionally, the whole project costs 24 months with only 90% acceptance qualification rate and hidden quality hazards.

5.3. Implementation of Digital Twin Collaborative Mode

To improve collaborative efficiency, this project adopts the digital twin collaborative management platform specified in Section 3.2. The detailed implementation procedures are as follows: (1). Develop a virtual twin model for the mountainous urban environment, and digitally integrate topographic features, building layouts, road networks, pipeline distribution and other information of the project area into a unified three-dimensional model. (2). Integrate Internet of Things (IoT) sensors with BIM models to collect real-time on-site data including construction progress, environmental parameters (such as temperature, humidity and noise), and safety

monitoring indicators, which are then synchronized to the digital twin platform. (3). All participating stakeholders access up-to-date information via the unified platform to realize data sharing and collaborative operation throughout the design, construction and operation phases.

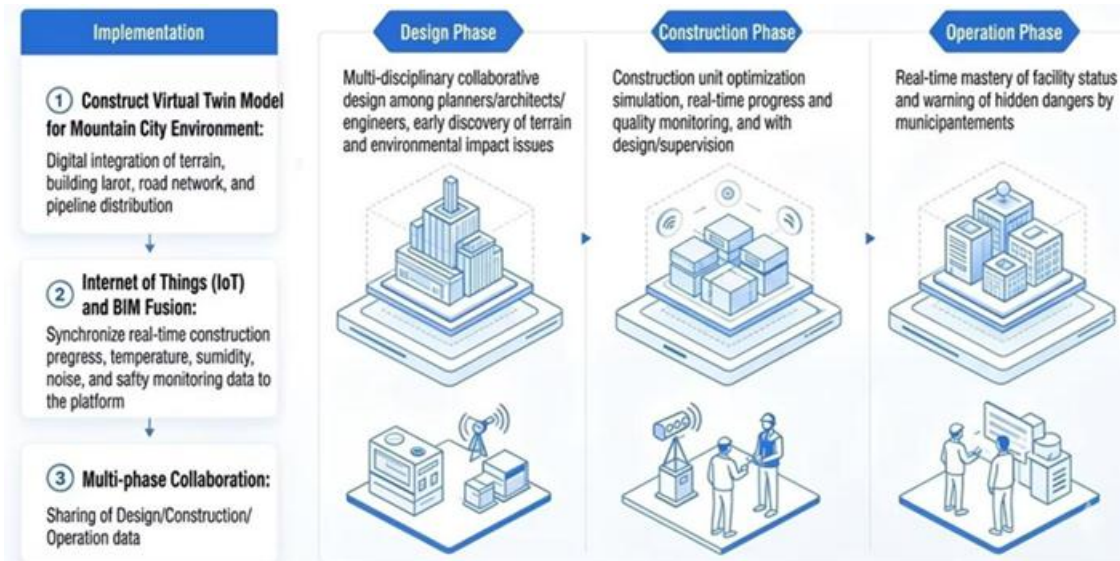


Figure 2. Digital Twin Collaborative Management Platform Implementation Flow.

Design phase: All designers conduct collaborative design on twin model to preview terrain influence and solve problems beforehand.

Construction phase: Builders simulate construction schemes and keep instant online communication with design and supervision teams.

Operation phase: Administrative departments monitor equipment status and eliminate potential risks timely via digital twin system [3].

6. Optimization Strategies for Collaborative Efficiency

6.1. Unify Data Specifications

Form unified format and coding rules for terrain, architecture, traffic and pipeline data to guarantee cross-source data compatibility, alongside data quality inspection mechanism to secure decision-making reliability.

6.2. Build Multi-Party Collaborative Platform

Develop exclusive cloud management platform integrated with project administration, BIM preview, real-time monitoring and instant messaging based on WebGIS and BIM. Set hierarchical user permission to balance information sharing and data security.

6.3. Promote Deep Integration between BIM and Digital Twin

BIM acts as a vital data source and carrier for Digital Twin, so the integrated application of BIM and Digital Twin needs to be further enhanced. At the preliminary stage of a project, BIM models are fully utilized to establish the foundational Digital Twin models, such as terrain models, architectural models and pipeline models. In the construction and operation phases, BIM models are continuously integrated with IoT

data and sensor data to realize real-time mapping and feedback of physical entities. For example, associating construction progress data with BIM models enables 3D visual monitoring of construction schedules; integrating environmental monitoring data into BIM models supports environmental impact analysis and early warning. The in-depth integration of BIM and Digital Twin helps improve the precision and efficiency of collaborative design and collaborative management [4].

In addition, it is necessary to promote the adoption of BIM standards and specifications to ensure consistency among all participating parties in BIM modeling and data exchange.



Figure 3. Analysis of BIM and Digital Twin Fusion Applications.

6.4. Strengthen Staff Training and Organizational Coordination

Carry out systematic training covering BIM modeling, platform operation and data analysis to improve digital literacy; optimize organizational structure, clarify job responsibilities and arrange regular cross-department coordination meetings.

6.5. Continuous Monitoring and Closed-Loop Optimization

Collect user feedback to upgrade platform functions; track platform running status to fix system bottlenecks; compare on-site measured data with simulated twin data to improve model accuracy and form sustainable optimization circulation.

7. Conclusions

Three core conclusions are drawn: (1) Digital twin effectively shortens construction period, controls cost, improves project quality and accelerates design communication, superior to traditional construction management [5]. (2) Main obstacles including inconsistent data standards, poor system integration and insufficient digital talents can be solved via standardized data, shared platform, BIM-DT integration and vocational training. (3) The proposed three-layer digital twin framework is verified effective through Chongqing case and provides practical digital reference for mountain urban construction.

This research innovatively introduces digital twin into mountain construction management and enriches relevant application researches; the proposed framework and strategies possess strong practical guiding value.

Future research can combine artificial intelligence and machine learning into digital twin for intelligent prediction and scientific decision-making. Related industrial policies and unified specifications shall be promoted to popularize digital twin in more mountain construction projects.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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