

Research on the Renovation and Transformation Strategies of Aging Urban Neighborhoods under the Coupling of AI Assistance and BIM Technology

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Abstract

To address fragmented information, coarse-grained decision-making methods, inefficient coordination, and absence of closed-loop feedback in the renewal of aging urban neighborhoods, this paper proposes an AI-BIM integrated renewal strategy. Aging urban neighborhoods are decomposed into five domains: buildings, municipal infrastructure, streets, public spaces, and community governance. A five-layer integration framework is then constructed, vertically spanning the full life cycle-data, design, implementation, and operation and maintenance-and horizontally covering all domains. The framework establishes a shared spatial data foundation through multi-source data governance, performs existing-condition assessment and needs assessment via AI analysis, drives parametric modeling, performance simulation, and carbon emission estimation through BIM-AI collaborative design, enables multi-party online collaboration on a BIM+GIS base with 4D/5D collaborative control, and realizes adaptive operation and maintenance and model iteration through digital twins and feedback of measured data. This framework establishes a closed loop of "AI-enabled perception and reasoning, BIM-based information representation, and application-driven feedback and iteration."

Keywords

AI-BIM Integration; Renewal of Aging Urban Neighborhoods; Urban Renewal; Digital Twin; Full Life Cycle Governance.

1. Introduction

Urban renewal has entered a stage where upgrading existing stock and adjusting incremental structure carry equal weight. Renewing aging urban neighborhoods is a key lever for improving urban environmental quality and advancing high-quality urban development; the fine-grained governance it requires urgently calls for digital technology support [1]. Recent years have seen advances in artificial intelligence, building information modeling, digital twins, and the IoT(Internet of Things), opening new technical pathways for aging neighborhood renewal. Existing research has largely followed three directions: coupling mechanisms and integration frameworks for AI and BIM, BIM applications in existing buildings and historic districts, and AI-assisted generation of renewal schemes. Overall, most findings have focused on new construction or individual buildings, seldom addressing the complex constraints of existing neighborhoods. Two common shortcomings stand out. The first is technological fragmentation: AI and BIM are mostly deployed as standalone tools at separate stages, lacking a closed-loop that links data collection to O&M(operation and maintenance). The second is single-dimensional scope: studies typically concentrate on a single element or single phase, making it difficult to address the neighborhood-scale reality that buildings, municipal infrastructure,

streets, public spaces, and community governance all carry comparable weight. In response, this paper proposes a coupling mechanism of "AI-enabled perception and reasoning, BIM-based information representation, and application-driven feedback and iteration": AI senses existing conditions, reasons about needs, and predicts performance; BIM carries the renewal scheme in a parametric model; and measured data from the application end feed back to recalibrate the models, forming a continuous iterative loop. Building on this, the paper defines the elemental composition of aging urban neighborhoods, unpacks the practical dilemmas at each stage of the full life cycle, and constructs a five-layer coupling strategy framework that runs vertically through the full life cycle and spans horizontally across the five element categories, offering a theoretical architecture and a technical pathway for aging neighborhood renewal.

2. Conceptual Foundation and Problem Analysis

2.1. Definition and Domain Composition of Aging Urban Neighborhoods

Aging urban neighborhoods are old districts in the existing urban stock. Their physical fabric has deteriorated. Business activity and community functions have declined. Governance no longer works well. This paper uses two policy sources to sort renewal objects into five groups. One is the block-scale indicators from the urban physical examination initiative of the Ministry of Housing and Urban-Rural Development. The other is the guidelines for building complete residential communities [2, 3].

Buildings make up the first group. They include structure, envelope, and defects. Municipal infrastructure is the second. It covers water supply and drainage, fire protection, energy networks, and related systems. Streets are the third. They involve cross-section, traffic capacity, and emergency-vehicle accessibility. Public spaces come next. These are squares, green spaces, courtyards, and similar places. Community governance is the last. It covers residents' needs, space usage, and operational management. These five groups define what renewal must tackle. They also set the basic dimensions for the technical layers that follow.

