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Multi-Objective Optimization Design of Traditional Soil Dwelling Renovation Based on Analytic Hierarchy Process—Quality Function Deployment—Non-Dominated Sorting Genetic Algorithm II: Case Study in Tuyugou Village in Turpan, Xinjiang

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Abstract: As the socio-economic landscape expands and tourism flourishes, the traditional earthen dwellings of Tuyugou Village, Turpan, Xinjiang, face significant challenges, including low energy efficiency and suboptimal living comfort, necessitating data-driven and scientifically robust renovation strategies. Existing renovation methods, however, often lack empirical support and rely heavily on the subjective judgments of architects, thus hindering the effective preservation and transmission of cultural heritage. This research addresses the renovation of these traditional dwellings by employing the AHP method to systematically evaluate user requirements, with input from diverse stakeholders, including homeowners, tourists, experts, and government authorities. The study then applies the QFD method to construct the House of Quality, translating user needs into specific design attributes; this is followed by a comprehensive quantitative analysis for optimization. A novel multi-objective optimization model (MOP) is introduced, with materials as the central focus, addressing key aspects of engineering, culture, and energy conservation. The NSGA-II algorithm is utilized to generate optimal Pareto solutions, which are then further refined using the entropy-weighted VIKOR method. Among the ten pre-selected renovation solutions, the sixth design plan was identified as the optimal choice, excelling in cost control, cultural integration, and energy performance. Specifically, it achieved a unit construction cost of RMB 340.566/m^2, a cultural adaptability score of 1.5364, and an energy cost of RMB 352.793/kWh, thereby demonstrating an effective balance between traditional architectural elements and modern requirements. The objective decision making enabled by the VIKOR method successfully balances cultural preservation with contemporary needs, enhancing both living standards and tourism appeal. This study offers innovative and empirically grounded renovation strategies for traditional dwellings in arid and semi-arid climates, providing a framework that effectively balances cultural preservation and modernization.

Keywords: traditional earth dwellings renovation; AHP; QFD; NSGA-II; VIKOR method

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1. Introduction

Over 8000 years ago, during the Neolithic era, earth was widely used as a primary building material, serving as a precursor to modern construction. Today, approximately 30% of the global population still utilizes earthen materials in buildings [1] (Figure 1), with over 100 million people in China residing in earthen houses [2] (Figure 2). The traditional earthen structures of Tuyugou Village, Turpan, are a key part of the region's architectural heritage. While these buildings reflect the historical lifestyle of local inhabitants and offer cultural value, modernization has become necessary due to changes in the needs and safety concerns of residents. Moreover, the growing interest in cultural heritage tourism supports their continued development [3]. However, the modernization process presents challenges: it requires preserving cultural significance while adapting to modern living standards, introducing new architectural considerations [4,5].

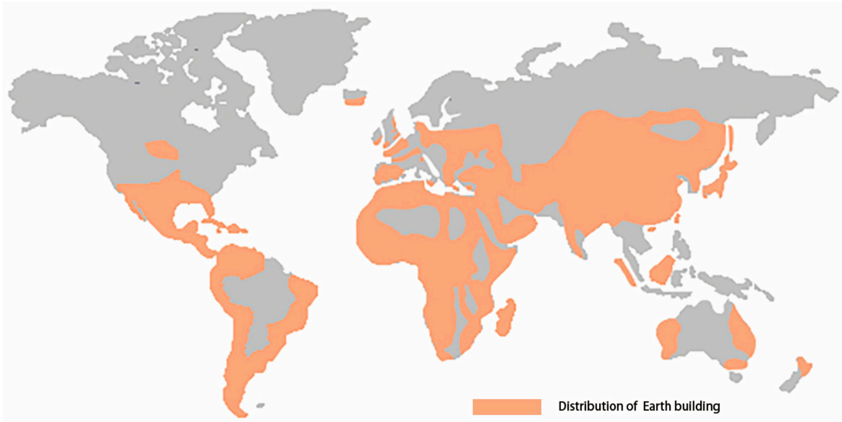

Figure 1. Earth building distribution in the world [6].

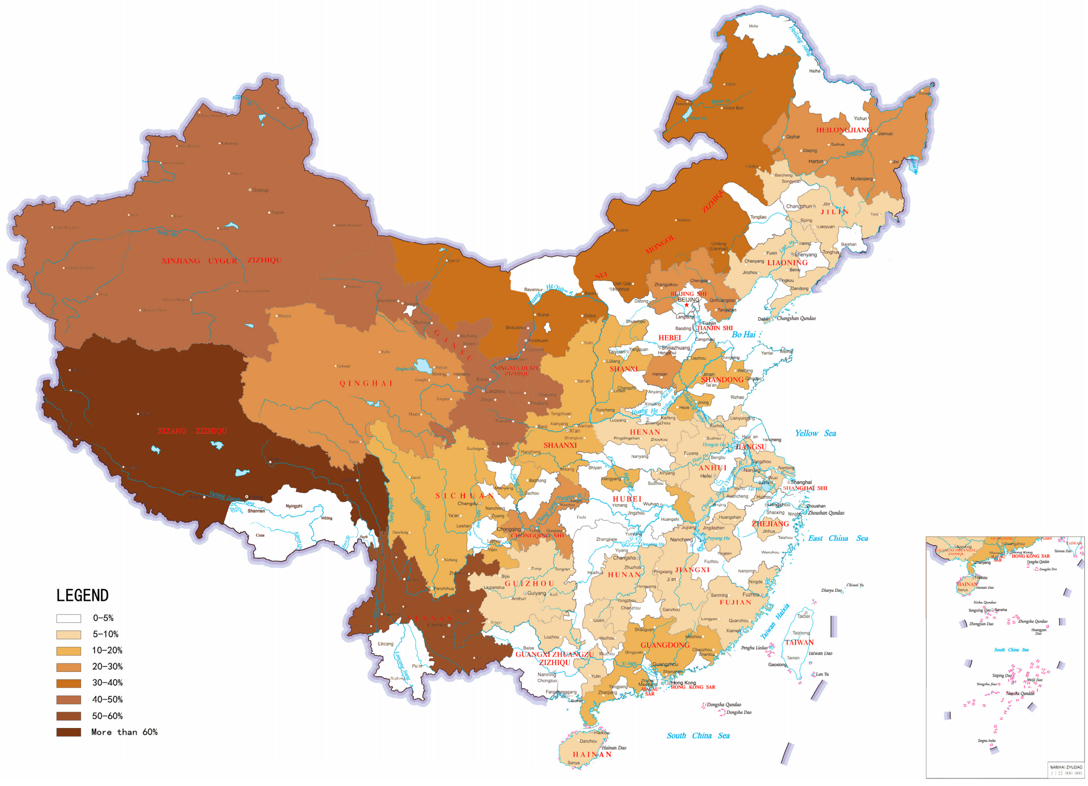

Figure 2. Earth building distribution in China (redesigned) [7].

In recent years, traditional dwellings have increasingly drawn scholarly interest due to their vital role as carriers of regional culture. Research on optimizing and modernizing these structures typically focuses on three primary areas: cultural preservation and architectural integration, sustainable materials and passive design, and digital and optimization technologies. This section synthesizes key studies within each of these themes, demonstrating the evolving strategies used in traditional building renovations.

Many studies have emphasized the importance of preserving the cultural and architectural heritage embedded in traditional dwellings. For instance, Luo and Wu's research on five villages in northwestern Jiangxi examines the cultural significance and modernization challenges these dwellings face. They propose renovation strategies that merge modern construction techniques with traditional craftsmanship, with a focus on enhancing functionality, durability, and aesthetic preservation [8]. Similarly, Jiang and Li leveraged spatial texture analysis and CityEngine's digital tools to create visual models of Xiaoxi villages in western Hunan, providing a structured approach for spatial evolution analysis and cultural preservation [9]. These studies underscore the need to integrate traditional aesthetics with contemporary construction demands, setting a foundation for developing renovation strategies that respect cultural heritage while meeting modern functionality standards.

A second significant theme in traditional dwelling renovation research is the use of sustainable materials and passive design techniques to reduce environmental impact and improve energy efficiency. Modern renovation practices increasingly favor eco-friendly, locally sourced materials, which support both environmental sustainability and cultural preservation [10]. Sandak, A. discussed how engineered living materials (ELMs), which incorporate biological components into building materials, can enhance the sustainability and resilience of architecture by enabling self-repair, environmental responsiveness, and resource efficiency [11]. Additionally, passive systems, including natural ventilation, thermal mass, and strategic building orientation, play a crucial role in enhancing energy efficiency and occupant comfort. For instance, Iskandar et al.'s study on a historic San Antonio residence demonstrated significant energy savings through natural ventilation, validated through CFD and energy models [12]. These studies advocate for a shift toward energy-saving designs that align with traditional architectural elements, providing a model for sustainable renovations that honor the cultural significance of these buildings.

The third category of research focuses on the use of digital tools and optimization technologies in renovation planning and decision making. With advancements in digitalization, tools such as 3D modeling and spatial databases allow for a more precise and systematic approach to renovation. Bibri, SE. argues that the integration of artificial intelligence and digital twin technology in urban planning significantly enhances the sustainability and efficiency of smart cities by optimizing resource management and environmental monitoring [13]. Additionally, Fu and Zhou applied remote sensing (RS), GIS, and GPS technologies to assess the environmental impacts of various renovation choices. Their spatial database framework provides a data-driven approach to restoration strategies, ensuring that renovation decisions are scientifically grounded [14].

Most renovation strategies for traditional dwellings, both domestically and internationally, tend to focus on single objectives, such as energy efficiency, comfort, structural safety, or cultural preservation. While these focused efforts contribute to specific aspects of modernization, a truly comprehensive renovation approach must balance multiple objectives, including modern living standards, cultural preservation, environmental sustainability, and economic viability [15]. Additionally, renovations involve a range of stakeholders—government agencies, residents, tourists, and industry experts—each with unique priorities and perspectives that influence the renovation process. Current methodologies often lack systematic frameworks and objective data, relying heavily on architects' subjective decisions, which can lead to unbalanced outcomes that may not align with the broader needs of these varied stakeholders [16].

To address these challenges, this research introduces an innovative integration of the Quality Function Deployment (QFD) model, the Analytic Hierarchy Process (AHP), and the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to create a comprehensive, multi-objective framework for the renovation of traditional earth dwellings. This framework enhances the functionality of Tuyugou Village's dwellings while providing a transferable model for similar projects, setting it apart from existing studies with key innovations, which are described here.

Holistic multi-objective optimization: Unlike prior research that addresses isolated objectives, this study simultaneously balances multiple and often conflicting goals, including cultural preservation, structural safety, environmental sustainability, and economic feasibility. By integrating QFD and NSGA-II, the proposed framework ensures that these diverse objectives are systematically considered, producing renovation solutions that achieve an optimal balance across all critical dimensions.

Systematic stakeholder-inclusive prioritization: Employing AHP to prioritize user needs through expert evaluations from four key stakeholder groups—homeowners, tourists, construction experts, and government officials—ensures a more inclusive and balanced approach to renovation planning. This structured method not only addresses the limitation of stakeholder neglect in traditional methodologies but also enhances decision making by objectively weighing each group's unique needs, creating a renovation process that aligns with all stakeholder perspectives [17].

