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BIM AND ORTHOGONAL TEST METHODS TO OPTIMIZE THE ENERGY CONSUMPTION OF GREEN BUILDINGS

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Abstract. The construction industry's rapid growth significantly impacts energy consumption and environmental health. It is crucial to develop optimization strategies to enhance green building energy efficiency and encompass comprehensive analysis methods. This study aims to introduce and validate a novel framework for optimizing energy efficiency design in green buildings by integrating Building Information Modeling (BIM) technology, Life Cycle Cost (LCC) analysis, and orthogonal testing methods, focusing on enhancing energy efficiency and reducing life cycle costs. The optimization parameters for the building envelope are identified by analyzing energy consumption components and key green building factors. The orthogonal testing method was applied to streamline design options. Building Energy Consumption Simulation (BECS) software and LCC analysis tools were employed to calculate each optimized option's total annual energy consumption and the current life cycle costs. Using the efficiency coefficient method, each optimization scheme's energy consumption and economic indicators were thoroughly analyzed. The framework's validity and applicability were confirmed through an empirical analysis of a campus green building case in Fujian Province, demonstrating that the optimized framework could reduce energy consumption by 4.85 kWh/m^2 per year and lower costs by 38.89 Yuan/m^2 compared to the reference building. The case study highlights the framework's significant benefits in enhancing environmental performance and economic gains. The results provide critical parameter selection and offer scientific and technological support for the design of building energy efficiency, promoting optimization techniques and sustainable development within the construction industry.

Keywords: green building, BIM (building information model), economic optimization, energy consumption, energy-saving technology, energy-efficient design.

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Abbreviations

BIM – Building Information Modeling;
BECS – Building Energy Consumption Simulation;
LCC – Life Cycle Cost;
LCCA – Life Cycle Cost Analysis;
LCC_{PV} – Present Value of Life Cycle Cost;
HVAC – Heating, Ventilation, and Air Conditioning;
XPS – Extruded polystyrene foam board;
EPS – Expanded polystyrene board;
Low-E – Low emissivity glass.

1. Introduction

During rapid urbanization and industrialization, the construction industry has experienced significant expansion, catalyzing growth in domestic consumption, infrastructure development, and employment (Ma et al., 2023). Despite its contributions, the industry remains a considerable energy consumer plagued by persistent challenges, including excessive resource utilization, high carbon emissions, and severe pollution (Dräger & Letmathe, 2022; Liu et al., 2019). Building construction and operational phases cumulatively account for 35% of the world's energy use and contribute 38% of global greenhouse gas emissions (Yildirim & Polat, 2023). As developing countries continue to experience economic expansion, these figures are expected to increase (Zhang et al., 2018).

Some studies have approached building energy consumption from a life-cycle perspective, revealing that construction-phase energy use constitutes merely 20% of a building's total life-cycle energy consumption. In comparison, the operational phase accounts for a staggering 70–80% (Huo et al., 2019; Wang et al., 2018). The substantial resource consumption by buildings underscores the significant potential for energy conservation (Baldini et al., 2020; Franco et al., 2023; Kiss & Szalay, 2020). Recent research has investigated various approaches to energy conservation in buildings, encompassing design methodologies, construction techniques, materials, and overall energy usage (Al-Sakkaf et al., 2020; Li et al., 2021a).

Concurrently, the advent of green buildings (Ding et al., 2018), low-energy buildings (Norouzi et al., 2022), and zero-energy buildings (Mora et al., 2018) reflects a trend toward optimizing energy efficiency at different developmental stages of buildings (Ismail, 2021; Javed et al., 2019). Researchers have devised numerous computational methods to assess building energy consumption (Seyedzadeh et al., 2020a), predominantly analyzing the entire life cycle with a focus on the construction stage (Jang et al., 2021). Given that energy consumption optimization can markedly influence cost-effectiveness, an impetus exists to pursue energy-efficient technologies that concurrently serve environmental and economic objectives (Chang et al., 2018; Sanchez & Haas, 2018; Seyedzadeh et al., 2020b).

Building Information Modeling (BIM) technology facilitates enhanced energy analysis and prediction by engineers in the design phase by providing precise building models and datasets. Ratajczak et al. (2023) leveraged BIM to comprehensively assess daylighting and energy consumption, contributing to the fruition of green building designs. When integrated with BIM, building projects exhibit elevated energy management efficiency and superior environmental performance over their entire life cycle (Xu et al., 2021). In the realm of specific architectural typologies, BIM has been pivotal. Yao et al. (2022) introduced a BIM-centric co-design approach for zero-energy buildings, orchestrating various specialty domains to fulfill sustainable building development objectives. BIM's significance extends to green building evaluations and the mitigation of carbon emissions (Li et al., 2021c; Yevu et al., 2023). BIM's precise quantification and examination of energy and carbon emissions during construction and operational stages buttresses the enactment of strategies for low-carbon buildings (Hao et al., 2020; Li et al., 2023). Recent inquiries have also delved into BIM's synergy with ancillary technologies, such as remote sensing and energy analysis software, amplifying the sustainable footprint of building ventures (Sadeghifam et al., 2019; Yu, 2023). Forthcoming studies are poised to broaden BIM's role as an informational nexus across diverse research methodologies.

Within green building energy efficiency enhancement, the orthogonal design of experiments methodology stands out for its substantial advantages in multi-objective optimization. Its versatility has been demonstrated across various domains to refine design and performance. For instance, an application in optimizing a magnetic fluid reciprocating seal structure through a case study substantiates the methodology's efficacy in augmenting the structure's pressure tolerance (Yang et al., 2021), thereby showcasing its strategic utility in addressing intricate engineering challenges. The method's efficacy in material property optimization is further evidenced by its successful application to the mechanical and thermal property enhancement of modified asphalt and recycled insulating concrete, highlighting its pivotal role in property augmentation within multivariate systems (Chen et al., 2022a; Deng et al., 2023). Moreover, integrating orthogonal testing with the EWM-TOPSIS decision-making framework in green building design elevates design objectivity and efficacy and ensures environmental and economic sustainability (Chen & An, 2024). This approach significantly contributes to achieving an optimal equilibrium among energy consumption, ventilation, and daylighting in building design, providing a systematic analytical tool for energy efficiency optimization in green buildings (Li et al., 2022). Additionally, the utility of this methodology is further corroborated through a case study on a nearly zero-energy building (nZEB) retrofit strategy developed via orthogonal array testing, underscoring its impact on improving building energy performance (Wang & Zhang, 2022).

Green building energy optimization strategies have gradually become diverse and highly integrated in recent years. These strategies include high-efficiency systems to optimize energy use in the operation phase (Li et al., 2021b) and involve efficient passive design techniques in the early phase (Liu et al., 2024). Existing energy-efficient design optimization strategies focus on combining BIM technology and energy analysis software, such as DesignBuilder, for office buildings (Rached & Anber, 2022). BIM combined with the DeST software algorithm compares the difference in energy consumption index between building materials (Xie & Tu, 2021). In addition, some linear regression models have been developed for building energy efficiency optimization designs (Tahmasebinia et al., 2022). Although existing research has promoted building energy efficiency design through various guiding design indicators, the traditional energy efficiency design model is still dominated by building issues and supplemented by other issues (Li et al., 2021a; Seyedzadeh et al., 2020a), which may weaken the environmental performance of buildings (Chang et al., 2018). With the rise of green buildings, more research on optimization strategies has begun to focus on incorporating sustainability into the project's pre-project phase (Arenas & Shafique, 2023) to improve building energy efficiency standards (Seyedzadeh et al., 2020b).

In summary, existing BIM combined with energy simulation tools mainly uses BIM's powerful data processing capability to optimize energy efficiency in a single dimension (Zhao et al., 2021). Few have combined BIM with orthogonal testing methods to optimize the energy consumption of green buildings in Fujian's hot summer and warm winter climates. Some optimization tools, such as the combination of linear regression models and BIM technology, still have limitations in their optimization effects (Tahmasebinia et al., 2023). In-depth analysis of the sustainability attributes embodied in the evaluation indicators and a comprehensive understanding of the economic costs are still limited. Current research on energy-efficient design techniques in engineering cases also shows gaps in understanding decision-making mechanisms (Illankoon et al., 2019). This study addresses these deficiencies by introducing a novel framework that synergizes these methodologies to enhance environmental and economic outcomes in green buildings. The contributions of this paper are threefold: firstly, it presents a validated model that merges BIM with energy optimization techniques; secondly, it offers empirical insights from a Fujian case study, elucidating both practical benefits and challenges; and thirdly, it enriches our understanding of how building envelope optimization impacts life-cycle energy consumption and costs.

