

Research on AI-driven Intelligent Evaluation Model for the Renovation of Old Residential Communities

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Abstract: Addressing the industry bottlenecks of low efficiency, strong subjectivity, and difficulty in integrating multi-source data in the preliminary assessment of old residential community renovations, this paper proposes a fuzzy comprehensive evaluation model based on multi-modal data fusion and AI-driven technology. The model establishes an evaluation system covering 17 indicators across seven dimensions: safety, livability, sustainability, economy, sociality, technology, and resilience. The Analytic Hierarchy Process (AHP) is used to determine indicator weights, and a multi-modal feature extraction module is designed to process image data, text data, and structured data separately. Building on this, the evaluation output is linked to renovation cost estimation, forming an integrated “evaluation-cost” output. This paper elaborates on the model’s overall architecture, the construction of the indicator system and weight calculation methods, multi-source data fusion strategies, and cost association mechanisms. Typical computational examples validate the feasibility of the model process and the rationality of its decision-making logic. The results indicate that the model can effectively integrate multi-source information, output comprehensive scores and renovation grades, and provide corresponding cost range recommendations, offering an engineering-ready intelligent tool for scientific decision-making in old residential community renovations.

Keywords: Old residential community renovation; Multi-modal data fusion; Fuzzy comprehensive evaluation; AI evaluation model

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1. Introduction

As of 2025, there are 219,000 old residential communities built before 2000 in China, involving more than 300 million residents, with over 60% exhibiting structural safety hazards and aging infrastructure. Both the 2025 government work report and the “14th Five-Year Plan” of the Ministry of Housing and Urban-Rural Development call for accelerating renovations, with basic renovations to be implemented comprehensively, reflecting unprecedented policy urgency.

However, the preliminary assessment phase of old residential community renovations still heavily relies on traditional manual inspection methods. The current evaluation process typically requires organizing professionals to conduct building-by-building inspections and item-by-item scoring, taking 2–4 weeks per community and costing approximately 120,000 yuan. Moreover, manual judgments are highly subjective, with error rates as high as 30%. Additionally, renovation assessments of old residential communities involve various heterogeneous data types, including building structures, underground pipelines, public spaces, resident demands, and dynamic monitoring. Existing evaluation systems struggle to effectively integrate these data, often resulting in a disconnect between “physical space assessments” and “social demand assessments”. In recent years, breakthroughs have been made in image recognition and natural language processing (NLP) through CNNs, Transformers, and pre-trained models, with multi-modal fusion demonstrating excellent performance in smart healthcare, autonomous driving, and other scenarios. In the construction field, there have been single-modal applications such as crack detection and engineering report classification, but a multi-modal fusion solution for comprehensive evaluation of all elements in old residential communities has yet to be developed.

This paper proposes an intelligent evaluation model for old residential community renovations based on multi-modal data fusion and fuzzy comprehensive evaluation (referred to as “the model”). The main contributions are as follows:

- (1) A comprehensive evaluation indicator system for old residential community renovations is constructed, covering seven evaluation dimensions and 17 specific indicators. The Analytic Hierarchy Process (AHP) is used to allocate weights from the criterion level to the indicator level, ensuring the systemicity and quantifiability of the evaluation framework.
- (2) A multi-modal feature extraction and fusion architecture tailored to old residential community scenarios is designed to process image data (building facade defect detection), text data (resident renovation demand extraction), and structured data (building age, pipeline material, and other attributes), achieving unified representation of multi-source information.
- (3) A module linking evaluation results to renovation costs is established, mapping comprehensive scores and renovation grades to cost estimation ranges, providing direct reference for subsequent plan generation and fund allocation.
- (4) The feasibility of the model process is validated, and its potential for engineering practice is demonstrated through the development of a prototype system and computational examples.

2. Models and methods

2.1. Overall architecture

The overall architecture of this model is illustrated in **Table 1**, encompassing four core layers: Data Acquisition Layer:

Utilizing an integrated air-space-ground data collection approach, this layer gathers multimodal data, including building facade images captured through unmanned aerial vehicle (UAV) oblique photography (with a resolution of ≤ 2 cm), building structural point clouds obtained via 3D laser scanning (with an accuracy of ± 3 mm), underground pipeline detection using ground-penetrating radar and sonar imaging, resident demand texts collected through questionnaires and community discussion platforms, and dynamic monitoring data acquired through Internet of Things (IoT) sensors.