Data-driven translation of needs into design: The application of QFD to translate stakeholder priorities into specific design attributes through the House of Quality is a novel approach in traditional dwelling renovation. Traditionally used in product development, QFD's adaptation here establishes a clear link between abstract user requirements and practical design features, mitigating the subjective bias commonly found in architect-led decision making and promoting a more objective and systematic framework [18].

Advanced optimization for informed decision making: The use of the NSGA-II algorithm for multi-objective optimization represents a significant advancement in achieving Pareto-optimal solutions tailored to the unique challenges of traditional architecture renovation. This process provides data-driven, balanced renovation solutions that enable informed decision making and offer a range of viable options aligned with both modern standards and traditional aesthetics.

By employing the integrated AHP-QFD-NSGA-II framework, this study establishes a comprehensive and innovative model for the sustainable renovation of traditional dwellings. This approach addresses key gaps in current methodologies, offering a balanced, objective, and replicable model for future projects in heritage conservation and sustainable building renovation [19]. The framework of this study is shown in Figure 3.

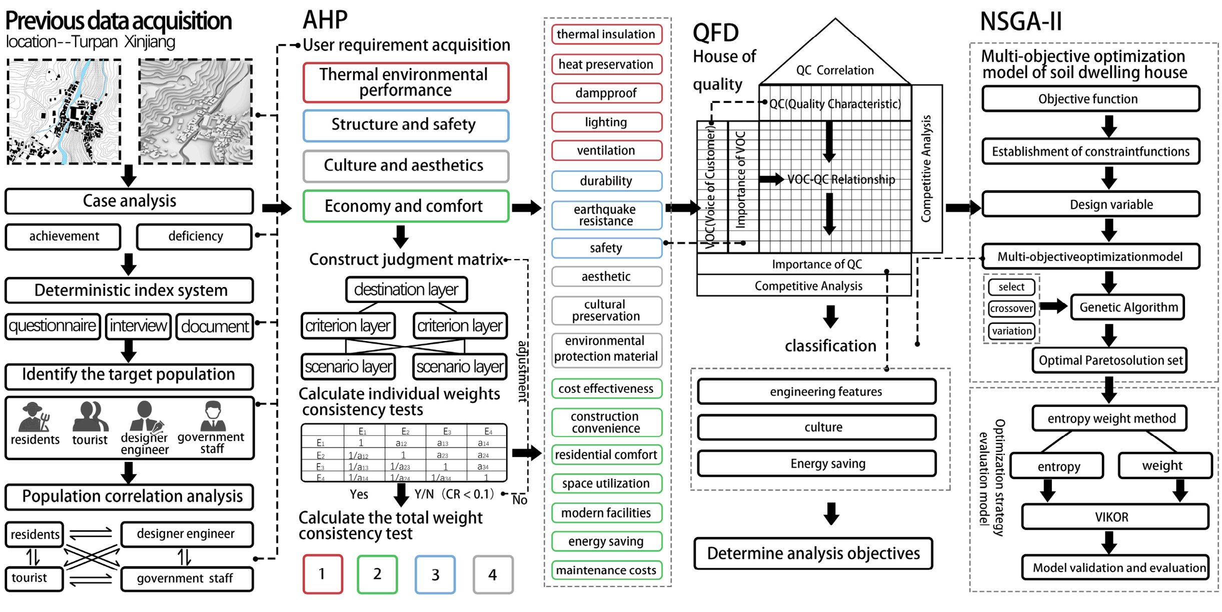

Figure 3. Design and research framework of indigenous residential renovation.

2. Theoretical Background

2.1. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), introduced by Saaty in the 1970s, is a multi-criteria decision-making tool that breaks complex problems into hierarchical levels, allowing experts to assign weights and facilitate comprehensive evaluations. AHP's strengths lie in its simplicity and ability to handle both qualitative and quantitative data [17]. Its use in construction has grown recently, with applications like Kamaruzzaman's weighted system for Malaysia's sustainability assessment program [20] and Saman Aminbakhsh's safety risk assessment framework for prioritizing risks within budget constraints [21].

2.2. Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a customer-focused method that translates customer needs into product design characteristics and quality requirements by establishing a relationship matrix between the two [18]. Its key tool, the "House of Quality", links customer requirements with product features to guide design and improvement. QFD is effective in capturing customer needs [18], improving product quality, and boosting competitiveness. In architecture, Adinyira and Kwofie identified the top five energy efficiency requirements for housing using QFD [22], while Singhaputtangkul developed an automated fuzzy decision support tool (KBDSS-QFD) to evaluate building materials in high-rise residential projects [23].

2.3. Non-Dominated Sorting Genetic Algorithm II (NSGA-II)

NSGA-II, introduced by Kalyanmoy Deb et al. in 2000, is an evolutionary algorithm designed to solve multi-objective optimization problems by addressing computational complexity, accuracy, and diversity in selection [24]. It improves upon earlier genetic algorithms by reducing complexity, increasing computational speed, and enhancing optimization precision [24]. Yao et al. used genetic algorithms to optimize prefabricated building site layouts, improving solution quality and reducing time [25]. Zhu and Song applied an enhanced genetic algorithm for project scheduling in prefabricated buildings, aiding strategy formulation in uncertain conditions [26]. Yu et al. employed a multi-objective genetic algorithm to optimize energy consumption and thermal comfort, offering sustainable building design solutions [27].

Each methodology—AHP, QFD, and NSGA-II—brings unique advantages, and their combination creates an effective multi-objective optimization framework that enhances decision making. AHP breaks down complex decisions, prioritizing and weighting user needs, which are then used in QFD to translate these needs into design attributes [22]. QFD serves as an intermediary, linking abstract requirements to specific design targets, laying the groundwork for NSGA-II. NSGA-II, in turn, balances multiple objectives, generating a set of non-dominated solutions that address factors like cultural preservation, energy efficiency, and comfort [26]. The integration of AHP, QFD, and NSGA-II strengthens the optimization process, making it both scientifically rigorous and flexible enough for real-world applications.

3. Case Study

3.1. Overview of Tuyugou Village

Tuyugou Village, situated in the Turpan region of Xinjiang (see Figure 4), is depicted in Figure 5. Extending from north to south, the village encompasses the Subashi Ruins, the Thousand Buddha Caves, and ancient tombs. In 2005, the village was designated as a national historical and cultural site, making it the first of its kind in Xinjiang [4]. The layout of the village maximizes the natural terrain, seamlessly integrating mountains, waterways, dwellings, and roads—a characteristic trait of oasis settlements [5]. Water from a branch of the Tianshan system irrigates surrounding fields via channels along the river, while buildings are harmoniously integrated with the surrounding hills and farmland. The primary water system creates a "川" ("The character '川', which means 'river' in Chinese, is used here to illustrate that the layout of the three rivers resembles this character.") -shaped configuration, merging natural and cultural features [4]. To conserve farmland, the village expands outward from its central structures, with houses positioned to optimize sunlight and protect against wind. The road network, intersecting with the water system, consists of primary roads, a central ring road, and smaller paths, all tailored to the terrain and designed to meet residents' transportation needs [28,29].

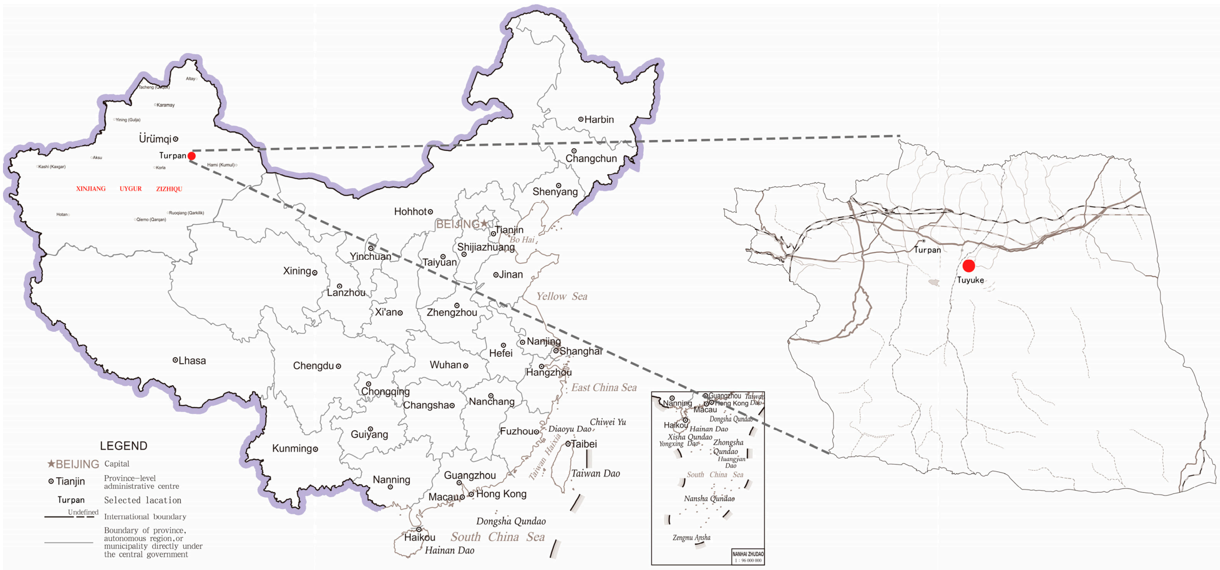

Figure 4. Location of Turpan.

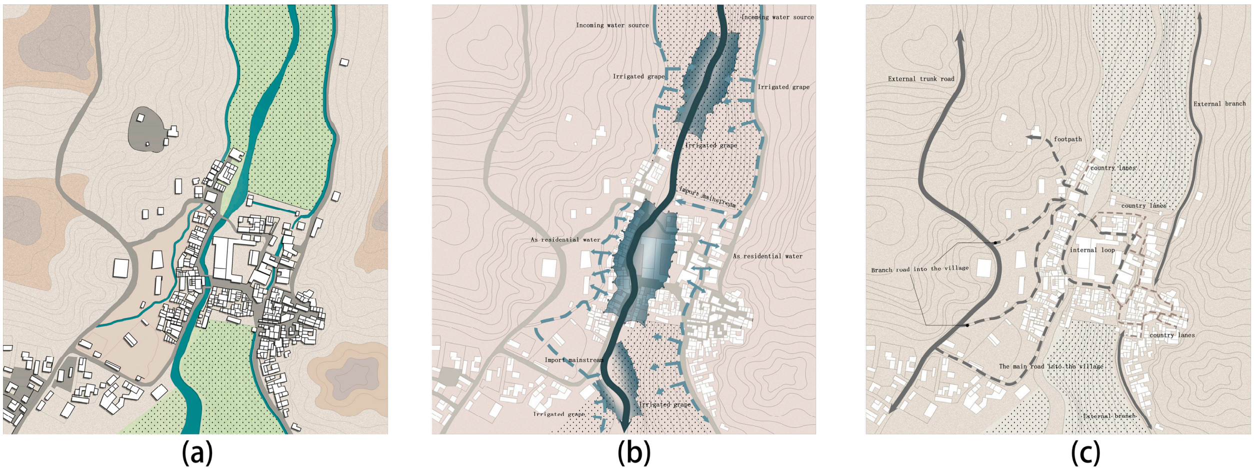

Figure 5. Layout of Tuyugou Village. (**a**–**c**) Building layout, water system layout, and road layout, respectively.