BIM technology has demonstrated its capacity to bolster energy efficiency and advance environmental sustainability, outpacing traditional methods (Gerbino et al., 2021; Rahimian et al., 2020; Theißen et al., 2020; Wang & Tang, 2021; Yuan & Fan 2018). Integrating Building Energy Consumption Simulation (BECS) software via the Industry Foundation Classes (IFC) data standard facilitates building energy consumption simulations, thereby enhancing the digitization, precision, and efficiency of assessment results. This study expands on the existing methodology by incorporating orthogonal testing methods to generate various optimization scenarios, enhancing design efficiency and improving energy performance. The efficiency coefficient method assists decision-makers in identifying the most effective energy-saving measures and energy efficiency optimization through precise quantification. Moreover, Life Cycle Cost Analysis assesses the total cost of a building from construction to demolition, fostering economically sustainable practices for building projects. The integrated optimization framework employed by this study not only refines energy consumption metrics but also accounts for the economic benefits throughout the building's life cycle, thus augmenting decision support capabilities for complex energy optimization scenarios (Gerbino et al., 2021; Theißen et al., 2020; Zhu et al., 2022). The primary challenge of this research is to amalgamate various tools and methods into a cohesive framework that meticulously addresses building parameters and considers long-term economic and sustainable development goals. This study used the term "optimization" in a relative sense to indicate the application of objective quantitative methods to find a better solution to energy consumption in green buildings. Creating this work platform could help formulate practical energy-saving measures and promote the sustainable development of cities.

The research framework is depicted in Figure 1. Firstly, this study identifies an optimized solution integrating BIM technology with energy-saving design based on the con-

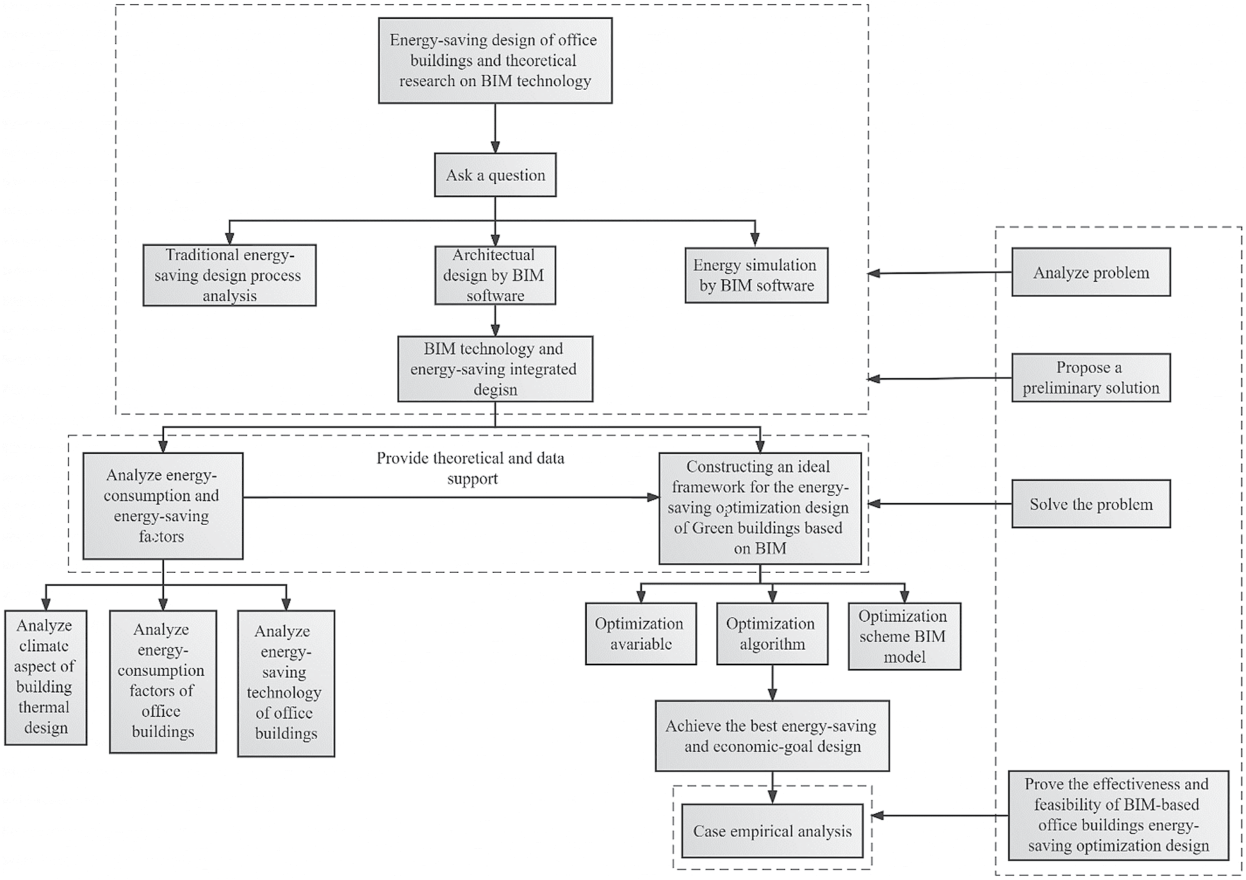


Figure 1. A flow chart showing the research framework and the procedures adopted in implementing the study

ventional energy-saving design process and the application of BIM technology. Secondly, related literature clarifies energy consumption factors and key energy-saving design parameters, constructing a green building energy-saving design optimization framework combining orthogonal test, BIM, BECS, and efficacy coefficient methods. Finally, the study selects a green building case in Fujian Province, China, for empirical analysis, energy consumption simulation and life-cycle cost calculation to determine the optimal energy-saving design solution for the project. The case demonstrates the effectiveness and applicability of the developed green building energy-saving optimization design framework. The findings could provide theoretical support for developing and applying the economic optimization method. The industry can use our method to assess project energy consumption and life-cycle costs at the initial planning stage.

2. Methods

2.1. Parameters to optimize green-building energy efficiency

The climatic environment, shape coefficient and building envelope performance can affect the energy-consumption simulation. It is necessary to analyze and judge the drivers of building energy consumption and select appropriate parameters to optimize the energy-saving design. Understanding the main factors can improve and expedite design-parameter selection.

2.1.1. Climatic aspect of building thermal design

This section emphasizes the importance of climate, including temperature, solar radiation, precipitation, and wind, in building design. Architecture must provide protection from adverse weather and ensure indoor comfort. This requirement considers the building climate based on climatic factors and their interaction with buildings, and thermal design for indoor comfort that varies across climatic zones (Azmi & Ibrahim, 2020). In China, climatic zones are categorized into three main types (Ministry of Housing and Urban-Rural Development, 2015). The study area in Fujian Province falls in the hot-summer and warm-winter zone A, characterized by high humidity and temperatures, demanding significant air-conditioning energy in summer.

2.1.2. Factors of building energy consumption in the hot-summer warm-winter zone

In the hot-summer warm-winter zone, building energy consumption, focusing on HVAC system power use, is influenced by internal and external factors (Misra et al., 2021). External factors include climatic conditions like temperature and solar radiation, impacting the indoor thermal environment (Wang, 2010). Internal factors involve indoor heating mechanisms and activity levels (Bracht et al., 2021). Additionally, building physical attributes like shape, thermal properties, and the HVAC system's efficiency and control play a significant role (Chang et al., 2018; Misra et al., 2021). These influences are categorized into five types with specific indicators for energy consumption (Table 1).

2.1.3. Energy-saving design of green buildings

Building energy-saving design should prioritize passive methods and actively control energy use (Shi et al., 2016; Si et al., 2016). This involves using natural conditions and low-energy methods for environmental goals, like natural lighting and ventilation, envelope insulation, and shading. Effectively regulating a building's heat gain and loss, lighting, ventilation, and humidity is crucial to minimize power consumption while maintaining comfort. Poor envelope performance is a major issue in China, causing about 75% heat loss, with exterior walls being the largest contributor (Gerbino et al., 2021; Zhang et al., 2021). Upgrading envelope design is a key to reducing heat loss.

(1) Energy-saving technology of the exterior wall

Wall energy-saving involves selecting appropriate insulation materials and structural forms, with materials needing a thermal conductivity of ≤ 0.23 $Wm^{-1}K^{-1}$ and properties like fireproofing and durability (Zhang et al., 2021). Common insulation methods include external insulation (using materials like EPS board, covered by plaster or cladding), internal insulation (less used, involves covering the inner wall with materials like gypsum boards), and self-insulation using materials like autoclaved aerated concrete, especially in the varying climatic zones of China (Ministry of Housing and Urban-Rural Development, 2015; Ilhan & Yaman, 2016).

(2) Energy-saving technology of the exterior window

For energy-saving in exterior windows, material choice and shading are key. Window frames vary in thermal insu-

Table 1. Five categories of building properties and HVAC system with influence on energy consumption and their associated indicators

Building attribute	Specific indicator	Source
Construction	Comprehensive thermal performance, orientation, window-to-wall ratio, exterior window shading, body shape coefficient of building envelope	Chen and An (2024), Wang and Zhang (2022)
Climate	Outdoor temperature, humidity, solar radiation, wind speed	Gao et al. (2021), Yuce et al. (2022)
System equipment	System type, energy efficiency, floor plan	Bui et al. (2020), Ji et al. (2024)
Operational management	Heating and air-conditioning system running time, lighting system control, equipment power density	Li et al. (2021b), Zhao et al. (2021)
Use functions	Use time, per capita occupied area, use, indoor design temperature, interior design, fresh air volume	Meng et al. (2019)

lation, with options like wood, UPVC steel, and aluminum alloys, each having different heat transfer coefficients (Zhang et al., 2021). Glass types such as insulating, low-E, and coated also contribute to energy efficiency (Illankoon et al., 2019). Shading structures, external, internal, or on the window, can lower cooling loads but may increase heating needs in colder regions (Chi et al., 2021; Hong et al., 2016). The design must consider local climatic conditions to balance energy savings effectively.