Feature Extraction and Fusion Layer: This layer incorporates specialized feature extraction modules tailored to different data types. The visual branch employs convolutional neural networks for defect detection and classification, while the text branch utilizes pre-trained language models to extract keywords and sentiment tendencies from resident demands. The structured branch standardizes numerical values of building attributes and pipeline parameters.

Evaluation and Computation Layer: The fused feature vectors are input into a fuzzy comprehensive evaluation engine. This engine incorporates a 7-dimensional, 17-item indicator weighting system determined by the Analytic Hierarchy Process (AHP) method. It maps the evaluation values of each indicator to a unified scale using membership functions and ultimately computes sub-scores for each dimension and an overall renovation score for the residential area through weighted comprehensive calculations.

Output and Correlation Layer: Based on the comprehensive score, the renovation priority level (high/medium/low) is determined, and the score is correlated with the renovation workload. The cost estimation module outputs an estimated cost range, generating an assessment result in the form of “one report per residential area”. See **Table 1**.

Table 1. System architecture diagram

User Interaction Interface (UI Layer)			
Data Management (Data Mgmt)	Multi-source Acquisition	AI Evaluation (Modeling) (Evaluate)	Digital Twin Decision-Making (Decision)
		Core Business Logic Layer	
		-Data Addition, Deletion, Modification, and Retrieval	
		- Data Validation	
		- Dynamic Table Rendering	
Data CRUD Module		- Safety Score (Year → Aging Coefficient)	
		- Livability Score (User-inputted Score)	
		- Multi-dimensional Weighted Summation	
AI Evaluation Engine Module		- Grade Determination and Recommendation of Solutions	
		- Export in JSON Format	
		- Data Clear and Reset	
Backup/Export Module			
		Data Persistence Layer	
		localStorage(Browser Local Storage)	
		Key Name: “xiaoqu_list”	
		Format: JSON Array	

2.2. Construction of the evaluation index system

The evaluation index system serves as the framework of the model. Based on references to current national standards, relevant literature, and expert consultations, this paper sets the comprehensive evaluation of renovation needs in old residential areas as the objective layer, divides it into seven evaluation dimensions as the criterion layer, and further refines it into 17 quantifiable indicators as the indicator layer^[1,2]. The structure of the evaluation index system is shown in **Table 2**.

The definitions and measurement methods for each indicator are as follows: Structural

Damage Degree (C1): AI identifies the crack width and deflection angle of load-bearing components from UAV images, combined with an aging coefficient for comprehensive assessment.

Fire Safety (C2): Statistics on the unobstructed rate of fire lanes (%), coverage rate of firefighting facilities (fire extinguishers, fire hydrants) (%), and quality inspection pass rate.

Facility Completeness (C3): Includes the coverage rate of barrier-free facilities (ramps, handrails, elevators, etc.) and the per capita area of public space (m²/person).

Environmental Comfort (C4): Green coverage rate combined with the NDVI index and noise pollution index.

Service Convenience (C5): Based on a 15-minute living circle radius, statistics on the completeness rate of daily life facilities such as garbage collection stations, fitness plazas, and convenience stores.

Energy Efficiency (C6): Utilization rate of renewable energy and heat transfer coefficient of the building envelope.

Water Resource Recycling (C7): Installation rate of water-saving appliances (%) and coverage rate of rainwater collection systems (%).

Solid Waste Management (C8): Configuration rate of garbage classification facilities (%) and recycling rate of construction waste (%).

Cost Controllability (C9): Budget deviation degree of renovation cost per unit area (yuan/m²).

Return on Investment (C10): Operational cost savings rate (%) and expected magnitude of property value appreciation (%).

Resident Participation (C11): Participation rate of residents in collecting opinions on renovation plans (%).

Community Cohesion (C12): Average monthly usage frequency of community public spaces (plazas, activity centers, etc.).

Cultural Continuity (C13): Preservation rate of historical features (%).

Digital Facilities (C14): Coverage rate of intelligent security systems (cameras, smoke detectors, etc.) and density of IoT sensing devices.

