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BIM-Based Comparative Analysis of Insulation Materials for Public Building Envelopes in Subtropical Climates: Energy, Cost, and SDG Perspectives

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ABSTRACT: In regions with Subtropical Climates, public buildings face ongoing challenges in reducing building energy consumption and carbon emissions. This study used Revit 2016 software to establish a BIM model for a public teaching building at Guangxi University in China, and dynamic simulation analysis was conducted using the THS-BECS 2022 simulation platform to evaluate the energy consumption, economic, and environmental performance of four insulation materials: glass wool, rock wool, XPS boards, and urethane foam. The results show that urethane foam has the highest energy savings (8.57%) and lowest carbon emissions (8.13 kg/m²), followed by XPS boards, while rock wool and glass wool perform moderately but have advantages in fire safety and durability. Although urethane foam has a higher initial cost, its life cycle cost-effectiveness is significant due to significantly lower operating costs. This study provides a replicable framework for integrating BIM with SDG-aligned material selection in public building retrofits, supporting the selection of insulation materials in building renovations. The findings offer practical guidance for architects, engineers, and policymakers aiming to align green building practices with the Sustainable Development Goals (SDGs).

KEYWORDS: Building Information Modeling (BIM), Building Energy Simulation, Building Insulation Materials, Carbon Emissions, Cost-Effectiveness, UN SDGs

I. INTRODUCTION

1.1 Background

The construction industry is one of the primary sources of global energy consumption and carbon emissions, accounting for 36% to 40% of global energy consumption (IEA,2022) and nearly 37% of global carbon emissions (UNEP,2022). primarily due to the demand for heating, cooling, and lighting. Climate change is accelerating, with 2023 marking the hottest summer on record, further heightening the urgency of improving building energy efficiency (WMO, 2022.). In subtropical climate regions, cooling energy consumption accounts for over 50% of operational energy consumption in public buildings (Yu et al., 2023). Enhancing the thermal insulation performance of building envelopes is a key measure to reduce energy consumption and carbon emissions (Ji et al., 2023).

Against this background, the United Nations 2030 Agenda for Sustainable Development established 17 Sustainable Development Goals (SDGs), among which SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) explicitly emphasize reducing building energy consumption, promoting green buildings, and achieving low-carbon urban development (UN,2015).

Consequently, global energy challenges, commitments to sustainable development goals (SDGs), and strong policy drivers collectively highlight the importance of building energy retrofits. This context provides a foundation for exploring BIM-enabled envelope optimization as a pathway to enhance energy performance and support sustainable development goals.

1.2 Research status and gaps

In subtropical regions, public buildings face high cooling demands due to the poor thermal insulation performance of their building envelopes, such as walls and roofs (Yu et al., 2023). Global policymakers have introduced targeted strategies. The EU's 'Green Deal' and 'Flood Wave' initiatives support large-scale building renovations to reduce energy demand (European Commission, 2020). China has committed to achieving carbon emissions peaking by 2030 and carbon neutrality by 2060 under its 'dual carbon' goals, and has listed public building

energy efficiency upgrades as a national priority (NDRC, 2021).

Although studies have shown that improving the performance of building envelopes can reduce energy consumption by 20–35% (Li et al., 2022; Zhao et al., 2025), research on renovation strategies for existing buildings remains scattered. and often lack comprehensive evaluation frameworks.

This study will clearly outline the current state of research from the following four aspects, aiming to identify research gaps in existing studies and fill critical gaps.

1.2.1 BIM in Building Energy Performance Analysis

Across multiple contexts, Building Information Modelling (BIM) has emerged as a valuable tool for improving energy efficiency in building design and retrofitting. BIM enables integrated architectural geometry, spatial relationships, and lifecycle data into a shared platform, enabling 4D (time), 5D (cost), and 6D (sustainability) analysis (Vaz et al., 2024). When combined with simulation tools such as Insight 360, DesignBuilder, and EnergyPlus, BIM enables early-stage analysis of building energy performance (Alhammad et al., 2024).

Numerous case studies have demonstrated BIM's potential. In China, the Pearl River Tower optimized its double-skin façade and shading system using BIM technology, reducing energy consumption by approximately 40% (Alaboud & Alshahrani, 2023). A commercial building project in Chengdu used Revit and THS software to simulate various building envelope parameters, achieving approximately 25% energy savings, with simulation results highly consistent with actual monitoring data (Liu et al., 2024). Studies from Malaysia and Indonesia also highlight that optimizing envelope design and window-to-wall ratios through BIM can reduce energy use by around 30% (Hmidah et al., 2023; Tanne et al., 2025). Despite these advances, BIM applications in subtropical public building retrofits remain limited (Ng et al., 2025).

