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# Grasshopper platform-assisted design optimization of fujian rural earthen buildings considering low-carbon emissions reduction

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**This work aims to explore optimization methods for the design of earthen buildings in rural Fujian to achieve low-carbon emissions and improve the structural stability of earthen buildings. First, parametric modeling and optimization algorithms are employed through the Grasshopper platform. An intelligent earthen building design is created by combining the optimization of factors such as the structure of earthen buildings, building materials, and orientation. Then, a comparison is made with the unoptimized, energy-efficient, and carbon emission reduction designs. Finally, the work concludes that the proposed design significantly optimizes the total carbon emissions, energy consumption, structural stability, and economic aspects. The proposed design scheme achieves the highest carbon emission reduction effect, with a reduction rate of 34.64%. The proposed design exhibits lower maximum stress and higher minimum safety factor in terms of structural stability compared to other scenarios, along with smaller structural displacement. It also performs well in terms of initial investment, annual operating costs, and construction period. The significance of this work lies in providing scientific guidance for the design and construction of rural earthen buildings, promoting the organic integration of rural development with low-carbon initiatives. This indicates that the use of intelligent optimization methods for earthen building design is feasible and can yield positive results in practice.**

**Keywords** Fujian rural earthen buildings, Optimization design, Low-carbon emission reduction, Structural stability, Grasshopper platform

Fujian rural earthen buildings, as traditional Chinese architectural culture treasures, carry rich historical and cultural heritage, and exhibit a unique architectural style. These ancient earthen buildings are scattered in the mountainous regions of northwest Fujian province, representing a significant aspect of the drum tower culture of ethnic minorities and playing a crucial role in the development of rural Fujian[1]. However, with the acceleration of modernization and the influence of urbanization trends, Fujian's rural earthen buildings are facing serious environmental challenges[2]. The geographical environment surrounding the earthen buildings is deteriorating, and natural disasters such as typhoons and landslides pose threats to their stability and safety[2]. Additionally, the outflow of population and the exacerbation of the aging phenomenon in rural areas have led to a decrease in population and the abandonment of villages, posing severe challenges to earthen buildings' preservation and inheritance[3]. Furthermore, the traditional building materials and construction techniques used in earthen buildings have certain limitations, hindering energy conservation, emission reduction, and environmental protection, conflicting with the modern societal demands for sustainable development[4]. Specifically, this work addresses the following scientific questions: How to utilize the Grasshopper platform for parametric modeling and optimized design of Fujian rural earthen buildings? How to effectively achieve carbon emission reduction in earthen building design? How can optimized design solutions enhance the structural stability and environmental adaptability of earthen buildings while preserving traditional architectural culture?

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Therefore, the pressing issue is how to achieve sustainable development of earthen buildings while preserving traditional culture[5]. In this context, this work aims to explore the use of modern technological methods, particularly employing parametric modeling and optimization techniques with the Grasshopper platform, to optimize the design of Fujian rural earthen buildings. Environmental factors such as low-carbon emission reduction are considered to promote the protection and sustainable development of earthen buildings. This work is expected to provide new ideas and methods for preserving and developing Fujian rural earthen buildings, serving as a reference for the protection and sustainable development of traditional buildings in other regions.

The methodology section of this work elaborates on data collection, model establishment, and optimization algorithms. In the results analysis section, a comparison and analysis of low-carbon emission reduction earthen building design schemes assisted by the Grasshopper platform is conducted. Finally, the conclusion section summarizes the main findings of this work. This work introduces the Grasshopper platform into the design of Fujian rural earthen buildings, leveraging its powerful capabilities in parametric modeling and optimization to achieve intelligent design optimization of earthen buildings. It employs multi-objective optimization algorithms and establishes a carbon emission model that comprehensively considers the characteristics of earthen buildings, offering new methods and solutions for carbon emission reduction in earthen building design. This work is expected to provide new ideas and methods for the conservation and development of Fujian rural earthen buildings, and serve as a reference for the sustainable development of other traditional buildings. The research innovation lies in its new approaches and methods for the conservation and development of Fujian rural earthen buildings, which can be a valuable reference for the conservation and sustainable development of traditional buildings in other regions as well.