(3) Energy-saving technology for the roof

Improving roof thermal insulation, which accounts for 7–9% of a building's envelope heat consumption, can significantly reduce heating and cooling energy use in top-floor rooms (Ascione et al., 2019). Roof insulation typically avoids materials with high bulk density or water absorptivity, favoring options like expanded perlite, vermiculite, polyurethane foam, polystyrene foam, and aerated concrete. This approach optimizes energy efficiency while considering structural and environmental factors.

This study analyzed green buildings' energy consumption factors in China's hot-summer and warm-winter regions. The calculated energy-consumption range provided the basis for green buildings' "passive" energy-saving design. The study focused on optimizing the energy-saving design of a green building envelope using some common construction materials and methods.

2.2. Applying BIM to optimize the green-building energy-saving design

The gist of an energy-saving design is meeting the prescribed standards. Optimizing the design entails selecting parameters according to evaluation standards. The BIM-based energy-saving optimization design adopted the BIM model as the core. Different schemes were generated by adjusting the exterior walls and windows using an optimization algorithm. The adjusted structures were comprehensively evaluated in tandem with an economic analysis. Finally, the building energy-consumption simulation and design process were integrated to automatically calculate, adjust, and compare the design schemes to identify the optimal one. The steps of the research framework are shown in Figure 2.

The optimization process includes the following steps.

(1) Establish a BIM model of the initial design scheme

The BIM Revit software for architectural project design established the building 3D model (Ahmad et al., 2016). The software determined the value of the elevation grid and arranged the components, such as walls, columns, beams, plates, doors, windows, roofs, etc., to complete the modeling of a green building.

(2) Optimize variables, algorithms, and BIM models

Using the above initial design scheme, the optimization variables were then determined. Referring to the research results of energy-saving optimization design in recent years, the critical design parameters were evaluated. The factors and their functions were clarified. The orthogonal table and listing of the test scheme were chosen. A suitable orthogonal table based on the factors and levels was selected. The factors in specific columns of the table were placed to simplify the design process and ensure the feasibility of tests. Finally, the test was performed according to the orthogonal table, and the results were recorded. The optimization algorithm adjusted the facade and window structures in the envelope using the orthogonal experimental design to optimize the BIM model.

(3) Conduct energy consumption and economic analysis

The energy consumption simulation and economic analysis were conducted based on the above optimized BIM model. The geometry (walls, doors and windows, etc.) and physical building information were output into the energy-consumption analysis software BECS (Hi-Tech Corp. Ltd, Shenzhen, China) (Xiang et al., 2019) in sxf file format. It was based on the optimized 3D model using the BIM Revit software. The energy-consumption and related parameters were set. The building's annual energy-consumption and other evaluation indexes were calculated. The economic analysis was conducted by the engineering

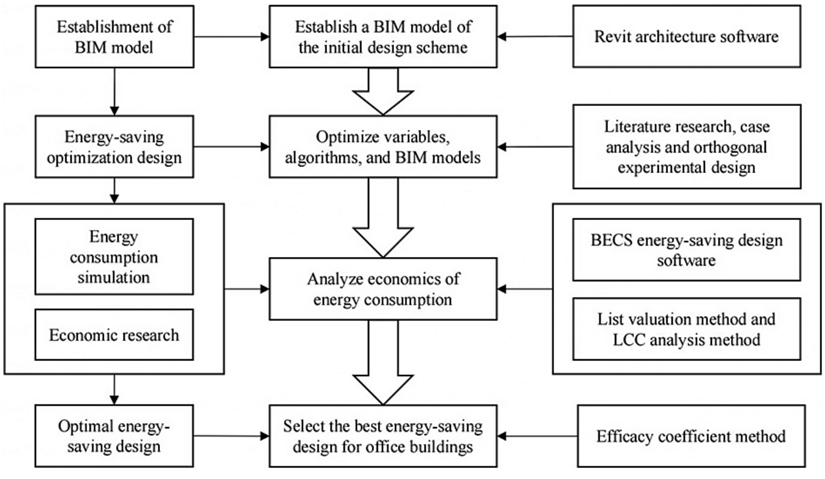


Figure 2. The steps adopted in developing the optimal BIM-based energy-saving building design

quantity list valuation and life-cycle cost (LCC) methods (Ferrara et al., 2016). Engineering quantity list valuation refers to all the costs required to complete the project, including partial and itemized project fees, measure project and other project fees, and taxes.

(4) Select the best energy-saving design scheme for the green building

The building's envelope was taken as the optimization object. The BIM model, energy consumption, and cost calculation results of the above steps were used to assess each scheme's performance. The efficiency coefficient method (Ilbeigi et al., 2020) was employed to analyze the schemes comprehensively using energy consumption results and economic evaluation indicators. The best energy-saving design scheme was accordingly identified.

2.3. Energy consumption analysis

2.3.1. Calculating the energy-consumption range

Building lighting accounts for a large proportion of the total energy consumption at 10–30% (Ma et al., 2019). However, most building energy research concentrated on HVAC loads, investigating thermal performance but excluding lighting. Good indoor natural lighting design can reduce energy consumption. The heat emitted by lamps can warm indoor spaces in winter to reduce the heating load but raise the air-conditioning cooling load in summer. Therefore, lighting energy consumption must be considered. The energy-consumption (as electricity equivalent) equations are as follows.

$$E = E_H + E_C + E_L, \tag{1}$$

where E – annual total energy consumption of heating and air conditioning (kWh/m^2); E_H – annual electricity consumption of air-conditioning (kWh/m^2); E_C – annual electricity consumption of heating (kWh/m^2); and E_L – annual electricity consumption of lighting (kWh/m^2).

$$E_C = \frac{Q_C}{A \times SCO_{P_T}}, \tag{2}$$

where Q_C – annual accumulated cooling energy consumption (kWh); A – building area (m^2); and SCO_{P_T} –comprehensive performance coefficient of the cooling system (Dimensionless), taking 2.50.

$$E_H = \frac{Q_H}{A \times \eta_1 \times q_1 \times q_2} \times \varphi, \tag{3}$$

where Q_H – annual accumulated heating energy consumption (kWh); A – building area (m^2); η_1 –comprehensive performance coefficient of the heating system (Dimensionless), taking 0.75; q_1 – standard calorific value of natural gas, taking 9.87 (kWh/m^3); q_2 – coal consumption needed for power generation, taking 0.36 (kgce/kWh); φ – conversion coefficient of natural gas and standard coal, taking 1.21 (kgce/m^3); and kgce – kilogram coal equivalent.

2.3.2. Analyzing and exporting energy-consumption data

This study used the BIM Revit software (Nagrale & Bais, 2020). An RVT format transformation was used to import the energy-consumption simulation software for calculation and analysis. This software ensured architectural design effectiveness and reliability of energy-consumption calculations. It also provided a new optimization process for energy-saving design. The main design specifications were based on three national standards: *Design Standard for Energy Efficiency of Public Buildings* (GB50189-2015) (Ministry of Housing and Urban-Rural Development, 2015), *Code for Thermal Design of Civil Building* (GB50176-2016) (Ministry of Housing and Urban-Rural Development, 2016), and *Test Methods of Air Permeability*, *Water Tightness*, *Wind Load Resistance Performance for Building External Windows and Doors* (GB/T 7106-2019) (Ministry of Housing and Urban-Rural Development, 2019).

In addition, the model processing and setting of related parameters followed the operating rules of the energy consumption software (Chen et al., 2022b). After importing the Revit model into BECS, the software automatically identified the physical and geometric parameters of the building components and divided the room units. However, the quality of the model was uneven, demanding checking and solving the problems. BECS provided examination functions such as overlap, column wall, and wall foundation inspections, which could effectively and quickly repair the model and improve its accuracy. Then, the material properties of the walls, columns, doors, and windows were supplied, and the thermal parameters of the envelope were set.

The material properties of a component include construction material type, thickness, and correction factor. Filling in or calculating the materials' heat transfer coefficients and thermal inertia indexes established the envelope's thermal parameters. Data on the materials were stored in an engineering materials library for easy modification and extraction (Nagrale & Bais, 2020).

After setting the building envelope, the function of each room in the building and the HVAC system parameters were defined. These attributes interact with each other. For example, internal disturbance factors such as lighting intensity, personnel conditions, the fresh air volume and indoor design temperature are related to the operational time and load of the air-conditioning system.

The building energy consumption was calculated after establishing the above model and parameters. We exported the results of the building model's prescriptive index, performance index, and energy-saving rate according to the design objectives.

2.4. Economic analysis

2.4.1. Life-cycle cost (LCC) concept

An economic cost analysis of the design options is required to optimize energy efficiency and achieve energy-efficient buildings' social, economic and environmental goals. We introduced the life-cycle cost (LCC) analysis method as a theoretical guide to optimizing the design's cost (Santos et al., 2020).