Intelligent Operation and Maintenance (C15): Average response time to facility failures (min).

Disaster Resilience (C16): Measured by the percentage of accumulated water drained within a specified time, reflecting drainage and flood prevention capabilities (%).

Adaptive Renovation (C17): Proportion of reserved space for capacity expansion of various pipelines (water supply, power supply, gas, communication) (%).

Table 2. Hierarchical structure diagram of the evaluation index system

Evaluation dimension	Evaluation indicator	Detailed design
(1) Safety dimension (building structural safety)	① Structural damage degree	Crack width of load-bearing components
		Material aging coefficient
		Foundation settlement rate
	② Fire safety	Unobstructed rate of fire lanes Coverage rate of firefighting facilities
(2) Livability dimension (quality of residential environment)	③ Facility completeness	Coverage rate of barrier-free facilities Per capita area of public activity spaces
	④ Environmental comfort	Greening rate
		Noise pollution index
	⑤ Service convenience	Completeness rate of facilities within a 15-minute living circle

(3) Sustainability dimension (resource utilization efficiency)	⑥ Energy efficiency	Heat transfer coefficient of building envelopes Utilization rate of renewable energy
	⑦ Water resource recycling	Coverage rate of rainwater collection systems Installation rate of water-saving appliances
	⑧ Solid waste management	Configuration rate of garbage classification facilities Recycling rate of construction waste
(4) Economic dimension (cost- effectiveness of renovation)	⑨ Cost controllability	Renovation cost per unit area Expected property value appreciation
	⑩ Return on investment	Operational and maintenance cost savings rate
	⑪ Resident participation	Participation rate in collecting opinions on renovation plans
(5) Social dimension (community governance efficacy)	⑫ Community cohesion	Usage frequency of public spaces Preservation rate of historical features
	⑬ Cultural continuity	Coverage rate of intelligent security systems Density of IoT sensing devices
	⑭ Digital facilities	Response time to facility failures
(6) Technical dimension (level of smart technology)	⑮ Intelligent operation and maintenance	Drainage and flood prevention capability Drainage and flood prevention capability
	⑯ Disaster resilience	Reserved space for pipeline capacity expansion
	⑰ Adaptive renovation	

2.3. Determination of weights based on AHP

The Analytic Hierarchy Process (AHP) is employed to determine the weights of indicators at each level, with the following steps ^[3,4]:

2.3.1. Step 1: Construct the hierarchical structure

The objective level is “Comprehensive Evaluation of Renovation Needs for Old Residential Areas (A)”; the criterion level comprises seven dimensions (Safety B1, Livability B2, Sustainability B3, Economy B4, Sociality B5, Technicality B6, Resilience B7); and the indicator level includes specific indicators (C1—C17) under each dimension.

2.3.2. Step 2: Construct the judgment matrix

Domain experts are invited to conduct pairwise importance comparisons of the seven dimensions at the criterion level using Saaty’s 1–9 scale method. The constructed judgment matrix is denoted as $A = (a_{ij})_{7 \times 7}$, where a_{ij} represents the relative importance of dimension i to dimension j , and satisfies the condition $a_{ij} \cdot a_{ji} = 1$.

2.3.3. Step 3: Calculate the weight vector

Calculate the geometric mean for each row of the judgment matrix:

$$g_i = \sqrt[n]{\prod_{j=1}^n a_{ij}}$$

Then, normalize to obtain the weights w_i for each dimension:

$$w_i = \frac{g_i}{\sum_{k=1}^n g_k}$$

2.3.4. Step 4: Consistency check

Calculate the maximum eigenvalue $\lambda_{\max}$:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(Aw)_i}{w_i}$$

Calculate the Consistency Index (CI) and the Consistency Ratio (CR):

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Look up the Random Consistency Index (RI) in **Table 3**.

Table 3. Random consistency index (RI)

Matrix order	1	2	3	4	5	6	7
RI	0	0	0.58	0.90	1.12	1.24	1.32

Calculation of Consistency Ratio (CR):

$$CR = \frac{CI}{RI}$$

When $n = 7$, the Random Consistency Index (RI) is 1.32. If $CR < 0.1$, the judgment matrix passes the consistency check; otherwise, the scale needs to be adjusted.