## Literature review

Low-carbon architectural design is currently one of the research hotspots in the global construction industry. Worldwide scholars have conducted extensive research using various methods to explore effective ways to reduce carbon emissions in buildings[6]. Using a life cycle assessment method, Zhang et al.[7] analyzed the impact of different building structures on carbon emissions and found that wooden structures had significant advantages in carbon reduction. Sui et al.[8] also proposed a low-carbon architectural design scheme centered around plant walls using ecological design concepts. They validated its effectiveness in reducing energy consumption and carbon emissions through simulation experiments. Afolabi & Farzaneh[9], employing an ecological approach, studied the impact of the production process of building materials on carbon emissions. They proposed a model for optimizing the selection of building materials to reduce the carbon footprint of buildings. Furthermore, through case studies, Schweiker et al.[10] analyzed building projects using renewable energy and efficient energy-saving technologies, finding significant achievements in reducing carbon emissions and energy conservation.

The application of the Grasshopper platform in architectural design has attracted considerable attention. Many researchers have achieved intelligent and efficient architectural design processes by combining Grasshopper's parametric modeling and optimization functions[11]. Especially in the context of low-carbon emission reduction, the Grasshopper platform plays a crucial role[12]. Previous studies have shown that combining the Grasshopper platform with ecological design principles can optimize building structures, reduce energy consumption, and lower carbon emissions[13]. Tan et al.[14], using the Grasshopper platform and environmental performance data of building materials, optimized the design of building structures, resulting in reduced energy consumption and carbon emissions. Elkadeem et al.[15], utilizing Grasshoppe's parametric modeling technology, achieved energy-saving and emission reduction goals through the optimized design of building facades. Xu & Genovese[16] optimized building spatial layouts using Grasshopper's optimization algorithms, minimizing carbon emissions to the greatest extent.

In recent years, low-carbon economy and sustainable development have become hot topics, with numerous scholars exploring various issues from different perspectives. Wang et al.[17] utilized a data platform management to implement the "5W" analysis framework, using the example of preventing grassroots government corruption to demonstrate the application of data management in public governance. In the field of online public opinion risk prediction and credibility detection, Wang et al.[18] developed a new method using blockchain technology, enhancing the efficiency and accuracy of public opinion management. In terms of economic resilience and policy interaction, Deng et al.[19] evaluated the economic resilience of coal resource-based cities in the low-carbon economy using artificial intelligence and proposed relevant policy recommendations. Li et al.[20] conducted quasi-natural experiments to study the relationship among low-carbon strategies, entrepreneurial activities, and changes in industrial structure. They found that low-carbon strategies could promote the optimization of industrial structure. Regarding the development path of clean energy, Li et al.[21] discussed the sustainable development path of clean energy in mining projects and the ecological environment under the drive of big data, emphasizing the promoting role of technological innovation in environmental protection. Li et al.[22] systematically analyzed the relationship between intellectual property pledge financing and enterprise innovation, highlighting that intellectual property financing could significantly promote enterprise innovation. Additionally, Li et al.[23] studied the impact of climate change on corporate ESG performance, revealing the critical role of improper resource allocation in corporate responses to climate change. Finally, Yu et al.[24] re-examined the Porter Hypothesis using a difference-in-difference-in-differences strategy. The impact of low-carbon pilot policies on low-carbon technology innovation further supported the incentivizing effect of policies on technological innovation.

Past research has focused on the field of low-carbon architectural design, exploring ways to reduce building carbon emissions through life cycle assessments, ecological design concepts, and renewable energy and energy-saving technologies. However, these methods have certain limitations in practice, such as not fully considering the impact of building structure optimization and spatial layout on carbon emissions. Meanwhile, the emergence of the Grasshopper platform has brought new ideas and methods to architectural design, achieving intelligent and efficient design processes through parametric modeling and optimization functions. This work aims to integrate the Grasshopper platform, utilizing its powerful capabilities, especially in the context of low-carbon emission reduction, to provide new solutions for the optimization of design for Fujian rural earthen buildings.