While BIM tools can simulate multiple energy scenarios, Existing studies often analyse material parameters (such as thermal conductivity or thickness) in isolation, without systematically comparing different insulation materials under actual operating conditions (Wang et al., 2024). In addition, cost, environmental performance and energy-saving effects are rarely included in comprehensive decision-making frameworks (Arowoiya et al., 2024; Cao et al., 2024; Moghaddam et al., 2023). As a result, there is insufficient integration of energy efficiency, sustainability, and economic feasibility in retrofit decision-making.

1.2.2 Role of Building Envelopes in Energy Efficiency

The thermal performance of building envelopes has a decisive impact on the overall energy efficiency of buildings (Liu et al., 2023). Appropriate envelope materials not only effectively reduce the thermal load of buildings, but also enhance their thermal stability and energy consumption response in extreme climates (Rashid et al., 2024). In recent years, new types of envelope structure materials with low thermal conductivity, high thermal inertia, and excellent ecological performance have emerged and played an increasingly important role in energy-efficient building design and renovation (Kitsopoulou et al., 2024).

From a thermodynamic perspective, heat transfer through building envelopes primarily occurs via conduction, convection, and radiation (Erzen et al., 2025). Materials with lower thermal conductivity (λ) provide higher thermal resistance (R-value), which directly determines the effectiveness of the envelope in slowing heat transfer (Arowoiya et al., 2024).

In addition to thermal conductivity, solar absorptance and thermal inertia are key parameters. High solar absorptance materials can lead to excessive heat gain and elevated cooling demands in summer, while materials with low absorptance are more effective for roofs and sun-exposed façades (Cao et al., 2024). Thermal inertia, reflecting a material’s ability to store and release heat, also contributes to stabilizing indoor temperatures and reducing reliance on mechanical cooling and heating systems (Moghaddam et al., 2023). These performance indicators must be evaluated comprehensively in material selection processes.

Recent studies emphasize that building envelope improvements can achieve 20%–40% reductions in energy consumption depending on climate type and material choice (Liu et al., 2023). For example, multi-layer wall assemblies combining high-performance insulation with reflective surface coatings have been shown to simultaneously reduce thermal transmittance (U-value) and improve annual energy efficiency (Ali et al., 2024). Moreover, the environmental impact of material production and its life-cycle carbon footprint are increasingly

recognized as critical considerations in selecting envelope systems (Wu & Zhang, 2022).

1.2.3 Comparative Studies on Insulation Materials

Currently, there are various thermal insulation materials available on the market for reducing heat loss in buildings and improving energy efficiency, including organic and inorganic types(Yuk et al., 2023). S Common organic materials include polystyrene foam (EPS/XPS), polyurethane foam (PUR/PIR), phenolic foam (PF), and cellulose-based products (e.g., sprayed cellulose pulp) (Liu et al., 2025). These materials feature low thermal conductivity, good thermal inertia, lightweight properties, and ease of installation, making them suitable for exterior walls, roofs, floors, and windows (Teng et al., 2025). Inorganic materials such as rock wool, glass wool, and wood wool also exhibit excellent thermal performance and are widely used in building envelopes (Asdrubali et al., 2023).

In addition to thermal performance, recent studies have emphasised the importance of cost-effectiveness and life cycle carbon emissions (LCA) when selecting insulation materials.

For example, while polyurethane foam can save more energy in the short term, mineral wool has lower embedded carbon emissions and higher recycling rates, making it more advantageous in LCA assessments (Hernando Castro et al., 2025). Teng et al. (2025) noted that phenolic foam offers high thermal insulation with thinner thicknesses, but its high production costs may undermine its short-term advantages unless considered from a lifecycle perspective. Studies indicate that the embedded energy consumption and carbon emissions of insulation materials account for a significant proportion of a building's total environmental impact (Méndez Echenagucia et al., 2023). Emphasizing the need to consider both operational carbon and embedded carbon in material selection (Abbasi Kamazani & Dixit, 2025).

Nonetheless, most studies lack an integrated decision framework that simultaneously evaluates energy performance, cost-effectiveness, and alignment with SDG targets.