3.2. *Ecological and Cultural Aspects of Tuyugou Village*

In line with the hot summer and cold winter climate that is typical of Xinjiang, the site selection for Tuyugou Village adheres to traditional Chinese principles, specifically "Avoid constructing high on ridges with limited water and avoid building low near water to reduce ditch construction effort" [4]. The village is situated between two mountains in the heart of a valley, which serves to shield it from cold winter monsoons and reduces direct solar exposure during the summer months. The majority of the buildings are oriented toward the water, capitalizing on evaporative cooling that reduces the temperature by approximately 2 °C while increasing humidity relative to the surrounding mountains. During the night, wind speeds toward the valley decrease, and in winter, temperatures within the valley are typically 2–3 °C warmer than those outside [30]. To evaluate Tuyugou Village's ecological adaptability, we utilized Ladybug simulation software 1.5.0 on the Rhino and Grasshopper platforms to model annual sunshine hours and prevailing wind patterns. The results, presented in Figure 6, reveal that the village experiences reduced sunlight exposure and lower wind speeds compared to the surrounding mountains, showcasing its exceptional ecological adaptability to extreme environments.

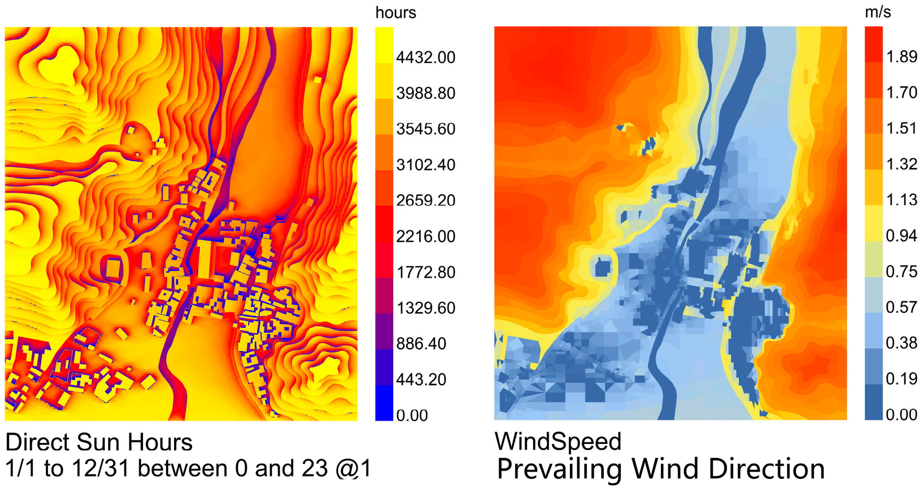

Figure 6. Simulations of the ecological adaptability of Tuyugou Villag.

4. Research Design

This research examined the developmental context of Tuyugou Village to identify the needs of various stakeholders, particularly those involved in the refurbishment and modernization of earthen dwellings. The primary stakeholders in this process included local residents, visiting tourists, construction experts (including architects and engineers), and governmental bodies responsible for the region. It is assumed that there are significant differences in the needs of local residents, tourists, architectural experts, and government agencies regarding the renovation of traditional adobe houses. Therefore, by employing the Analytic Hierarchy Process (AHP) and Quality Function Deployment (QFD) methods, systematic collection and prioritization of these needs can effectively capture the weighting of different stakeholder groups, achieving a balanced design. To systematically gather and interpret the perspectives, expectations, and priorities of these groups, the study utilized structured surveys, focus group discussions, and comprehensive interviews (Table 1) [31]. This method not only uncovered critical stakeholder requirements but also highlighted the initial relationships between the differing priorities of these groups. These insights were instrumental in formulating design criteria that were more specific and tailored to the renovation of Tuyugou Village's traditional earthen architecture. The methods employed, including AHP, QFD, and NSGA-II, may be limited by the completeness of the architectural data and the computational capabilities of the models. Additionally, it is assumed that the materials, techniques, and energy systems used during the research implementation are available.

Table 1. Analysis of local residents' needs.

Group	Main Needs	Key Concerns	Group Characteristics
Local residents	Living comfort, energy efficiency, maintenance costs, cultural heritage preservation	Improving quality of life, balancing cultural heritage with modern living needs	Sensitive to comfort and living costs, highly valued cultural and emotional attachments
Tourists	Cultural experience, comfort, safety, aesthetic experience	Preserving cultural atmosphere, ensuring comfort in the living experience	Short-term visitors, focused on appearance and cultural features
Professionals in the construction industry	Innovative design, technical feasibility, cost control	Combining innovation with tradition, improving functionality and durability	Focus on innovation and technical feasibility, concerned with balancing cost and quality
Relevant government departments	Policy implementation, economic and cultural benefits, cultural preservation	Guiding renovation direction, balancing cultural preservation with economic development	Balancing local development with cultural preservation, focused on the long-term benefits of the project

4.1. Priority Ranking Using the AHP Method

The restoration of traditional earthen dwellings in Tuyugou Village requires a comprehensive approach that addresses the diverse needs of stakeholders, including homeowners, government officials, tourists, and construction experts. To systematically define and prioritize these needs, data collection was organized into two stages to establish the design criteria and inform the renovation strategy.

The first stage involved fieldwork that assessed the physical and environmental conditions of the dwellings. This on-site assessment helped identify specific renovation requirements, taking into account the local climate and structural characteristics unique to Tuyugou Village. In addition, data from comparable renovation projects, local climate studies, and relevant cultural preservation policies were gathered. This preliminary research offered essential insights into the practical challenges and objectives of the renovation, creating a foundation for the development of design criteria.

In the second phase, a stakeholder survey was conducted, distributing 200 questionnaires (see Appendix A Table A1) and yielding 177 valid responses. This survey aimed to capture the priorities and expectations of various stakeholders. Analysis of the responses revealed four primary needs that are crucial for the renovation strategy: thermal performance, structural safety, cultural and aesthetic values, and economic/comfort considerations, as well as 18 secondary needs. These insights allowed for a nuanced understanding of stakeholder demands, emphasizing the renovation's multidimensional nature.

To effectively prioritize these identified needs, the Analytic Hierarchy Process (AHP) was employed. AHP was selected due to its ability to manage complex decision-making scenarios involving multiple criteria and stakeholder perspectives. The criteria selection for AHP was based on the four primary needs identified from the survey, with secondary needs providing additional specificity to the evaluation process. Using Saaty's 1–9 scale, the research team assigned relative weights to each criterion, allowing stakeholders to indicate the importance of each need. Judgment matrices were constructed from these responses, facilitating pairwise comparisons among indicators. The geometric mean method was applied to calculate the weight of each criterion, establishing a hierarchy of renovation priorities. This structured and data-driven approach enabled the development of a balanced renovation strategy, designed to align traditional aesthetic values with modern standards for performance and functionality.

The AHP method addressed challenges in traditional QFD models, particularly in managing subjectivity and integrating both qualitative and quantitative data [32]. Utilizing Saaty's 1–9 rating system, the team conducted pairwise comparisons across four secondary and 19 tertiary user needs specific to Tuyugou Village. In this system, a score of 1 indicates equal importance, while a score of 9 signifies that one factor is considerably more important than another. Weight calculations were performed using judgment matrices, which compared factors on a 1–9 scale [33].

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \quad (1)$$

In the formula, $a_{ij} = \frac{1}{a_{ij}}$ and $a_{ij} = 1$.

The ranking weights for each factor are extracted from the judgment matrix. To estimate the eigenvector, known as M, the square root method is applied. The corresponding normalized vector, symbolized as ω, indicates the relative significance of user needs. Each element within ω represents the weight allocated to a particular need at the current level, using the needs from the preceding level as a reference. To ensure the results are consistent, the maximum eigenvalue, λ_{max}, of the judgment matrix is computed. The procedure for this calculation is outlined in the following steps [33]:

$$M_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \tag{2}$$

$$\omega_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{3}$$

$$\lambda_{max} = \sum_{i=1}^{n} \left(\sum_{j=q}^{n} a_{ij} \cdot \omega_j \right) / \omega_i \tag{4}$$

To ensure the judgment matrix is accurate and free of bias, consistency validation is conducted. This involves calculating the consistency index (*CI*) and consistency ratio (CR). The *CI* measures the alignment within the matrix, while the random index (*RI*) acts as a comparison benchmark. A *CI* of zero indicates perfect consistency [33].

Once the *CI* is calculated, the CR accounts for random variations affecting reliability. If the CR is below 0.1, the matrix is deemed consistent, validating the weight rankings. If it exceeds 0.1, revisions are needed. Together, the *CI* and CR offer a comprehensive check of the matrix's consistency, ensuring reliable data.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

$$R = \frac{CI}{RI} \tag{6}$$

After performing data calculations using the software, the weight matrix W = [0.4787, 0.1865, 0.1183, 0.2165] was obtained. Specifically, the weight for thermal performance is 0.4787, the weight for structure and safety is 0.1865, the weight for culture and aesthetics is 0.1183, and the weight for economics and comfort is 0.2165. The calculated maximum eigenvalue is λ_{max} = 4.0934; additionally, CR = 0.0346, *CI* = 0.0311, and CR = 0.0346 < 0.1, indicating that the judgment matrix has high reliability. Similarly, by combining the primary indicator weights, the weights for the secondary indicators are calculated, and the comprehensive weights for the secondary indicators are derived as a reference for the optimization design of earthen dwellings. See Table 2 for details.

Table 2. Weights of indicators at all levels.

Level 1 Indicator	Level 2 Indicator	Same Level Weight	Comprehensive Weight	Ranking	Consistency Ratio
Thermal environmental performance	Thermal insulation	0.4067	0.1946	3	0.02335
	Heat preservation	0.1971	0.0943	5	
	Dampproof	0.1069	0.0511	13	
	Lighting	0.2307	0.1104	14	
	Ventilation	0.0586	0.0281	17	
Structure and safety	Durability	0.6352	0.1185	1	0.0121
	Earthquake resistance	0.1469	0.0274	10	
	Safety	0.2179	0.0406	15	
Culture and aesthetics	Cultural preservation	0.5328	0.0630	2	0.0362
	Aesthetic	0.2913	0.0345	4	
	Environmental protection material	0.2913	0.0208	6	

Table 2. *Cont.*

Level 1 Indicator	Level 2 Indicator	Same Level Weight	Comprehensive Weight	Ranking	Consistency Ratio
Economy and comfort	Cost effectiveness	0.2574	0.0557	12	0.013
	Construction convenience	0.1612	0.0349	8	
	Residential comfort	0.0739	0.0160	16	
	Space utilization	0.1393	0.0302	11	
	Modern facilities	0.1393	0.0116	18	
	Energy saving	0.1393	0.0355	7	
	Maintenance costs	0.1505	0.0326	9	

4.2. Determination of Quality Characteristics

Using the weights of user needs derived from the AHP analysis, the research team translated these into precise quality characteristics. To maintain scientific rigor and objectivity, the team collected feedback from a wide range of stakeholders. The participants included five local residents, five craftsmen specializing in earthen construction, five cultural preservation officials, ten architectural designers, and five professors from the Civil Engineering Department of Xinjiang University. A comprehensive review of these discussions allowed the team to pinpoint 11 key design quality characteristics. By incorporating expert input alongside a multidimensional analytical approach, the renovation design was crafted to address diverse stakeholder needs, ensuring both practical feasibility and scientific validity.