## Optimization methods for the design of Fujian rural earthen buildings

### Data collection

This work employs multiple approaches for data collection to support the optimization of design for Fujian rural earthen buildings. First, basic information about Fujian rural earthen buildings, including architectural structure, materials, and historical and cultural backgrounds, is gathered through on-site investigations and literature reviews. Moreover, environmental impact factors and data related to low-carbon emission reduction involved in the earthen building design process are collected through on-site measurements, literature reviews, and database queries. These data encompass environmental performance data of earthen building materials, energy consumption patterns, carbon emission levels, and other relevant aspects.

Table 1 provides specific details regarding the collected data.

### Establishment of earthen building design model

Initially, parametric modeling is conducted using the Grasshopper platform to abstract various design parameters of the earthen building into variables and establish the corresponding parameter model. These design parameters encompass the earthen building's structural form, building materials, dimensions, and orientation[25]. The design parameters of the earthen building are represented as $x = (x_1, x_2, \ldots, x_n)$, where $x_i$ denotes the $i$-th parameter. Specifically, considering the structural form of the earthen building, which includes different forms such as circular, square, and polygonal. Each form affects aspects such as stability, use of building materials, and energy consumption. Therefore, the structural form is considered as one of the design parameters, denoted as $x_1$. Building materials are a crucial factor influencing earthen building design. Traditional materials (such as adobe, wood, bamboo) or modern materials (such as reinforced concrete, and bricks) can be utilized in earthen building construction[26]. Different materials possess varying environmental impacts and carbon emissions, making building materials another design parameter denoted as $x_2$. The building dimensions, including height, width, and length, are significant factors influencing the design. These dimensions impact the earthen building's functional use, structural stability, and energy consumption. Hence, building dimensions are considered as design parameters denoted as $x_3$. Orientation is a vital factor influencing lighting, ventilation, and energy utilization in earthen buildings. Different orientations affect energy consumption and indoor comfort[27], making orientation another design parameter denoted as $x_4$.

In the model, an objective function $f(x)$ is defined to measure the goodness or badness of the earthen building design solution. The objective function aims to optimize the earthen building design, considering factors such as structural stability, energy efficiency, and carbon emissions[28]. Specifically, the objective function can be defined as Eq. (1):

$$f(x) = w_1 \cdot f_1(x) + w_2 \cdot f_2(x) + \cdots + w_m \cdot f_m(x). \tag{1}$$

$f_i(x)$ represents the function for the i-th optimization objective, and $w_i$ denotes the corresponding objective's weight. x is the parameter vector for earthen building design, including design parameters such as structural form, building materials, building dimensions, and orientation.

Several aspects are considered when specifying the objective functions for the earthen building design. First, for the objective of structural stability, the stability of the earthen building structure is assessed using structural analysis methods such as finite element analysis to minimize deformation and inadequate load-bearing capacity. The objective function in finite element analysis is as follows[29]:

$$f_1(x) = \frac{1}{V} \int_V \sigma(x) dV, \tag{2}$$

$V$ represents the volume of the earthen building. $\sigma(x)$ represents the distribution of internal stresses within the earthen building, and it is a function of the design parameters $x$.

Next, for the energy efficiency objective, the consideration is given to the energy efficiency of the earthen building, including minimizing energy consumption and maximizing thermal comfort. Building energy simulation software (EnergyPlus) is utilized to simulate the energy consumption of the earthen building, along with the proportion of renewable energy used[30].

Lastly, for the carbon emissions objective, the consideration is given to the carbon emissions of the earthen building, treating carbon emissions as part of the objective function to minimize the carbon footprint of the

| Data type | Data source | Data content |
|---|---|---|
| Basic information about earthen buildings | On-site investigation, literature information | Earthen building name, architectural structure, materials |
| Environmental impact factors | On-site measurement, literature review | Environmental performance of building materials, energy consumption patterns, carbon emission levels |
| Grasshopper Platform Data | Literature information, online resources | Application cases, optimization algorithm principles, parameter settings |

**Table 1.** Specific content of collected data.

earthen building[31]. The carbon emissions are calculated based on the building materials and energy consumption of the earthen building. This work employs a life cycle assessment-based method for carbon emissions calculation, and the equation is as follows[32]:

$$Q = \sum_{i=1}^{n} (E_i \times CF_i). \tag{3}$$

$E_i$ represents the quantity of the $i$-th material or energy used, and $CF_i$ represents the carbon emission coefficient of the $i$-th material or energy.