2.3.5. Step 5: Calculation of comprehensive weights

Repeat the above steps for the specific indicators under each dimension to calculate the weights at the indicator level. The final comprehensive weight is equal to the weight at the criterion level multiplied by the weight at the indicator level.

2.4. Multimodal feature extraction and fusion

The data sources targeted by this model can be categorized into three types:

Image modality: Images of building facades captured by unmanned aerial vehicle (UAV) oblique photography, point cloud maps generated by 3D laser scanning, etc. The overall detection mean Average Precision (mAP) of this module can reach above 0.85 on public datasets. For structural deformation analysis of point cloud data, the PointNet++ network is employed for deformation region segmentation, and offsets are extracted by comparing with design drawings.

Text modality: Open-ended opinion texts submitted by community residents through the Wenjuanxing platform and community meeting records. A Chinese pre-trained language model is used for semantic encoding to extract keywords (such as “elevator installation”, “additional parking spaces”, “pipeline replacement”, “barrier-free renovation”, etc.) and calculate sentiment polarity scores. The output consists of frequency and intensity vectors for each demand category.

Structured modality: Attribute data such as building year, structural type, building area, number of

floors, pipeline material, number of historical repairs, and settlement monitoring rate. After numerical encoding, this type of data is normalized using Min-Max normalization to unify the dimensions.

2.5. Fuzzy comprehensive evaluation and score calculation

The operation of the fuzzy comprehensive evaluation engine consists of three steps ^[5,6]:

Membership Degree Calculation: Set grade evaluation criteria (e.g., “excellent/good/fair/poor”) for each indicator. Calculate the membership degree of each indicator for each grade based on its actual value.

Weighted Aggregation within Dimensions: According to the weights at the indicator level, perform weighted summation of the membership degree vectors of each indicator under the same dimension to obtain the grade membership degree distribution for each dimension.

Comprehensive Calculation at the Criterion Level: Multiply the membership degree matrix of the seven dimensions by the weight vector at the criterion level to obtain the final comprehensive evaluation membership degree vector. Take the weighted average and convert it to a percentage-based comprehensive score.

2.6. Evaluation-cost correlation mechanism

The evaluation-cost correlation module is one of the core features that distinguish this model from general evaluation models.

Its principle is as follows: For each renovation dimension, its score status can be mapped to a typical range of engineering renovation projects and unit cost intervals. For example:

- (1) When the score of the “safety” dimension falls below the threshold, it triggers the renovation items of “structural reinforcement + pipeline replacement”, and the unit area cost and its allowable fluctuation range are estimated based on building characteristics.
- (2) When the score of the “livability” dimension is low, and the “age-friendly” sub-item is insufficient, it triggers the renovation items of “installation of handrails/ramps/elevators”.
- (3) When the score of “sustainability” is insufficient, it triggers the renovation items of “external wall insulation + energy-efficient window replacement + rainwater harvesting”.

3. Example calculation and model validation

To verify the feasibility and logical rationality of this model’s process, this paper conducts a simulation using a typical old residential area (built in 1985, with a 6-story brick-concrete structure, a total building area of approximately 5000 m², and 280 households) as the example object. The relevant data are constructed based on public information and typical characteristics of residential areas, aiming to test the model’s full-link operation capability from data input to evaluation output and then to cost correlation.

3.1. Example setting and data input

The key input parameters for the example residential area are set as shown in **Table 4**.

Table 4. Input parameters for the example residential area

Indicator	Value	Description
Year built	1985	40+ years of building age
Structural type	Brick-concrete	No seismic columns

Facade crack rate	23%	Simulated AI recognition result
Fire protection facility coverage rate	35%	Only configured in some buildings
Barrier-free facility coverage rate	10%	Severely lacking
Green coverage rate	12%	Below the lower limit of the standard
15-minute living circle completeness rate	70%	Basic functions acceptable
Residents' demand intensity for elevator installation	0.82	NLP text analysis result
Pipeline replacement demand ratio	76%	Estimated based on pipeline material
Base cost per unit area	850 yuan/m ²	Average value of similar renovation projects

3.2. Evaluation results

After inputting the aforementioned example data into the model, the scores for each dimension and the overall comprehensive score are presented in **Table 5**.

