Synergistic Mechanism and Progressive Path of BIM Application in Historic Building Restoration: A Case Study of the Zhengyangmen Gate Tower Restoration Project

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Abstract

To address the persistent challenge of “high-value recognition but low adoption intention” of Building Information Modeling (BIM) in the field of historic building restoration, this paper takes the Zhengyangmen Gate Tower restoration project in Beijing as a typical case and adopts a chain-of-evidence analysis method to systematically investigate the application mechanism of BIM in real engineering contexts. The study finds that the Zhengyangmen project has developed a synergistic closed loop of “environmental drivers → organizational innovation → technological empowerment → value recognition”. In this loop, policy support and public attention constitute the external driving forces, while organizational mechanisms and tool innovations form the responsive layer. This effectively mitigates the complexity of modeling non-standard components, allowing the technical advantages of monitoring and early warning, nesting recording, and concealed craftsmanship preservation to materialize, thereby fostering value recognition among practitioners. Based on this, a three-stage progressive promotion path of “digital documentation → process integration → lifecycle management” is constructed, and synergistic barrier-breaking strategies are proposed from the technology, organization, and environment dimensions. This study provides an actionable engineering path for the systematic promotion of BIM technology in historic building restoration and offers practical guidance for the digital preservation of cultural heritage.

Keywords

BIM; Historic Building Restoration; Zhengyangmen; Progressive Promotion Path; Organizational Innovation.

1. Introduction

China possesses a large number and wide variety of historic buildings, with ancient architecture accounting for 42.7% of the national key cultural relic protection units [1]. However, due to natural erosion, material aging, inappropriate repairs, and other factors, many historic buildings are in a “sub-healthy” state. Historic building restoration is fundamentally different from general construction engineering. Its core challenges are embodied in: the value constraint of “authenticity first” – any intervention must be reversible and identifiable; the lack of historical information – a large amount of component data needs to be re-verified; the interruption of traditional craftsmanship – construction practices exist only in the experience of elderly craftsmen; and the non-standardization of components – modern standardized construction methods cannot be directly applied [2].

Building Information Modeling (BIM) technology provides a digital pathway to address the above challenges. Through 3D laser scanning, HBIM modeling, collaborative management platforms, and other means, BIM can integrate historical information, simulate traditional craftsmanship, and assist in restoration decision-making. However, this technology generally suffers from the paradox of "high-value recognition but low adoption intention" in the field of historic building restoration: practitioners generally acknowledge the technical advantages of BIM, yet its adoption rate in actual projects remains low [3]. Existing research has mostly focused on the methodological development of HBIM (e.g., scan-to-BIM workflows, semantic enrichment), lacking in-depth analysis of the "how-to-implement" mechanisms in real engineering contexts, and even fewer studies have extracted replicable promotion paths from successful cases [4–5].

This paper selects the restoration project of the Zhengyangmen Gate Tower in Beijing as a core case. Zhengyangmen is located at the core of Beijing's Central Axis and is a key node for the inscription of the "Central Axis" on the World Heritage list. The project comprehensively applied digital technologies such as 3D laser scanning, HBIM modeling, and collaborative management platforms, accumulating 13 billion point cloud data points and constructing a full-cycle digital archive covering the pre-construction, during-construction, and post-construction periods [6]. Through chain-of-evidence analysis, this paper aims to answer two questions: (1) What is the synergistic mechanism behind the successful application of BIM in the Zhengyangmen project? (2) How can this experience be distilled into a replicable staged promotion path? The research findings provide an engineering basis for the systematic promotion of BIM technology in historic building restoration.

2. Research Design

2.1. Case Selection Justification

The Zhengyangmen Gate Tower restoration project was selected as a typical case for the following three reasons:

(1) High project level: Zhengyangmen is a national key cultural relic protection unit, located in the core area of the Beijing Central Axis nomination. In 2024, the "Beijing Central Axis" was inscribed on the World Heritage List. This restoration project is a key project of the three-year action plan for the Central Axis nomination and has received high attention from the National Cultural Heritage Administration and the Beijing Municipal Government.

(2) Systematic technology application: The project comprehensively applied digital technologies such as 3D laser scanning, HBIM modeling, and collaborative management platforms, forming a full-process technology loop from data acquisition to construction management, providing a typical demonstration.

(3) Publicly available and verifiable information: The project is supported by abundant documentation, including approval documents from the National Cultural Heritage Administration, implementation plans from the Beijing Municipal Cultural Heritage Bureau, technical reports, and media coverage. Multiple sources can cross-validate each other, ensuring the completeness and credibility of the chain of evidence.

2.2. Data Collection and Analysis Methods

This study adopts a chain-of-evidence analysis method, following the single-case study process proposed by Yin [7]. Data collection covers three types of sources:

(1) Official documents: Approval letters from the National Cultural Heritage Administration (Wenwu Bao Han [2021] No. 246, No. 450), replies from the Beijing Municipal Cultural Heritage Bureau (Jing Wenwu [2021] No. 725, Jing Wenwu [2026] No. 115), and the *Beijing Central Axis Protection Management Plan.

(2) Technical reports: Project feasibility study report, post-evaluation report, and 3D laser scanning results report.

(3) Media coverage and interviews: Publications from Xinhua Net, Beijing News, official releases from Beijing Construction Engineering Group (BCEG), and public interviews with project leaders.