In addition to optimization objectives, the model also takes into account some constraints on the design of the earthen building, including structural stability, building functional requirements, and material feasibility. Specifically, for the constraint of force balance, according to the principles of mechanics, the components of the earthen building structure need to satisfy the conditions of force balance when subjected to various loads. Each component of the earthen building structure needs to meet certain load-bearing capacity requirements to ensure that the earthen building does not undergo structural failure during use[33]. The design of the earthen building needs to fully consider its functional requirements to meet the practical needs of users. The feasibility of the building materials used in the earthen building needs to consider factors such as material supply, cost, and construction technology.

These constraints can be expressed as a set of equality and inequality constraints, as shown in Eq. (4)

$$g_j(x) \leq 0, j = 1,2,\ldots,p. \tag{4}$$

$g_j(x)$ represents the function for the j-th constraint.

## Optimization algorithm

In order to achieve intelligent optimization of earthen building design, considering the complexity and diversity in the design process, this work adopts an innovative optimization algorithm based on the principles of natural evolution, namely the "Natural Evolutionary Optimization Algorithm" (NEOA). The NEOA algorithm is an optimization algorithm based on the principles of natural evolution, simulating the evolutionary process in nature, including operations such as selection, crossover, and mutation. Its basic idea is to gradually find the optimal solution through continuous evolution and survival of the fittest. Figure 1 illustrates the characteristics of the NEOA algorithm[34].

