

Multidimensional Evaluation of Old Building Renovation Schemes

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Abstract: In the backdrop of global climate change, the construction industry accounts for approximately 40% of global carbon emissions, making the renovation of old buildings a crucial pathway to sustainable urban development. However, existing evaluations are often limited to a single aspect, lacking synergistic analysis of carbon emissions, costs, and disaster risks. This research develops a tri-dimensional framework that integrates Life Cycle Assessment (LCA), cost accounting, and flood risk analysis. The LCA carbon emission factor used in this study is based on relevant standards and the latest data from the local power grid. Using a case study of an office building in Taiyuan City that suffers from structural aging and flood risk, it compares renovation and reconstruction strategies. Results show that the initial cost and carbon dioxide emissions of the renovation scheme are only 21% and 33% of the reconstruction scheme, respectively, demonstrating superior short-term cost savings and carbon reduction advantages. However, the reconstruction scheme can minimize flood losses by 77% under a 50-year return period rainfall scenario and optimize operational maintenance costs along with carbon emissions by over 25%. Therefore, renovating old buildings involves multidimensional trade-offs: renovation in suitable, low-risk, low-budget conditions, while reconstruction offers greater benefits in high-risk locations and supports long-term sustainability objectives. This study provides a scientific decision-making foundation for urban renewal, emphasizing the need to coordinate safety, economic, and environmental benefits within carbon neutrality goals. The flood risk analysis was validated based on a high-precision Digital Elevation Model (DEM) and historical water accumulation data to ensure the reliability of the assessment results.

Keywords: Life cycle assessment (LCA), flood, retrofitting, risk analysis.

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1. Introduction

The construction sector contributes to approximately 40% of total carbon emissions in the world (48.3% in China), and the refurbishment of old buildings plays a significant role in the sustainable development of the urban sector. Nevertheless, its synergistic analysis is a bottleneck due to the joint effects of investment, service life, risks, and carbon emissions (IPCC, 2023). Forster et al. (2025) established that the potential to enhance energy efficiency, with gains in carbon, is limited by materials and technologies. Angelakoglou et al. (2025) stressed that the significance of life cycle and dynamic coupling, as well as standardized economic renovation schemes, was evaluated using the Building Energy Sustainability Tool (BEST) in terms of costs. The renovation of an old building is also a matter of flood risks. Reasonable design has been identified as an effective measure to counter disasters (Calot, 2025). Technologies such as optimizing the drainage system (Tseng et al., 2025), natural-grey infrastructure (Esraz-Ul-Zannat et al., 2024), and disaster reduction at the building level (Ruig et al., 2020) have been introduced. Machine learning and digital twins have enhanced the accuracy of simulation and optimization of energy (Aleke et al., 2025; Nie et al., 2025). The literature includes carbon emissions, cost, and risk of flooding, but the majority of these studies examine them as pairs: e.g., the compatibility of renovation economics and carbon reduction (Felicioni et al., 2025), the difference between carbon and cost (Cuce et al., 2025), the relationship between socioeconomic vulnerability (Pala et al., 2025) and flood losses (Tseng et al., 2025). However, none of them has managed to accomplish a combined study of the three dimensions. To conclude, there is a deficiency in synergistic research on carbon emissions, costs, and flood hazards. To address this gap, this study develops a comprehensive assessment scale incorporating LCA, cost accounting, and flood risk analysis, comparatively quantifies the performance of building renovation and reconstruction plans, and develops more sustainable methods for renovating old buildings. However,

existing studies focus on the coupling analysis of two of these dimensions, such as the compatibility between the economics of modification and carbon emission reduction, the synergistic relationship between carbon and cost, and the relationship between socioeconomic vulnerability and flood losses. Nevertheless, research that can simultaneously integrate Life Cycle Cost (LCC), carbon emission LCA, and geospatial flood risk for a three-dimensional synergistic assessment is still lacking. This study constructs a three-dimensional assessment framework that integrates LCA (Zhang et al., 2022), cost accounting (Saygin et al., 2025), and Geographic Information System (GIS) flood risk analysis (Wang et al., 2025). This study uses a systematic research model of problem definition, model construction, case calculation, and comparative analysis when creating an evaluation system based on four stages (Fig. 1). The first determines a lack of research worldwide in the area of synergistic assessment of carbon emissions, costs and flood risks, limits the stages of LCA, and focuses on regional stages from building material manufacturing to sales. Second, it develops a coupled cost model (bill of quantities), LCA models (carbon emission factor method), and flood risk models (GIS simulation and loss function), but uses a modular design, with the aim of unifying all data interfaces. The third step involves an office building in the city of Taiyuan as the case study, evaluates structural, material, and geographical data, enters the parameters of transportation distance and operating costs into the models, and checks the reliability of these parameters through sensitivity analysis. The last phase carries out multidimensional comparisons, trade-off analysis to expose the relations between cost, reduction of carbon emissions, risk resistance, and draw scheme suggestions, depending on various preferences for decisions.