4.3. Constructing the Relationship Matrix

After identifying user needs and design quality characteristics, the team established their relationship by assigning the following values: 9—very strong correlation; 7—strong correlation; 5—moderate correlation; 3—weak correlation; 1—very weak correlation; and 0—no correlation [32]. This matrix enabled the association between the quality characteristics of Tuyugou earthen dwellings and user needs, facilitating the calculation of the weight scores for each characteristic.

4.4. Determining the Priority of Quality Characteristics

The bottom part of the House of Quality evaluates the importance of each quality characteristic by taking into account its difficulty coefficient, overall benefits, and associated trade-offs to establish its priority. Characteristics with higher priority are those that should be addressed first, as they have a greater impact on boosting customer satisfaction, loyalty, competitiveness, and profitability of earthen dwellings. The formula used for this calculation is as follows:

$$S_i = \sum_{j=1}^{n} \left(W_j \cdot R_{ij} \right) \tag{7}$$

In the formula, S_i represents the total score of design quality characteristic i. W_j represents the weight of user need j. R_{ij} represents the strength of the relationship between user need j and design quality characteristic Q_i, typically expressed using 9, 7, 5, 3, 1, or 0 to indicate the degree of association. n is the total number of user needs.

4.5. Competitive Analysis

To assess the design's industry competitiveness, the project team integrated competitive analysis modules into the right and bottom sections of the House of Quality. These modules enabled a comprehensive evaluation of the strengths and weaknesses of each project, emphasizing specific design attributes. Five prominent earthen architecture projects in China were selected, representing key industry trends. The selected projects were the "Anju Fumin" demonstration [1], the Tongwei County residence renovation

(Dingxi) [34], the Urho earthen hotel in Karamay [35], the Yellow River Loess Geological Museum [36], and the Li family earthen house renovation [37]. A symbolic scoring matrix evaluated each project's design indicators. The resulting scores offered insights into each project's performance across different design attributes and their alignment with client expectations [38]. Through the analysis of these results, the team developed a House of Quality model, facilitating a detailed comparison of each design's competitive positioning, as illustrated in Figure 7.

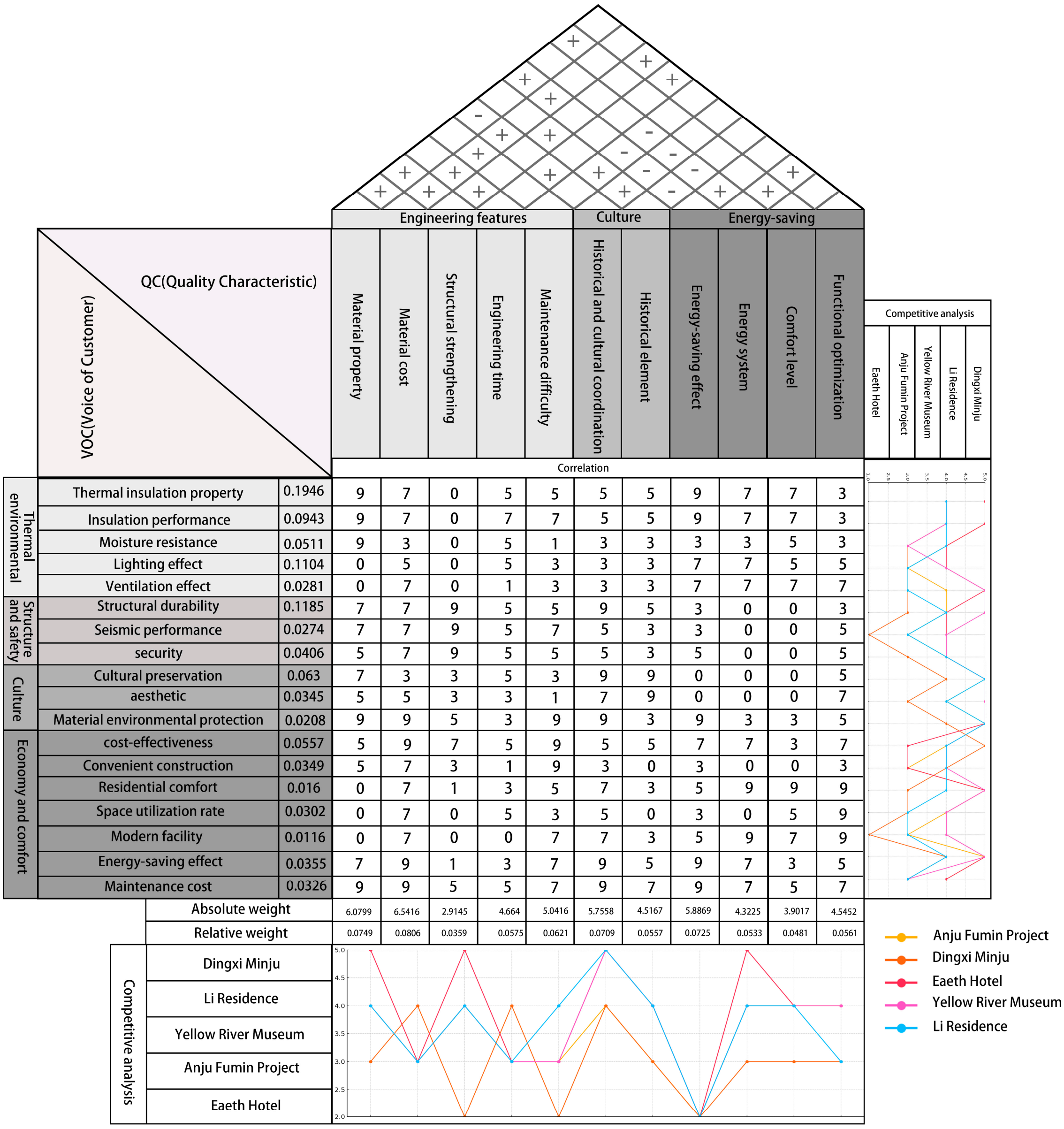

Figure 7. House of Quality model drawing.

4.6. *Converting Quality Characteristics into Optimization Objective Functions*

In the context of multi-objective optimization, the objective function organizes quality attributes into three primary categories, each comprising eleven sub-objectives (See Appendix A Table A2). Through the integration of engineering parameters, a robust and practical evaluation framework is developed. This systematic approach effectively balances trade-offs between competing project objectives, resulting in design solutions that are both efficient and feasible.

4.6.1. Developing the Optimization Objective Model for Engineering Characteristics

In construction projects, evaluating key quality factors, including building materials, scheduling, and construction methods, is crucial. These factors are optimized through the application of established engineering principles. Key considerations such as cost management, ease of maintenance, construction speed, and budget control are closely linked to material selection and project timelines. Consequently, these factors form the foundation for assessing the economic viability of a project, taking into account material costs and scheduling (see Tables 3 and 4). By assigning suitable weights to these variables, costs related to materials, maintenance, and construction, alongside project timelines, can be effectively managed, shaping the final optimization outcomes.

$$f_1 = C_{total} = \sum_{i=1}^{n} (C_{mi} \cdot Q_i) + \left(C_{li} \cdot \frac{100}{P_m} + C_{labor} \cdot T \right) \cdot e^{-\lambda \cdot T} \tag{8}$$

Table 3. Unit price of building materials, maintenance costs, and related parameters.

Category	Material	Unit Price (RMB)	Maintenance Cost (RMB/Year)	Maintenance Period	Durability (Years)	Cultural Adaptability
Traditional enclosure material	Raw earth	25/m^3	25 (RMB/year/m^3)	5–10 years	35	0.9
	Modified raw earth	75/m^3	18 (RMB/year/m^3)	10–20 years	50	0.85
	Bricks	238/m^3	5–15 (RMB/year/m^3)	20–30 years	70	0.6
	Local wood	1120/m^3	50–100 (RMB/year/m^3)	5–15 years	50	0.85
Modern enclosure material	Concrete	455/m^3	20–50 (RMB/year/m^3)	30–50 years	100	0.3
	Steel	27,082.5/m^3	100–200 (RMB/year/m^3)	20–40 years	100	0.2
Glass material	Ordinary glass	65/m^2	10–30 (RMB/year/m^2)	10–20 years	50	0.65
	Low-E insulated glass	360/m^2	20–50 (RMB/year/m^2)	20–30 years	40	0.2
Insulation material	50 mm rock wool insulation board	65/m^2	11 (RMB/year/m^2)	15–25 years	35	0.25
	50 mm glass wool insulation material	25/m^2	9 (RMB/year/m^2)	15–25 years	40	0.15
	20 mm polyurethane (PU)	128/m^2	13 (RMB/year/m^2)	10–20 years	30	0.1
	20 mm EPS exterior wall insulation board	95/m^2	7 (RMB/year/m^2)	15–25 years	35	0.2

Table 4. Construction labor cost and duration related parameters.

Job Type	Labor Cost (RMB/Day)	Duration (Days)
Foundation Construction Worker	210	20
Raw Earth Construction Worker	220	18
Modified Raw Earth Construction Worker	230	22
Brick Construction Worker	250	25
Concrete Construction Worker (Long-Term)	260	30
Concrete Construction Worker (Short-Term)	240	20
Glass Installation Worker	250	15
Insulation Material Construction Worker	230	15
Electrical Installation Worker	270	10
Traditional Decorative Arts Worker	300	5–30

Among them, the material cost C_{mi} is the unit price of the i-th material, and Q_i is the quantity of material used. This part reflects the cost of the selected material. C_{li} is the annual maintenance cost of the material. P_m is the maintenance cycle, C_{labor} is the labor cost, T is the project duration, and $e^{-\lambda \cdot T}$ is the exponential decay term, which reflects the gradual decline in overall project economics as the project duration increases. The value of

λ can be adjusted to fit different engineering scenarios. The specific material parameters are shown in Table 3; The relevant parameters of construction labor cost and construction period are shown in Table 4.

4.6.2. Stablishing the Cultural Optimization Objective Model

Traditional earthen dwellings are built from rammed yellow clay, featuring essential components such as boundary and courtyard walls, partition walls, short fences, gates, corridors, high sheds, storage rooms, hearths, grape-drying rooms, toilets, and livestock pens [39]. Decorative elements were added to the walls of these structures to enhance their artistic value. Unique geometric patterns were created by strategically placing bricks on door pillars and hollowing out sections of the short fences. Certain buildings highlighted their significance through the use of brick arches [39,40]. Intricately carved columns with distinctive shapes and vibrant colors enhanced the artistic appeal within the courtyards. Sheds were classified into inner courtyard sheds, external support sheds, roof sheds, built-in sheds, and corridor sheds. Windows, often adorned with hollow carvings, were available in square, arched, or strip shapes. These decorative techniques were employed to beautify the environment, enhance the architectural facade, and emphasize the building's overall theme. As illustrated in Figure 8, the exterior elements are divided into five major categories and 69 individual components.