The analysis employs pattern matching and time-series analysis to map case facts onto theoretical constructs and to distill the synergistic mechanism.

3. Process Mechanism of BIM Application in the Zhengyangmen Gate Tower Restoration Project

3.1. Project Overview and Core Challenges

Zhengyangmen was first built in the 19th year of the Yongle reign of the Ming Dynasty (1421) and was the main gate of the inner city of Beijing during the Ming and Qing dynasties, known as the "first of the nine gates". It was damaged many times in history; the existing building was rebuilt after a fire in 1902. In 1988, Zhengyangmen was announced as a national key cultural relic protection unit [6]. This restoration faced three major core challenges:

Fig 1. Real scene of Zhengyangmen Gate Tower restoration project (image source: internet)

Table 1. Three major core challenges of the Zhengyangmen restoration project

Challenge dimension	Specific manifestation	Impact on restoration work
Difficulty in preserving information	Ministry of Works archives were burned in 1902; historical drawings scattered; existing 2D data incomplete	Lack of original basis for component dimensions and construction details; need to re-verify
Difficulty in transmitting craftsmanship	Woodworking, masonry, painting, coloured patterns etc. rely on oral transmission from master to apprentice; young craftsmen unfamiliar with digital tools	Unclear process standards, risk of losing traditional techniques
Difficulty in multi-disciplinary collaboration	Information transmission lag among design, construction and heritage management units; low decision-making efficiency	Prone to construction deviations and rework; affects project progress and quality

3.2. Environmental Drivers: Dual Role of Policy and Social Pressure

The digital practice of the Zhengyangmen restoration project was driven by two types of external environmental factors, forming an external pressure field intertwining policy rigidity and public expectations.

Policy level: The protection of the Beijing Central Axis was incorporated into the *Beijing Urban Master Plan (2016–2035)* and the core area control detailed plans. The *Beijing Central Axis Protection Management Plan (2022–2035)* explicitly required the "establishment of a digital archive of the Central Axis heritage", transforming digital recording from an optional item in traditional restoration into a mandatory requirement. The Beijing Municipal Cultural Heritage Bureau repeatedly emphasised in project approval documents the need to "strengthen the recording of technical disclosure and consultation processes, and properly organise technical archives" [8]. These policy documents together form a hierarchical and clearly defined system of policy constraints.

Social level: As the Central Axis nomination entered a critical stage, the frequency of mainstream media coverage of the Zhengyangmen restoration project increased significantly. The public's insistence on the "restore the old as it was" principle and their expectation of a "transparent restoration" process translated into an urgent demand for visibility and traceability of the construction process. The project leader noted in an interview: "Now every process must consider what the public will think. Digital recording is not only a technical need but also a necessary means to respond to public concerns."

Table 2. Major policy documents and digital requirements for the Zhengyangmen restoration project

Date	*Document name*	*Issuing authority*	*Core digital requirements*
2021.3	Reply on the Design Change of the Zhengyangmen Arrow Tower Protection and Restoration Project	National Cultural Heritage Administration	Do well in archival recording; reduce disturbance to original ground
2021.5	Reply on the Design Plan of the Zhengyangmen Gate Tower Restoration Project	National Cultural Heritage Administration	Strengthen recording of technical disclosure and consultation processes; properly organise technical archives
2022.5	Beijing Central Axis Cultural Heritage Protection Regulations	Standing Committee of Beijing Municipal People's Congress	Establish protection monitoring archives; build heritage information platform
2025.12	Reply on the Design Change Plan of the Zhengyangmen Gate Tower Restoration Project	Beijing Municipal Cultural Heritage Bureau	Strengthen technical quality control; do well in recording of concealed works

3.3. Organizational Response: Mechanism Innovation and Process Reengineering

In the face of external environmental pressure, the project team did not simply react passively; instead, they systematically transformed external institutional constraints and social expectations into drivers of internal capacity building through organisational innovation.

(1) Mechanism innovation: Institutionalised design of a joint working group

Beijing Construction Engineering Group (BCEG) established an "Ancient Building Restoration Craftsmanship Innovation Studio" within the project department, adopting a "headquarters + project" matrix organisational structure. This structure vertically and horizontally integrates the R&D capabilities of the headquarters' technical team with the practical experience of the front-line project team, breaking down the organisational barriers between technical departments and construction departments found in traditional restoration projects. Zhang Yupin, Deputy Chief Engineer of BCEG, noted: "Relying on big data and information technology, we began systematic exploration of digital applications in ancient building restoration five years ago. The establishment of this studio marks the systematic transformation of our earlier exploratory achievements into project practice."

(2) Process reengineering: Explicitisation of tacit knowledge

The core task of the studio was to systematically break down traditional construction processes such as plastering, woodworking, masonry, painting, and coloured patterns, and to independently develop a “public benefit collection mini-program” for recording images and archiving data throughout the construction process. Zhang Yupin pointed out: “In the past, the transmission of technical processes was mostly achieved through oral teaching from master to apprentice, which easily led to unclear process standards and unfixed operation methods.” Through digital means, the team transformed the tacit knowledge embedded in the individual experience of craftsmen into explicit process standards that are recordable, traceable, and replicable, gradually building an “Ancient Building Digital Craft Dictionary”.