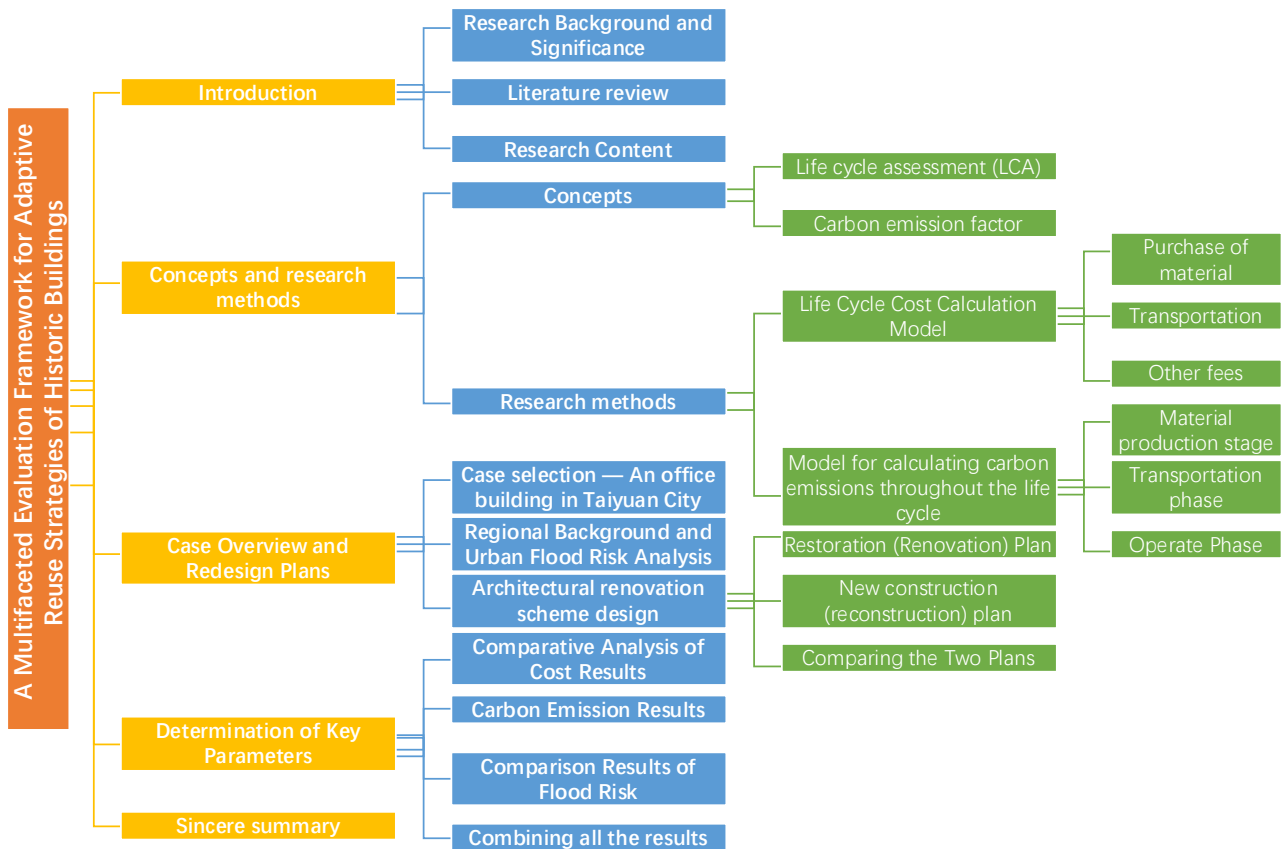


Fig. 1. Research methodology

2. Research Methods and Evaluation Model Construction

2.1. Life Cycle Cost Calculation Model

2.1.1. Cost composition and accounting framework

Cost accounting adopts a life cycle perspective, covering all economic inputs from construction through operation termination. The core principle is the “unit price × quantity” approach. Costs are categorized into: Initial Investment Cost, Raw Material Cost, Labor Cost, Equipment Cost, Transportation Cost, and Other Expenses. The total cost is the sum of all sub-items. Each sub-item cost follows a unified accounting logic. Raw Material Cost = $\sum (\text{Unit Price of Material } i \times \text{Quantity of Material } i)$. Transportation Cost = $\sum (\text{Transport Volume of Mode } j \times \text{Distance} \times \text{Freight Unit Price})$. Table 1 presents this method, which uses dynamic market price reflection to ensure both complete and current pricing.

2.1.2. Cost Quantification Method

The cost accounting framework consists of total cost and sub-item costs. The total cost is the sum of each sub-item, i.e., Total Cost = Raw Material Cost + Labor Cost + Equipment Cost + Transportation Cost + Other Expenses. Each sub-item cost follows a unified accounting logic, as shown in Eq. (1): labor cost is calculated as the product of the labor unit price

and total working hours, while equipment cost is determined by the equipment unit price, usage time, and depreciation rate. The accounting methods for other sub-items are analogous.

$$\begin{aligned}
 \text{Raw Material Cost} &= \sum (\text{Unit Price of the } i\text{-th Material} \times \text{Quantity of the } i\text{-th Material}) \\
 \text{Transportation Cost} &= \sum (\text{Transportation Volume of the } j\text{-th Transportation Mode} \times \\
 &\quad \text{Transportation Distance} \times \text{Freight Unit Price of that Mode})
 \end{aligned}
 \tag{1}$$

Table 1. Categories of costs and their corresponding meanings

Cost Category	Meaning
Initial Investment Cost	One-time expenditures directly incurred during the implementation of the renovation project.
Raw Material Cost	Procurement costs of various building materials (such as concrete, steel, blocks, waterproof materials, etc.)
Labor Cost	Labor expenses involved in the construction process
Equipment Cost	Rental or purchase costs of construction machinery, transportation tools, etc.
Transportation Cost	Rental or purchase costs of construction machinery, transportation tools, etc.
Other Expenses	Indirect engineering costs that cannot be classified into the above categories, such as measuring project fees, management fees, and profits

Under the material cost accounting, the model computes the total cost as a product of the unit prices of building materials and their actual application and dynamically reacts to market price variations to ensure timely outcomes. The input of construction machinery and transportation equipment is reflected in the equipment cost, which is measured by equipment unit price, hours of use, and depreciation rate.

The systematic benefits of this approach are: First, unlike the traditional methods that omit direct costs in the estimation process (like materials, labor and equipment), the method uses them separately and hence offers a comprehensive cost view covering the construction process to the life cycle of the building in terms of the indirect costs (like maintenance and energy consumption).

2.1.3. LCC based on net present value

To scientifically compare costs across different time spans, this study introduces Net Present Value (NPV) to discount the total LCC, as shown in the following formula.

$$NPV = C_0 + \sum_{t=1}^n \frac{C_{op,t} + C_{m,t} + C_{risk,t}}{(1+r)^t}
 \tag{2}$$

Where C represents the net cash flow in year t (with negative cost expenditures), T represents the analysis period (50 years in this study), and r represents the discount rate. Key parameters are set as follows: the discount rate r is 5%, referencing the yield on long-term Chinese government bonds and commonly used values in the evaluation of similar construction projects; operating and maintenance costs consider an average annual price inflation rate of 2%. Through NPV calculations, future costs can be discounted to the present, enabling a fair comparison of the life-cycle economic performance of renovation and reconstruction schemes on a common time value.

2.2. Life Cycle Carbon Emission Assessment (LCA) Model

This section constructs a systematic model for assessing building carbon emissions. Based on LCA theory, it quantifies the carbon footprint of old building renovation processes through the carbon emission factor method, providing a scientific basis for environmental impact assessment in scheme comparison and selection.

2.2.1. Carbon emission source analysis and accounting framework

This study adopts an LCA framework to systematically account for carbon emissions from the production of building materials through the final demolition. In combination with the characteristics of old building renovation, carbon emissions are divided into three stages: materialization (initial stage, Table 2), transportation, and operation. Each stage is quantified using activity data and carbon emission factors.

Embodied carbon from material production and construction is a major contributor, accounting for 38% of total life cycle emissions. Using project quantity data and standard emission factors, the calculation for key materials (concrete, steel, masonry, waterproofing, insulation) shows emissions of 89.27 tons CO₂e. Concrete and steel are the primary sources, responsible for over 65% of this stage's emissions. Utilizing low-carbon concrete and recycled steel can reduce these embodied emissions by 15-20%.

The transportation sector accounts for about 1% of total emissions. For the case study in Taiyuan, with an average haul distance of 50 km, transport emissions total 2.33 tons CO₂e. Concrete and steel transport alone account for 72% of this. Sourcing materials locally or using prefabrication could cut transport emissions by 10-15% (Table 3).

The operational stage is the largest source, accounting for -60% of total life-cycle carbon (598.9 tons CO₂e over 50 years), with heating and air conditioning accounting for 64% of that. Implementing high-efficiency heat pumps, LED lighting, and passive design can reduce operational carbon emissions by 20-30%. (4) Stage Proportion and Trend Analysis

Comprehensive results from the three stages: 89.27 tons of CO₂e (38%) in the initial stage, 2.33 tons (1%) in the transportation stage, and 598.9 tons (61%) in the operation stage. Due to long-term energy consumption impacts, the operational stage is the most significant, indicating that the emission-reduction potential of energy-saving renovation and operational optimization in old building renovation is much higher than that of the construction link. The introduction of solar water heating systems and energy-saving lighting can further reduce life cycle carbon emissions by approximately 15%-18%.