The initial cost, also called the construction cost, is the sum of all the costs incurred before the construction, including the costs of the development-stage feasibility analysis, the preparatory stage, and the construction stage. The future cost refers to all costs incurred from the beginning of construction to the end of demolition, including operating, maintenance, and residual costs. The full life cycle LCC calculation formula is shown in Eqn (4). Initial costs define the energy-efficient materials and technologies to be used, while operational costs directly influence long-term energy consumption. Therefore, in the simple LCC analysis of this study, only the initial and operating costs were analyzed.

$$LCC = IC + OC + MC + PDC + DC, \tag{4}$$

where IC – initial cost (Yuan/m^2); OC – operational cost (Yuan/m^2); MC – maintenance cost (Yuan/m^2); PDC – potential damage cost (Yuan/m^2); and DC – demolition cost (Yuan/m^2).

2.4.2. Economic evaluation indicators

LCC employs the present value of the project as the basis for the analysis (Peymankar et al., 2021). This study used the present value as the main index to select the optimization scheme and evaluate its costs. Applying this method, the present value of the design's LCC should be calculated first.

Considering the time value of money, the present value can analyze the total cost of different schemes over the life cycle. Eqn (5) can calculate the LCC present value (LCC_{PV}). Comparing the schemes, the one with the smallest present value has the lowest total LCC.

$$LCC_{PV} = F + A\frac{\left(1+r\%\right)^{C}-1}{r\%\times\left(1+r\%\right)^{C}}, \tag{5}$$

where LCC_{PV} – life-cycle cost present value (Yuan/m^2); F – initial cost (Yuan/m^2); A – annual energy cost (Yuan/m^2); r – discount rate (%); and c – research period (years).

The factors driving the LCC analysis of the envelope structure are summarized in Table 2.

Table 2. Factors of the life cycle cost analysis (LCCA)

Serial number	Factor	Value
1	Base date	Initial investment
2	Design and construction stage	a
3	Service period	b
4	Research period	$c = a + b$
5	Initial construction cost (Yuan/m^2)	F
6	Discount rate (%)	Real interest rate
7	Discount rate (%)	r
8	Tax rate	Not considered
9	Energy cost (Yuan/m^2)	A
10	Life span of the envelope (years)	40–70

2.5. Optimizing energy-efficient design

2.5.1. Optimization variables

Referring to research on the optimization of energy-efficient buildings in recent years (Ding et al., 2018; Sanchez & Haas, 2018), this study focused on the optimization parameters of the building envelope. They included building orientation, window-to-wall area ratio, wall-to-floor ratio, insulation thickness, glass type, and envelope thermal performance. The heat transferred through the building envelope could account for the largest heat-loss proportion. Therefore, the exterior envelope was chosen as the optimization object. Different design schemes were proposed for the optimization analysis based on its three parts: exterior wall, exterior window, and roof.

2.5.2. Multi-index orthogonal test design

In the optimization design, the impacts of multiple factors on the indicator results are usually tested in combination (Derazgisou et al., 2018; Wu et al., 2001). However, too many combinations will be generated by multiple factors. Testing all combinations will be excessively arduous and unrealistic. An experimental method can be identified to select optimal representative test combinations to reduce the number of tests and obtain sufficient information.

The orthogonal test method has less resistance than other algorithms (Wi et al., 2021). First, it can overcome the minimum deception problems of other algorithms. The deception problem refers to generating all the individuals that hinder the high fitness value in the genetic algorithm that may affect the normal work of the genetic algorithm (Wu et al., 2001). Second, the results of the evaluation indicators can be calculated directly using the performance simulation software, which can be combined effectively with the simulation software to fully utilize the advantages of accurate and fast calculations (Derazgisou et al., 2018). Finally, the experimental calculation results can be analyzed by other methods, such as range analysis, comprehensive balance method, efficiency coefficient method, etc., to ensure that the architectural design objectives are achieved (Wi et al., 2021). Therefore, this study employs this method to establish an effective optimization model. The four main steps of the orthogonal test design are explained below.

(1) Define the purpose of the test and specify the inspection index

Before the test, the key points were grasped, and the corresponding test indexes were determined according to critical decision-making. A test often requires two or more indicators to measure the results, called multi-index tests. For example, a test of rubber products will specify the number of indicators, such as the maximum possible voltage, disassembly resistance and wear resistance, to measure the test results.

(2) Select the factors and determine the levels of each factor

This step determined the main factors that might change the test indexes and set the corresponding levels for these factors. Each level covered an appropriate range based on practical experience and theoretical analysis. The energy-consumption factors of buildings were analyzed to prepare for the orthogonal- test application.

(3) Select the orthogonal table, determine the statement heading and list the test scheme

The appropriate orthogonal table was selected according to the factors and levels. Many orthogonal tables have been summarized in previous studies (Wu et al., 2001). Determining the statement heading defined the placement of factors in particular columns. The actual design work was simplified as much as possible to reduce the number of tests and ensure their applicability.

(4) Implement the test

According to the designed orthogonal table, the combined test was performed, and the results were recorded.

2.5.3. Determining optimal energy-saving design scheme by the efficiency coefficient method

The efficiency coefficient method, also known as the efficiency function method, was proposed by E. C. Harrington in 1965 for multiple-target optimization and subsequently applied to evaluate orthogonal tests (Foroughi et al., 2021). The method transforms the experimental indicators by the efficiency function, and the values of the same group of indicators are normalized to obtain a total efficiency coefficient for evaluation. This method is especially suitable for cases with different dimensions. If the orthogonal test evaluates n indexes, the efficiency coefficient of each test result can be calculated. For example, the efficiency coefficient of the test group l in index i is d_{il}, and the equation is:

$$d_{il} = \frac{x_{il} - s_i}{h_i - s_i}, \tag{6}$$

where d_{il} – efficiency coefficient of the group l test in the index i; x_{il} – test result of the group l under the index i; s_i – the impermissible value of the test result; and h_i – the most satisfactory value of the test results.

For an orthogonal test of n indicators, n efficiency coefficients can be obtained. The average of these n efficiency coefficients can be calculated to obtain the total efficiency coefficient (Dimensionless):

$$d_l = \frac{\sum_{i=1}^{n} d_{il}}{n}. \tag{7}$$

In this study, the efficiency coefficient method was used to analyze the results of the multi-index orthogonal test. Finally, the analysis results allowed a comprehensive evaluation of each scheme to select the best one.

3. Case study and evaluation

3.1. Project overview

We selected a school administrative green building in Fuzhou city, Fujian Province, China, as our case study (hereinafter labeled Project S) to test our proposed method. The building has five floors and a typical room size, with the main design parameters summarized in Table 3. More details are provided in the Appendix.

Table 3. The main structural attributes of Project S

Structural attribute	Value
Number of building layers (layers)	5
Building height (m)	18.3
Building area (m^2)	5,392
Facade orientation from north (°)	11
Body shape coefficient	0.21
Calculated volume (m^3)	19,856
External surface area (m^2)	4,087
Location	Fujian, China

The thermal performance requirements of the building envelope structure are stipulated in the *Design Standard for Energy Efficiency of Public Buildings* (GB 50189-2015) (Ministry of Housing and Urban-Rural Development, 2015). The annual energy consumption per unit area of the building exceeded the reference building and did not meet the design specifications described in Table 4. Therefore, this study applied energy-saving technology to the building envelope to choose the most appropriate technology combination to optimize the design.

3.2. Design of the orthogonal experiment table

3.2.1. Choosing factors and levels

The building envelope has the greatest impact on energy consumption. Its proportion of the building volume is directly related to the project's economic cost. Therefore, the heat transfer coefficients of three critical factors were selected: exterior walls (A), exterior windows (B) and roof (C). Furthermore, three levels were selected for each factor according to the *Energy Conservation Engineering Practices for Civil Building Envelopes in Fujian Province and Data* (DBJT13-97 2015) (Fujian Academy of Building Science, 2015) and the *National Technical Measures for Design of Civil Construction Special Edition: Energy Conservation* (JSCS-D) (Ministry of Construction Engineering Quality and Safety Supervision and Industry Development Division, 2007). The values of factors and levels are shown in Table 5, and the corresponding structure type of each value is given in Table 6.