2.2. Fundamentals of AI and BIM Technologies and Their Applicability in the Renewal of Aging Urban Neighborhoods

AI, as the term is used here, means computer systems that copy human intelligent behavior. This includes how they perceive, learn, reason, and decide. BIM is a digital technology built around a three-dimensional digital model. That model pulls together information from across a building's whole life cycle. It becomes a single source that holds renewal information. Studies of BIM modeling for existing buildings show something straightforward: geometric forms, material information, equipment parameters, and O&M records can all be kept inside one computable and collaborative digital model [4]. Some neighborhoods have protected buildings or existing buildings with distinctive architectural character. BIM can store extra information where that is the case. It can hold protection grades, construction practices, material defects, and repair techniques. This makes digital documentation and fine-grained management possible [5, 6]. BIM models can also be connected with IoT sensor data. Once linked, they turn into digital twins. These twins support real-time monitoring and predictive maintenance [7, 8].

2.3. Full Life Cycle Stages of Aging Urban Neighborhood Renewal and Practical Dilemmas

A project can be managed from start to finish. It runs from planning and design, through construction and operation, to decommissioning and disposal. This is the full life cycle. When the work is aging neighborhood renewal, the cycle breaks down into four parts: data collection, design, implementation, and O&M. Each part runs into practical difficulties because of how technology fits.

Data collection is where the trouble starts. Information comes from different sources, in formats that are hard to match up. Drawings go missing or are too old to be useful. No shared spatial reference sits underneath the work. No semantic links tie the datasets together. The design stage then leans on qualitative expert judgment. What is missing is a way to run dynamic simulations-of spatial quality, energy use, carbon emissions-and to weigh different objectives against each other in a systematic way. Implementation stretches the chain of communication across too many parties. Responsibilities get blurred. Public participation stays at the level of formality. No single platform exists where demands can be gathered and worked through. The O&M stage still sees only patchy use of AI and BIM tools. The semantic links that would let BIM, GIS(Geographic Information System), and AI systems talk to each other are not yet strong enough. The framework in Section 3 is designed to deal with these practical difficulties.

3. Construction of the strategic framework under AI-BIM integration

3.1. Overall Framework

Based on the above concepts, this paper constructs a five-layer integration framework including the Data Layer, AI Analysis Layer, BIM-AI Collaborative Design Layer, Implementation Layer, and O&M Layer. Vertically, it runs through the full life cycle, forming a closed-loop chain of “data-analysis-design-implementation-O&M” and thereby overcoming technological fragmentation. Horizontally, each layer covers the five domains of buildings, municipal infrastructure, streets, public spaces, and community governance, addressing single-dimensional approaches. The alignment between layers, life cycle stages, renewal dilemmas, and domains is shown in Table 1.

The framework is driven by diagnostic conclusions rather than requiring linear execution: when problems are concentrated in physical domains, renewal is completed through the design and implementation layers; when physical conditions are sound but problems are concentrated mainly in governance mechanisms, the physical engineering design and construction processes may be bypassed, with AI analysis results directly supporting O&M and governance intervention.

Table 1. Alignment between framework layers, life cycle stages, renewal dilemmas, and domains

Framework layer	Corresponding life cycle stage	Full-Life-Cycle Technological Dilemma	Covered domains
Data Layer	Data stage	Multi-source data fragmentation	Buildings, Municipal Infrastructure, Streets, Public Spaces, Community Governance
AI Analysis Layer	Design stage	Coarse-grained decision-making methods	Buildings, Municipal Infrastructure, Streets, Public Spaces, Community Governance
BIM-AI Collaborative Design Layer	Design stage	Front-end discontinuity in the technical loop	Buildings (primary), Municipal Infrastructure, Streets, Public Spaces, Community Governance
Implementation Layer	Implementation stage	Low multi-party collaboration efficiency	Buildings, Municipal Infrastructure, Streets, Public Spaces, Community Governance
O&M Layer	Operation and Maintenance stage	Back-end discontinuity in the technical loop	Buildings, Municipal Infrastructure, Streets, Public Spaces, Community Governance