Overall, the building's life cycle carbon emissions are approximately 690 tons of CO₂e, with operational energy consumption as the main source. This result provides a quantitative basis for subsequent optimization of carbon emission reduction strategies and for scheme comparison.

(1) Initial Stage (Building Material Production and Construction Links)

Table 2. Carbon emission statistics by stage (initial stage)

Building Material Category	Usage	Unit	Carbon Emission Factor (kgCO ₂ e/unit)	Subtotal (kgCO ₂ e)	Proportion in Initial Stage (%)
Concrete (C30)	125.6	m ³	295	37,052	41.3
Steel Reinforcement	9.8	ton	2,380	23,324	26.0
Autoclaved Aerated Concrete Blocks	45.2	m ³	230	10,396	11.6
Waterproof Membrane (SBS)	314.6	kg	3.0	944	1.1
Thermal Insulation Material (Rockwool)	180.3	m ²	40	7,212	8.1
Doors and Windows (Broken Bridge Aluminum)	120	m ²	3,200	3,840	4.3
Others (Coatings, Adhesives, Decoration Materials)	—	—	—	6,500	7.6
Total	—	—	—	89,268	100.0

Table 3. Energy consumption of main equipment during building operation cycle

Energy Project	Annual Power Consumption (kWh)	Carbon Emission Factor (kgCO ₂ /kWh)	Design Service Life (a)	CO ₂ Emissions (kgCO ₂ e)
Heating System	100,000	0.8095	50	4,047,500
Fan System	58,000	0.8095	50	2,347,610
Air Conditioning System	88,000	0.8095	50	3,560,000
Water Pumps and Lighting	50,000	0.8095	50	2,023,750
Total	11,978,860 ≈ 11.98 tons CO ₂ e/year × 50 = 598.9 tons CO ₂ e (50 years)			

2.2.2. Carbon emission quantification method

The quantification of carbon emissions at each stage uses the internationally accepted carbon emission factor method, calculated according to Eq. (3), with the core being the accurate definition of activity data and carbon emission factors.

$$\text{Carbon Emissions at Stage} = \Sigma (\text{Activity Data} \times \text{Carbon Emission Factor}) \tag{3}$$

Activity data refers to the physical, economic activity volumes that lead to carbon emissions, including building material consumption, distance traveled, and energy consumption. The carbon emission factor refers to carbon dioxide emitted per unit of activity and serves as a key coefficient for converting physical quantities into environmental impacts. The general calculation formula is carbon emissions at each stage = $\Sigma(\text{Activity data} \times \text{Carbon emission factor})$.

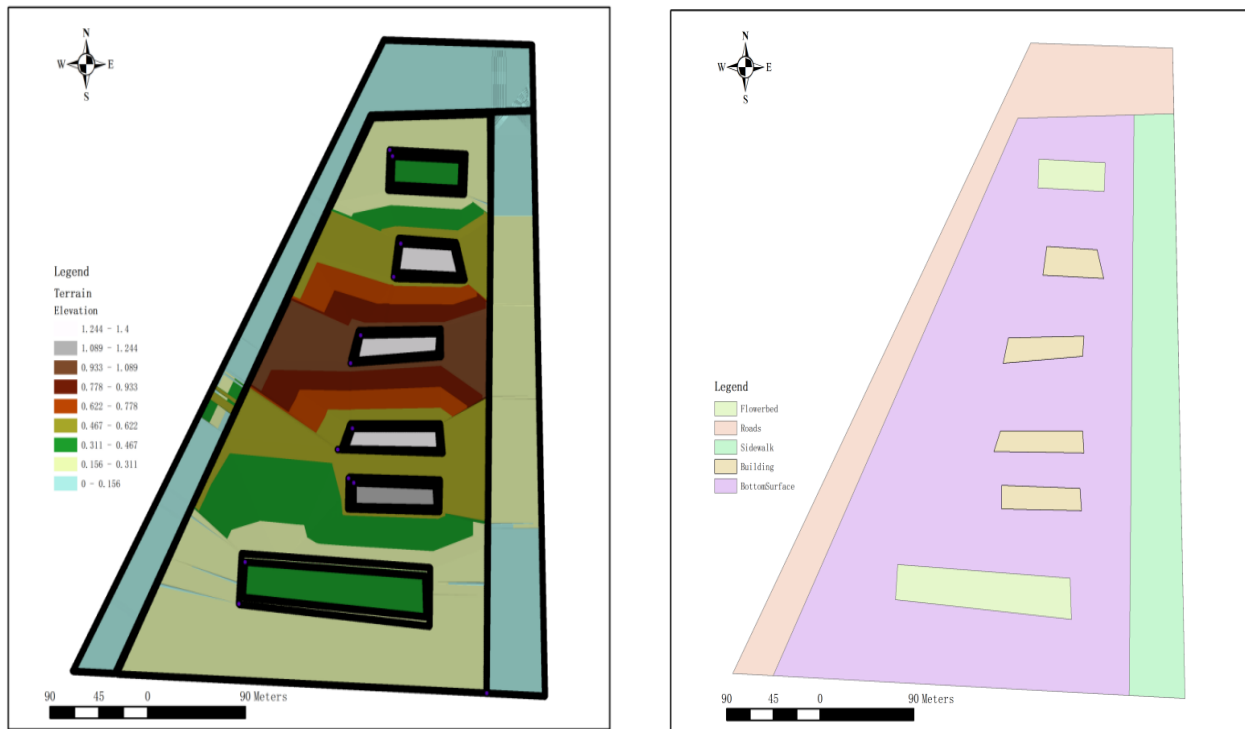
In order to achieve the relevance and validity of data, determining the key parameters is grounded on dependable sources: the materialization and transportation stage factors are calculated on the basis of the standard calculation of a building's carbon emissions, the most up-to-date data concerning the power grid of the city of Taiyuan the operation stage factors are calculated. The model, in accordance with the essential assumption that the discrepancy between the industry-averages and actual local conditions is tolerable, targets the core stages of the engineering process, including raw materials production, transportation, and operation, and presents a scientific method of assessment of carbon emission during building renovation of the old buildings.

2.3. Waterlogging Disaster Risk Assessment Model

2.3.1. Waterlogging simulation and DEM construction

This study models assuming drainage system failure, bypassing detailed pipe network calculations. Using GIS-based

hydrological analysis of physical terrain and water balance, it simulates natural confluence and identifies ponding areas (see Fig. 2). The simulation employs a high-resolution (1m) DEM, refined from 30m data using vector interpolation and supplementary elevation points in key areas to meet building foundation accuracy standards.



(a) DEM

(b) Vector layers

Fig. 2. Parameter calibration area for model validation

2.3.2. GIS-based waterlogging hazard analysis

Based on the structural characteristics, topographical conditions, and regional hydrological characteristics of the case building, and the impact on the building (including furniture, electrical appliances, and the building structure), this study systematically analyzes the specific damage and presents the results in Table 4.

