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Collaborative Mode of Smart Facility Management Based on BIM and Big Data Analytics in the Building Operation and Maintenance Phase

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Abstract. As the core phase of the whole building life cycle with the longest duration (accounting for more than 80% of the total service life) and the highest cost consumption (exceeding several times the total investment), the building operation and maintenance phase directly determines the realization of the overall value of the building. Currently, the application of BIM technology in the construction field suffers from an imbalance of "emphasizing design and construction while neglecting operation and maintenance". Problems such as the disconnect between as-built BIM models and operation and maintenance needs, scattered multi-source operation and maintenance data, and poor collaboration among multiple stakeholders restrict the digital transformation of building operation and maintenance. Combining the background of civil engineering specialty and the development needs of intelligent construction, this study focuses on the construction of OBIM standards, integration and analysis of big data, design of multi-stakeholder collaborative mode, and value evaluation system. Through the technology integration of "BIM + Big Data", a smart operation and maintenance framework of "Data - Model - Collaboration - Evaluation" is built. This study provides theoretical support and technical paths for the digital operation and maintenance in the field of civil engineering, and meanwhile offers the research idea of "engineering demand orientation + digital technology implementation" for researchers in intelligent construction.

Keywords: Building Operation and Maintenance, BIM Technology, Smart Facility Management, Digitalization of Civil Engineering

1. Introduction

From the perspective of the whole building life cycle, operation and maintenance (O&M) is a key phase connecting design-construction achievements and realizing building use value. Industry data shows its duration exceeds 80% of the total service life, with costs reaching 3-5 times the total building investment (even higher for high-energy-consuming buildings). However, in building digital transformation, BIM technology has long focused on front-end scenarios (e.g., design visualization, construction collision inspection), leaving O&M as a shortcoming: essentially

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reflecting the disconnect between the traditional "construction-over-operation" concept and the "whole-life cycle management" concept of intelligent construction.

Field pain points are concentrated in three aspects: first, as-built BIM models are disconnected from O&M needs, lacking core O&M data (e.g., equipment maintenance cycles) and a unified OBIM delivery standard; second, O&M data is fragmented (scattered in monitoring systems, manual records) with inconsistent formats and weak correlation, failing to support decision-making; third, multi-stakeholder collaboration faces information barriers, relying on traditional methods (e.g., telephone, paper work orders) and resulting in low response efficiency.

In recent years, domestic and foreign explorations on "BIM + O&M" have provided references for civil engineering digitalization, but suffer from "more single-point breakthroughs than system integration". In BIM application, some studies made progress but failed to link models with dynamic data [1-3]. In data integration, some research verified big data value but had single data sources and insufficient integration of algorithms with engineering experience [4]. In collaborative management, some domestic studies built frameworks but lacked intelligent collaborative decision-making [5].

Combined with civil engineering digital transformation and intelligent construction needs, existing research has four core gaps: 1) lack of OBIM standards (BIM model reuse rate < 30% in civil projects); 2) superficial big data analysis, unable to support system-level decisions; 3) passive collaboration modes, without full-process automation; 4) one-sided value evaluation, ignoring long-term value.

This study significance lies in: exploring the implementation path of "BIM + Big Data" in O&M to promote the transformation of civil engineering O&M from "experience-based" to "data-driven"; constructing a collaborative mode and value evaluation system to provide "technical feasibility + economic rationality" references for civil digital projects, and establishing the "engineering demand-digital technology integration" research thinking for intelligent construction researchers.

2. Literature review

2.1. Research progress on BIM application in the building operation and maintenance phase

BIM application in building operation and maintenance (O&M) started in the early 21st century, initially focusing on information visualization. A building asset management framework was proposed in BIM Handbook, linking equipment parameters, maintenance records with BIM models, establishing the "model as database" concept and laying the foundation for O&M BIM [1].

In the past five years, research has deepened into technology integration and scenario adaptation. A BIM + Blockchain solution was proposed to record large-scale equipment life-cycle data via blockchain’s tamper-proof feature, enhancing data credibility [6]. A dynamic emergency evacuation system was developed by combining real-time crowd monitoring data to optimize high-rise building evacuation routes [7]. Domestic research is more practice-oriented: a BIM-based subway station O&M platform integrating real-time monitoring and fault alarms was built [2]; an existing building BIM model update method was proposed [3]; AI semantic segmentation was integrated to realize automatic component identification, improving modeling efficiency by 60% and accuracy to 92% [8].