3.2. Data Layer: Accurate Collection and Standardized Governance of Multi-source Heterogeneous Data

This layer receives multi-source heterogeneous data for the five domains and addresses the dilemma of data fragmentation in the full life cycle through a three-stage pipeline of “registration-semantic extraction-ETL(Extract-Transform-Load) integration.” First, a unified spatial coordinate benchmark and semantic standards are established. Deep learning then accomplishes point cloud registration, semantic segmentation, and object-based extraction, generating structured intermediate data. An ETL process maps these data onto a BIM/GIS platform, merging cross-source information according to BIM-GIS collaboration logic. Prior work has already confirmed that this multi-source integration pathway works for aging urban neighborhoods [6], and established deep learning solutions for point cloud semantic segmentation are available when needed [9]. What the Data Layer hands off, in the end, is a set of well-structured, governed spatial data plus a BIM semantic library-assets that together form a computable starting point for the AI Analysis Layer.

3.3. AI Analysis Layer: Domain-specific Existing-condition Assessment and Needs Assessment

The AI Analysis Layer takes structured data and the semantic library from the Data Layer. It looks at existing conditions and needs across all five domains, then packages the findings into structured decision-support information. That is a shift for the design stage. Instead of relying solely on coarse-grained, qualitative expert judgment, the process now rests on data-driven structured diagnosis. The underlying logic is to turn data into knowledge, then use that knowledge to inform decisions. AI-generated conclusions are supplementary only; they do not replace expert judgment.

For buildings, deep learning reads CAD drawings, point clouds, and site photographs. Components are recognized and extracted parametrically. The output is standardized data packages. A material defect image database is then brought in. It grades typical defects-cracking, leakage, decay, rust-and produces repair priority lists together with conservation recommendations. Separately, machine-learning models combine building age, envelope characteristics, and local weather records. The combination feeds predictions of post-renewal energy consumption and carbon emissions.

Graph Neural Networks are applied to municipal infrastructure. They model risk propagation across the pipe network topology. High-risk segments are flagged, and the cascade that would follow a failure is mapped. That output shapes decisions on renewal scope and the sequencing of pipe network upgrades [10].

Streets and public spaces draw on the same spatial topology data. Block-level data serve two functions. One is to check street cross-section capacity and emergency-vehicle access; bottleneck nodes emerge from this. The other is to combine Space Syntax models [11] with usage intensity data, evaluating how quality and vitality are distributed across public spaces. Underused pockets and candidate activation nodes surface from this. Both sets of findings feed into scheme optimization.

Community governance employs Natural Language Processing to parse multi-source texts: policy feedback, questionnaires, complaint tickets. The parsing yields demand heatmaps, conflict issue lists, and stakeholder concern matrices. Where physical spaces are intact yet underused, satisfaction and usage data reveal governance weaknesses. Scattered resident appeals are converted into structured information, which then steers design and operations. Yu and Tian [12] demonstrated this approach in mega-city renewal planning; the present study extends it from planning into governance revitalization during O&M. Regulatory texts are also folded in-building codes, conservation regulations, energy-saving standards, and local

guidelines. Semantic retrieval of provisions and rule-based compliance alerts both assist scheme review [13].

3.4. BIM-AI Collaborative Design Layer: Model Development, Performance Simulation, Carbon Estimation, Option Comparison, and Constructability Review

Building on the structured decision-support information supplied by the AI Analysis Layer, this layer produces an editable, collaborative, and simulation-ready BIM digital scheme. The workflow covers model construction, simulation, carbon emission estimation, AI-assisted comparison and selection, and constructability review. In doing so, the layer closes the front-end gap in the design-stage technical loop and becomes the point where AI outputs are translated into engineering practice [13]. Buildings remain at the center of the process, while municipal infrastructure, streets, public spaces, and community governance are coordinated in parallel, giving rise to a cross-domain, linked design paradigm.

For the building domain, AI-extracted component data packages are injected into the BIM platform through APIs, triggering the automatic generation of parametric components. Regular components are batch-generated from family library templates; existing buildings of conservation value go through hierarchical parametric modeling. The models carry both geometric form and conservation or repair information, which enables a lossless transfer from AI recognition results into the design model [13].

Geometric and thermal parameters are extracted directly from the BIM model and routed to simulation engines for energy, wind environment, and daylighting. Once the multi-physics analyses are complete, AI checks key quantitative indicators against relevant standards and flags possible non-compliance, while professionals retain the final judgment on compliance. What emerges is an iterative “design-analysis-optimization” closed loop.