1.2.4 Integration of SDG Targets in Building Retrofit Research

Research on energy-efficient retrofits of public buildings is driving progress toward global sustainable development goals, aligning building-level outcomes with the three pillars of the Sustainable Development Goals (SDGs) 7, 11, and 13: energy, sustainable cities, and climate action. In 2022, buildings accounted for 34% of final energy demand and 37% of energy- and process-related carbon dioxide emissions, highlighting the urgency of transformative action to achieve the Paris Agreement goals (IEA,2022). Meanwhile, the SDGs call for universal access to affordable, reliable, sustainable, and modern energy for all (SDG 7), inclusive and resilient urban systems (SDG 11), and urgent action to combat climate change and its impacts (SDG 13) (UN,2015).

Moreover, SDG-aligned retrofitting research remains underdeveloped. For SDG 7, building envelope upgrades have been shown to cut energy intensity by 20–40%(Elnagar et al., 2023.). For SDG 11, improvements to thermal comfort and urban resilience have been noted (Vandewiel et al., 2025). For SDG 13, low-carbon materials have been proven to reduce operational emissions by up to 35% over 20 years (Papadakis & Katsaprakakis, 2023). Despite these encouraging results, the integration of BIM simulation tools into an SDG-informed retrofit framework remains insufficient.

Overall, research on energy-efficient retrofits of public buildings in subtropical climates faces several gaps:

(1) a lack of comparative studies on insulation materials under realistic operating conditions;

(2) limited integration of economic and environmental factors in material selection;

(3) insufficient application of BIM tools tailored to local standards and climates;

(4) inadequate linkage between retrofit decisions and SDG targets.

Addressing these gaps requires the development of BIM-driven multi-scenario frameworks that evaluate material options based on energy efficiency, cost, and SDG compatibility.

This study addresses these gaps by employing the following approaches: using the THS-BECS 2022 software, adapted to local policies and climate data, to conduct BIM simulations of public buildings in a subtropical region (Nanning City, China), conducting multi-condition comparative analyses of insulation materials, and integrating an energy-cost-SDG evaluation framework. This contributes to achieving sustainable development goals.

International Journal of Engineering, Management and Humanities (IJEMH)
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1.3 Research objectives

This study uses BIM as a decision-support tool to evaluate the impact of different insulation materials on the energy performance of subtropical public buildings. Taking Building No. 5 of Guangxi University in Nanning, China, as the case study. Revit modelling and THS-BECS 2022 were used for simulation analysis. By comparing four material schemes and verifying the consistency of the results with actual data, the study identified the optimal solution that aligns with Sustainable Development Goals (SDGs) 7, 11, and 13 in terms of energy efficiency and cost-effectiveness.

This study aims to construct a BIM model of the target building and conduct baseline energy consumption simulations. Based on this, it compares the trends in building energy consumption under different insulation material conditions. By comprehensively evaluating energy-saving effectiveness, material cost-effectiveness, and alignment with Sustainable Development Goals (SDGs), it proposes an optimal insulation material selection framework guided by sustainability principles.

Ultimately, this research further explores the integrated application of BIM in energy-saving material selection and SDG-oriented architectural design, providing technical support and practical pathways for green, low-carbon retrofitting of public buildings in subtropical regions.

1.4 Significance and Novelty

This study provides a practical framework for selecting insulation materials for energy-efficient retrofits of subtropical public buildings, which have high energy consumption due to high cooling loads. By combining BIM simulation with material selection, this study supports retrofit strategies guided by the Sustainable Development Goals (SDGs) (SDGs 7, 11, 13), offering both theoretical and practical guidance for sustainable retrofits in China and similar regions.

The novelty of this study lies in four aspects. First, the study focuses on energy-saving retrofits of public buildings in typical subtropical climate regions, thereby enhancing the regional adaptability of retrofit strategies. Second, using BIM as a platform, the study conducts multi-condition simulations of different insulation materials and systematically compares their energy-saving effects, costs, and sustainability performance. Third, it introduces an SDG evaluation perspective and establishes an insulation material selection optimization model based on the "energy consumption-cost-SDG compatibility" framework. Finally, the study applies the THS-BECS 2022 software developed in China, which is compatible with local regulations and climate datasets, ensuring strong policy relevance and practical applicability.

II. METHODOLOGY

2.1 Research Framework

This study adopts a combined approach of quantitative simulation analysis and case study, focusing on energy consumption optimization strategies for typical public buildings in China's subtropical climate zone.

First, a typical public building (a university teaching building) located in Nanning, Guangxi, was selected as the research object. The building is located in a subtropical climate regions with high cooling load requirements and is highly representative (Hamdane et al., 2024). The research team collected complete design drawings, construction information, and operational data for the building, providing a solid foundation for subsequent modeling and calibration.