(3) Tool innovation: Collaborative management platform

The “public benefit collection mini-program” built by the project team incorporated daily image collection, completion status, material usage, and other information into a unified data platform. All participating units (design, construction, heritage conservation, supervision, etc.) could perform real-time collaborative management online, tracking and verifying process execution and material delivery and usage at any time. This tool effectively solved the problems of traditional modes, where information transmission relied on paper documents and offline meetings, leading to information lag, high communication costs, and low decision-making efficiency.

3.4. Technological Adaptation: Evolution from Barriers to Value

With organisational innovation as a support, the Zhengyangmen project introduced digital technologies, and the application process showed a trajectory of adaptation from technical barriers to value demonstration.

(1) Real manifestation of technical complexity: The project accumulated 13 billion point cloud data points to build a high-precision model of the gate tower, a data volume far exceeding that of conventional construction engineering digitisation. The technical feasibility report showed that modelling non-standard components of ancient buildings (e.g., brackets, roof trusses, caissons) is several times more labour-intensive than standard components, and existing commercial BIM software libraries generally lack component types for ancient buildings, requiring substantial customised development during model construction. Furthermore, processing high-precision point cloud data demands high-end hardware and professional software.

(2) Proactive response to compatibility issues: When Zhengyangmen was burned down in 1902, the Ministry of Works archive of city gate documents was also destroyed. Existing 2D drawings, restoration records and other files are diverse in format and inconsistent in standards. Facing this problem, the project team adopted a “multi-source data integration” strategy: using 3D laser scanning point cloud data as the geometric reference, historical photographs as texture and detail references, and 2D drawings as dimensional and structural references. Through data registration, semantic alignment, information fusion and other technical means, data from these three different sources and formats were uniformly integrated into the modelling workflow.

(3) Gradual emergence of relative technical advantages: Structural monitoring – The project installed hydrostatic leveling instruments and Beidou monitoring stations at the arrow tower, achieving 0.1 mm-level real-time monitoring of structural deformation, with automatic early warning triggered when displacement exceeded 0.3 mm. Ecological protection – Laser scanning recorded the precise locations of over one hundred Beijing swift nests, giving the “little homes” originally hidden in the brackets their own 3D images, thus achieving simultaneous preservation of historical and ecological information. Craftsmanship transmission – 720° panoramic images recorded construction techniques from concealed parts, transforming the

tacit knowledge traditionally transmitted orally from master to apprentice into traceable and replicable digital assets.

Table 3. Specific manifestations of relative technical advantages**

Application scenario	*Technical means*	*Achieved effect*	*Application scenario*
Structural safety monitoring	Hydrostatic leveling + Beidou monitoring station	0.1 mm-level real-time monitoring, automatic early warning when exceeding limit	Structural safety monitoring
Ecological information preservation	Laser scanning for nest localisation	3D recording of swift nests; simultaneous preservation of ecological and historical information	Ecological information preservation
Recording of concealed craftsmanship	720° panoramic imaging	Permanent archiving of craftsmanship inside brackets and roof truss concealed parts	Recording of concealed craftsmanship
Multi-source data integration	Point cloud + historical photos + 2D drawings registration	Transformation of scattered historical information into unified digital integration	Multi-source data integration

3.5. Value Recognition: The Dominant Role of Perceived Usefulness

The Zhengyangmen case provides a complete chain of evidence for examining the cognitive transformation of practitioners.

Attitude shift of craftsmen: Initially, some craftsmen resisted the 3D models, thinking “it is better to just do it by hand”. However, as the “Ancient Building Digital Craft Dictionary” was enriched and the accumulation of images from concealed parts increased, their attitudes changed fundamentally. One woodworking craftsman involved in the project said in an interview: “In the past, only the master knew how to do some nodes; now you can see the 3D model on your phone, and complex procedures become easy to understand at a glance.” The AR tool increased the on-site model access rate from less than 30% to 90%, and 80% of craftsmen agreed that the AR tool reduced the difficulty of understanding complex structures [9].

Value recognition from the management perspective: BCEG used the Zhengyangmen restoration as a systematic integration of its earlier digital explorations, driving a leap from a pilot project to corporate strategy. The project’s post-evaluation report stated: “The great value of BIM technology in plan rehearsal, risk early warning, and craftsmanship transmission has led the company to fully promote digital applications in subsequent ancient building projects.”

Value-first adoption logic: The case evidence shows that craftsmen were willing to overcome the learning threshold and persist in using BIM technology because the fundamental driver was that the tool could address the core pain point of craftsmanship transmission: the value perception that “complex procedures are easy to understand at a glance” outweighed the instrumental rationality consideration of “whether it is convenient to operate”. This is highly consistent with the statistical finding that “perceived usefulness dominates adoption, while perceived ease of use is not significant”, revealing the unique “value-first” adoption logic in the field of historic building restoration.

4. From Single Case to General Path: A Three-Stage Progressive Promotion Model

The successful practice of the Zhengyangmen Gate Tower restoration project demonstrates that effective application of BIM technology in historic building restoration is not achieved in one step, but follows a gradual evolution from “technologically available” to “technologically useful” to “technologically common”. Based on this finding, this paper extracts a three-stage progressive promotion path of "digital documentation → process integration → lifecycle management". The path follows the core principles of "from easy to difficult, value progression, and risk controllability", aiming to systematically break the promotion dilemma of "high-value recognition but low adoption intention".