Table 4. Comparison of annual energy consumption between the designed building and the reference building

Types of energy	Design construction	Reference construction
Total annual electricity consumption for heating and air conditioning (kWh/m^2)	27.93	26.75
Power consumption for cooling (kWh/m^2)	21.05	19.27
Heating power consumption (kWh/m^2)	6.88	7.48
Energy consumption by cooling (kWh/m^2)	52.63	48.17
Energy consumption by heating (kWh/m^2)	15.16	16.11
Basis of the standard	Article 3.4.2 of *The Design Standard for Energy Efficiency of Public Buildings* (GB50189-2015) (Ministry of Housing and Urban-Rural Development, 2015)	
Standard requirement	The energy consumption of the designed building is greater than that of the reference building	
Conclusion	Does not meet the requirement	

Table 5. The heat transfer coefficients of the three building envelope factors (A, B and C) and their three test levels (1, 2 and 3)

	Heat transfer coefficient, W/(m^2·K)		
Level	Exterior wall A	Exterior window B	Roof C
1	0.466	2.03	0.552
2	0.505	2.20	0.788
3	0.613	2.89	1.078

Table 6. The horizontal structure types of the three levels (1, 2 and 3) of the building envelope types (A, B and C) of Project S

Level	Exterior wall A	Exterior window B	Roof C
1	Cement mortar (20 mm) + extruded polystyrene foam board XPS (30 mm) + autoclaved aerated concrete block (B07 grade) (200 mm) + cement mortar (20 mm)	Aluminum-plastic co-extrusion window (6 low-transparent double-silver Low-E+12A+6 transparent glass)	C20 fine stone concrete (40 mm) + low-grade mortar insulation layer (10 mm) + XPS board (50 mm) + cement mortar (20 mm) + light aggregate concrete 2% slope finding layer (30 mm) + reinforced concrete (100 mm)
2	Cement mortar (5 mm) + rock wool board vertical fiber (30 mm) + autoclaved aerated concrete block (B07 grade) (200 mm) + cement mortar (20mm)	Heat-dissipating aluminum alloy window (6-through double silver Low-E+12A+6 transparent glass)	C20 fine stone concrete (40 mm) + low-grade mortar insulation layer (10 mm) + EPS board (40 mm) + cement mortar (20 mm) + light aggregate concrete 2% slope finding layer (30 mm) + reinforced concrete (100 mm)
3	Cement mortar (20 mm) + inorganic thermally insulated mortar (20 mm) + autoclaved aerated concrete block (B07 grade) (200 mm) + crack resistant mortar (20 mm)	Plastic window (6 transparent + 9A + 6 transparent)	C20 fine stone concrete (40 mm) + low-grade mortar insulation layer (10 mm) + cement mortar (20 mm) + light aggregate concrete 2% slope layer (30 mm) + foam glass insulation board (40 mm) + reinforced concrete (100 mm)

Note: XPS is Extruded polystyrene foam board. EPS is Expanded polystyrene board. Low-E is Low emissivity glass.

3.2.2. Selecting the orthogonal table

For the three factors and the three levels of the test, interactions among the factors were not considered in full. Instead, an orthogonal test of three rows and four columns was adopted. The fourth column of the L9 (3^3) orthogonal table was selected as the test error to measure the test's reliability. The three levels, namely, "1", "2", and "3" of the L9 (3^3) in Table 7, correspond to inspection levels 1, 2, and 3, respectively. Their permutations generated nine combined schemes to assess their energy-saving efficacy. First, the BECS energy-saving calculation software was used to simulate the nine combined schemes for the design building and the reference building. The main attributes included: annual air-conditioning power consumption per unit area, heating power consumption per unit area, cumulative

Table 7. The L9 (3^3) orthogonal table of the nine test schemes

Scheme	Column number			
	1	2	3	4
	Exterior wall A	Exterior window B	Roof C	Blank column
1	1(A1)	1(B1)	1(C1)	1
2	1	2(B2)	2(C2)	2
3	1	3(B3)	3(C3)	3
4	2(A2)	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3(A3)	1	3	2
8	3	2	1	3
9	3	3	2	1

power consumption per unit area, and area lighting power consumption. The Revit software extracted the engineering quantity, calculated the economic evaluation index, and statistically analyzed the results.

3.3. Application of BIM to optimize the energy-saving design

3.3.1. Simulating energy consumption

(1) Importing the BIM model into BECS

Using an RVT format data conversion, the BIM model was transformed into an SXF file recognized by BECS. Then, this file was imported into BECS to complete the initial construction of the energy-consumption model (Figure 3). New components were built in the component library to edit the envelope, and the required materials were selected according to the design scheme, including the heat transfer coefficient and thickness. For example, the setting of the first floor south exterior wall in BECS is shown in Figures 4 and 5, and the heat transfer coefficient of the exterior wall was 0.466 W/(m^2·K).

After completing the envelope settings, the use function and HVAC system parameters of the building's rooms were defined. They were set according to the *Design Standard for Energy Efficiency of Public Buildings* and design documents (Ministry of Housing and Urban-Rural Development, 2015). The specific parameters are shown in Table 8, and the operational interfaces are given in Figure 5.

Finally, the building's geographical position was defined to obtain the meteorological data for energy-consumption simulation. We used Fuzhou's meteorological data in CSWD format, covering a typical meteorological year. The data consisted of real-time observations from a station developed by Tsinghua University and the China Meteorological Administration (Ren et al., 2021).

(2) Calculating energy consumption of test schemes

The building energy consumption was calculated after constructing the above model and setting the parameters. The energy consumption data for lighting, heating and air-conditioning, and the annual total of the building model were exported according to different design objectives.

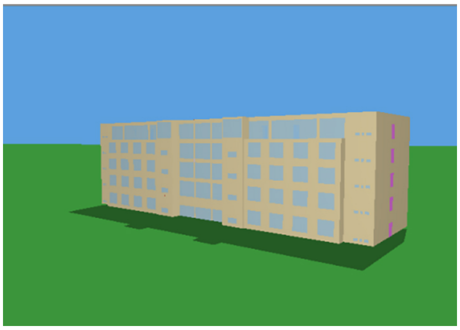


Figure 3. The energy simulation model generated by BECS

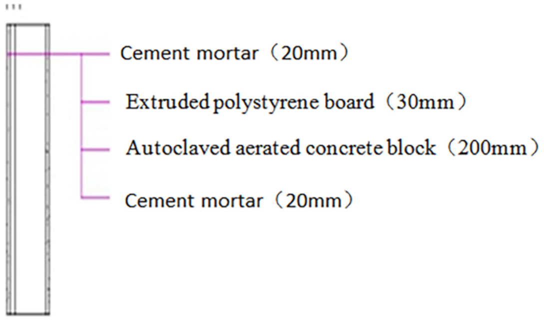
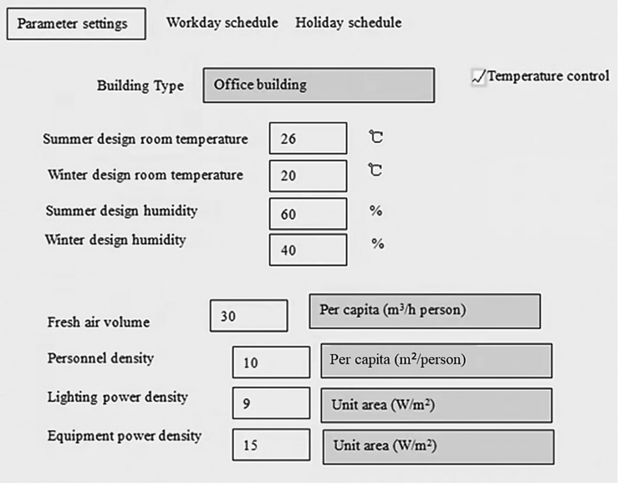


Figure 4. Examples of exterior wall structures considered by BECS



Building Type: Office building

☑ Temperature control

Summer design room temperature: 26 ℃

Winter design room temperature: 20 ℃

Summer design humidity: 60 %

Winter design humidity: 40 %

Fresh air volume: 30 Per capita (m³/h person)

Personnel density: 10 Per capita (m²/person)

Lighting power density: 9 Unit area (W/m²)

Equipment power density: 15 Unit area (W/m²)

Figure 5. Interior design thermal environment

Table 8. The energy-related parameters of Project S in relation to the HVAC system, personnel, lighting and green equipment design

Design attribute	Value
Heating, ventilation and air-conditioning system (HVAC)	Full air-conditioning system: urban power grid
Heating room temperature (°C)	20 °C (low operational temperature load is 5 °C)
Cooling room temperature (°C)	26 °C (pre-cooling temperature is 28 °C)
Per capita fresh air volume (m^3/h • person)	30 m^3/h • person
Natural ventilation permeability (times/h)	Air exchange rate of 0.5, ventilation times 0.25 times/h
Operational hours (day)	Standard working day
Personnel density (m^2/person)	10 m^2/person
Target illumination (lux)	400 lux (workspace), 100 lux (public area)
Electrical equipment power density (W/m^2)	15 W/m^2 (workspace)

The design lighting intensity and lighting area were set uniformly for the schemes at 20.31 kWh/m^2. Therefore, the reference building's annual heating and air-conditioning energy consumption was 26.75 kWh/m^2. The orthogonal test results of the energy-consumption simulation are shown in Table 9.

3.3.2. Calculating the initial construction, annual operational and life-cycle costs

(1) Initial construction cost and annual operational cost

The unit cost of each construction type was calculated using inventory pricing, and the unit cost was converted into the unit area building cost, as shown in Appendix Table A5. By utilizing the Quantity Takeoff feature in Revit software, it was possible to directly calculate the quantities of various building components, such as external walls and window areas. The total building area for this project was 5392 m^2, with the specific data detailed in Table 10. The thickness of the reinforced concrete was set as 120 mm, which was not included in calculating the unit cost.