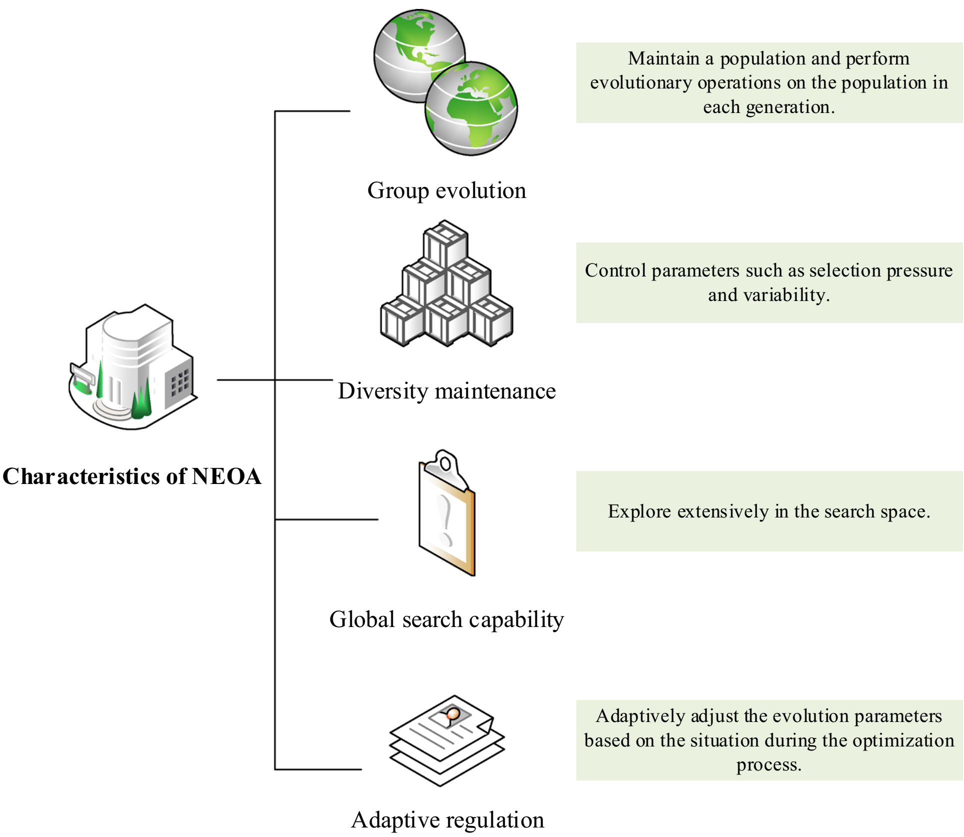


**Figure 1.** Characteristics of the NEOA algorithm.

In Fig. 1, the NEOA exhibits distinctive features. Population evolution: The NEOA algorithm optimizes through population evolution, maintaining a population and performing evolution operations in each generation, such as selection, crossover, and mutation, to gradually improve the quality of solutions. Diversity maintenance: The NEOA algorithm emphasizes maintaining diversity in the population during the evolution process. It preserves the population's diversity, preventing it from getting stuck in local optimal solutions by controlling parameters such as selection pressure and mutation rate. Global search capability: The NEOA algorithm possesses strong global search capabilities, enabling extensive exploration in the search space to discover potential optimal solutions. Adaptive adjustment: The NEOA algorithm can adaptively adjust evolution parameters, such as selection pressure, crossover probability, and mutation rate, based on the optimization process. This adaptive tuning enhances the algorithm's search efficiency and convergence speed.

The NEOA algorithm, based on the definition of the objective function and constraints, iteratively adjusts the design parameters of the earthen building through the optimization process to minimize the value of the objective function while satisfying the constraints. Figure 2 illustrates the specific steps[35].

Based on the content of Fig. 2, the optimization algorithm proceeds as follows:

First, it randomly generates an initial population, and assigns appropriate initial values within the range of values for the earthen building design parameters.

Subsequently, each individual's fitness is calculated, representing the value of the objective function. This step is pivotal in the optimization process, as the evaluation of individual fitness determines their relative quality, facilitating subsequent selection operations. Population initialization is illustrated by Eq. (5)[36]:

$$x_{ij}^{(0)} = \text{rand}\left(x_{min,j}, x_{max,j}\right), j = 1,2,\ldots,n;\ i = 1,2,\ldots,N \tag{5}$$

In this context, $x_{ij}^{(0)}$ represents the initial value of the j-th design parameter for the $i$-th individual, while $x_{min,j}$ and $x_{max,j}$ respectively denote the lower and upper limits of the $j$-th design parameter's range. $N$ represents the population size, and $n$ represents the number of design parameters.

Subsequently, based on individual fitness, a portion of individuals is selected as the next-generation population's parents using a roulette wheel selection method. The mathematical expression for the roulette wheel selection is defined as Eq. (6)[37]:

$$P(x_i) = \frac{\text{fitness}\ (x_i)}{\sum_{i=1}^{N} \text{fitness}\ (x_i)}. \tag{6}$$

$P(x_i)$ represents the probability of selecting the $i$-th individual.

Following the selection operation, crossover and mutation operations are applied to the selected parent individuals to generate new individuals. This step aims to increase the diversity of the population and introduce new combinations of genes for a more extensive exploration of the search space. The equations for crossover and mutation are represented by Eqs. (7) and (8)[38]:

$$\text{Crossover}\left(x_i, x_j\right) = \begin{cases} x_i' = x_i + \alpha\left(x_j - x_i\right) \\ x_j' = x_j - \alpha\left(x_j - x_i\right) \end{cases}, \tag{7}$$

$$\text{Mutation}(x_i) = x_i\prime = x_i + \beta \times \text{rand}(-1,1). \tag{8}$$

Here, $\text{Crossover}\left(x_i, x_j\right)$ represents the new individual generated by the crossover operation, and $\text{Mutation}(x_i)$ represents the new individual generated by the mutation operation. $\beta$ denotes the mutation rate, and $\alpha$ denotes the crossover rate.