Critical thresholds for building damage exist: 100cm can cause structural collapse, while 330cm leads to severe foundational damage. Aging drainage and weak foundations exacerbate these risks. The hazard analysis uses a GIS platform to simulate surface waterlogging via a high-precision DEM under extreme rainfall scenarios. By calculating net rainfall and performing catchment analysis, it generates spatial maps of water depth distribution to assess building-specific flood hazard.

3. Case Overview and Renovation Scheme Design

3.1. Case Selection Basis and Building Object Description

The case study is a two-story frame-structure office building in Taiyuan (area: 281.2 m², age: 50 years) (Fig. 3). Existing problems include wall cracks, aging pipes, peeling exterior walls, and high embodied carbon. It is located in a basin center, surrounded by mountains on three sides, making it prone to water concentration during heavy rain. The regional drainage network is an old, combined sewer system with insufficient capacity, resulting in frequent waterlogging and potential foundation settlement. The surrounding soil is silty loam to loamy clay, susceptible to liquefaction when saturated.

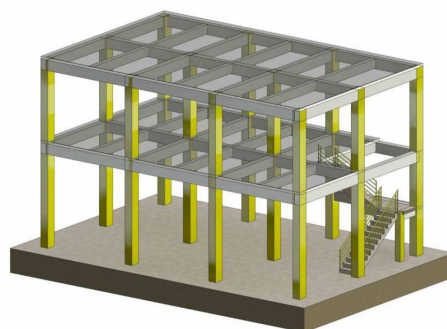


Fig. 3. Structural diagram of the case building

3.2. Regional Environment and Background Analysis

Taiyuan City is located in central Shanxi Province along the Fenhe River, within a valley basin flanked by the Luliang and Taihang mountains. It experiences a temperate continental monsoon climate with an average annual temperature of 10.3°C and significant seasonal variation. Annual precipitation averages 420 mm, with over 60% concentrated in July and August. Recent years have shown fluctuation, although increasing rainfall trends, including a peak of 600 mm in 2021, indicating a rise in the frequency and intensity of heavy rains that elevate short-term flood risks (see figs. 4 and 5).

According to historical records, Taiyuan City is prone to waterlogging. The highest rainfall in July 2025 reached 61mm, exceeding the drainage design specification, resulting in foundation leaks, flooding of the garage, and equipment short-circuiting. The principal causes are the basin's topography, which concentrates heavy rainfall over a short period, and the water body's low-lying nature. The old, combined stormwater and sewage drainage pipeline will not have sufficient drainage capacity due to blockages. The urban heat island effect will increase the disproportion of precipitation, and long-term water immersion is likely to lead to foundation liquefaction, and some buildings have ailed wall inclination or ground subsidence. The drainage system should be improved to minimize the risk of flooding during building development (see Fig. 4).

3.3. Design of Building Renovation Schemes

The design of old building renovation schemes is essentially a decision-making process that coordinates the inherent trade-offs between cost, environmental impact, and safety risks. Generally, a higher initial investment would improve building performance and disaster resilience, thereby reducing long-term operational and risk costs, while a lower initial investment would require bearing higher long-term risks and performance constraints. The renovation and reconstruction schemes in this study are two typical representatives of this trade-off.

3.3.1. Renovation scheme

The renovation scheme in this study involves maintaining the original structure, replacing outdated materials, selecting materials based on environmental sustainability and economic viability, and strengthening multiple flood-resistant measures.

(1) Renovation strategies for flooding (balancing low carbon and low cost)

Flood protection includes site and building design optimization, as well as the selection of water-resistant materials.

① Elevating Living Spaces: Elevate core functional areas above the historical high water levels, which can be achieved by setting up stilt floors or raising the ground while using local stone and recycled materials to reduce costs and carbon emissions.

② Installing Waterproof Barriers: Install external water baffles or low walls and strengthen door and window sealing. Recycled wood and brick walls can achieve both economic and durability.

③ Setting "Sacrificial Zones": Arrange garages and storage rooms on the ground floor, using cement and lime-based materials for easy post-flood cleaning and reduced maintenance.

④ Guiding Drainage: Optimize site slope and add rain gardens or infiltration wells. Permeable pavement has both drainage and low-carbon landscape functions.

In terms of material selection, walls should adopt cement boards or mold-resistant materials, and floors should use self-leveling cement and epoxy resin. Furniture should avoid water-absorbent, expandable panels and instead use suspended and metal structures.

(2) Low-Carbon and Low-Cost Construction Methods

Including passive design, low-carbon local materials, renewable energy, and water resource management.

① Passive Design: Enhance ventilation and lighting, strengthen roof and exterior wall insulation to reduce operational energy consumption. Consider cellulose or wood fiber insulation materials.

② Local and Low-Carbon Materials: Bamboo, rammed earth, and lime materials can reduce carbon emissions and transportation costs.

③ Renewable Energy: Gradually introduce solar energy systems for hot water or partial lighting to reduce long-term energy consumption.

④ Water Resource Management: Set up rainwater collection and gray water reuse systems for flushing toilets and irrigation, reducing water resource consumption.

3.3.2. Reconstruction scheme

The reconstruction scheme involves complete demolition and rebuilding. It enables extensive use of green materials, including prefabricated components, though strict cost control is required due to high material volume. It offers systematic flood resilience, incorporating measures such as raising foundations by at least 0.5 meters, using high strength reinforced

concrete frames, installing external drainage systems linked to municipal networks, and applying multi-layer waterproofing for doors, windows, and walls. These features enhance resistance to heavy rainfall, improve climate adaptability, provide a replicable model for urban building resilience, and deliver combined economic and environmental benefits.

With changes in machine transportation efficiency, urban pattern, and policy requirements over time, factors such as those shown in Table 5 need to be considered when planning building renovation.

3.3.3. Scheme Trade-Off Relationship

The two schemes represent the relationship of trade-off that exists in the old building renovation: the renovation scheme is the low initial cost, low carbon emissions, high-risk approach, which can be applied in low-budget scenarios with hard-to-control risks. The reconstruction scheme is a high initial cost, high carbon emissions, low-risk approach that can be applied in high-risk, and long-term operational situations. This means that multi-objective decision-making lacks an ideal optimal solution, and such decisions must be made by decision-makers in attempts to determine the optimal balance between the two available options, depending on various risks, budgets, and sustainability considerations.

The method for scheme trade-off in this study is demand matching analysis, as shown in Table 6, evaluating the extent to which each scheme can meet core needs.

3.4. Determination of Key Parameters

To ensure methodological rigor and comparability of the evaluation results, this study clearly delineates the system boundaries and articulates all key parameters. The evaluation is uniformly calculated based on a 50-year life cycle, which comprehensively considers the expected service cycle, investment payback period, and relevant policy requirements after building renovation, and can fully reflect the long-term performance of the schemes.