Then, through a year-long field monitoring of energy consumption under normal operating conditions, actual electricity consumption data for systems such as air conditioning, lighting, outlets, and ventilation were collected to obtain the total annual energy consumption (Hamdane et al., 2024).

After verifying the validity of the simulation model, this study further set up multiple scenarios for replacing the thermal insulation materials of the building envelope, selecting four different thermal insulation materials(Glass Wool/ Rock Wool/ XPS Board / Urethane Foam) to replace the original exterior wall and roof materials of the building, and conducting multi-condition simulations(Alrasheed, 2023).

Finally, by comparing the performance of various material combinations in terms of annual cooling load, total energy consumption density, energy reduction rate, and economic efficiency, a set of energy-saving optimization evaluation criteria oriented toward achieving the SDG sustainable development goals was established, and the optimal envelope renovation plan was proposed, providing data support and decision-making references for the green transformation and energy-saving upgrade of public buildings in subtropical climate zones. Figure

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

2.1 summarizes the research design process of this paper.

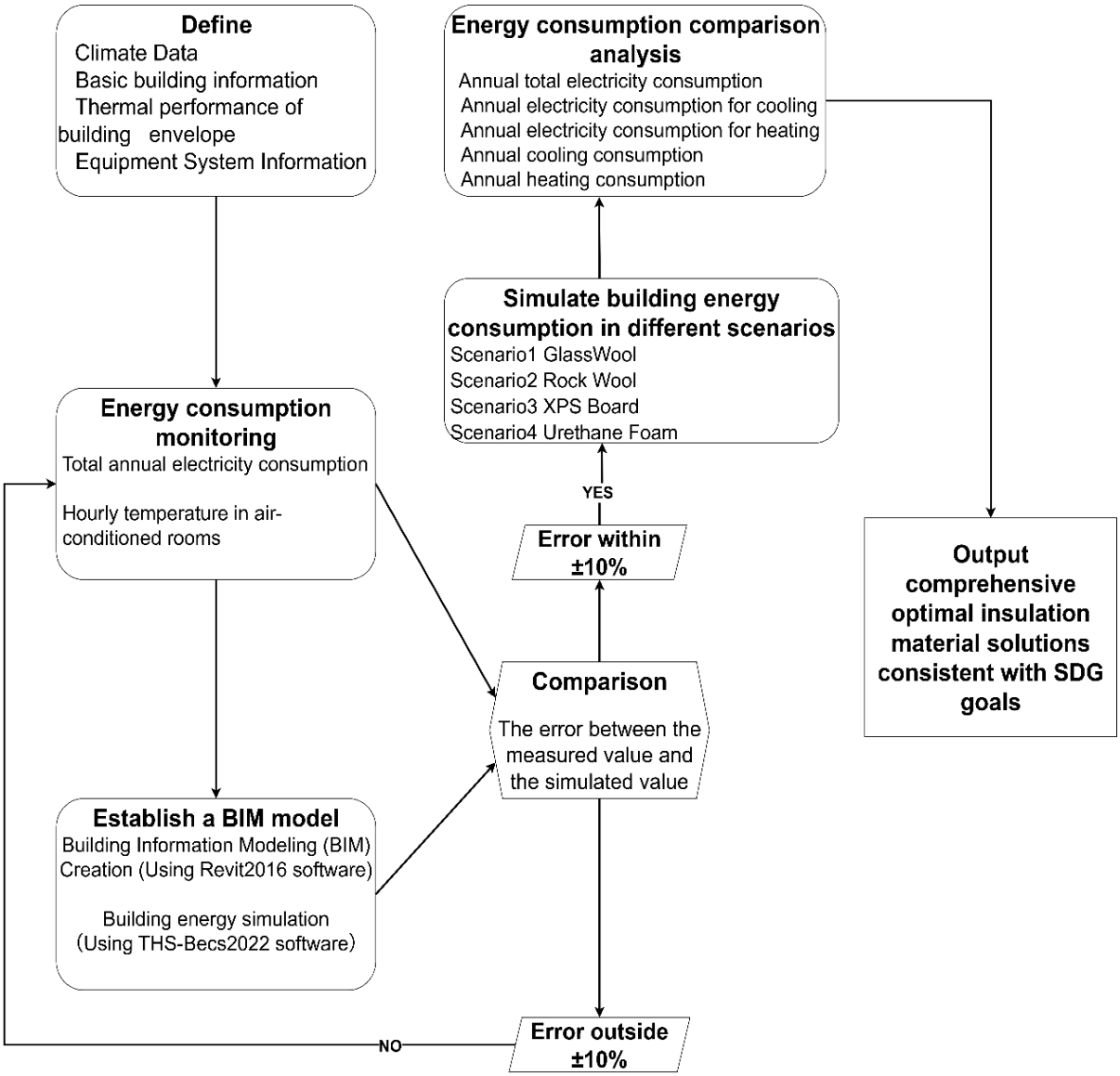

Figure 2.1 Research process

2.2 Case Study Building Description

This study selected the Guangxi University No. 5 Teaching Building located in Nanning City, Guangxi Province, China, as the research object, focusing on the energy consumption performance and energy-saving optimization potential analysis of typical public buildings in a subtropical climate zone (Zhou & Wang, 2023). The region is situated in a subtropical climate zone, characterized by hot and humid summers and mild winters, with significant cooling loads throughout the year, imposing higher requirements on the thermal performance of building envelopes (Tang et al., 2025) .

The total floor area of the building under study is 4,271 m², with five above-ground floors and no underground space. The total building height is 23.4 m, oriented approximately 90° north, and the structural form is a reinforced concrete frame structure, ensuring good seismic resistance and structural stability (Azzazy et al., 2025). This building is a typical educational public building, primarily serving daily teaching, office, and meeting

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

functions (Liu et al., 2025). It has high personnel mobility and stringent requirements for indoor thermal comfort and the continuity of energy supply (Fan et al., 2024).

The selection of this building was based on three key factors. First, it is representative of public institutional buildings in China's subtropical regions in terms of structure, usage, and energy demand characteristics, making it an ideal prototype for retrofit research. Second, the availability of detailed architectural drawings, historical energy consumption data, and an existing BIM model makes it feasible for accurate simulation and validation. Third, the building is located in a climate zone typical of southern China, providing a valuable case for studying energy efficiency strategies tailored to subtropical climatic conditions. These attributes ensure that the findings of this study can offer transferable insights for similar public buildings across the region.