Finally, the newly generated individuals are combined with the original population and sorted based on fitness, and individuals with higher fitness are selected as the next generation population. The update population process is outlined in Eqs. (9) and (10)

$$\text{Population}_{\text{ new}} = \text{Population}_{\text{ old}} \cup \text{Offspring}, \tag{9}$$

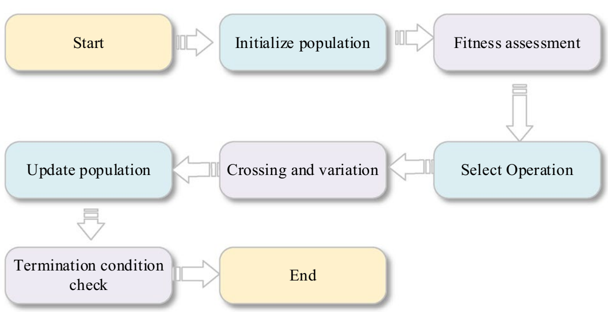


**Figure 2.** Steps of optimization algorithmy.

$$\text{Population}_{\text{new}} = \text{Select}\left(\text{Population}_{\text{new}}, N\right). \tag{10}$$

Population $_{old}$ represents the original population, Offspring denotes the collection of new individuals generated through crossover and mutation, and Select represents the operation of selecting individuals based on fitness.

The aforementioned steps are repeated until the termination conditions are met, such as reaching the maximum number of iterations or the objective function converging to a predefined threshold.

The variables set are as follows:

Energy-saving design variables:

Insulation material thickness (cm): Affects the thermal conductivity of the building.

Window type and area ($m^2$): Influences natural lighting and ventilation.

Solar panel installation area ($m^2$): Impacts the efficiency of solar energy utilization.

Carbon emission reduction variables:

Carbon emission coefficient of building materials (kg $CO_2/m^3$): Selects low-carbon emission materials.

Carbon emissions from construction processes (kg $CO_2$/operation): Optimizes construction processes to reduce carbon emissions.

Energy usage (kWh/year): Adopts renewable energy sources to lower carbon emissions.

## Optimization results analysis for Fujian rural earth building

### Comparison of low carbon emission

In the assessment of the design proposals in this study, comparative scenarios encompass the unoptimized design, energy-efficient design, and carbon emission reduction design. The comparison of design scenarios is conducted within the architectural information modeling software. Figure 3 reveals the comparison of total carbon emissions and energy consumption. To comprehensively evaluate the optimized design effectiveness of Fujian rural earthen buildings, this work establishes various design scenario models, including the non-optimized design model, energy-saving design model, and carbon reduction model. The non-optimized design model is based on traditional earthen building design methods, using conventional building materials and techniques without considering modern energy-saving and carbon-reduction technologies. The energy-saving design model applies energy-saving technologies based on traditional design, such as efficient insulation materials, natural ventilation design, and solar energy utilization, to reduce energy consumption. The carbon reduction model introduces carbon emission calculations, optimizing building material selection and construction techniques to minimize carbon footprint, meeting the requirements of low-carbon development.

First, the comparison of total carbon emission reduction rates among the three design schemes shows that the proposed design achieves the highest carbon emission reduction effect, with a reduction rate of 34.64%. The carbon reduction design scheme follows with a reduction rate of 29.11%, while the energy efficiency design scheme has the lowest total carbon emission reduction rate at 20.09%. Besides, in terms of energy consumption reduction rates, the proposed design scheme also performs remarkably well, achieving a reduction rate of 24.50%, which is higher than the 18.45% for the carbon reduction design scheme and 12.92% for the energy efficiency design scheme. Therefore, considering both carbon emissions and energy consumption reduction metrics, the proposed design scheme performs best in optimizing Fujian rural earthen buildings, demonstrating higher environmental friendliness and sustainability.

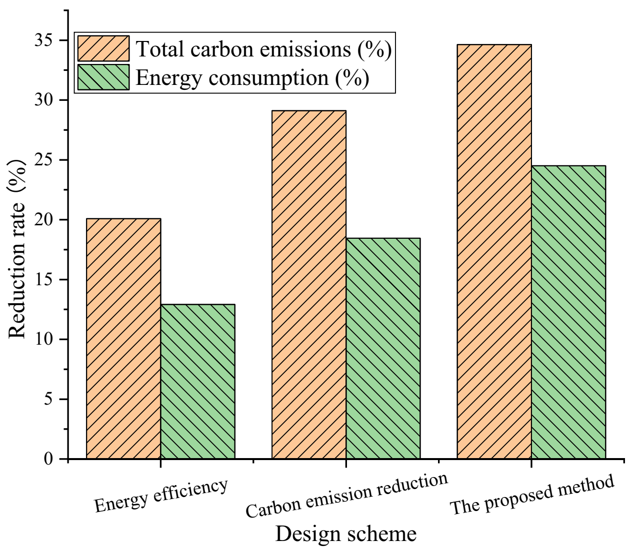


**Figure 3.** Comparison of carbon emissions and energy consumption results.

## Structural stability analysis

Figure 4 shows the results of comparing the structural stability of different schemes using the same building information modeling software.