Existing limitations include: 1) OBIM standardization lags: 62 Chinese civil engineering projects were surveyed, finding only 18% defined model delivery information depth, and cross-project information coding difference exceeded 60% [9]; 2) Insufficient integration of models and business processes: only 23% of applications realize "automatic work order generation for equipment maintenance cycles," most remaining at information query level [10].

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2.2. Research status of big data analytics in building operation and maintenance

Big data drives building O&M from experience-based judgment to data-driven decision-making, focusing on energy consumption analysis and fault diagnosis (aligned with civil engineering's "energy conservation, safety assurance" goals).

In the past five years, energy consumption analysis broke free from single-data dependence: a neural network energy consumption prediction model integrating user behavior data was built, raising accuracy to 91% [11]; a dynamic energy optimization strategy combining meteorological data and equipment aging coefficients was proposed, reducing winter heating energy consumption of northern Chinese commercial buildings by 28% [12]. In fault diagnosis, Graph Neural Network (GNN) was used to construct an equipment correlation network, improving diagnosis coverage by 50% compared to single-equipment models [13]; a multi-feature fusion fault prediction model integrating civil engineering knowledge was built to enhance scenario generalization [4].

Shortcomings of existing research: 1) Most focus on conventional buildings (offices, commercial buildings), with less coverage of special scenarios (hospitals, industrial plants); 2) High hardware and technical costs for algorithm deployment, limiting popularization in small and medium-sized projects.

2.3. Literature review on multi-stakeholder collaborative management in building operation and maintenance

Multi-stakeholder collaboration in building O&M focuses on solving information barriers, with research centered on collaborative mechanisms and platforms (aligned with civil engineering's "multi-participant, complex process" characteristics).

In the past five years, foreign research strengthened intelligent technology application: a "BIM + Cloud Platform + AI Decision-Making" collaborative system was proposed, shortening maintenance work order response time to 1.5 hours (62% efficiency improvement vs. traditional mode) [14]. Domestic research focuses on implementation: the BIM collaborative management framework was optimized, clarifying stakeholder rights/responsibilities and developing mobile offline functions [15]; the "BIM + Mobile Application" mode was upgraded, enabling automatic linking of user repair requests to OBIM equipment locations, shortening average repair time to 2.8 hours [5].

Existing shortcomings: 1) Insufficient intelligent decision-making: most platforms only realize information sharing, not maintenance priority suggestions; 2) Lack of emergency scenario (fire, earthquake) collaborative processes, conflicting with civil engineering's "safety first" principle.

2.4. Comprehensive review of existing research

Existing research has made progress in BIM O&M application, big data analysis, and collaborative management, but practice in the past five years has still exposed three core contradictions: 1) The contradiction between "model standards and O&M needs" – the lack of OBIM standards leads to 82% of project models requiring manual supplementary information to support O&M [7]; 2) The contradiction between "scattered data and system decision-making" – the data integration rate across systems such as energy consumption monitoring, access control, and equipment management is less than 30%, making it impossible to form a joint force for O&M; 3) The contradiction between "manual collaboration and intelligent efficiency" – only 25% of collaborative platforms realize partial automation, and work order assignment and acceptance still rely on manual judgment, which is inconsistent with the needs of intelligent construction.

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These contradictions essentially reflect the "insufficient integration of traditional engineering experience and digital technologies". For example, big data fault diagnosis models do not fully integrate the mechanical characteristics of civil engineering equipment (e.g., steel structure fatigue, concrete aging); collaborative modes are not adapted to complex on-site environments such as poor network at construction sites and cross-operation of multiple types of work, resulting in a technology implementation rate of less than 40%. Therefore, research needs to be oriented to engineering needs, deeply integrating civil engineering knowledge such as equipment maintenance cycles and fault handling processes into BIM and big data technologies, and constructing a smart O&M collaborative mode more in line with practice.

3. Research content

3.1. Research on standards and data accumulation of operation and maintenance BIM (OBIM)

OBIM is the core carrier connecting design, construction and operation and maintenance (O&M), and its standard construction must align with civil engineering's actual O&M needs. Combined with commercial complex O&M practice, the OBIM standard requires breakthroughs in three aspects: "information dimensions, delivery process, and data accumulation".