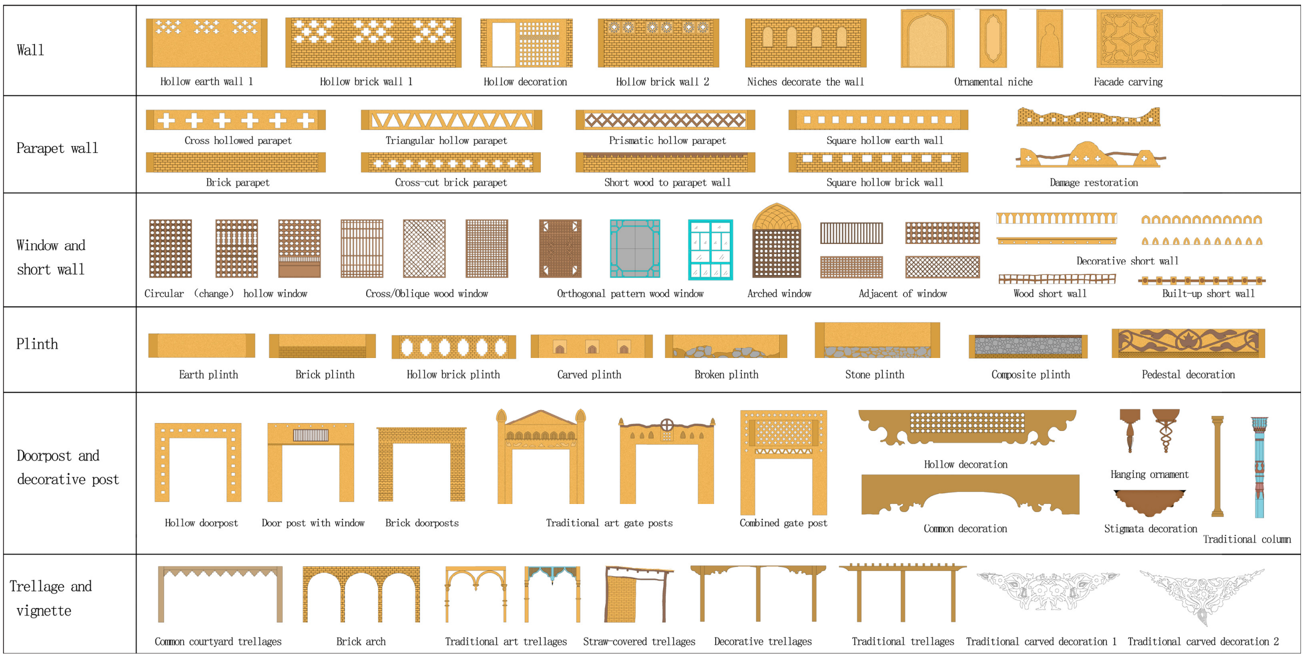

Figure 8. Classification of traditional elements of indigenous dwellings.

The cultural adaptability of materials is assessed by examining their composition, traditional relevance, and proportional use in construction. This assessment considers how well each material aligns with the cultural heritage of the project, offering a balanced evaluation of both functional and cultural significance. The calculation formula for this adaptability is provided below:

$$f_2(x) = \sum_{i=1}^{n} (Q_i \cdot C_{cultural}) \cdot \frac{\mathrm{M_{trad}}}{\mathrm{H_{total}}} \cdot \frac{\mathrm{E_{trad}}}{69} \tag{9}$$

Among them, $\mathrm{M_{trad}}$ represents the total amount of traditional materials. $\mathrm{H_{total}}$ represents the total amount of materials (including all materials), and Q_i is the quantity of material used. $C_{cultural}$ is the cultural adaptability score of the material, representing its coherence and adaptability in historical culture. $\mathrm{E_{trad}}$ is the number of traditional elements used, and 69 represents the total summarized traditional elements. Given the inherent difficulty in quantifying cultural values, this research relies on subjective evaluations from experts and community members for cultural adaptability scoring, which may introduce a degree of bias.

4.6.3. Establishing the Energy-Saving Optimization Objective Model

Energy efficiency refers to the amount of energy required by a building and its systems to meet specific load demands. In both building design and equipment selection, enhancing energy efficiency not only minimizes energy consumption and operational costs but also promotes environmental sustainability and improves the overall comfort of the building. The energy efficiency optimization method presented in this paper integrates the thermal properties of building materials with equipment selection and operational control strategies. The equipment involved in the transformation process is shown in Table 5.

Table 5. List of building equipment.

Equipment	Category	Energy Efficiency Level	Cost (RMB)	Energy Utilization	Energy Consumption (kWh)
Air conditioning equipment	Wall-mounted air conditioning	I, II, III	2000–5000	I: Energy efficiency ≥ 4.5 (SEER standard) II: Energy efficiency 3.9–4.5 III: Energy efficiency 3.5–3.9	I: 0.33
	Mobile air conditioning	I, II, III	1000–3000		I: 0.29
Lighting equipment	LED lamp	I	200	I: ≥ 210 lm/w (LED) I: ≥ 90 lm/w	I: 0.01
	Energy-saving lamp	I, II, III	10–50		I: 0.015
Heating equipment	Wall-hanging stove	I, II, III	300–2000	I: Heat efficiency ≥ 98%	I: 0.01
	Electric radiator	None	300–2000	None	1.96
	Underfloor heating	None	2000–5000	None	5
Hot water facilities	Electric water heater	I, II, III	1000–5000	I: Energy efficiency ratio ≥ 0.9 II: Energy efficiency ratio between 0.8 and 0.9 III: Energy efficiency ratio between 0.7 and 0.8	Level I: 2.22 Level II: 2.35 Level III: 2.67
	Gas water heater	I, II, III	1000–15,000		I: 2.2
	Solar water heater	None	3000–15,000		None

It is assumed that the climate conditions (such as temperature and humidity) and the basic architectural parameters of traditional adobe houses in the region remain relatively stable during the research period, allowing for simulation and optimization analysis based on the existing environment [41]. Data collection for the research is based on current climatic conditions and technical feasibility, without considering the potential impacts of future climate change on renovation plans.

To reveal the daily activity schedule and room usage patterns of the local residents, the research team conducted questionnaire interviews with residents of Tuyugou Village. The results, as shown in Figure 9, illustrate the daily routines and activities of an extended family, highlighting traditional roles, shared family times, and the energy consumption needs necessary for their daily lives. These data are instrumental in understanding how housing design can be adapted to optimize energy use according to the specific activities of various family members throughout the day.

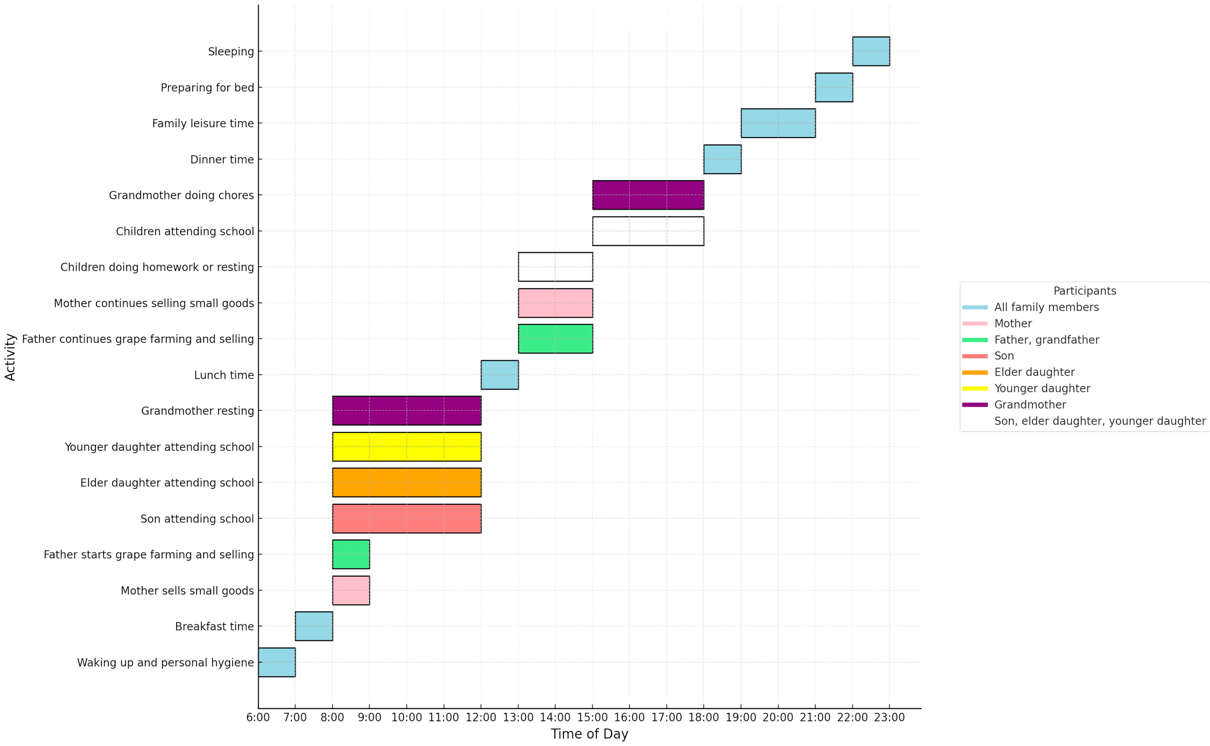

Figure 9. Family daily activity schedule.

Given that building loads and equipment performance fluctuate in a dynamic environment, real-time adjustments to equipment operations and optimization of thermal management are essential for maximizing energy efficiency [42–45]. Building load demands vary according to factors such as time of day, seasonal changes, and equipment operating conditions. To effectively capture these fluctuations, this study utilizes day–night load models, seasonal load models, and equipment load models. The variation in daily and nightly loads is modeled using a sine function, as demonstrated in the day–night load model described below.

$$L_{day-night}(t) = L_{avg} + L_{amp} \cdot sin(\frac{2\pi}{24} \cdot t) \quad (10)$$

where L_{avg} is the daily average load (unit: kW), L_{amp} is the load amplitude (unit: kW), and t is the time (unit: hours).

The load of each device varies with time and load demand. The equipment load model is as follows:

$$P_{device}(t) = C_{load} \cdot P_{rated} \cdot l_{operating}(t) \quad (11)$$

where C_{load} is the load factor (unit: 0–1), representing the ratio of the actual working load to the rated load of the equipment. P_{rated} is the rated power of the equipment (unit: kW), $P_{rated}(t)$ is actual power load (unit: kW), and $l_{operating}$ is the indicator function, used to describe whether the equipment is in operation at time t.

Based on the above information, the equipment operation time for the local traditional soil dwellings is shown in Figure 10a, and the power output distribution is shown in Figure 10b. This indicates that, due to Turpan's extreme climate conditions, the power consumption of air conditioning and heating fluctuates significantly. Their usage frequency is concentrated during specific climate conditions, while the power consumption of lighting and water heaters remains relatively stable. However, there are some fluctuations as the seasonal climate changes.