F_a denoted the unit area building cost of exterior walls, F_b the unit area building cost of exterior windows, F_c the unit building area cost of the roof, and F the initial construction cost. The calculations used Eqns (8)–(11).

$$F_a = S_a \times m, \quad (8)$$

where m – total area of the exterior walls/total floor area (m^2); S_a – unit area cost of exterior walls (Yuan/m^2).

$$F_b = S_b \times n, \quad (9)$$

where n – total area of exterior windows/total floor area (m^2); S_b – unit area cost of exterior windows (Yuan/m^2).

$$F_c = S_c \times p, \quad (10)$$

where p – proportion of roof area/total floor area (m^2); S_c – unit area cost of the roof (Yuan/m^2).

$$F = F_a + F_b + F_c. \quad (11)$$

The unit area cost of each structure was calculated using the part list, and the results are given in Appendix Table A5.

Each scheme's initial construction cost in unit building area was computed (Table 11). BECS reckoned each scheme's annual electricity consumption, and each scheme's annual operational cost was calculated accordingly.

(2) Calculating the life-cycle cost

A discount refers to a reduction in the present value of cash flow in a certain period in the future. The selected discount rate can influence the discounted value and the scheme's economic evaluation index. A scheme with a high discount rate will be underestimated, and a scheme with a low discount rate will be overestimated. Generally, the discount rate is equal to the industry benchmark yield. The discount rate of this study was based on the industry benchmark of 12% (Ministry of Housing and Urban-Rural Development, 2006). For the green building, the life of the project and the study period were set at 50 years. This study optimized the energy-saving technologies for the exterior walls, windows, and roofs regardless of the tax rate during the project life cycle. The operational cost was the annual energy cost calculated from the annual energy consumption. Finally, each optimization scheme's LCC_{PV} (Yuan/m^2) was calculated according to the present value using Eqn (12). The results are shown in Table 12 and Figure 6.

Table 9. The orthogonal test results of the nine schemes

Scheme	Column number				Annual heating and air-conditioning power consumption (kWh/m^2)	Annual total electricity consumption (kWh/m^2)
	1	2	3	4		
	Exterior wall A	Exterior window B	Roof C	Blank column		
1	1(A1)	1(B1)	1(C1)	1	16.09	41.93
2	1	2(B2)	2(C2)	2	16.57	42.70
3	1	3(B3)	3(C3)	3	20.87	46.51
4	2(A2)	1	2	3	16.20	42.39
5	2	2	3	1	16.76	43.28
6	2	3	1	2	20.69	45.83
7	3(A3)	1	3	2	16.44	43.13
8	3	2	1	3	16.56	42.66
9	3	3	2	1	20.78	46.36

Table 10. Breakdown of external wall and window areas

Wall direction	External wall area (m^2)	External window area (m^2)	Window-to-wall area ratio
East	1103.49	394.16	0.36
West	1103.72	463.56	0.42
North	384.46	–	–
South	383.49	–	–

Table 11. The initial construction cost of the design plan and annual energy costs of the optimized plan of nine schemes of Project S

Scheme number	A exterior wall type	B window type	C roof type	Initial construction cost (Yuan/m^2)		Annual power consumption (kWh/m^2)	Annual energy cost (Yuan/m^2)
1	Extruded polystyrene foam board XPS+ autoclaved aerated concrete block	Aluminum-plastic co-extrusion window (6 low-transparent double-silver Low-E+12A+6 transparent glass)	XPS board + reinforced concrete	204.06	23.48	41.93	23.48
2	Extruded polystyrene foam board XPS+ autoclaved aerated concrete block	Heat-dissipating aluminum alloy window (6 low-transition single silver Low-E+12A+6 transparent glass)	EPS board + reinforced concrete	185.32	23.91	42.7	23.91
3	Extruded polystyrene foam board XPS+ autoclaved aerated concrete block	Plastic window (6 transparent +9A+6 transparent)	Foam glass insulation board + reinforced concrete	150.26	26.05	46.51	26.05
4	Rock wool board vertical fiber + autoclaved aerated concrete block	Aluminum-plastic co-extrusion window (6 low-transparent double-silver Low-E+12A+6 transparent glass)	EPS board + reinforced concrete	220.42	23.74	42.39	23.74
5	Rock wool board vertical fiber + autoclaved aerated concrete block	Heat-resistant aluminum alloy window (6 low-transition single silver Low-E+12A+ transparent glass)	Foam glass insulation board + reinforced concrete	209.39	24.24	43.28	24.24
6	Rock wool board vertical fiber + autoclaved aerated concrete block	Plastic window (6 transparent + 9A + 6 transparent)	XPS board + reinforced concrete	163.07	25.66	45.83	25.66
7	Inorganic thermally insulated mortar + autoclaved aerated concrete block	Aluminum-plastic co-extrusion window (6 low-transparent double-silver Low-E+12A+6 transparent glass)	Foam glass insulation board + reinforced concrete	203.81	24.15	43.13	24.15
8	Inorganic thermally insulated mortar + autoclaved aerated concrete block	Heat-dissipating aluminum alloy window (6 low-transition single silver Low-E+12A+6 transparent glass)	XPS board + reinforced concrete	181.53	23.89	42.66	23.89
9	Inorganic thermally insulated mortar + autoclaved aerated concrete block	Plastic window (6 transparent +9A+6 transparent)	EPS board + reinforced concrete	138.75	25.96	46.36	25.96

Table 12. The original data for the two evaluation indexes of the nine schemes

Scheme number	Total energy consumption (kWh/m^2)	LCC_{PV} (Yuan/m^2)
1	41.93	399.06
2	42.70	380.32
3	47.51	345.26
4	42.39	415.42
5	43.28	404.39
6	45.83	358.07
7	43.13	398.81
8	42.66	376.53
9	46.36	333.75

Note: LCC_{PV} is the present value of life cycle cost.

$$LCC_{PV} = F + A\frac{\left(1+12\%\right)^{50}-1}{12\%\times\left(1+12\%\right)^{50}}, \tag{12}$$

where LCC_{PV} – present value of the life-cycle cost (Yuan/m^2); A – annual energy cost (Yuan/m^2); r – discount rate (%), set at 12%; and c – study period (years), set at 50 years.

3.4. Applying the efficiency coefficient method to identify the optimal design

We adopted the total energy consumption and LCC_{PV} values of the optimized energy-saving design scheme for a green building as the evaluation indexes. The efficiency coefficient method (Sun et al., 2020) was applied to the nine schemes of the orthogonal test, and then the optimal energy-saving design scheme was selected. Table 12 shows the original data of the two evaluation indexes.

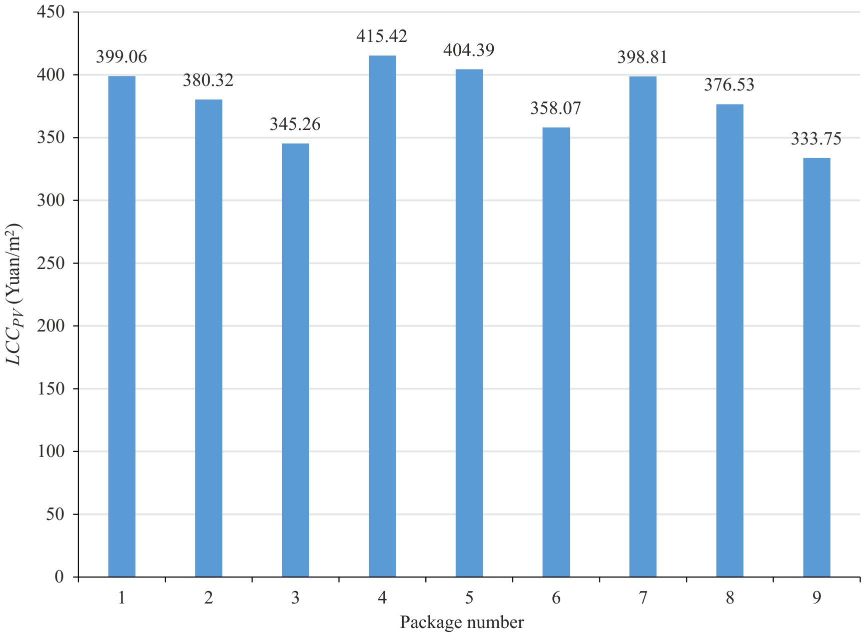


Figure 6. The present value of the life cycle cost (LCC_{PV}) of the nine schemes of Project S

According to the performance index requirements of the *Design Standard for Energy Efficiency of Public Buildings* (GB50189-2015) (Ministry of Housing and Urban-Rural Development, 2015), the annual energy consumption of air conditioning and heating in the design building was lower than in the reference building. Therefore, the total annual energy consumption of the reference building (47.06 kWh/m^2) was not acceptable. The optimal value was the lowest total energy consumption in the optimization scheme (41.93 kWh/m^2). The optimal and impermissible values of LCC_{PV} are the minimum and maximum values of LCC_{PV} in the design scheme, which were 333.75 Yuan/m^2 and 415.42 Yuan/m^2, respectively (Table 13).

The efficiency coefficient of each index was calculated according to Eqns (6) and (7). An analysis was conducted for each scheme's range of total efficiency coefficients. The sum of data (K_1, K_2, K_3), mean value ($\overline{K}_1$, $\overline{K}_2$, $\overline{K}_3$) and range (R) of each test index was calculated according to each level of each column. The calculation results are shown in Tables 14 and 15.