2.3 Data Collection and Field Measurement

The research team conducted a year-long energy consumption monitoring and climate measurement of the building to ensure the scientific accuracy of subsequent BIM energy consumption simulations (Roka et al., 2025). Long-term actual measurement data is crucial for verifying the reliability of BIM energy consumption simulations and calibrating model parameters, thereby effectively improving the consistency between simulation results and actual operating conditions (Cherif Louazani et al., 2025.).

The field measurements included annual average hourly outdoor temperatures, hourly indoor temperatures in air-conditioned rooms, and total annual electricity consumption of the building, to provide reliable basic data to support the setting of simulation parameters and model calibration.

The monitoring covered the electrical energy consumption of the cooling and heating systems during building operation, the total electricity consumption of the entire building, and the thermal performance parameters of key parts of the building envelope (roof and exterior walls)(Zhan et al., 2025).

To gain a comprehensive understanding of the thermal environment changes within a building, the team selected the Testo 176-T4 four-channel temperature and humidity recorder, paired with TJ36 K-type thermocouple sensors (Ben Ratmia et al., 2024). The system continuously and automatically records the average outdoor temperature of the building and the hourly temperatures of the air-conditioned rooms on the roof and in the east, west, south, and north directions of the building, with a sampling interval of one hour (Saragih et al., 2024).

Additionally, to obtain actual annual energy consumption data for the building, the research team installed the WEISUN DTS353F-4Z three-phase rail-mounted intelligent electricity meter in the main circuit of the distribution system. This meter continuously monitors the total electricity consumption of various systems, including lighting, air conditioning, and electrical outlets. The basic information of the building is shown in Table 2.1.

Table 2.1 Basic Information About The Building

Project Category	Parameter Content	Value/Description
Building Information	Project location	Nanning, Guangxi, China
	Climate Classification	Subtropical humid climatic zone summer hot and winter warm region (GB 50176-2016)
	Geographical Coordinates	North latitude 23.00° east longitude 108.35°
	Total building area	4271 m²
	building volume	17236.04 m³
	Number of floors	5，No underground space
	Total height	23.4m
	Orientation	90° northeast
	Building structure	Reinforced concrete frame structure
Thermal performance of building envelope	Thermal insulation materials	Expanded polystyrene bead insulation mortar