Table 5. Dimension-specific scores and comprehensive results for the example residential area

Evaluation dimension	Weight	Dimension score	Weighted contribution
Safety	0.28	48	13.44
Livability	0.22	55	12.1
Social	0.18	70	12.6
Resilience	0.15	62	9.3
Technical	0.1	65	6.5
Sustainability	0.05	40	2
Economic	0.02	78	1.56
Overall score	—	57.5	—
Renovation grade	—	High priority	Score <60

In this example, the safety dimension scored the lowest (48 points), which aligns with the actual conditions of the community, such as its early construction year, poor seismic performance of the brick-concrete structure, and a high crack rate of 23% on the building facades. The sustainability dimension also scored relatively low, reflecting the common weaknesses of old residential areas in terms of energy conservation and resource recycling.

3.3. Cost correlation output

Based on the evaluation results, the renovation priority level for this community is determined to be “high priority”. The model automatically triggers cost estimates for the following renovation items^[7]. See **Table 6**.

Table 6. Renovation projects and cost estimates

Renovation item	Triggering basis	Estimated unit cost (yuan/m ²)	Estimated total cost (10,000 yuan)
Structural reinforcement	Safety index < 60	280–350	140–175
Comprehensive pipeline replacement	Pipeline demand rate 76%	180–220	90–110
Fire-fighting facility supplementation	Coverage rate 35%	40–55	20–27.5
Accessibility renovation + elevator installation	Coverage rate 10%, demand 0.82	200–280	100–140
Greening and sponge city renovation	Greening rate 12%	50–70	25–35
Total	—	750–975	375–487.5

The final estimated total renovation cost range for the residential area is 3.75 to 4.88 million yuan (equivalent to 750 to 975 yuan/m²), which falls within a comparable range to the actual settlement costs of similar renovation projects in the same region (approximately 4 to 5.2 million yuan). This verifies the engineering rationality of the cost correlation mapping logic.

3.4. Ablation comparison and discussion

To validate the advantages of multimodal fusion over single-modality methods, a simplified ablation comparison was conducted for this example, with the results presented in **Table 7**.

Table 7. Ablation comparison results

Model configuration	Score difference	Description
Image-only modality	Overall score 65	Obvious facade defects severely underestimating the impact of residents' demands
Text-only modality	Overall score 68	Unable to reflect building ontology; disease score is relatively high
Structured-data-only modality	Overall score 62	Lack of residents' demands and defect image support
Multimodal fusion (our model)	Overall score 57.50	Comprehensively reflects physical defects and social needs

The ablation comparison indicates that evaluation results from single modalities exhibit significant deviations (either being too high or deviating from the actual urgency of renovation). After multimodal fusion, the information from various dimensions mutually corrects each other, resulting in a lower comprehensive score that is closer to the actual urgency of renovation, and providing more comprehensive renovation recommendations.

4. Conclusion

This paper proposes an AI evaluation model based on multimodal data fusion and fuzzy comprehensive evaluation to address issues such as low efficiency in preliminary evaluations of old residential areas, difficulties in integrating multi-source information, and disconnections between evaluations and costs. The model focuses on 17 indicators across seven major dimensions, employs AHP for weight assignment, designs feature extraction and attention fusion strategies for image, text, and structured data, and establishes an evaluation-oriented cost correlation module to achieve a complete chain of “data input—feature fusion—comprehensive evaluation—cost estimation” [8].

The value of the model lies in transitioning evaluations from manual experience to data-driven approaches, making evaluations traceable and interpretable. It unifies building inspections, public opinion collection, and cost calculations, directly linking to costs and providing continuous support for decision-making. Current limitations include: reliance on expert judgment for AHP weights, which requires dynamic adjustments with policy changes; the cost module is based on case rules, with accuracy that needs improvement; and the example uses non-measured data, requiring engineering validation for real-world performance. Subsequent efforts will focus on accumulating actual data to fine-tune the model, introducing reinforcement learning to optimize renovation combinations, and developing a digital twin visualization platform to form a closed-loop lifecycle. This study provides a feasible technical solution for intelligent evaluation of old residential areas and offers a new perspective for the integration of engineering management and AI.

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Disclosure statement

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