4.1. Logical Framework of the Path Design

The design of the three-stage path is based on the synergistic closed loop of "environmental drivers → organizational innovation → technological empowerment → value recognition" observed in the Zhengyangmen case. This closed loop indicates that external driving forces (policy and social pressure) are transformed through organisational responses (mechanism reengineering and tool innovation) into enhanced technological capability, ultimately fostering value recognition among practitioners. Following this logic, the promotion path should start by lowering the technological threshold, then progressively prove the technological value, and finally achieve system-level application. The three stages are not a strictly linear progression; iteration and feedback can occur between them. For organisations that already possess a certain level of digital foundation, they may start directly from the intermediate or advanced stage; for small restoration teams with weak digital capacity, it is recommended to start from the primary stage and gradually accumulate experience and resources.

4.2. Primary Stage: Technical Feasibility Verification and Digital Documentation

The core objective of the primary stage is to establish practitioners' initial trust in BIM technology through low-cost, small-scale practice, to alleviate the usage barriers caused by technical complexity, and thereby enhance perceived ease of use. At this stage, the focus is not on building a complete BIM system but on allowing practitioners to get in touch with and become familiar with digital tools at low risk and cost, creating a positive initial experience.

Specific tasks include three items. First, digitisation of key components: select typical complex components such as brackets, beam ends, and caissons for high-precision 3D laser scanning and BIM modelling, forming reusable "digital specimens". Because ancient building components are highly non-standard, focusing on a few key components rather than full-scale modelling can significantly reduce initial investment costs while verifying technical feasibility. Second, conversion from 2D to 3D digital representation: transform traditional survey drawings into 3D visualisation models. 3D models present building structures and component relationships intuitively, greatly reducing the difficulty of technical understanding, enabling craftsmen and managers without a BIM background to understand and participate in discussions. Third, establishment of a basic component library: build a parametric accumulation of reusable components based on individual component modelling, gradually forming a sustainably expandable digital asset. HBIM research has confirmed that a reusable parametric object library is an important foundation for digital modelling of historical buildings – once a typical component is modelled, subsequent projects only need to adjust parameters to reuse it, significantly reducing repetitive modelling costs.

The expected outcomes of this stage include a pilot digital component library, 3D visualisation archives, and lightweight display models. These outcomes are characterised by high visualisation and intuitive presentation, effectively conveying the value of technology application to managers and decision-makers, thereby gaining sustained support for subsequent promotion. In terms of risk control, it is recommended to select small, low-risk projects or local areas within a large project (e.g., a courtyard, a single building) for initial piloting, avoiding large initial investments that, in case of failure, could hinder overall promotion.

4.3. Intermediate Stage: Core Process Integration and Risk Control

The core objective of the intermediate stage is to embed BIM into one or two key business processes on the basis of digital documentation, applying it in areas such as restoration plan comparison, accurate quantity take-off, complex process simulation, and structural monitoring integration, so that practitioners tangibly experience the improvement in core work performance, thereby strengthening perceived usefulness. The key at this stage is that the application of BIM must produce quantifiable benefits – such as cost savings, risk reduction, and efficiency improvement – rather than remaining at the level of “demonstration effect”.

Specific tasks include four items. First, restoration plan simulation. Ancient building restoration follows the “authenticity first” principle; choosing an intervention plan often requires balancing conservation value and engineering feasibility. Traditional methods rely on 2D drawings and expert experience, making it difficult to visually assess the impact of different plans on the heritage body. Using BIM models for multi-scenario comparison and virtual rehearsal allows simulation of the visual effects, structural response, and material consumption of different intervention measures without touching the heritage body, providing a scientific basis for decision-making. Second, accurate quantity take-off. Restoration of ancient buildings involves a large number of non-standard components and traditional materials; quantity estimation has long relied on empirical judgment, with large errors. BIM models can automatically extract geometric information and material properties of components to generate accurate bills of quantities. The post-evaluation report of the Zhengyangmen project showed that BIM-based material statistics significantly improved estimation accuracy, reducing material waste by about 12%. Third, construction process simulation. Operations such as dismantling and straightening of timber frames in ancient building restoration are irreversible; mistakes can cause irrecoverable damage. Using 4D BIM technology to integrate the time dimension with the 3D model, virtual rehearsal and optimisation of complex construction processes can identify issues such as process conflicts and spatial interference before construction, and adjust the construction plan accordingly. The practice of the Huatang Wang’s Ancestral Hall restoration project shows that construction rehearsal based on 3D scanning and 4D simulation successfully transformed empirical correction into a quantifiable and traceable decision-making process. Fourth, structural monitoring integration. Integrate the BIM model with sensor data from on-site instruments such as hydrostatic levels and Beidou monitoring stations to achieve millimetre-level real-time monitoring and automatic early warning of structural deformation. When displacement exceeds a set threshold, the system automatically triggers an early warning and locates the risk area, enabling the management team to take timely measures.

The main outcomes of this stage include digital plan comparison reports, accurate bills of quantities, 4D construction simulation results, and structural health monitoring platforms. These outcomes provide strong evidence of BIM’s value through quantifiable indicators such as cost savings, risk reduction, and efficiency improvement, thereby strengthening practitioners’ perceived usefulness. In the Zhengyangmen project, when engineers saw monitoring data updating in real time on the model and early warning information being pushed automatically, their perception of “BIM being useful” was significantly enhanced.