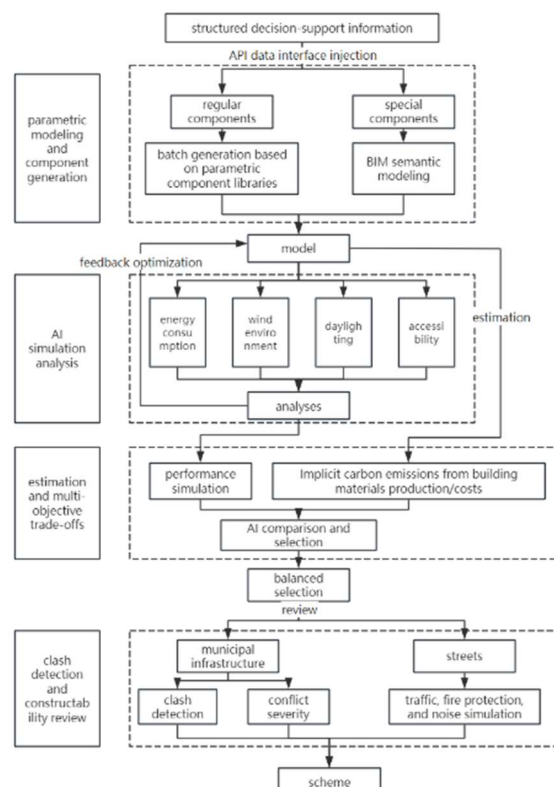


Figure 1. Coupling Mechanism Diagram of the BIM-AI Collaborative Design Layer

To handle carbon emissions tied to the building elements, a carbon estimation module is built into the BIM environment. The module first computes material quantities and envelope thermal parameters automatically. It then connects to a carbon emission factor database, from which it derives estimates of embodied carbon emissions and costs. When these estimates are brought together with the multi-physics simulation, multi-objective trade-offs become possible, yielding a solution that strikes a balance across several dimensions. Since the accuracy of such estimates is influenced by the choice of emission factor values and the completeness with which material quantities are captured, the results are best applied to relative comparisons among design schemes.

For municipal infrastructure and streets, BIM clash detection identifies conflicts among pipelines, structures, and equipment. AI then grades both the severity and the rework risk. Simulations cover temporary traffic circulation, emergency-vehicle access maintenance, and material laydown. Construction noise and phased implementation models are included too. The combined output shows the degree of disturbance to residents.

3.5. Implementation Layer: Digital-intelligence-driven Scheme Verification and Construction Collaboration

The Implementation Layer, supported by a BIM+GIS base and 4D/5D collaborative management and control, advances through two progressive stages. During scheme verification-which concentrates on streets, public spaces, and buildings-progressive interactive AI design and VR/AR(Virtual Reality/Augmented Reality) visualization are combined to coordinate spatial arrangements. Community governance demands are handled together with conflicting requirements, while the character of the architecture and streetscape is kept intact. The construction stage, covering buildings, municipal infrastructure, and streets, leans on 4D/5D BIM to pull together construction simulation, schedule-cost coordination, and safety early warning. Out of these capabilities come dynamic linkage and a resilient construction organization. Tying scheme verification and construction management into a single collaborative chain helps untangle the implementation-stage knots of fragmented stakeholder relations and lengthy information chains.

Scheme verification builds outward from a three-dimensional neighborhood base that merges BIM and GIS. The spatial plan is laid out in a deliberate sequence-street network, pedestrian network, building cluster-which locks in accessibility, pedestrian comfort, and streetscape coherence from the start. VR/AR walkthroughs and digital sand tables put the proposals into a form that non-professional stakeholders can grasp without technical background. Once construction gets moving, 4D/5D BIM takes on the management role, translating design intent into precise construction instructions. Most sites are cramped, and residents have little tolerance for disruption, so modular techniques are brought in where they are workable; factory prefabrication paired with on-site assembly cuts both waste and disturbance. Where green building materials are used, a traceability system can be embedded to track the carbon footprint of insulation, energy-saving windows, and photovoltaic components. A Common Data Environment brings government regulators, designers, contractors, and resident representatives onto one shared online platform. Change orders, site variation approvals, and quality issues are fully recorded, which guarantees traceability. Direct reporting nodes for resident representatives and traceability rules for construction disturbances serve to shorten communication chains and clarify where responsibility falls [14]. The layer ultimately delivers digital collaborative governance results and digital assets of the construction process, and hands over as-built digital assets to the O&M layer.