First, clarify OBIM's core information dimensions. Unlike the design phase that focuses on geometric information, the O&M phase emphasizes engineering practicality: the equipment dimension includes parameters (model, power), maintenance information (cycle, responsible person, spare part model), and fault records (historical fault type, handling plan); the spatial dimension links to usage data (personnel flow, occupancy rate) and environmental data (temperature, humidity) to support space optimization (e.g., office layout adjustment). Front-line O&M engineers must participate in determining information dimensions to ensure the information serves O&M work and avoids redundancy.

Second, design the OBIM delivery process. In civil engineering projects, design, construction and O&M belong to different stakeholders, so the delivery process needs to define responsibility boundaries: the design phase submits a BIM model with basic equipment information; the construction phase supplements data like equipment installation accuracy and construction technology (pipeline slope, electrical wiring method); the completion phase completes O&M information entry (maintenance cycle, manufacturer contact) and passes O&M party acceptance to ensure model-building consistency. Meanwhile, referring to standards such as IFC and COBie, formulate OBIM data format specifications (e.g., IFC for geometric information storage, XML for maintenance records) to ensure the model connects to different O&M systems.

Third, establish an OBIM data accumulation mechanism. Civil engineering O&M is a dynamic process that requires continuous model updates: on one hand, IoT sensors automatically collect equipment operation data (temperature, energy consumption) and synchronize it to the OBIM model in real time to realize "model as a real-time database"; on the other hand, maintenance records (maintenance time, cost) are manually entered and linked to corresponding equipment in the model. The "automation + manual supplementation" mode is adopted to reduce O&M personnel workload and ensure data integrity.

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3.2. Research on facility performance analysis and predictive maintenance based on big data

Big data analysis needs to combine the operation rules of civil engineering equipment to construct a closed loop of "data integration - performance analysis - predictive maintenance".

First, construct a multi-source operation and maintenance data integration framework. The data collection scope covers core operation and maintenance scenarios: equipment data (energy consumption, vibration, temperature), spatial data (personnel flow, occupancy rate), and environmental data (temperature, humidity, air quality). The collection method balances real-time performance and economy: high-frequency collection (once every 15 minutes) is adopted for key equipment (central air conditioners), and low-frequency collection (once every hour) is adopted for ordinary equipment (lighting) to reduce data storage and transmission costs. Data processing needs to solve the problem of heterogeneity, such as unifying the unit of energy consumption data to "kWh" and encoding fault data as "electrical fault - 01, mechanical fault - 02" to ensure that the data is comparable and analyzable.

Second, conduct facility performance analysis. Energy consumption analysis needs to combine civil engineering scenarios, such as distinguishing the energy consumption rules of "working hours and non-working hours" for office buildings, avoiding evaluating energy-saving effects solely based on "total energy consumption"; the evaluation of equipment operation status needs to combine equipment technical manuals and operation and maintenance experience, considering differences in scenario characteristics to ensure that the evaluation results are in line with reality.

Third, realize predictive maintenance. Fault prediction models balance accuracy and interpretability: a hybrid algorithm of Random Forest + LSTM is adopted, where Random Forest extracts key fault features of equipment (vibration frequency, temperature change), and LSTM captures temporal patterns (e.g., the gradual increase of vibration value 3 days before a fault). The model output needs to include fault cause suggestions to provide support for operation and maintenance personnel to locate problems. Predictive maintenance needs to issue early warnings 1-3 days in advance to reserve time for spare part procurement and personnel arrangement, which is in line with the work logic of advance planning in civil engineering.

3.3. Research on multi-stakeholder collaborative mode

Multi-stakeholder collaboration needs to clarify "stakeholder responsibilities, platform functions, and communication mechanisms", and construct a data-driven intelligent collaborative platform that is in line with the on-site work habits of civil engineering.

First, clarify the collaborative responsibilities of all parties. Facility managers are responsible for platform operation and decision-making (e.g., formulating annual maintenance plans); users, as the initiators of demands, need to submit repair information accurately (fault location, phenomenon); service providers, as executors, need to respond in a timely manner and feedback progress. Clarify the responsibility boundaries, such as the joint responsibility of users and managers for maintenance quality acceptance to ensure service quality.

Second, develop core functions of the collaborative platform. The intelligent work order assignment module combines engineering practice and prioritizes service providers who are "within 5 kilometers of the site and have maintenance experience with the same model of equipment" to reduce response time; the user interaction module simplifies operations, such as mobile repair requests realized through "taking photos + selecting fault types", and the system automatically links to the equipment location in the OBIM model; the process control module realizes full-process visualization, allowing managers to check the maintenance progress in real time (work order

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assigned - service provider received - under maintenance - accepted), solving the problem of "untransparent progress" in traditional operation and maintenance.