The information in Fig. 4 demonstrates that the optimized design solution exhibits superior performance in terms of structural stability. It shows lower maximum stress, higher minimum safety factor, and smaller structural displacement than other scenarios. This indicates that through the optimization methods proposed, the structural stress and deformation of the earthen building have been successfully reduced without compromising its stability. In contrast, the structural stability of the unoptimized design is poorer, with higher structural stress and displacement, and lower safety factor, making it more prone to structural instability. During the optimization of energy efficiency and carbon reduction, changes such as using new materials or altering traditional structures may impact the stability of the earthen buildings. Specific reasons include: Mechanical properties of new materials: Some energy-efficient materials may be lighter than traditional materials but may have insufficient strength, affecting the overall structural stability. Changes in construction techniques: Adopting new construction techniques may lead to uneven stress distribution in the structure, thereby reducing stability.

In the optimized models, conflicts indeed arise. For instance, there is a clear trade-off between structural stability and initial investment costs. Increasing structural stability: Using higher-strength materials and more complex construction techniques increases initial investment costs. Controlling initial investment costs: Opting for lower-cost materials and simpler construction methods may compromise structural stability.

## Economic evaluation comparison

Figure 5 shows the comparative economic evaluation results of different schemes. The setting of initial investment costs and operational costs is based on the following: a. Initial Investment Costs: building material costs: Based on market prices and project budget. Construction costs: including labor costs, equipment rental fees, and other construction-related expenses, referring to local construction cost standards. Design costs: including engineering design and optimization design costs. b. Operational costs: energy costs: based on local electricity and energy prices, considering estimated energy consumption after implementing energy-saving measures. Maintenance costs: Including regular maintenance and repair costs, based on traditional earthen building maintenance costs and modern material maintenance requirements. Other operating expenses: Such as management fees and miscellaneous expenses, set based on actual operational experience and budgeting.

Figure 5 demonstrates that in terms of economic evaluation, the proposed design performs well in terms of initial investment and annual operating costs. Although the initial investment is slightly higher than the unoptimized design scheme, the significant reduction in annual operating costs results in total economic costs being on par with or slightly lower than the unoptimized design. This is mainly due to the proposed design's optimization of carbon emission reduction and energy efficiency. By adopting more environmentally friendly and energy-efficient design strategies, the operating costs of the earthen building are reduced, enhancing its economic viability.

Table 2 displays a construction period comparison of different scenarios.

Table 2 shows that the proposed design scheme performs optimally in terms of the construction period, lasting only 15 months. This is a significant reduction compared to other design scenarios, saving 3 months (unoptimized design), 1 month (energy-efficient design), and 2 months (carbon emission reduction design), respectively. This may be attributed to the optimization of the structural, material, and orientation aspects in the proposed design, incorporating more efficient construction techniques and processes, thereby shortening the construction period.