Table 4. Waterlogging situation analysis table

Waterlogging Depth (cm)	Damage to the First Floor	Damage to the Second Floor
10	Flooring: Edge expansion of wood flooring, water seepage in tile joints Furniture: Moisture and mold at the legs of low furniture	No direct damage, but need to check if water seepage from the first floor rises through capillary action of the wall
40	Flooring: Complete scraping of laminate flooring, warping and deformation of solid wood flooring Furniture: Rot at the bottom of wooden furniture, water immersion in the lower part of fabric furniture	Water stains on the walls of stairwells
60	Walls: Peeling of wall plaster 30cm above the skirting line, blistering of latex paint Furniture: Delamination of cabinet panels, rusting of drawer slides Electrical Appliances: Damage to internal components of built-in ovens and disinfection cabinets Walls: Peeling of plaster layer below 1.2 meters, short circuit in circuit pipelines	Backflow of floor drains in bathrooms, local deformation of flooring due to water seepage at thresholds
100	Furniture: Mattresses and sofa sponges unusable after absorbing water Electrical Appliances: Water ingress in indoor air conditioning units, scraping of gas water heaters Structure: Collapse of lightweight partition walls, rusting of load-bearing wall reinforcement	Water seepage at floor slab joints, moisture and leakage in lamp switches
150	Doors and Windows: Deformation of aluminum alloy window frames, glass breakage Electrical Appliances: Complete submersion and destruction of central air conditioning main units Structure: Inclination of brick-concrete walls, foundation settlement	Penetrating cracks in floor slabs, rusting and sagging of ceiling keels
200	Doors and Windows: Anti-theft doors deformed by water pressure and unable to open Electrical Appliances: Complete scraping of distribution boxes, requiring circuit system reconstruction Structure: Severe damage to the main structure, requiring safety assessment by professional institutions	Reduction in floor slab bearing capacity, inclination of stairwell columns
330	Interior Decoration: Peeling of all wall decoration layers, comprehensive paralysis of pipeline systems	

Furniture and Electrical Appliances: Most lose usability, only a small amount of metal frames can be recycled

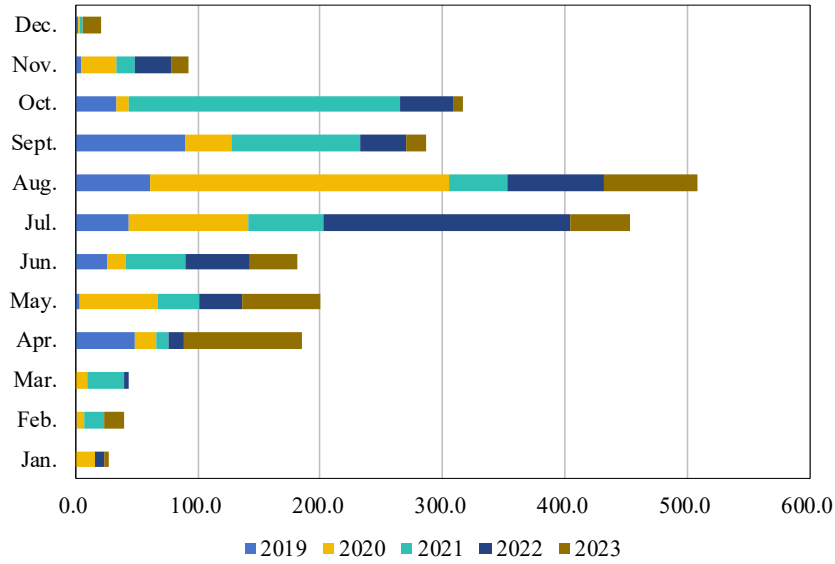


Fig. 4. Monthly precipitation in Taiyuan City over 5 years

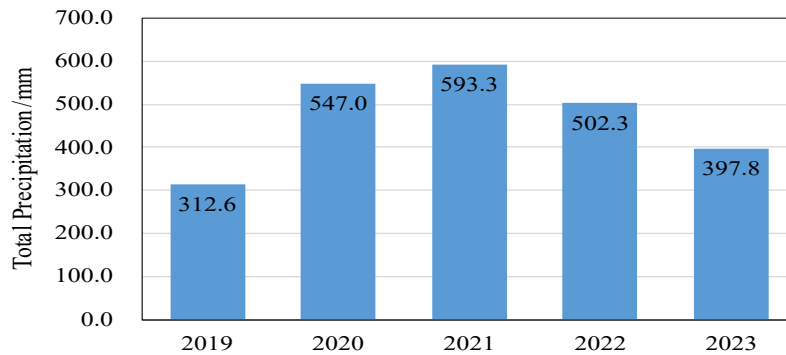


Fig. 5. Annual precipitation in Taiyuan City over five years

Table 5. Partial building material usage of the original building and renovation schemes

Name, Specification, and Model of Raw Materials	Unit	Carbon Emission Factor	Original Building	Renovation	Modified Material	Carbon Emission Factor of Modified Material	Reconstruction
Standard Bricks	1000/pieces	0.35	63.07	15	Autoclaved Aerated Concrete Blocks	0.23	45.15
Elastic Asphalt Waterproof Cold Adhesive SBS	kg	3	314.6	100	SBS Modified Asphalt Waterproof Membrane	2.2	314.6
Face Bricks with Perimeter Over 2400mm	m ²	0.5	180.27	60	Real Stone Paint Finish	0.2	180.27
Plastic Steel Windows	m ²	2.5	9.48	3	Broken Bridge Aluminum	3.2	9.48
Commercial Concrete C25 32.5R	m ³	0.3	125.62	0	c30	0.33	125.62
	m ²				Rock Wool Insulation Board	0.04	180.27
	kg				Waterproof Coating	0.002	40

(1) Main bill of quantities

Based on the characteristics of the case building and the scheme design, the engineering quantities of the two schemes are compared in Table 7.

(2) Determination of key calculation parameters.

The key parameters adopted in this study are all from authoritative data sources to ensure the reliability of the evaluation. The specific parameters and sources are shown in Table 8.4. Results Analysis and Discussion

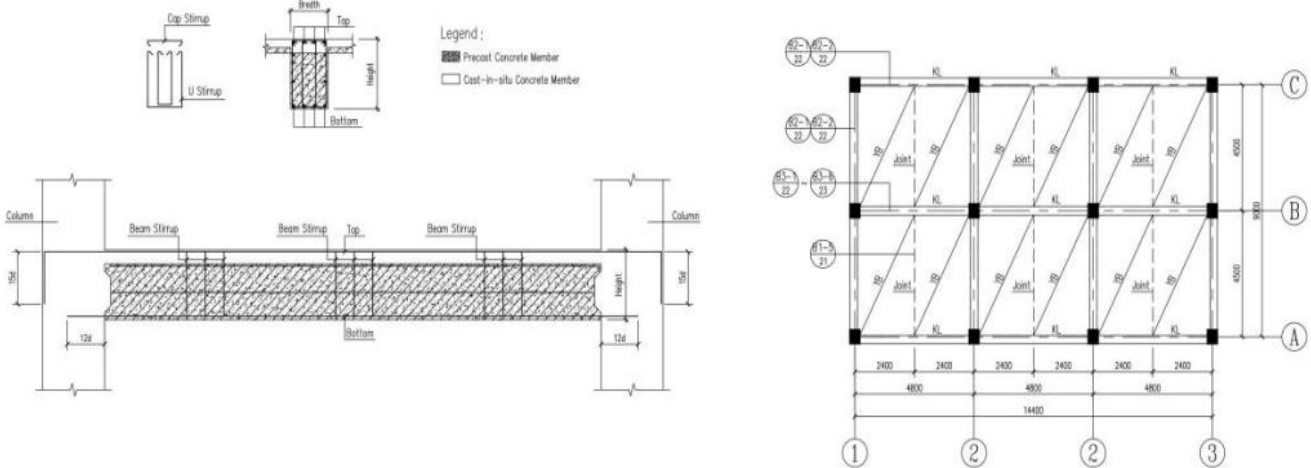
4.1. Comparative Analysis of Cost Calculation Results

The current research will conduct cost accounting for renovation and reconstruction schemes. Results of the calculations are also presented intuitively in Table 9, which displays the composition and the total cost for each scheme, providing a clear economic basis for comparison and selection.