Table 15 indicates that Scheme 3 had more heating and air-conditioning energy consumption than the reference building. Therefore, it was not adopted because its performance indicators did not satisfy the requirements of the *Design Standard for Energy Efficiency of Public Buildings* (Ministry of Housing and Urban-Rural Development, 2015). Scheme 8 had the highest efficiency coefficient of 0.667. It also had the best combination of factors ($A_3B_2C_1$) for the envelope obtained by the range analysis of orthogonal experimental design.

Table 13. The optimal and impermissible values of the two evaluation indexes

Value	Total energy consumption (kWh/m^2)	LCC_{PV} (Yuan/m^2)
Optimal value	41.93	333.75
Impermissible value	47.06	415.42

Table 14. The functional effect values of the two evaluation indexes and the total efficiency coefficient of the nine schemes

Scheme number	Efficiency coefficient		
	Total energy Consumption (kWh/m^2)	LCC_{PV} (Yuan/m^2)	Total efficiency coefficient
1	1.000	0.200	0.600
2	0.850	0.430	0.640
3	–0.088	0.859	0.386
4	0.910	0.000	0.455
5	0.737	0.135	0.436
6	0.240	0.702	0.471
7	0.766	0.203	0.485
8	0.858	0.476	0.667
9	0.136	1.000	0.568

To meet the holistic demands of economic and energy performance, Scheme 8 was the optimal choice. The best energy-saving design scheme of the building envelope had the following design parameters: exterior wall with cement mortar (20 mm) + inorganic thermally insulated mortar (20 mm) + autoclaved aerated concrete block (200 mm) + anti-crack mortar (20 mm); exterior window with a heat-dissipating aluminum alloy window; and roof structure with C20 fine aggregate concrete (40 mm) + low-grade mortar insulation layer (10 mm) + XPS board (50 mm) + cement mortar (20 mm) + light aggregate concrete with a 2% slope (30 mm) + reinforced concrete (100 mm).

The annual electricity consumption of Scheme 8 was 42.66 kWh/m^2, and the LCC_{PV} was 376.53 Yuan/m^2. Compared with Scheme 3, with the highest energy consumption, Scheme 8 could reduce the energy consumption

Table 15. The energy efficiency coefficients of the nine schemes

Scheme	Column number				Total efficiency coefficient
	1	2	3	4	
	Exterior wall A	Exterior window B	Roof C	Blank column	
1	1	1	1	1	0.600
2	1	2	2	2	0.640
3	1	3	3	3	0.386
4	2	1	2	3	0.455
5	2	2	3	1	0.436
6	2	3	1	2	0.471
7	3	1	3	2	0.485
8	3	2	1	3	0.667
9	3	3	2	1	0.568
K_1	1.626	1.539	1.737	1.605	
K_2	1.362	1.743	1.662	1.596	
K_3	1.719	1.425	1.308	1.509	
$\bar{K}_1$	0.542	0.513	0.579	0.535	
$\bar{K}_2$	0.454	0.581	0.554	0.532	
$\bar{K}_3$	0.573	0.475	0.436	0.503	
R	0.119	0.106	0.144	0.032	

Note: The K value is the sum of the energy efficiency coefficients corresponding to the test for a particular factor at a particular level (e.g., facade A). The $\bar{K}$ value is the average value of the energy efficiency coefficients for a particular factor at that level. The R value is the degree of variability that determines the effect of a change in a particular factor (e.g., facade A) on the total efficiency coefficients across different levels.

by 4.85 kWh/m^2 per year. Compared with the reference building, Scheme 8 could reduce energy consumption by 4.4 kWh/m^2 per year. Compared with Scheme 4, it had the largest LCC_{PV} and could reduce costs by 38.89 Yuan/m^2.

3.5. General discussion

This study evaluated energy-saving building design through a literature review. The present status suffers from some notable shortcomings, including the lack of integrated design and low design efficiency. The increase in accuracy using the Revit three-dimensional modeling software is limited in sustainable analysis. The application of BIM technology is proposed under the integrated design based on the BIM energy-saving design process. The technical feasibility of the approach has been verified by functional research of BIM software.

After modeling, the RVT file format is the default the Revit software saves, which contains the physical information and spatial relationship data of building components. After the RVT file is imported into the BECS software, the model data is rendered more complete, which is conducive to efficient energy consumption modeling and comprehensive realization of sustainability analysis. The integration of Building Information Modeling (BIM) and Building Energy Consumption Simulation (BECS) enhances data sharing between BIM software, prevents the formation of information silos, and boosts software interoperability (Sampaio et al., 2023). With the support of BIM technology, the parameter relationship between all components in the model could be comprehended and utilized. After successful applications in some building projects, the importance of energy performance analysis in the pre-design stage of sustainable buildings is demonstrated (Kim et al., 2011). The methodology of this study demonstrates a more integrated approach to the assessment of energy-efficient building design compared to previous studies (Chen et al., 2020; Guo et al., 2021), where design elements from various specialty areas can be integrated to achieve high performance and sustainable design. These methods focus more on integrating multiple assessment tools, including value engineering, at the early stages of design to achieve optimal energy savings, aligning with the findings of Wei and Chen (2020).

Given the substantial contribution of cooling and heating load losses through the building envelope to overall energy efficiency, prioritizing passive design approaches becomes essential (Gondal et al., 2021). Analyzing energy-consumption factors and selecting appropriate parameters for energy-saving design and optimization can provide a reference for variable and scheme selection. This strategy can identify parameters sensitive to energy efficiency and thermal comfort. In comparing optimization parameters with similar studies, we meticulously selected key parameters, including exterior wall insulation thickness, roof heat transfer coefficient, solar heat gain coefficient of exterior windows, and window-to-wall area ratio (Li et al., 2020). The results offer a scientific reference to optimize parameter selection.

The annual total energy-consumption and life-cycle cost present value of each optimization scheme can be assessed using the 3D modeling Revit software, energy-consumption simulation BECS software, and life-cycle theory. Combined with the efficiency coefficient method, each scheme's energy consumption and economic indicators are comprehensively analyzed, and the best scheme can be identified. Our proposal, therefore, presents a holistic energy-saving design optimization framework. Based on building energy consumption simulation, optimization, multi-criteria decision-making, sensitivity study and adaptive comfort analysis, the optimal passive design of residential buildings can be comprehensively investigated. Applying our framework to a case study resulted in an energy consumption reduction of 4.85 kWh/m^2 per year compared to the reference building, leading to cost savings of 38.89 Yuan/m^2. Despite comparisons with other case studies indicating similar energy reduction levels, our framework also considers the economic costs' impact (Li et al., 2020; Lu et al., 2020). Further economic analysis reveals that integrating BIM and orthogonal testing enhances energy efficiency and reduces life cycle costs by approximately 9.3%, a significant saving given the rising costs of building materials and energy (Ferrara et al., 2016). Our method effectively solves the problems of collaborative design, economic analysis and accuracy in traditional energy-saving design and provides a theoretical and methodological reference for building energy-saving design.

Using our new method, we empirically analyzed a school administration green building in Fuzhou, Fujian Province. Among the nine energy-saving options tested, Option 8 was found to have the highest efficiency coefficient of 0.667, striking an optimal balance between energy consumption and cost. Option 8 incorporates various energy-saving technologies, including exterior wall insulation, window thermal insulation, and roof insulation optimization. This composite structure has been demonstrated to effectively reduce thermal bridging and heat transfer, corroborating previous research findings on the efficacy of such integrated approaches (Chandhran & Elavenil, 2023; Tkalčić et al., 2023). In summary, this study confirms the proposed framework's feasibility and effectiveness through rigorous theoretical analysis and detailed case studies. To address the research questions, we employed a novel hybrid approach consisting of energy simulation, comprehensive life cycle costing, and orthogonal array testing. It can pinpoint concrete design changes to bring significant energy conservation in a green building. The approach can facilitate future deep research and offer a reliable reference basis. The empirical testing of the theoretical framework for energy conservation design has verified its feasibility. The method may generate a ripple effect to accelerate the transformation of traditional buildings to green and energy-efficient buildings.

4. Conclusions

This study develops and validates an innovative framework for optimizing green building energy efficiency, integrating Building Information Modeling (BIM), Life Cycle Cost (LCC) analysis, and orthogonal testing methods. Through empirical analysis of a green building on a campus in Fujian Province, the study achieved significant energy efficiency and cost-effectiveness enhancements, demonstrating the framework's potential to advance building design sustainability. The following main conclusions can be drawn:

(1) A literature review and empirical data were employed to evaluate the energy consumption coefficients of green buildings and pinpoint the building envelope as crucial to energy-efficient design. Case study results confirm that enhancing the thermal performance of the building envelope contributes significantly to energy conservation. Factors such as building orientation, shape factor, exterior wall insulation, and roof insulation are identified as primary influencers of energy-efficient building design.

(2) Revit and BECS software facilitate 3D modeling and energy simulation, while orthogonal experimental design allows various optimization scheme combinations. The efficiency coefficient method comprehensively assesses energy consumption and life cycle costs. These methodologies jointly establish a practical framework for optimizing building performance and cost, offering designers a novel and more effective approach to green building design, essential for policy development and standardization of sustainable building practices.