Third, establish a collaborative communication mechanism. Support offline communication, such as service providers can submit records offline after completing maintenance in areas without network, and the records are automatically synchronized after the network is restored; the platform generates collaborative reports regularly (monthly ranking of service provider response time, user satisfaction statistics) to provide a basis for managers to optimize collaborative strategies. Realize full-process data recording from demand initiation to acceptance evaluation to support subsequent tracing and improvement.

3.4. Research on value evaluation system

Value evaluation needs to balance short-term benefits and long-term value, in line with the whole-life cycle cost concept of civil engineering, and provide a basis for owners' digital investment decisions.

Evaluation indicators are designed from three dimensions: the cost dimension selects "operation and maintenance cost reduction rate" and "labor cost saving rate" to quantify the direct cost savings of smart operation and maintenance; the efficiency dimension selects "fault response time reduction rate" and "maintenance task completion rate" to reflect the optimization effect of the collaborative mode; the benefit dimension includes user satisfaction and equipment service life extension, and adds the indicator of "digital investment payback period" (e.g., if the initial investment in smart operation and maintenance is 1 million yuan and the average annual cost saving is 250,000 yuan, the payback period is 4 years) to provide quantitative reference for owners.

The index weight is determined by the AHP (Analytic Hierarchy Process) + expert scoring method, inviting owners, operation and maintenance engineers, and scholars in the civil engineering field to participate to ensure that the weight is in line with engineering practice (e.g., owners focus on cost and payback period, while operation and maintenance engineers focus on efficiency). The value evaluation model adopts the weighted summation method, with a comprehensive score of ≥ 80 as "excellent", 60-80 as "good", and <60 as "to be improved", assisting owners in judging the application effect of smart operation and maintenance.

4. Conclusions

Focusing on the collaborative mode of smart facility management in building operation and maintenance (O&M) and combining civil engineering background with intelligent construction needs, this study concludes: First, the OBIM standard must center on engineering practicality, clarify the equipment and spatial information dimensions for O&M, and design a "design-construction-O&M" full-process delivery mechanism to resolve the model-O&M disconnect. Second, big data analysis should integrate engineering experience and algorithms, cover core O&M scenarios via multi-source data integration, and output interpretable fault causes through prediction models to enhance engineering applicability. Third, the multi-stakeholder collaborative mode needs a "smart platform + clear responsibilities" system, improving efficiency via intelligent work order assignment and visual process control to fit civil engineering on-site needs. Fourth, the value evaluation system must balance "cost-efficiency-benefit-payback period" to provide comprehensive basis for owners' digital investment decisions.

This study's core contribution is constructing the "engineering demand-oriented digital technology application logic": digital technologies must connect closely with civil engineering

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practical issues (e.g., equipment maintenance, cost control) for effective implementation. This logic guides future intelligent construction research: deepen integration of civil engineering domain knowledge (structural mechanics, engineering management) and digital technologies (digital twin, AI) to avoid technology-engineering disconnect.

This study has three limitations: First, the OBIM standard excludes special engineering types (hospitals, industrial plants); their O&M needs (e.g., hospital clean environment control) differ from commercial buildings and require follow-up supplementation. Second, the big data model has insufficient generalization, is untested in different climate zones and building types, and needs more engineering data support. Third, the collaborative platform ignores emergency scenarios (fires, earthquakes), requiring emergency collaboration function upgrades in follow-up research.

From the trend of intelligent construction-civil engineering digitalization integration, future research can focus on two directions: First, explore digital twin's application in O&M. Compared with BIM, it has higher real-time performance and interactivity, enabling the "O&M scenario simulation-decision optimization-execution feedback" closed loop, aligning with intelligent construction trends. Second, study large AI models in O&M knowledge management: convert civil engineering O&M engineers' experience into knowledge graphs, and use large models to realize fault diagnosis semantic understanding (e.g., identifying faults when users describe "water pump abnormal noise") to solve O&M experience inheritance issues.

As civil engineering and digital technologies integrate deeply, building O&M will shift from "passive maintenance" to the smart mode of "proactive prediction + intelligent collaboration", supporting building whole-life cycle value maximization and advancing civil engineering digital transformation.

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