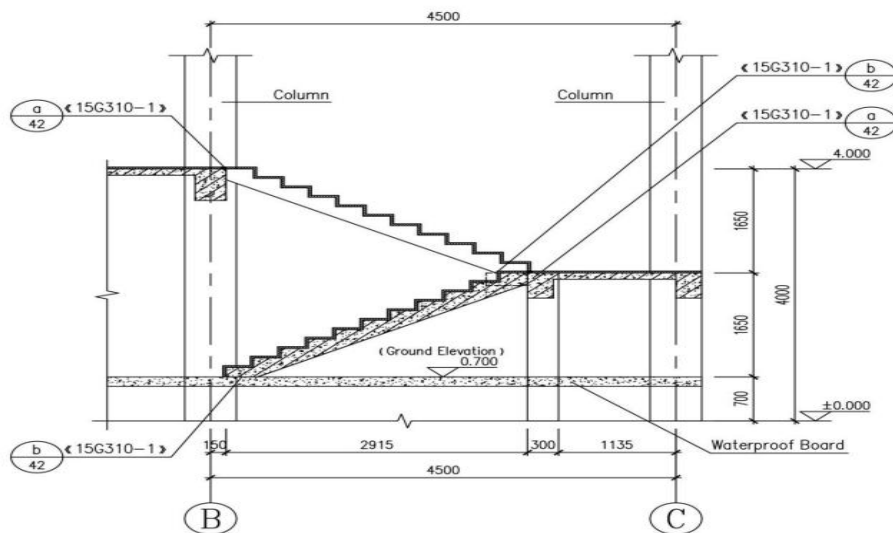
The analysis indicates that the reconstruction scheme costs 4.87 times as much as renovation. Key drivers are a significant rise in material costs (e.g., low-carbon concrete), foundation resetting comprising 40% of expenses, and higher logistics expenditures. The renovation scheme has low initial investment but carries high long-term risks. Retaining the original structure leads to recurring maintenance from wall cracks and pipe deterioration. Flood damage exceeding 100cm causes rapid loss escalation, potentially offsetting initial savings and making full-cycle economic performance unpredictable.

From a life-cycle perspective, renovation entails low upfront costs but high operational, maintenance, and risk expenses, yielding unstable long-term benefits. Conversely, reconstruction requires a substantial initial investment but improves building quality and disaster resilience, extends service life, reduces maintenance frequency, and offers superior full-cycle economic returns.

In summary, the schemes represent short-term savings versus long-term stability. The decision must balance initial investment with life cycle value, considering budget, risk tolerance, and long-term operational objectives.



(a) Prefabricated beams and slabs



(b) Prefabricated stairs

Fig. 6. Prefabricated component scheme of reconstruction (low carbon method)

Table 6. Matching degree analysis table for scheme comparison

Evaluation Dimension	Renovation Scheme	Reconstruction Scheme
Spatial Layout	Restricted by the original structure, it may not be possible to achieve the optimal layout.	Completely free, can be designed according to the latest living concepts.
Disaster Prevention Performance	Can be improved through reinforcement, elevation, etc., but may be limited by the original foundation.	Can be completely solved, constructed according to the highest disaster resistance standards from foundation to roof.
Energy Efficiency	Can carry out "clothing and hat wearing" (thermal insulation, energy-saving windows), but the effect may not be as good as new construction.	Can achieve optimal performance, such as passive house standards, saving energy from the source.
Low Carbon and Environmental Protection	Significant advantages. Retains the original "embodied carbon" and reduces construction waste.	High "embodied carbon" but can reduce "operational carbon" through the use of green building materials and high energy efficiency design.
Construction Period	Relatively short, can be carried out in phases, with relatively little impact on life.	Very long, including demolition, approval, construction, etc., requiring temporary resettlement.

Table 7. Comparison of main engineering quantities between renovation and reconstruction schemes

Engineering Category	Engineering Quantity of Renovation Scheme	Engineering Quantity of Reconstruction Scheme	Unit
Concrete Engineering	45	125	m ³
Steel Reinforcement Usage	3.2	9.8	tons
Wall Masonry	280	280	m ²
Waterproof Treatment Area	350	480	m ²
Door and Window Replacement	85	120	m ²
Pipeline Renewal Length	680	920	meter
Prefabricated Components	-	45	piece

4.2. Comparative Analysis of Carbon Emission Calculation Results

Using an LCA model, this study quantifies stage-by-stage and total carbon emissions for both the renovation and reconstruction schemes, as detailed in Table 10 and Fig. 7. This quantification provides a definitive basis for comparing the environmental impacts of the two alternatives. The reconstruction scheme's embodied carbon emissions (12,345.33 tCO_{2e}) are significantly higher than those of the renovation scheme (4,542.19 tCO_{2e}), primarily due to extensive use of new, emission-intensive materials such as concrete and steel. By retaining the main structure, the renovation scheme reduces embodied carbon by 63%, offering clear short-term carbon-reduction and resource-efficiency benefits. However, its long-term carbon-reduction potential is constrained by limitations in upgrading insulation and equipment efficiency, and in integrating advanced low-carbon technologies within the existing framework.

Conversely, the reconstruction scheme, despite its high initial carbon footprint, achieves superior full life cycle low-carbon performance. Through systematic integration of technologies such as low-carbon concrete, prefabricated components, and solar photovoltaics, it reduces operational carbon emissions to 8,135.19 tCO_{2e}, approximately 25% lower than conventional methods.

Therefore, the renovation scheme is suitable for achieving rapid short-term carbon reduction, whereas the reconstruction scheme offers greater potential for long-term low-carbon benefits. The decision should balance these timeframes based on the specific project's emission-reduction goals.

4.3. Comparative Analysis of Risk Loss Assessment Results

Through the “waterlogging depth loss rate” function, it quantitatively evaluates the direct economic losses of the renovation and reconstruction schemes. Simulation results (Fig. 8) show significant differences in waterlogging depth and economic losses between the two schemes. Under a 10-year return period rainfall (70mm/h), the average depth in the renovation scheme area is 85cm, with a loss of about 452,000 yuan. Due to foundation elevation and drainage optimization, the depth of the reconstruction scheme is less than 25cm, with a loss of less than 80,000 yuan. Under a 50-year return period rainfall (110mm/h), the average depth of the renovation scheme reaches 210cm, with a loss of up to 1.568 million yuan. The average depth of the reconstruction scheme is 62cm, and through systematic flood control design, the loss is controlled within 354,000 yuan, only 22.6% of that of the renovation scheme. Sensitivity analysis shows that the loss function is extremely sensitive to the critical water depth threshold. For example, when the critical water depth threshold is reduced from 100cm to 80cm, the estimated loss of the retrofit scheme under extreme rainfall will increase by about 35%, highlighting the importance of accurately assessing the flood resistance of buildings.