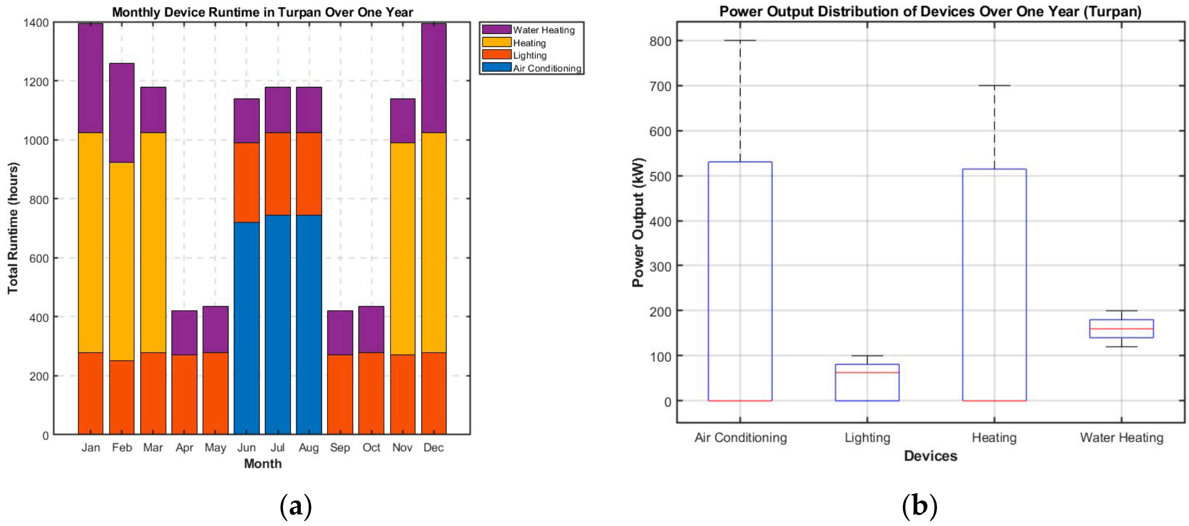

Figure 10. (**a**) Equipment operation time; (**b**) equipment power output distribution.

Based on the above, in a discrete-time model, the total energy consumption of the equipment combined with the load model at different time periods can be expressed as:

$$E_{device} = \sum_{t=1}^{T} P_{device}(t) \cdot \Delta t \tag{12}$$

Based on the dynamic load, equipment selection, and thermal storage system, the heat transfer process of the building envelope also incurs energy consumption. Considering factors such as material density, specific heat, thermal conductivity, and thickness, the building's energy consumption is related to heat transfer, temperature differences, and thermal storage characteristics, based on the principles of heat transfer and energy conservation. The heat transfer through the building envelope can be described using Fourier's law:

$$Q_{dynamic} = \frac{A \cdot \lambda \cdot \Delta T \cdot t}{d} \tag{13}$$

In the formula, Q is the heat transferred through the building envelope, measured in joules (J) or kilowatt-hours (kWh). A is the area of the building envelope, measured in square meters (m^2). ΔT is the temperature difference between the interior and exterior, measured in kelvins (K); t is the time, measured in seconds or hours; λ is the thermal conductivity of the material, measured in watts per meter-kelvin (W/m·K); d is the thickness of the material.

The heat storage coefficient (S) determines a material's ability to retain and release heat, influencing a building's thermal performance. Materials with higher S values stabilize indoor temperatures by absorbing and releasing heat over time, which is beneficial in fluctuating climates [42]. Calculating S involves specific heat capacity, density, and thickness, with higher values indicating improved energy efficiency.

$$Q_{heat} = S \cdot A \cdot \Delta T \tag{14}$$

where Q_{heat} is the heat absorbed or released by the material, measured in joules (J). S is the heat storage coefficient of the material, measured in watts per square meter-kelvin (W/(m^2·K)). A is the area of the building envelope, measured in square meters (m^2). ΔT represents the temperature change, measured in kelvins (K). The specific material parameters are shown in Table 6.

Table 6. Thermal parameters of materials.

Material Type	Thickness (mm)	Density (kg/m^3)	Thermal Conductivity [W/(m·K)]	Thermal Storage Coefficient S [W/(m^2·K)]	Specific Heat C [kJ/(kg·K)]
Raw earth	500	1800	0.93	11.03	1.01
Modified raw earth	500	1700	0.58	7.69	1.01
Bricks	500	1800	0.81	9.96	1.05
Local wood	50	500	0.14	3.85	2.51
Concrete	400	2500	1.74	17.2	0.92
Steel	20	7850	58.2	126	0.48
Glass	5	2500	0.76	10.69	0.84
Rock wool insulation board	20	120	0.041	0.45	1.22
Glass wool insulation material	20	40	0.035	0.35	1.22
Polyurethane (PU)	20	35	0.024	0.29	1.38
EPS exterior wall insulation board	20	20	0.047	0.7	1.38

The thermal storage coefficient (S) presented in Table 6 quantifies a material's ability to store and release heat energy per unit area and temperature difference, expressed in units of W/(m^2·K). It essentially measures how effectively a material can absorb heat during periods of temperature rise and release it when temperatures fall, thus acting as a thermal reservoir. Materials with a high thermal storage coefficient can significantly stabilize indoor temperatures by absorbing excess heat during the day and releasing it during cooler periods. By moderating indoor temperatures, these materials can decrease the reliance on heating and cooling systems, leading to energy savings and reduced utility costs.

Taking into account the heat transfer and thermal storage characteristics of materials, the building's energy consumption can be expressed as the sum of the heat transfer energy consumption and the thermal storage energy consumption of the building envelope.

$$E_{total} = Q_{heat} + Q_{dynamic} \tag{15}$$

By omitting considerations like solar radiation gains, ventilation energy usage, and internal heat contributions, the energy consumption of both the building and its energy system is calculated. The final formula for this calculation is formulated by integrating the economic benefits of the energy system with its energy-saving advantages.

$$f_3(x) = \sum_{i=1}^{n} \left(\frac{C_{device}}{E_{device}} + \frac{C_{mi} \cdot Q_i}{E_{total}} \right) \tag{16}$$

5. Design Results

5.1. Parameter Settings

This research employed MATLAB 2024a to develop the necessary scripts and functions for the analysis. In the main script, several key parameters were defined: a population size (N) of 100, a maximum of 200 iterations, a crossover probability of 0.8, and a mutation probability of 0.2. Figure 10 illustrates the Pareto optimal solution set generated after applying the NSGA-II algorithm to solve the multi-objective optimization problem. Additionally, Figure 11a–c present the iteration diagrams for each objective derived from the NSGA-II model.

Once the algorithm reaches the predefined limit for iterations, it halts, producing a set of Pareto-optimal solutions that conform to the established constraints. These solutions, depicted in Figure 12, represent distinct construction strategies, each specifically designed to align with the various objectives outlined during the optimization. By taking into account factors such as cost-effectiveness, preservation of cultural heritage, and energy efficiency, these solutions offer a diverse array of alternatives for decision makers to assess [43]. The range of strategies demonstrates the algorithm's capability to balance conflicting priorities, thereby making it a powerful tool for resolving complex construction challenges within the specified parameters.

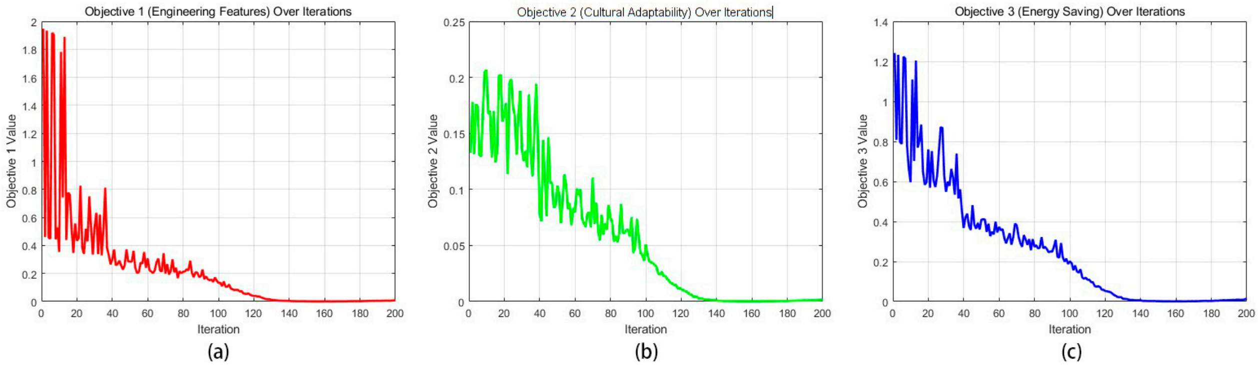

Figure 11. NSGA-II solution iteration diagrams. (**a**–**c**) Iteration diagrams for engineering features, culture, and energy savings, respectively.

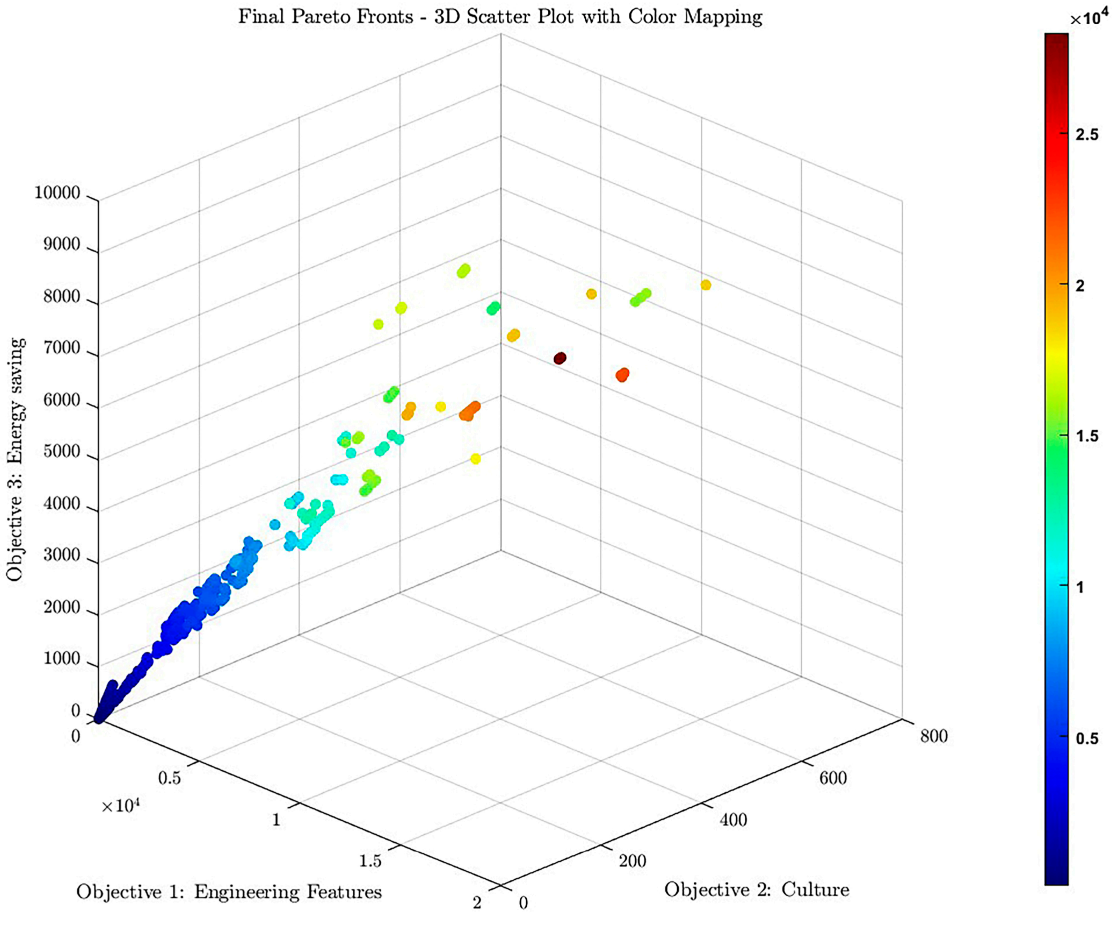

Figure 12. NSGA-II Pareto solution set diagram.