4.4. Advanced Stage: Full Lifecycle Management and Innovative Activation

The core objective of the advanced stage is to build a digital asset platform covering the entire process of ancient building survey, design, construction, monitoring, and operation and maintenance, upgrading BIM technology from a “project-level tool” to a “platform-level capability”. This stage reflects the systematic integration of the three elements of the TOE framework: at the technology level, promoting multi-source data fusion and digital twin applications; at the organisation level, forming long-term mechanisms for cross-departmental collaboration; at the environment level, advancing the gradual solidification of relevant policies and technical standards.

Specific tasks include four items. First, *full-lifecycle digital archive construction*. Integrate survey, design, construction, and monitoring data to form a sustainably updatable digital twin asset. This means that the location, dimensions, material, and craftsmanship of every component are traceable, and every restoration intervention is recorded. The Gulangyu cultural heritage protection project has completed digital archiving of all 63 cultural relic protection units at or above the district level, created 3D models for many key buildings, and transformed the entire island into a sustainably updatable digital heritage archive system. Second, *establishment of a preventive protection system*. By combining BIM models with long-term monitoring data, achieve dynamic assessment of structural health status and risk prediction, promoting a shift from traditional “rescue-oriented restoration” to “proactive maintenance”. The Changting Nan Dajie historic district protection project used sensors to continuously monitor building settlement, temperature, humidity, and crack changes, combined with algorithmic models for risk prediction, forming a dynamic monitoring system. Third, *public interaction and cultural activation*. Utilise VR, AR, and digital twin technology to expand the means of dissemination and display space of cultural heritage, giving historic buildings new life in the digital environment. The Nanjing Grand Bao’en Temple Ruins Museum used digital reconstruction and VR technology to build an immersive display platform, allowing visitors to experience the historical scenes of the Ming-era Grand Bao’en Temple glazed pagoda in a virtual manner. Fourth, *platformisation and regional collaborative management*. Relying on a City Information Model (CIM) platform, integrate information from multiple historic buildings to achieve intelligent management at the regional level. Sichuan Province built a “2D-3D one-map” of the province’s historical and cultural resources based on a CIM platform, integrating planning management and protection supervision functions; Suzhou City built a “CIM + Digital Twin Ancient City” platform, carrying out fine-grained modelling of traditional residences and historical courtyards, and establishing a complete database of ancient city buildings.

The main outcomes of this stage include a digital twin archive platform, a preventive protection system, digital display applications, and a regional protection management platform. These outcomes are characterised by scalability and sustainability: data can be reused across projects, the platform can support multiple types of application scenarios, and digital outcomes can be further transformed into cultural dissemination and cultural tourism service resources. Table 5 summarises the core objectives, key tasks, expected outcomes, and major risks of each stage.

Table 4. Summary of core elements of the three-stage promotion path

Stage	*Core objective*	*Key tasks*	*Expected outcomes*
Primary stage	Verify feasibility, improve perceived ease of use	Digitisation of key components, 2D→3D conversion, basic component library construction	Digital component library, 3D visualisation archive, lightweight model
Intermediate stage	Prove technical value, strengthen perceived usefulness	Restoration plan simulation, accurate quantity take-off, construction process simulation, structural monitoring integration	Comparison reports, BoQ, 4D simulation results, monitoring platform
Advanced stage	Platform capability, systematic application	Full-lifecycle digital archive, preventive protection, public interaction/activation, regional collaborative management	Digital twin platform, preventive protection system, CIM integration
Stage	Core objective	Key tasks	Expected outcomes

5. Multi-Dimensional Synergistic Barrier-Breaking Strategies

The experience of the Zhengyangmen case shows that relying solely on the technology tool itself cannot break through the barriers to promotion; instead, a systematic barrier-breaking system must be formed through synergistic measures from the three dimensions of technology, organisation, and environment. The specific strategies for each dimension are elaborated below.

5.1. Technology Dimension: Tool Adaptation and Integration

Barriers at the technology dimension mainly stem from the significant negative impact of technical complexity on perceived ease of use and the lack of technical compatibility. Barrier-breaking strategies include four aspects: tool lightweighting and mobilisation, open-source component library construction, AI-assisted intelligent modelling, and AR/VR on-site interaction technology.

(1) Tool lightweighting and mobilisation. The suppression of ease-of-use perception by technical complexity largely originates from the mismatch between existing BIM tools and the on-site restoration environment – high-precision point cloud data typically require professional workstations, and complex models cannot run smoothly on mobile terminals, making it difficult for front-line craftsmen to understand and use digital models. The lightweight AR inspection system developed for the Zhengyangmen project transformed the high-precision BIM model into an AR display layer that runs smoothly on mobile devices such as phones and tablets, allowing construction personnel to view the overlay of component models and traditional craftsmanship at any time, significantly increasing the on-site model access rate (from less than 30% to 90%). In the future, a “cloud-edge-device” collaborative architecture can be further built: high-precision models stored in the cloud, edge nodes responsible for data preprocessing and lightweight conversion, and mobile terminals for visualisation display and interaction. This layered strategy can meet the on-site requirements for rapid response and ease of use while maintaining model accuracy.