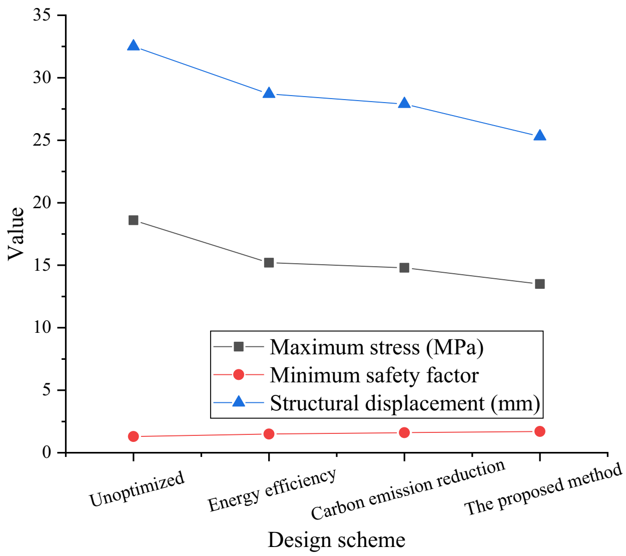


**Figure 4.** Comparison results of structural stability.

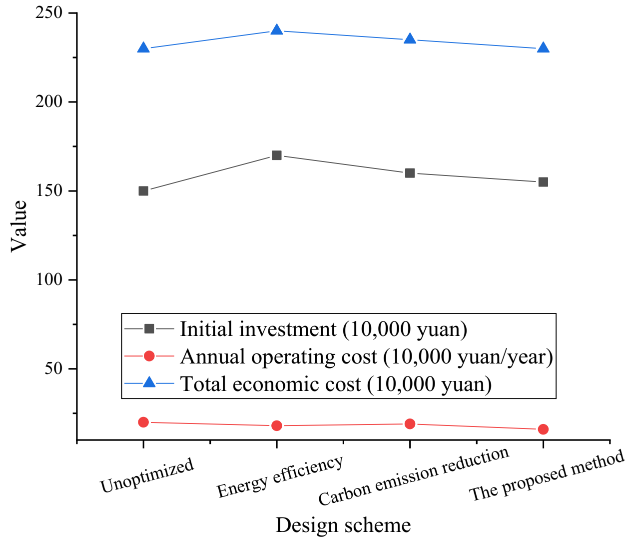


**Figure 5.** Comparison of economic evaluation results.

| Design scenarios | Construction period (month) |
|---|---|
| Unoptimized design | 18 |
| Energy-efficient design | 16 |
| Carbon emission reduction design | 17 |
| The design proposed here | 15 |

**Table 2.** Construction period comparison.

Since this work employs a multi-objective optimization method, the optimization results form a set of Pareto front solutions. These solutions represent the optimal trade-offs between different objectives. In order to select the final optimized scheme, the following criteria and methods are adopted: a. Selection criteria: structural stability: choose solutions with higher structural stability to ensure the safety of the earthen building under various environmental conditions. Initial investment cost: select solutions within the budget to control the project's initial investment cost. Energy efficiency: opt for solutions with significant energy-saving effects to reduce operational costs and carbon emissions. b. Selection methods: weighted scoring method: assign weights to each Pareto solution based on the above criteria and calculate an overall score. The weight distribution is based on expert opinions and actual needs. Decision matrix analysis: construct a decision matrix to quantitatively analyze each solution's indicators and select the solution with the highest score.

## Conclusion

This work, utilizing the Grasshopper platform for parametric modeling and optimization algorithms, coupled with the optimization of factors such as structure, building materials, and orientation, has developed an intelligent design scheme for earthen buildings. The results indicate a significant optimization in total carbon emissions, energy consumption, structural stability, and economics compared to unoptimized and other design schemes. This indicates that employing intelligent optimization methods can achieve excellent results in practice. The significance of this work lies in providing scientific guidance for the design and construction of rural earthen buildings, promoting the organic integration of rural development with low-carbon initiatives. However, limitations such as limited data collection and a lack of extensive practical applications exist. Future research directions could include further refining the parameter settings and variable selection of the optimization model to enhance its accuracy and applicability. For instance, considering more environmental factors and actual construction conditions can improve the model's adaptability to real-world scenarios. Expanding the application range of optimization algorithms, strengthening field research and case validation, exploring more low-carbon building materials and technologies, and incorporating socio-economic factors for comprehensive optimization are also promising areas for future exploration.

## Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Conceptualization, J.P., Y.Y.; methodology, X.F., Y.D.; software, Y.H.; validation, Y.D.; formal analysis, Y.Y.; investigation, J.P.; resources, L.H.; data curation, X.F., Y.H.; writing—original draft preparation, X.F., Y.H., Y.D.; writing—review and editing, J.P., Y.Y.; visualization, X.F.; supervision, Y.H.; project administration, Y.Y. All authors have read and agreed to the submitted version of the manuscript.

## Competing interests

The authors declare no competing interests.

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