(3) The case study illustrates that the optimized design solution yielded an energy consumption reduction of approximately 4.85 kWh/m^2 per year and cost savings of 38.89 Yuan/m^2 compared to the reference building. These savings underscore the effectiveness of the integrated approach in reducing operational expenditures and the environmental impact of the building, affirming the feasibility of the proposed framework.

(4) Testing identified the most effective design – combining inorganic insulating mortar with heat-dissipating aluminum alloy windows and an XPS panel insulated roof – achieving considerable improvements in insulation and cost-effectiveness. The case study results provide actionable data to guide the optimization of building parameters and future retrofit projects.

This study confirms the efficacy of BIM and orthogonal testing methods in enhancing building energy performance. It delineates a structured approach for future research and practical applications in sustainable building. The application of this study extends to designing new buildings and retrofitting existing structures through a systematic energy and cost optimization methodology. It aims to fulfill dual economic and environmental sustainability objectives, thereby supporting the sustainable development goals of urban areas. Moreover, the proposed methodology facilitates parameter selection. It offers scientific and technical support for energy-efficient building design, providing a reference for governments and enterprises to develop and enhance building energy efficiency policies and regulations.

5. Limitations and future studies

Although the objectives of this study were achieved, some limitations could be evaluated. First, the study focused solely on economic aspects of energy efficiency without considering ecological impacts such as carbon emissions. Additionally, the methodology was tailored to the specific climatic and regulatory context of Fujian Province, China, which may not apply directly to other regions with different environmental conditions. Another limitation is the exclusion of multi-year climate variability and building occupancy data, which is crucial for assessing building energy performance.

Future research could enrich this framework by incorporating a broader range of sustainability indices, thus extending the scope of optimization from purely economic considerations to ecological and social dimensions. Local climatic variations and regulatory conditions necessitate adjustments to the optimization parameters to ensure the framework's wide applicability across diverse geographic environments. Moreover, integrating long-term climate data and occupancy patterns will enhance the accuracy of energy consumption models, enabling the implementation of more precise and effective energy-saving measures. Establishing a detailed and systematic parameter database for various design stages will also facilitate the development of tailored energy-efficient architectural solutions.

This study lays the groundwork for a more holistic and adaptable approach to green building design, providing a strategic framework that balances economic efficiency with environmental sustainability. It is well-positioned to address global energy conservation challenges effectively.

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APPENDIX

Table A1. Construction of envelope structure

Envelope part	Structure
Roof type (from top to bottom)	Cement mortar (20 mm) + fine stone concrete (internal reinforcement 40 mm) + rock wool insulation board (32 mm) + cement mortar (20 mm) + light aggregate concrete 2% slope layer (25 mm) + reinforced concrete (100 mm) + cement Mortar (20 mm)
Exterior wall (from outside to inside)	Cement mortar (20 mm) + autoclaved aerated concrete block (200 mm) + inorganic thermal insulation mortar (20 mm) + crack resistant mortar (5 mm)
Hollow floor	Cement mortar (20 mm) + reinforced concrete (100 mm) + inorganic thermal insulation mortar (30) + crack resistant mortar (5 mm)
Exterior window	Dark gray ordinary aluminum alloy doors and windows +6 medium through Low-E+9 air +6 transparent glass
Ground	Vitrified brick (10 mm) + cement mortar (20 mm) + coal slag concrete (800 mm) + concrete roof (300 mm)

Table A2. Building model static index trade-off results

Static index			Design building			Reference building		
Roof heat transfer coefficient *K* [W/(m^2·K)]			0.93(D:3.08)			0.80		
Heat transfer coefficient *K* [W/(m^2·K)] for exterior walls (including non-transparent curtain walls)			1.02(D:4.36)			1.50		
The heat transfer coefficient *K* [W/(m^2·K)] of the overhead or external pick-up floor with the bottom surface contacting the outside			1.32			1.50		
Exterior window (including transparent curtain wall)	Orientation	Facade	Window-to-wall ratio	Heat transfer coefficient	Solar heat gain coefficient	Window-to-wall ratio	Heat transfer coefficient	Solar heat gain coefficient
	Eastward	East – default facade	0.36	2.71	0.29	0.36	3.00	0.35
	Westward	West – default facade	0.42	2.71	0.29	0.42	2.70	0.35

Note: The reference building is the performance limit requirement in the "Design Standard for Energy Efficiency of Public Buildings" (GB50189-2015).

Table A3. Comparison of annual energy consumption between design and reference buildings

Energy type	Design building	Reference building
Total electricity consumption for heating and air conditioning throughout the year (kWh/m^2)	27.93	26.75
Cooling power consumption (kWh/m^2)	21.05	19.27
Heating power consumption (kWh/m^2)	6.88	7.48
Cooling capacity (kWh/m^2)	52.63	48.17
Heat consumption (kWh/m^2)	15.16	16.11
Standard basis	Section 3.4.2 of the "Design Standard for Energy Efficiency of Public Buildings" (GB50189-2015) (Ministry of Housing and Urban-Rural Development, 2015)	
Standard requirement	The energy consumption of the design building is greater than the reference building	
Conclusion	Not satisfied	

Table A4. Life cycle cost of the optimization plan

Scheme number	A	B	C	Initial construction cost (Yuan/m^2)	Annual energy cost A (Yuan/m^2)	LCC_{PV} (Yuan/m^2)
1	Extruded polystyrene foam board XPS + autoclaved aerated concrete block	Aluminum-plastic co-extrusion window (6 low-transparent double-silver Low-E+12A+6 transparent glass)	XPS board + reinforced concrete	204.06	23.48	399.06
2	Extruded polystyrene foam board XPS + autoclaved aerated concrete block	Heat-dissipating aluminum alloy window (6 low-transition single silver Low-E+12A+6 transparent glass)	EPS board + reinforced concrete	185.32	23.91	380.32
3	Extruded polystyrene foam board XPS + autoclaved aerated concrete block	Plastic window (6 transparent + 9A + 6 transparent)	Foam glass insulation board + reinforced concrete	150.26	26.05	345.26
4	Rock wool board vertical fiber + autoclaved aerated concrete block	Aluminum-plastic co-extrusion window (6 low-transparent double-silver Low-E+12A+6 transparent glass)	EPS board + reinforced concrete	220.42	23.74	415.42
5	Rock wool board vertical fiber + autoclaved aerated concrete block	Heat-dissipating aluminum alloy window (6 low-transition single silver Low-E+12A+6 transparent glass)	Foam glass insulation board + reinforced concrete	209.39	24.24	404.39
6	Rock wool board vertical fiber + autoclaved aerated concrete block	Plastic window (6 transparent + 9A + 6 transparent)	XPS board + reinforced concrete	163.07	25.66	358.07

End of Table A4

Scheme number	A	B	C	Initial construction cost (Yuan/m^2)	Annual energy cost A (Yuan/m^2)	LCC_{PV} (Yuan/m^2)
7	Inorganic thermal insulation mortar + autoclaved aerated concrete block	Aluminum-plastic co-extrusion window (6 low-transparent double-silver Low-E+12A+6 transparent glass)	Foam glass insulation board + reinforced concrete	203.81	24.15	398.81
8	Inorganic thermal insulation mortar + autoclaved aerated concrete block	Heat-dissipating aluminum alloy window (6 low-transition single silver Low-E+12A+6 transparent glass)	XPS board + reinforced concrete	181.53	23.89	376.53
9	Inorganic thermal insulation mortar + autoclaved aerated concrete block	Plastic window (6 transparent + 9A + 6 transparent)	EPS board + reinforced concrete	138.75	25.96	333.75

Table A5. Construction cost for various parts of the envelope structure

Structural part	Structural form		
An exterior wall type	Extruded polystyrene foam board XPS + autoclaved aerated concrete block	Rock wool board vertical fiber + autoclaved aerated concrete block	Inorganic thermally insulated mortar + autoclaved aerated concrete block
Comprehensive unit price (Yuan/m^2)	184.60	229.72	171.41
Unit construction area cost (Yuan/m^2)	72.60	90.35	67.41
B window type	Aluminum-plastic co-extrusion window (6 low-transparent double-silver Low-E+12A+6 transparent glass)	Heat-dissipating aluminum alloy window (6-through double silver Low-E+12A+6 transparent glass)	Plastic window (6 transparent + 9A + 6 transparent)
Comprehensive unit price (Yuan/m^2)	659.48	474.14	288.75
Unit construction area cost (Yuan/m^2)	104.48	87.14	45.75
C roof type	XPS board + reinforced concrete	EPS board + reinforced concrete	Foam glass insulation board + reinforced concrete
Comprehensive unit price (Yuan/m^2)	138.41	131.27	163.72
Unit construction area cost (Yuan/m^2)	26.98	25.58	31.91

Table A6. Exterior wall thermal properties settings

Material	Number	Thickness (mm)	Thermal conductivity (W/m·K)
Cement mortar	1	20	0.93
Extruded polystyrene board	22	30	0.03
Autoclaved aerated concrete block	39	200	0.18
Cement mortar	18	20	0.93