(2) Open-source ancient building component library co-construction and sharing. The highly non-standard nature of ancient building components is an important cause of modelling complexity. HBIM theory indicates that historical building modelling relies on a reusable parametric component library, but in current practice, different projects often repeatedly model complex components such as brackets and caissons, leading to low efficiency and high costs. Based on the “Ancient Building Digital Craft Dictionary” accumulated in the Zhengyangmen project and related parametric research, it is recommended to establish an open-source component library platform at the industry level, adopting a “contribute → review → share” community mechanism to encourage project teams from various regions to upload locally characteristic component models. At the same time, unified data standards should be established, clarifying metadata specifications such as component geometric accuracy, attribute information (e.g., material, age, craftsmanship features), and historical traceability, to improve the reusability and interoperability of models.

(3) AI and intelligent modelling technology integration. Artificial intelligence technology provides a new path to solve the problem of complex component modelling. By converting traditional construction rules (such as the modular relationships in the Yingzao Fashi of the Song Dynasty and the *Gongcheng Zuofa* of the Qing Dynasty) into algorithmic logic, component models that conform to specific period and regional characteristics can be automatically generated after inputting key parameters. Existing research has attempted deep learning-based automatic component recognition and 3D data completion. For example, a research team at Hunan University proposed a multi-dimensional semantic modelling framework for traditional villages based on street view images and deep learning, using the Mask R-CNN model to achieve automatic recognition and segmentation of building components.

As these technologies mature, ancient building modelling is expected to move from "manual and detailed" to "intelligently assisted", significantly improving modelling efficiency.

(4) AR/VR on-site interaction technology. Compatibility problems exist not only between software systems but also in the cognitive gap between digital models and physical construction – construction personnel face actual building components, while BIM models typically exist on a computer screen, creating an information translation barrier. Augmented reality and virtual reality technologies can effectively bridge this gap. The AR assistance system in the Zhengyangmen project has proven that when digital models are overlaid onto real components, construction personnel can more intuitively understand design intentions and process requirements. In the future, AR construction assistance systems can be further developed to achieve precise alignment of BIM models with physical components (e.g., through QR codes or visual markers for positioning), while using VR technology to build virtual training environments, allowing young craftsmen to practise complex procedures repeatedly in digital space, reducing on-site trial-and-error risks.

The synergistic implementation of the above four types of strategies can systematically resolve barriers at the technology dimension: lightweighting tools lower the on-site application threshold, directly enhancing perceived ease of use; the open-source component library reduces the cost of modelling non-standard components at the source; AI technology improves modelling efficiency, further alleviating technical complexity; AR/VR technology bridges the digital-physical divide, enhancing technical compatibility.

5.2. Organization Dimension: Collaborative Models and Incentive Mechanisms

Barriers at the organisation dimension mainly include shortages of compound talents, high costs of cross-disciplinary collaboration, and insufficient motivation for investment. Barrier-breaking strategies cover four aspects: talent cultivation, collaboration mechanisms, professional service market nurturing, and intellectual property incentives.

(1) "University-industry-enterprise" collaborative education. Shortage of compound talents is the core bottleneck restricting BIM application in ancient buildings. Such talents need to simultaneously master ancient building forms, traditional craftsmanship, and cultural heritage knowledge, as well as digital skills such as 3D scanning, BIM modelling, and data management – a long and costly training process. Solving this problem requires establishing a collaborative education system involving schools, industries, and enterprises. The Hebei Ancient Building Digital Resource Science and Technology Innovation Centre is an exemplary model: jointly built by a vocational college, a surveying technology enterprise, and a cultural tourism organisation, it conducts teaching and practice around digital protection of ancient buildings, training students in 3D modelling and digital archive construction through real projects. Shaanxi Vocational and Technical College explored a "university-industry-enterprise" collaborative, dual-certificate, dual-orientation training model, jointly building training platforms with industry associations and enterprises, incorporating real projects such as historical building scanning and modelling and cultural relic digital restoration into the teaching process, implementing a "campus mentor + enterprise mentor" dual-mentor system and a "academic certificate + professional qualification certificate" dual-certificate system.

(2) "BIM coordinator + traditional craftsman" pairing mechanism. Restoration of ancient buildings involves collaboration across multiple fields, including cultural heritage conservation, structural engineering, traditional craftsmanship, and digital modelling. Cognitive differences between different professions often lead to high communication costs. Establishing a pairing mechanism between BIM coordinators and traditional craftsmen, using a dedicated role to bridge digital technology and traditional craftsmanship, can effectively reduce collaboration costs. The "BIM-Craftsman Joint Working Group" established in the Zhengyangmen project is an effective example: BIM coordinators are responsible for translating technical information

from digital models into drawings and visual content understandable to craftsmen, while craftsmen verify and correct the process parameters of the models based on their own experience. This mechanism enables timely and accurate feedback of digital model information to the construction site, forming a virtuous cycle of “model-driven construction, construction-feedback to the model”. In the future, the BIM coordinator role should be promoted in the industry, becoming an important link between digital technology and traditional craftsmanship.

(3) Professional technical service market cultivation. Currently, digital work on ancient buildings is mostly undertaken by project teams themselves, lacking specialised social division of labour, leading to inconsistent efficiency and quality. Establishing a professional technical service market is an important way to address organisational resource bottlenecks. The National Cultural Heritage Administration has issued policies encouraging social forces to participate in the protection, repair, digital recording, and cultural utilisation of heritage buildings, guiding social capital into the heritage protection field through financial subsidies, operating subsidies, and fund support. In practice, three types of professional institutions should be cultivated: ancient building BIM consulting agencies (providing scanning, modelling, and collaborative management technical services), digital training institutions (providing professional skill training for industry practitioners), and component library development and operation agencies (responsible for the maintenance and standard-setting of HBIM component libraries). As the professional service market matures, project teams can obtain technical support by purchasing services, improving resource allocation efficiency and lowering technical thresholds.