5.2. PRCC Sensitivity Analysis

To achieve an appropriate balance among multiple objectives while fulfilling overall design requirements, this paper performs a trade-off analysis of the Pareto-optimal solutions [44], as illustrated in Figure 13. A clear trade-off exists among cost control, cultural adaptability, and energy efficiency.

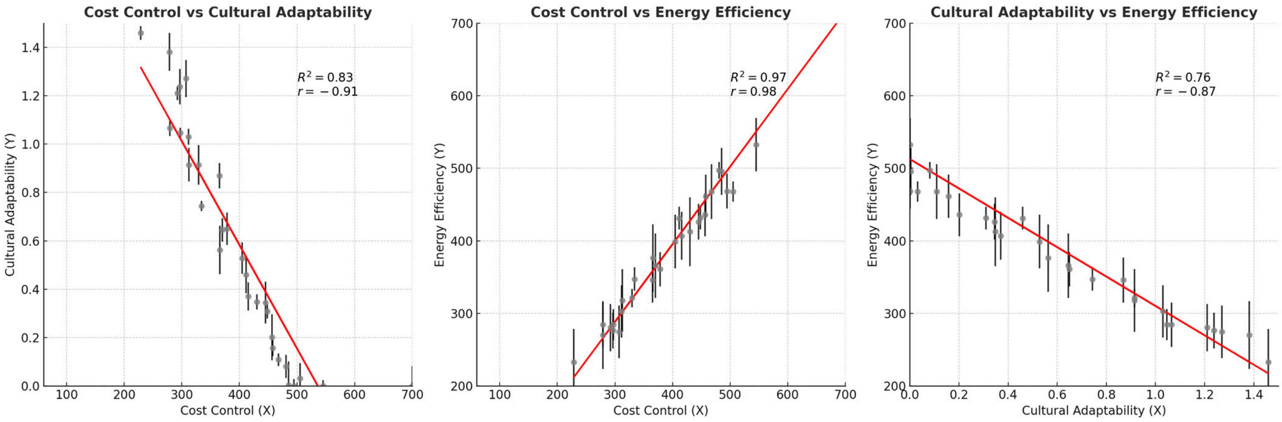

Figure 13. Trade-off analysis.

First, cost control and cultural adaptability exhibit a negative correlation (r = −0.91, R^2 = 0.83), indicating that cost reduction often compromises cultural preservation. A balance must be achieved between these two factors.

Second, cost control and energy efficiency demonstrate a positive correlation (r = 0.98, R^2 = 0.97), suggesting that enhancements in energy efficiency typically entail increased costs.

Finally, cultural adaptability and energy efficiency exhibit a negative correlation (r = −0.87, R^2 = 0.76), implying that the preservation of traditional culture may diminish energy efficiency. Therefore, prior to decision making, it is essential to balance these three objectives and conduct a sensitivity analysis of the design variables.

The sensitivity analysis results, as shown in Figure 14, reveal the varying effects of different input parameters on cost control, cultural adaptability, and energy efficiency. The analysis shows that labor costs and project duration significantly impact all objectives, making them key factors that require close attention. Annual maintenance costs and material types play a crucial role in energy efficiency and long-term cost control. To achieve a balance among the three objectives, optimizing labor costs and construction duration is a core strategy. Moreover, a thoughtful selection of material types is needed to balance cultural preservation and energy-saving requirements between cultural adaptability and energy efficiency. Overall, decision makers can achieve the optimal combination of cost and performance by flexibly adjusting key parameters while meeting project goals [45].

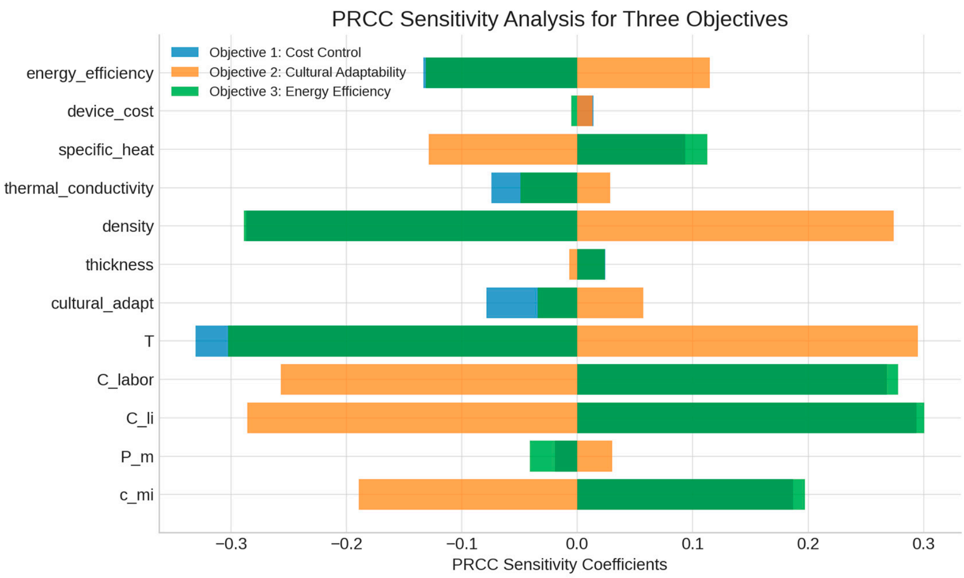

Figure 14. PRCC sensitivity analysis.

Based on the above analysis, this paper selects 10 solutions from the Pareto optimal set as reference solutions. These solutions made reasonable selections of material types and screened labor costs and construction duration. Specific data are shown in Table 7.

Table 7. To select the 10 best solutions.

Number of Schemes	Objective 1	Objective 2	Objective 3
1	463.256	0.2206	510.68
2	487.645	0.0053	517.559
3	389.281	1.0441	309.324
4	491.14	0.0569	509.351
5	342.984	1.3529	359.501
6	340.566	1.5364	352.793
7	444.202	0.3164	455.745
8	341.584	1.4151	350.897
9	396.549	0.6516	403.486
10	415.835	0.4931	419.515

5.3. Entropy Weight-VIKOR Method

To minimize external influences on decision making, this study adopts an objective approach by combining the entropy weight method with the VIKOR technique [46]. This integrated method addresses limitations in other multi-criteria decision-making techniques, such as AHP's subjectivity and TOPSIS's emphasis on a single criterion. The process starts by applying the entropy weight method to calculate objective weights, ensuring a fair and rational distribution. After determining the weights, the VIKOR method is employed to comprehensively evaluate and rank the objectives, selecting the optimal solution. This combined approach offers a scientifically grounded and balanced selection of Pareto-optimal solutions, ensuring fairness and consistency throughout the decision-making process [47]. Zhong and Cheng introduced this hybrid method to evaluate the usability of in-vehicle HUDs, an area where subjective perceptions greatly influence design assessments. By integrating entropy and VIKOR methods, this approach minimizes subjective biases, resulting in greater reliability when identifying the optimal HUD design based on usability metrics. The study's findings demonstrate that the entropy–VIKOR hybrid model is both effective and reliable for practical applications in design optimization, particularly in contexts that require a balanced consideration of subjective and objective factors.

The detailed steps for entropy method calculation include evaluating 10 decision alternatives (m = 10) and 3 criteria (n = 3), constructing an initial matrix to represent these parameters.

$$x = \begin{bmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & \cdots & x_{23} \\ \vdots & \ddots & \vdots \\ x_{10,1} & \cdots & x_{10,3} \end{bmatrix} \quad (17)$$

To make the scores under different criteria comparable, the data need to be normalized. For positive criteria (such as culture), where higher scores are better, normalization is performed using the following formula:

$$r_{ij} = \frac{x_{ij} - min(x_j)}{max(x_j) - min(x_j)} \quad (18)$$

For negative criteria (such as engineering features and energy-saving effects), where lower scores are better, the following formula is used for normalization:

$$r_{ij} = \frac{max(x_j) - x_{ij}}{max(x_j) - min(x_j)} \quad (19)$$

After normalization, the percentage of each score is further calculated as follows:

$$R_{ij} = \frac{r_{ij}}{\sum_{j=1}^{m} r_{ij}} \tag{20}$$

The final normalized matrix R is obtained as follows:

$$R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & \cdots & R_{23} \\ \vdots & \ddots & \vdots \\ R_{10,1} & \cdots & R_{10,3} \end{bmatrix} \tag{21}$$

Next, the entropy method is used to calculate the entropy value for each evaluation criterion:

$$e_j = \frac{1}{\ln m} \cdot \sum_{i=1}^{m} R_{ij} \ln R_{ij} \tag{22}$$

$$Rw_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)} \tag{23}$$

Here, R_{ij} represents the normalized score value, m is the number of decision options, and to avoid the situation where ln(0) appears, the 0 values in R_{ij} can be replaced with a very small value, such as 1×10^{-10}, during calculation. Finally, the entropy values and weights for each objective are obtained, as shown in Table 8:

Table 8. Entropy values and weights for each evaluation criterion.

Evaluation Criteria	Engineering Features	Culture	Energy Savings
Entropy Values	0.8628	0.8414	0.8459
Weights	0.3050	0.3525	0.3425

After determining the weights for each criterion, the VIKOR method is used to rank the solutions. During the VIKOR method process, we will calculate the S, R, and Q values for each solution through the following steps, and ultimately select the optimal solution. The ideal solution is the best and the anti-ideal solution is the worst [46]. These are described here.

The ideal solution f_j^* is the best value for each criterion (for positive criteria, take the maximum value; for negative criteria, take the minimum value).

The anti-ideal solution f_j^- is the best value for each criterion (for positive criteria, take the maximum value; for negative criteria, take the minimum value) [46].