As shown in Fig. 8, the “waterlogging depth loss” relationship of both schemes shows a significant non-linear growth (Fig. 9). When the depth exceeds 100cm, the damage rate accelerates significantly, and the curve shows an exponential rise. At this stage, not only are the decoration and equipment on the ground floor damaged, but the safety of the main building structure is also threatened.

The reconstruction scheme results in significantly lower economic losses than the renovation scheme at equivalent depths. For instance, at 100cm, losses are approximately 200,000 yuan for renovation versus 60,000 yuan for reconstruction, a reduction exceeding 70%. At 200cm, losses are about 640,000 yuan and 190,000 yuan, respectively, underscoring the superior economic resilience of reconstruction.

This advantage stems from systematic enhancements such as elevated foundations, advanced waterproofing, sealed underground spaces, and elevated equipment placement, which collectively mitigate water ingress risks to the structure and contents.

The loss curve for reconstruction grows much more slowly, with its rapid-loss inflection point delayed from around 80cm (renovation) to approximately 150cm, indicating a higher flood resistance threshold. In shallow water (<50cm), loss differences are minimal, as damage is largely confined to finishes and electrical equipment.

Overall, the loss growth rate for the renovation scheme at medium-to-high water depths is about 2.8 times that of the reconstruction scheme. The renovation scheme enters a “high-damage zone” once rainfall exceeds design intensity, with single-event losses potentially surpassing 80% of the building’s replacement value. In contrast, even under extreme waterlogging (250cm), reconstruction losses can be contained within 230,000 yuan, highlighting its exceptional disaster resilience.

Table 8. Key parameters and data sources

Parameter Category		Parameter Value	Unit	Data Source
Economic Parameters	Concrete Unit Price	580	yuan/m ³	“Shanxi Provincial Construction Project Cost Information” 2024
	Steel Reinforcement Unit Price	4,200	yuan/ton	“Shanxi Provincial Construction Project Cost Information” 2024
	Labor Unit Price	280	yuan/man-day	2024 Standards of Taiyuan Municipal Bureau of Human Resources and Social Security
Carbon Emission Parameters	Concrete Unit Price	580	yuan/m ³	“Shanxi Provincial Construction Project Cost Information” 2024
	Concrete Carbon Emission Factor	295	kgCO ₂ e/m ³	“Standard for Calculation of Building Carbon Emissions” GB/T 51366-2019
	Steel Reinforcement Carbon Emission Factor	2,380	kgCO ₂ e/ton	“Standard for Calculation of Building Carbon Emissions” GB/T 51366-2019
Risk Parameters	Transportation Carbon Emission Factor	0.19	kgCO ₂ e/t·km	2024 Data of China Communications and Transportation Association
	Transportation Distance	50	kilometer	Taiyuan City Logistics Planning Data
	Rainfall Return Period	50 years	-	2024 Statistics of China Meteorological Administration

In summary, the reconstruction scheme presents a markedly lower and more controllable economic risk across varying flood depths, validating the critical role of optimized structural, waterproofing, and drainage design in reducing urban waterlogging losses.

Table 9. Cost calculation results of renovation and reconstruction schemes

Cost Composition	Renovation Scheme (yuan)	Reconstruction Scheme (yuan)	Reconstruction Scheme Cost/Renovation Scheme Cost
Raw Material Cost	87,099.36	423,500.64	4.86
Transportation Cost	2,606.00	14,281.53	5.48
Other Expenses	60,969.55	296,450.45	4.86
Total Cost	150,674.91	734,232.62	4.87

Table 10. Carbon emission assessment results and comparison

Stage	Renovation Scheme (tCO ₂ e)	Reconstruction Scheme (tCO ₂ e)	Reconstruction Scheme Cost/Renovation Scheme Cost
Materialization Stage	4,542.19	12,345.33	2.72
Transportation Stage	2,475.70	13,567.45	5.48
Operation Stage	4,371.30	8,135.19	1.86
Total Carbon Emissions	11,389.19	34,047.97	2.99

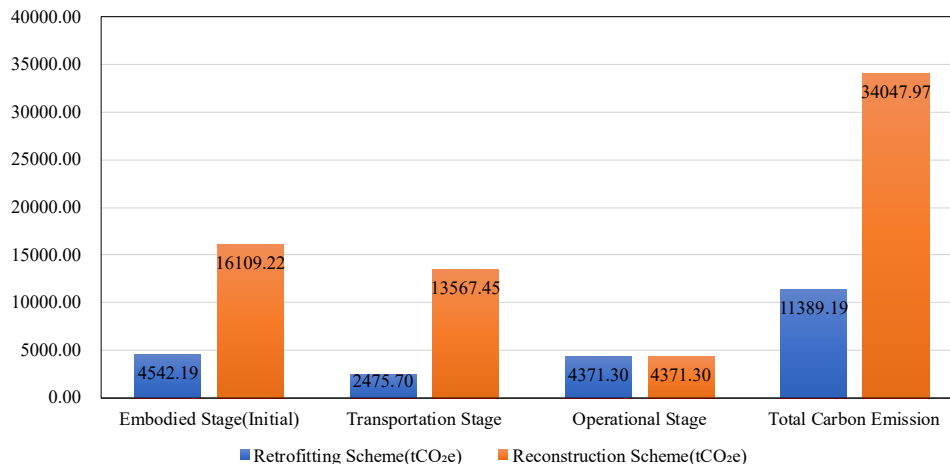


Fig. 7. Carbon emission assessment results of renovation and reconstruction schemes

4.4. Comprehensive Discussion of Multi-Dimensional Results

Considering the life-cycle aspect, this paper provides a comprehensive comparison of the performance of old building renovation and reconstruction schemes across three dimensions: cost, carbon emissions, and flood risk. According to the results of the quantitative analysis in Sections 4.1 to 4.3, this section will summarize the core findings, demonstrate the difference between both schemes in the short and long-term, economic and environmental, risk and benefit aspects in Table 11, and also the implications of multi-dimensional trade-offs in the renovation decision.

A comprehensive evaluation reveals a fundamental trade-off between renovation and reconstruction schemes across cost, carbon, and flood risk. This can be visualized as a spectrum from low input/low resistance (renovation) to high input/high resistance (reconstruction). The choice is a strategic resource allocation decision, balancing upfront investment against long-term risk, and must be based on local hazard probability and financial capacity.

As shown in Table 12, the reconstruction scheme has significant advantages in long-term comprehensive benefits. Despite the high initial investment, its life cycle net present value cost is reduced by about 39%, annualized risk loss is reduced by 92%, and carbon emissions are reduced by 25%. Especially in flood-prone areas, this scheme, through structural optimization and energy-saving design, simultaneously improves the project's economic efficiency, low-carbon performance, and safety.