(4) Intellectual property and value distribution mechanism. An important reason for insufficient motivation is that the value of digital outcomes is difficult to realise in the short term, and property rights are unclear. Currently, many cultural heritage digitalisation projects lack clear definitions of data property rights at the contract level, leading to potential conflicts of interest between heritage protection units and technical service providers. Clarifying data sovereignty and benefit-sharing mechanisms is an important condition for enhancing the willingness of all parties to cooperate. At the industry level, a *Guideline on Intellectual Property of Digital Outcomes of Ancient Buildings* could be formulated, clarifying three basic principles: the core sovereignty of relic data belongs to the state; reusable assets such as common component libraries are developed collaboratively through a “contribute-share” mechanism; and a reasonable benefit distribution mechanism is established for secondary development outcomes such as digital cultural creativity and VR displays. The Zhangzhou Ancient City digitalisation project, by building a high-precision 3D data base and a digital gene library, clarified that the technical institution assumes the responsibility of data construction but not data ownership, thereby protecting the data sovereignty of the heritage protection unit institutionally. Through institutional design, digital outcomes can be transformed from a pure cost item into a confirmable and appreciable cultural asset.

5.3. Environment Dimension: Standard System and Targeted Policies

Barriers at the environment dimension mainly stem from the lack of detailed implementation guidelines for policies, the absence of industry standards and certification systems, and insufficient incentive mechanisms. Barrier-breaking strategies cover four aspects: establishment of a hierarchical standard system, transformation of policies from “standardised supply” to “targeted empowerment”, improvement of intellectual property protection and value distribution mechanisms, and cultivation of a social-force participation ecosystem.

(1) Establish a hierarchical standard system. The lack of unified standards for model information content, level of detail, and deliverable formats in BIM application for ancient buildings has long led to a lack of clear basis for technical implementation and acceptance. In

recent years, progress has been made in standard development: Shanghai issued the *Technical Standard for Digital Surveying and Mapping of Outstanding Historical Buildings*, specifying systematic requirements for technical processes, data accuracy, and outcome quality; Shanxi Province issued the *Digital Acquisition Specification for Ancient Buildings – Part 1: Main Body*, regulating 3D scanning, photogrammetry, and data archiving; the *Building Information Modeling – Industry Foundation Classes – Ancient Architecture* compiled by the China Association for Engineering Construction Standardisation has formed a draft for comments, aiming to improve the semantic system of ancient building BIM. On this basis, a hierarchical standard system should be built consisting of national standards, industry specifications, and local detailed rules: at the national level, focus on addressing data semantics and information structure issues (e.g., component classification codes, attribute set definitions); at the industry level, establish model delivery and quality assessment specifications; at the local level, formulate implementation rules in light of regional architectural characteristics. Improving the standard system will enhance technical compatibility and implementation certainty, strengthening the actual effect of policy support on technology adoption.

(2) Shift policies from “standardised supply” to “targeted empowerment”. Some current policies adopt a “one-size-fits-all” approach of unified component library promotion, generic training, or general subsidies. However, ancient buildings have significant regional and non-standard characteristics, and such models often fail to effectively respond to actual needs, even potentially aggravating practitioners’ doubts about technology applicability. Recent policy practice has begun to shift towards targeted empowerment: the Ministry of Finance and the Ministry of Housing and Urban-Rural Development issued a notice on the construction of traditional village characteristic protection zones, clarifying that from 2026 to 2028 the central finance will provide special subsidies (RMB 50 million per county) to selected counties, and include digital protection in the scope of funding support. Future policy design should further strengthen three innovations: first, establish a special innovation fund for BIM technology in ancient building restoration, focusing on supporting R&D of key technologies such as parametric modelling of non-standard components, lossless conversion of heterogeneous multi-source data, and heritage-adaptive lightweight tools; second, establish an evaluation indicator system centred on professional values such as “degree of authenticity information preservation” and “contribution to traditional craftsmanship transmission”, rather than using only modelling output as the assessment basis; third, improve a dynamic policy effect evaluation mechanism, optimising policy tools promptly based on industry feedback to enhance policy implementation efficiency.

(3) Improve intellectual property protection and value distribution mechanisms for digital outcomes. Unclear property rights are an important institutional obstacle restricting the willingness of all parties to cooperate. Currently, many cultural heritage digitalisation projects lack clear definitions of data property rights at the contract level, leading to potential conflicts of interest between heritage protection units and technical service providers. In the Zhangzhou Ancient City digitalisation project, by building a high-precision 3D data base and digital gene library, relying on a real-scene 3D platform for multi-source data integration and dynamic management, it was made clear that the technical institution assumed the responsibility of data construction but not data ownership, thereby protecting the data sovereignty of the heritage protection unit institutionally. The Changzhou Jiaoxi Ancient Town Hefeng Academy project achieved win-win cooperation through a “technology breakthrough + site support” joint outcome mechanism. At the industry level, a *Guideline on Intellectual Property of Digital Outcomes of Ancient Buildings could be formulated, clarifying basic principles such as the core sovereignty of relic data belonging to the state, the “contribute-share” mechanism for reusable assets like common component libraries, and reasonable benefit distribution for secondary

development outcomes. Through institutional design, digital outcomes can be transformed from a pure cost item into a confirmable and appreciable cultural asset.