The S value represents the weighted distance between each solution and the ideal solution [48]. The calculation formula is as follows:

$$S_j = \sum_{i=1}^{m} W_j \left(\frac{f_j^* - f_{ij}^-}{f_j^* - f_j^-} \right) \tag{24}$$

R value: The maximum weighted distance in each solution:

$$R_i = MAX_j \left(W_j \cdot \frac{f_j^* - f_{ij}^-}{f_j^* - f_j^-} \right) \tag{25}$$

Q value: A weighted calculation that combines the S and R values, with the compromise coefficient v generally set to 0.5.

$$Q_i = v \cdot \frac{S_i - S^*}{S^- - S^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*} \tag{26}$$

After analyzing the final *S*, *R*, and *Q* values, Figure 15 is obtained.

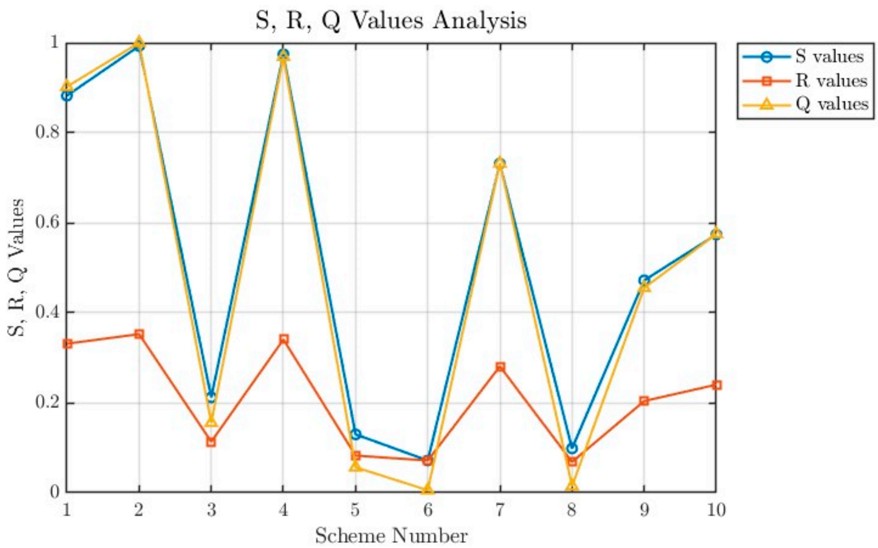

Figure 15. *S*, *R*, and *Q* values analysis.

Based on the analysis of the S, R, and Q values graph obtained above, the researchers found that the values are relatively close. To ensure the final evaluation results are more scientifically authoritative, a weighted comprehensive score incorporating the weights is used for the ranking, as follows [49].

Using the S, R, and Q values along with their respective weights, a comprehensive score is calculated, and then the solutions are ranked based on this score.

The formula for the comprehensive score is as follows: Score = $w_Q \cdot Q + w_R \cdot R + w_S \cdot S$, where w_Q, w_R, and w_S are the weights for Q, R, and S, with w_Q = 0.6, w_R = 0.3, and w_S = 0.1. After calculating the comprehensive score [46], the solutions are ranked from lowest to highest, as shown in Table 9.

Table 9. Ranking of alternative solutions by score.

Ranking	6	8	5	3	9	10	7	1	4	22
Scores	0.0319	0.0391	0.0716	0.1484	0.3816	0.4744	0.5968	0.7292	0.7812	0.8050

The sixth optimization plan stands out as the most optimal solution, excelling in areas such as cost control, cultural adaptability, and energy efficiency. The unit construction cost is RMB 340.566, reflecting its economic feasibility. With a cultural adaptability score of 1.5364, this plan effectively integrates local historical and cultural features by modernizing the architecture without compromising its traditional aesthetic and building techniques. In terms of energy performance, the plan achieves an energy cost of RMB 352.793/kWh. Through improvements to the building envelope and the implementation of efficient energy systems, it successfully reduces energy consumption while addressing daily operational demands.

To assess the effectiveness of the renovation plan, five case study buildings were evaluated across three key areas: engineering features, cultural adaptability, and energy efficiency. The materials and related equipment were rated and then compared to the renovation plan. The results are shown in Figure 16: the Tuyugou Village project outperformed the others in energy efficiency, with an energy cost of RMB 352.793/kWh. In contrast, the energy costs for the Tongwei County residential project and Li's house were 26% to 27% higher. The rammed-earth hotel and Yellow River Geology Museum exhibited even greater energy costs, with increases of 381% and 436%, respectively, likely due to their reliance on more energy-intensive systems or materials.

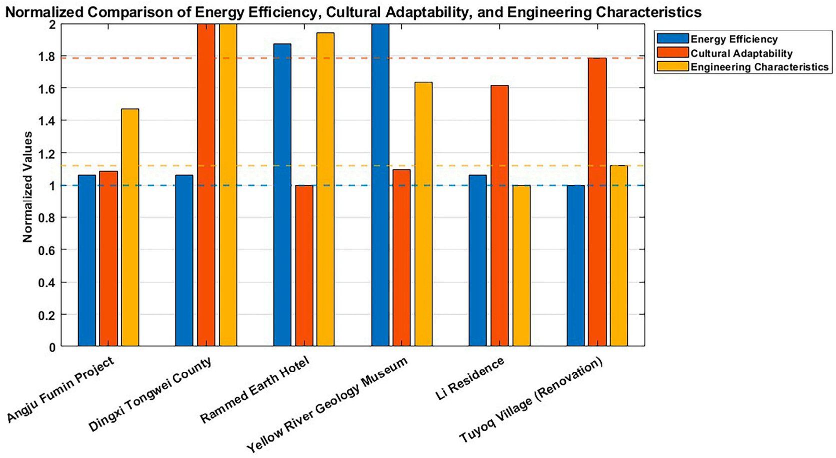

Figure 16. Comparison of competing schemes.

Regarding cultural adaptability, the Tuyugou Village project showed strong integration with local traditions, second only to the Tongwei County residential project, which had a 16% higher cultural adaptability score. On the other hand, the Anju Fumin Demonstration Project, the rammed-earth hotel, and the Yellow River Geology Museum demonstrated significantly lower cultural adaptability, with reductions ranging from 55% to 60%.

In terms of engineering features, the Tuyugou Village renovation had a unit cost of RMB 340.566/m^2, reflecting reasonable construction costs. The Anju Fumin Demonstration Project and Li's house had even lower costs, reduced by 32% and 11%, respectively. However, the Tongwei County residential project and the rammed-earth hotel experienced substantial cost increases, of 80% and 75%, respectively, due to the use of more expensive materials and more intricate designs.

In summary, the Tuyugou Village renovation project achieved a well-balanced combination of cost control, cultural adaptability, and energy efficiency, positioning it as a strong example of sustainable development. Future renovation efforts should continue to focus on harmonizing traditional values with modern efficiency to ensure long-term viability.

6. Conclusions

The optimization of traditional earthen dwellings in Tuyugou Village, Turpan, integrates engineering performance, cultural preservation, and energy efficiency. This study employs AHP (Analytic Hierarchy Process), QFD (Quality Function Deployment), and NSGA-II (Non-Dominated Sorting Genetic Algorithm II) to address the needs of residents, tourists, architects, and government officials. By balancing modern living standards with cultural heritage, it provides a data-driven strategy specifically tailored for arid regions.

Through AHP, the research identified key priorities such as thermal efficiency, structural integrity, cultural preservation, and economic feasibility. These priorities were transformed into actionable design features using QFD, which were then optimized using NSGA-II to find a balance between cost, cultural value, and energy performance. The VIKOR method further refined and ranked these solutions to facilitate objective decision making.

The sixth design was identified as the optimal choice, excelling in cost management, cultural integration, and energy performance. With an engineering cost of RMB 340.566 and a cultural adaptability score of 1.5364, it successfully blended traditional architectural elements with modern technology. Its energy efficiency, at RMB 352.793/kWh, contributed to sustainability and improved living conditions.

This research presents a framework for renovating traditional rural dwellings in arid environments, effectively balancing cultural preservation and modernization. It offers both theoretical guidance and practical solutions for developing sustainable housing in regions where cultural and environmental sensitivities are critical. However, the study has some limitations: its applicability is mainly confined to specific areas (such as Tuyugou Village), and the quantification of cultural value remains subjective. The complex optimization process may also be challenging to implement in communities with limited resources, and the energy efficiency metric may not be directly applicable to other contexts. Although the conclusions are well-supported by the results, discussing how this methodology could be adapted to different regions or types of buildings would enhance the practical relevance of the research. Future research could focus on broadening cultural impact assessment and simplifying the model to make it suitable for diverse environments and building types.

Author Contributions: W.G., the leading author, initially conceived and designed the research. He conducted software analysis and manuscript preparation under the guidance of the corresponding author. H.S., the corresponding author, developed the original ideas of this study and provided suggestions for overall analysis. J.S. proposed some constructive suggestions for the content of the article. M.Y. provided assistance for software analysis of papers. T.Z. provided assistance in collecting raw materials for the paper. All authors participated in the preparation of the paper and discussed the results. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. AHP questionnaire.

Needs	Weight Score																	Needs
	Importance Ranking								Equally Important	Importance Ranking								
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Thermal environmental Performance																		Structure and safety
Thermal environmental Performance																		Culture and aesthetics
Thermal environmental Performance																		Economy and comfort
Structure and safety																		Thermal environmental Performance
Structure and safety																		Culture and aesthetics
Structure and safety																		Economy and comfort
Culture and aesthetics																		Thermal environmental Performance
Culture and aesthetics																		Structure and safety
Culture and aesthetics																		Economy and comfort
Economy and comfort																		Thermal environmental Performance
Economy and comfort																		Structure and safety
Economy and comfort																		Culture and aesthetics

Table A2. Detailed list of quality characteristics.

Primary Objective	Quality Characteristic	Detailed Description
Engineering Features	Material Property	The characteristics of the material used, including strength, durability, environmental impact, and material sustainability. Examples include concrete, steel, earthen materials, or wood.
	Material Cost	The cost associated with the acquisition, transportation, and usage of materials such as concrete, steel, wood, or insulation materials.
	Structural Strengthening	Techniques and materials used for reinforcing structural stability, such as steel reinforcements, load-bearing walls, and advanced composites.
	Engineering Time	The total time required for construction, influenced by material availability, construction techniques, and complexity of design.
	Maintenance Difficulty	The level of difficulty and the materials required for maintaining the building over its lifecycle, including wood treatments or repairs to concrete or earthen structures.
Culture	Historical and Cultural Coordination	The use of traditional materials such as adobe, local stone, or wood that align with the historical and cultural heritage of the region.
	Historical Element	Specific architectural materials like wooden beams, mudbrick walls, or traditional earthen plaster that preserve historical significance.
Energy-Saving	Energy-Saving Effect	The efficiency with which materials (e.g., insulation, energy-efficient windows, solar panels) and design contribute to energy conservation.
	Energy System	The integration of operational equipment such as HVAC systems, solar power generation, and smart energy meters to optimize energy use.
	Comfort Level	The materials used for insulation (e.g., rock wool, low-E glass) and climate control systems (e.g., air conditioning units, natural ventilation) that provide indoor comfort.
	Functional Optimization	Materials and operational systems designed to maximize energy efficiency, such as passive design strategies, adaptive insulation, and energy-efficient appliances.

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