3.6. O&M Layer: Digital Twin-driven Adaptive O&M and Closed-loop Feedback

The digital assets that feed the O&M Layer depend on the renewal pathway chosen. Under the physical renewal pathway, the neighborhood receives as-built digital assets handed over from the Implementation Layer; under the governance revitalization pathway, neighborhoods that the AI Analysis Layer has diagnosed as physically sound but suffering from concentrated governance problems do not require delivery from the Implementation Layer. On this basis, real-time IoT sensing and AI intelligent diagnosis build an adaptive O&M system of "sensing-diagnosis-decision-execution-feedback," providing equipment status monitoring, energy consumption optimization, and predictive maintenance instructions. Measured O&M data are fed back into the AI Analysis Layer or the BIM-AI Collaborative Design Layer to recalibrate prediction models and update the digital twin, repairing the back-end discontinuity in the technical loop during the O&M stage and creating a virtuous cycle of continuous iteration across the full life cycle.

The O&M base is constructed according to the pathway: in the physical renewal pathway, the as-built BIM model serves as the foundation; in the governance revitalization pathway, the existing BIM/GIS base is integrated with the demand heatmaps, facility diagnosis, and other semantic information output by the AI Analysis Layer. IoT sensors are deployed and bidirectionally mapped with BIM component codes to form a dynamic digital twin [7]. At the application level, predictive maintenance is realized for the buildings domain; AI behavioral analysis monitors pedestrian flow and anomalies for the public spaces domain; BIM and IoT are linked for the municipal infrastructure domain to optimize energy consumption and precisely locate faults; dynamic parking guidance and staggered sharing are implemented for the streets domain; and for the community governance domain, services are allocated based on demand heatmaps and integrated into an age-friendly intelligent support system [7, 15]. For governance-revitalization neighborhoods, the O&M layer directly receives the demand information from the AI Analysis Layer, generates revitalization strategies accordingly, and continuously iterates through data feedback.

Data from O&M flow back to the layers below through "data feedback-model update-strategy iteration." The AI Analysis Layer uses these operational data to recalibrate prediction models and update knowledge graph rules. Physical renewal also refreshes the model in the BIM-AI Collaborative Design Layer, so the digital twin matches actual conditions. Organizationally, the setup rests on a BIM collaboration center and the Common Data Environment. Regulator oversight data enter by default. Property O&M data need authorization before sharing. Resident personal data are anonymized first. The user-friendly interface records change orders, maintenance records, and quality issues, and it tracks who is responsible for each.

4. Conclusion

This study set out to address two problems in aging neighborhood renewal: technological fragmentation and single-dimensional scope. We built a five-layer integration framework around the Data Layer, AI Analysis Layer, BIM-AI Collaborative Design Layer, Implementation Layer, and O&M Layer. The closed-loop mechanism rests on three elements: AI perception and reasoning, BIM representation and expression, and application-driven feedback and iteration. These layers thread through the full life cycle. They also stretch across all five domains. Data collection and intelligent analysis come first; collaborative design and digital construction follow; adaptive O&M sits at the end. Together they form a complete chain. Diagnosis drives the framework, so it can adapt to varying renewal needs. It gives aging urban neighborhoods a systematic theoretical architecture and a technical pathway for stock renewal. The shift from experience-driven to data-driven practice is what it supports.

The study has limits. Data quality constrains model robustness. Multi-platform integration costs remain high. Full life cycle linkage and component-level validation still need work. Future research can test lightweight integration of multimodal large models with BIM platforms. Differentiated data standards need building too. The framework's generalizability across diverse neighborhood types also calls for testing.

Acknowledgments

Sichuan Provincial Innovation Training Program for College Students (S202610615287).

Key Project of the 24th Extracurricular Open Experiment Program of Southwest Petroleum University (2025-2026) (2024KSZ08008).

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