(4) Cultivate a social-force participation ecosystem. Relying solely on government investment cannot support large-scale digital documentation of cultural heritage; it is necessary to bring in social capital and professional institutions to participate jointly. The *Opinions on Encouraging and Supporting Social Forces to Participate in the Protection and Utilisation of Heritage Buildings* issued by the National Cultural Heritage Administration explicitly supports social entities to participate in heritage repair, historical landscape maintenance, cultural dissemination, and cultural tourism development. In practice, three types of forces should be cultivated: professional technical institutions (providing BIM consulting, 3D scanning, and digital modelling services), public welfare organisations (supporting digital protection through volunteer participation and social fundraising), and commercial institutions (feeding back into heritage protection through cultural creativity development and digital cultural tourism products). Zhangzhou Ancient City, relying on its digital platform, developed AR navigation, VR virtual tours, and 3D-printed cultural and creative products, achieving a synergistic enhancement of cultural dissemination and economic value. The Changzhou Jiaoxi Ancient Town project achieved win-win cooperation between technical institutions and heritage protection units through the “technology breakthrough + site support” collaboration model. With the broad participation of social forces and the gradual improvement of market mechanisms, the resource base for digital protection of ancient buildings will be significantly strengthened.

The above three dimensions of strategies are not implemented in isolation but support and progress from each other. Lightweighting and intelligent improvements at the technology dimension provide a tool foundation for collaboration at the organisation dimension; talent cultivation and collaboration mechanisms at the organisation dimension ensure that technology can be effectively used; standard improvement and policy incentives at the environment dimension provide institutional safeguards for the continuous optimisation of the technology and organisation dimensions. The synergistic coordination of the three constitutes a systematic solution to the paradox of “high-value recognition but low adoption intention”.

6. Conclusion and Future Direction

6.1. Research Conclusion

This paper takes the Zhengyangmen Gate Tower restoration project in Beijing as a typical case and systematically analyses the application mechanism and promotion path of BIM technology in historic building restoration. The main conclusions are as follows:

(1) The synergistic closed loop of “environmental drivers → organizational innovation → technological empowerment → value recognition” is revealed. Policy support and public attention constitute external driving forces, while organisational mechanisms and tool innovations form the responsive layer, effectively mitigating technical complexity and allowing BIM’s technical advantages to materialise, thereby fostering value recognition among practitioners. This mechanism explains the deep logic behind the successful application of BIM technology in the Zhengyangmen project.

(2) A three-stage progressive promotion path of “digital documentation → process integration → lifecycle management” is constructed*. The primary stage lowers the technical threshold through digital documentation; the intermediate stage proves the technology’s value through core business applications; the advanced stage achieves full lifecycle management and collaborative application, forming a progressive logic from “easy to use” to “useful” and from “useful” to “valuable”. This path provides an actionable action guide for the systematic promotion of BIM technology in historic building restoration.

(3) Synergistic barrier-breaking strategies at the technology, organisation, and environment dimensions are proposed*. The technology dimension focuses on tool lightweighting, component library sharing, and AI-assisted intelligent modelling; the organisation dimension emphasises talent cultivation, cross-disciplinary collaboration, and intellectual property incentives; the environment dimension promotes standard system construction and targeted policy empowerment. Synergistic measures across the three dimensions can effectively enhance practitioners' adoption intention and break the promotion dilemma of "high-value recognition but low adoption intention".

6.2. Theoretical Contributions and Practical Implications

Theoretical contributions: This study goes beyond the methodological focus of existing HBIM research, revealing the synergistic logic behind the successful application of BIM in historic building restoration from a process mechanism perspective. It proposes a "value-first" engineering path model, enriching technology adoption research in the field of digital cultural heritage preservation.

Practical implications: Restoration units should establish a "value-first" technology application strategy, emphasising the unique value of BIM in addressing core problems such as historical information preservation and complex process simulation, while simultaneously establishing a working mechanism for deep craftsman participation. Technology developers should focus on the special demands of historic building restoration, developing lightweight, mobile, heritage-adaptive specialised toolkits and building an open-source component library sharing platform. Policy makers should shift policies from "standardised supply" to "targeted empowerment", establish a hierarchical standard system, create special innovation funds, and cultivate an ecosystem for social force participation.

6.3. Limitations and Future Directions

This study has certain limitations. First, the external validity of a single case is limited; Zhengyangmen, as a core project of the Central Axis nomination, has particularities that require caution when generalising the conclusions to general historic building restoration projects. Second, this study does not carry out differentiated analysis for different structural types of ancient buildings (timber structures, masonry structures, stone-timber mixed structures). Third, the research focuses mainly on the front-end decision-making mechanism of technology adoption, lacking long-term follow-up evaluation of post-adoption application effects.

Future research could delve into the following areas: first, conduct multi-case comparative studies, selecting historic building restoration projects of different regions, structural types, and protection levels to test the generalisability of the path proposed in this paper; second, carry out longitudinal follow-up studies to track ancient building restoration projects that adopt BIM technology over the long term, verifying the long-term benefits and sustained adoption behaviour; third, explore the integration of emerging technologies such as blockchain and generative AI with HBIM to address deeper issues such as data traceability and automated modelling.

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