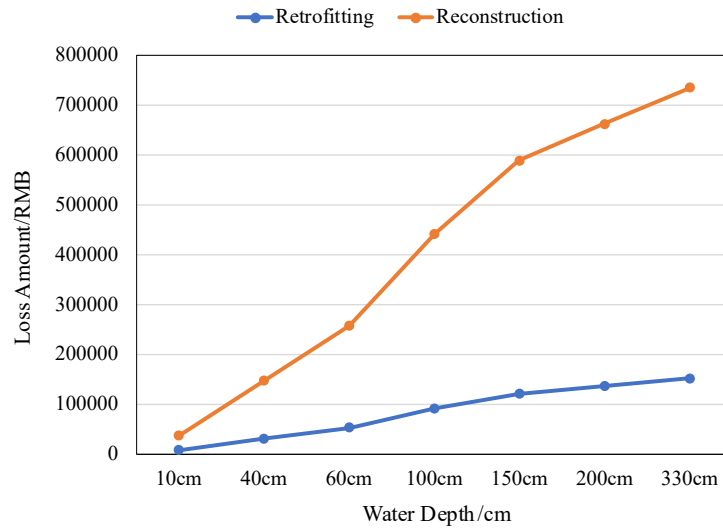


Fig. 8. Functional graph of waterlogging depth and loss of two schemes

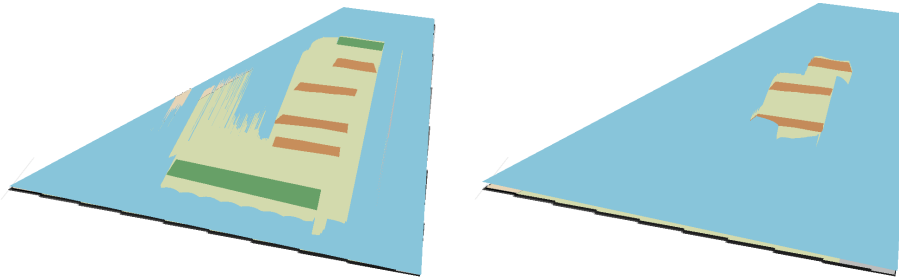


Fig. 9. Schematic diagram of waterlogging disaster impact

In the light of multi-dimensional trade-offs, the relationship between economic input, environmental performance, and disaster risks is very much correlated. Increased investment in the capacity to lessen carbon emissions and disaster risks at the same time can be done through structural upgrading and energy-saving renovation. Under the monetization price of about 50 yuan/t CO₂e, the reconstruction scheme will have implications of about 0.085 million yuan/year of implicit benefits, and the life cycle cost is expected to decrease further by around 4%. It implies that renewing cities with references to climate adaptation and low-carbon transformation requires thoroughly optimizing the economy-environment-risk nexus rather than treating each indicator separately. Overall, the reconstruction scheme has clear advantages in economic benefits, carbon emissions intensity, and disaster resilience. Although the renovation scheme can save funds in the short term, it entails significant long-term risks, costs, and environmental burdens. The reconstruction scheme effectively reduces energy consumption, carbon emissions, and extreme waterlogging losses through structural optimization, the use of green building materials, and improvements to the drainage system. Therefore, future urban renewal should establish a multi-objective evaluation model based on a life cycle perspective to achieve a dynamic balance between economic benefits and environmental sustainability.

Furthermore, the three-dimensional evaluation framework constructed in this study is essentially a multi-criteria decision-making problem. Decision-makers can assign different weights to the three dimensions of economic cost, carbon emissions, and flood risk loss based on the specific project context and preferences, and conduct sensitivity analysis. For example, in areas with extremely limited budgets and controllable risks, the significant cost advantage of the 'reconstruction plan' may make it the Pareto optimal choice, while in high-flood-risk areas or under the background of clear long-term low-carbon development goals, even if the initial investment of the 'reconstruction plan' is higher, its comprehensive advantages in risk mitigation and long-term carbon emission reduction may make it a better solution. This weight-based trade-off analysis helps to transform the quantitative results of this study into a scientific basis applicable to different decision-making scenarios.

5. Conclusion

This paper draws a comparison between old building renovation and reconstruction plans based on LCA. Findings indicate that the renovation scheme offers major benefits in terms of cost and carbon emissions, with reductions of only 21 and 33 percent, respectively, compared to the reconstruction scheme. Nevertheless, it has inherent limitations in

addressing flood risk, and losses are bound to soar as water levels rise. Despite the fact that the reconstruction program greatly enhances resilience through systematic flood control and optimized building materials, its high cost, carbon emissions, and other complex concerns, including land occupation and resettlement, limit its overall cost-effectiveness. Thus, in a situation like this case, a renovation scheme is a more practical option, assuming manageable flood risks.

Table 11. Qualitative comparative analysis of multi-dimensional results

Influencing Factor	Performance and Characteristics of Renovation Scheme	Performance and Characteristics of Reconstruction Scheme	Key Comparisons and Trade-Offs
Cost	Low initial investment, only 21% of the reconstruction scheme, but high long-term maintenance costs and large potential flood loss risks.	High initial investment, but low life cycle maintenance costs and controllable flood risk losses.	The renovation scheme has superior short-term economic efficiency, while the reconstruction scheme has more stable long-term economic efficiency, risk costs should be prioritized in high-risk areas.
Carbon Emissions	Low total carbon emissions, 63% reduction in materialization stage emissions, but limited improvement in operational energy efficiency and constrained carbon emission reduction potential.	High total carbon emissions, but 25% reduction in operational carbon emissions through green technologies, with significant long-term low-carbon benefits.	The renovation scheme is suitable for rapid carbon reduction, and the reconstruction scheme provides a path for deep decarbonization, decisions need to balance short-term goals and long-term decarbonization needs.
Flood Risk	High risk exposure, inability to fundamentally reinforce the foundation, large losses under extreme events and significant vulnerability.	Low risk exposure, through raising the floor level and optimizing drainage system design, controllable losses and enhanced resilience.	The renovation scheme is vulnerable under extreme climates, and the reconstruction scheme improves safety through systematic design, the weight of the risk dimension should be increased in high-risk areas.

Table 12. Comprehensive comparative analysis of multi-dimensional quantitative results

Evaluation Dimension	Indicator Meaning	Renovation Scheme	Reconstruction Scheme	Advantage/Disadvantage
Economic Efficiency	Life Cycle Net Present Value Cost (10,000 yuan)	186.9	113.8	The reconstruction scheme is 39.1% lower, with better long-term costs
Operational Stage Cost	Annual Operation and Maintenance Cost (10,000 yuan/year)	1.5	1.2	The reconstruction scheme saves energy by about 20%
Carbon Emissions	Life Cycle Carbon Emissions (tCO _{2e})	690	520	The reconstruction scheme reduces by about 25%
Flood Risk Loss	Annual Expected Loss (10,000 yuan/year)	5.64	0.45	The reconstruction scheme reduces by about 92%
Disaster Resistance Threshold	Inflection Point of Sharp Loss Rise (cm)	≈80	≈150	The reconstruction scheme's threshold is delayed by 70 cm
Comprehensive Benefit Index	Standardized Weighted Comprehensive Value of Three Indicators (higher is better)	0.58	0.89	The reconstruction scheme has the best comprehensive performance

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Declaration of Artificial Intelligence (AI) Tools

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