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

		(Thermal Conductivity: 0.060W/mK)
	Insulation type	Internal insulation
	External wall thermal transmittance coefficient (K value)	1.479 W/(m2·K)
	External wall solar radiation absorption coefficient	0.68
	Roof heat transfer coefficient (K value)	0.926 W/(m2·K)
	Roof solar radiation absorption coefficient	0.86
	Outer window heat transfer coefficient (K value)	3.0 W/(m2·K)
	Window-to-wall ratio(average)	0.239
Energy consumption monitoring configuration	Data collection frequency	Automatically records every hour
	Data collection cycle	2024.1-2024.12
	Temperature and humidity monitoring	Testo 176 T4 - Temperature data logger + TJ36 K-Type Thermocouple
	Annual electricity consumption monitoring equipment	DTS353F-4Z Three-Phase Rail-Mounted Intelligent Electricity Meter

2.4 BIM Model Development

This study uses Autodesk Revit 2016 software to construct a building information model (BIM) for energy consumption analysis and energy conservation strategy simulation.

The construction plan of the building is shown in Figure 2.2.

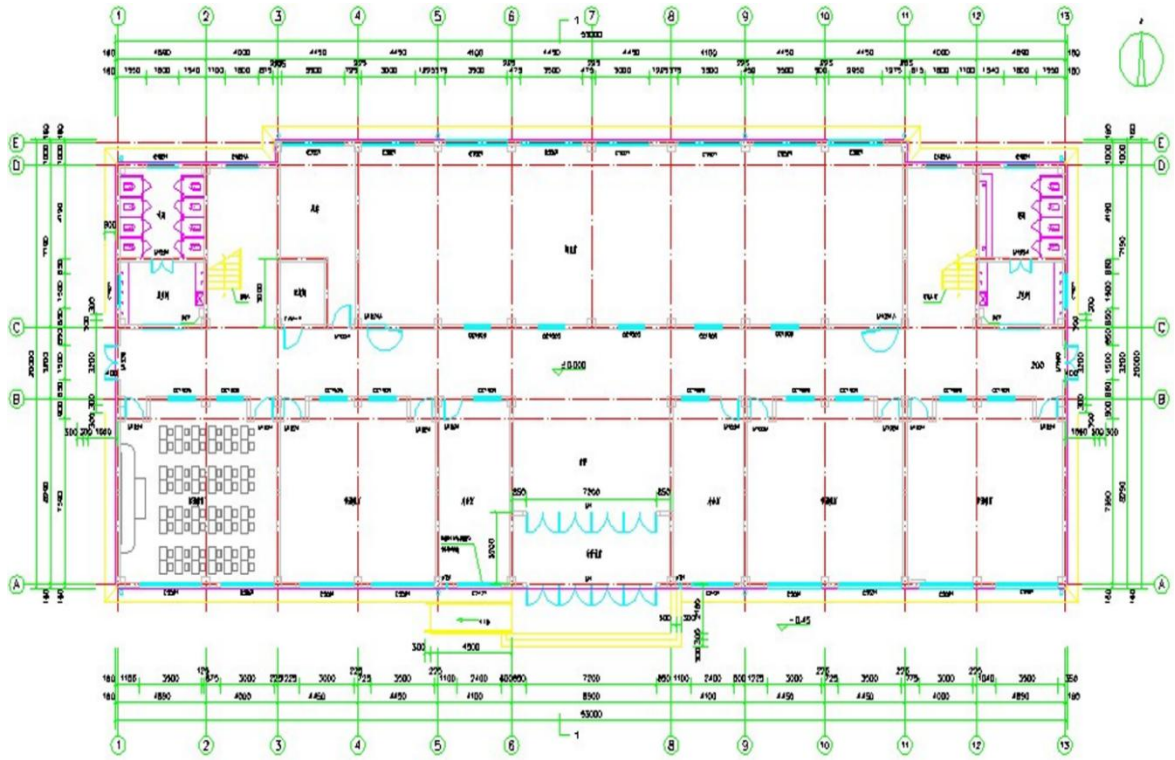

Figure 2.2 Ground floor plan

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

The BIM model of the target building was accurately constructed based on the construction drawings, site survey data and parameters provided in Form 2.1, covering key structural elements such as the main structure, exterior walls, roof, floor slabs, windows, doors and shading devices.

. During the modeling process, ensure the accuracy and completeness of the model, especially for building envelopes (exterior walls and roofs, doors and windows, floor slabs, etc.) involving heat transfer.

Enter detailed parameters, including material thermal conductivity, thermal resistance, thickness, and other information. The construction drawing of the main enclosing structure is shown in Figure 2.3.

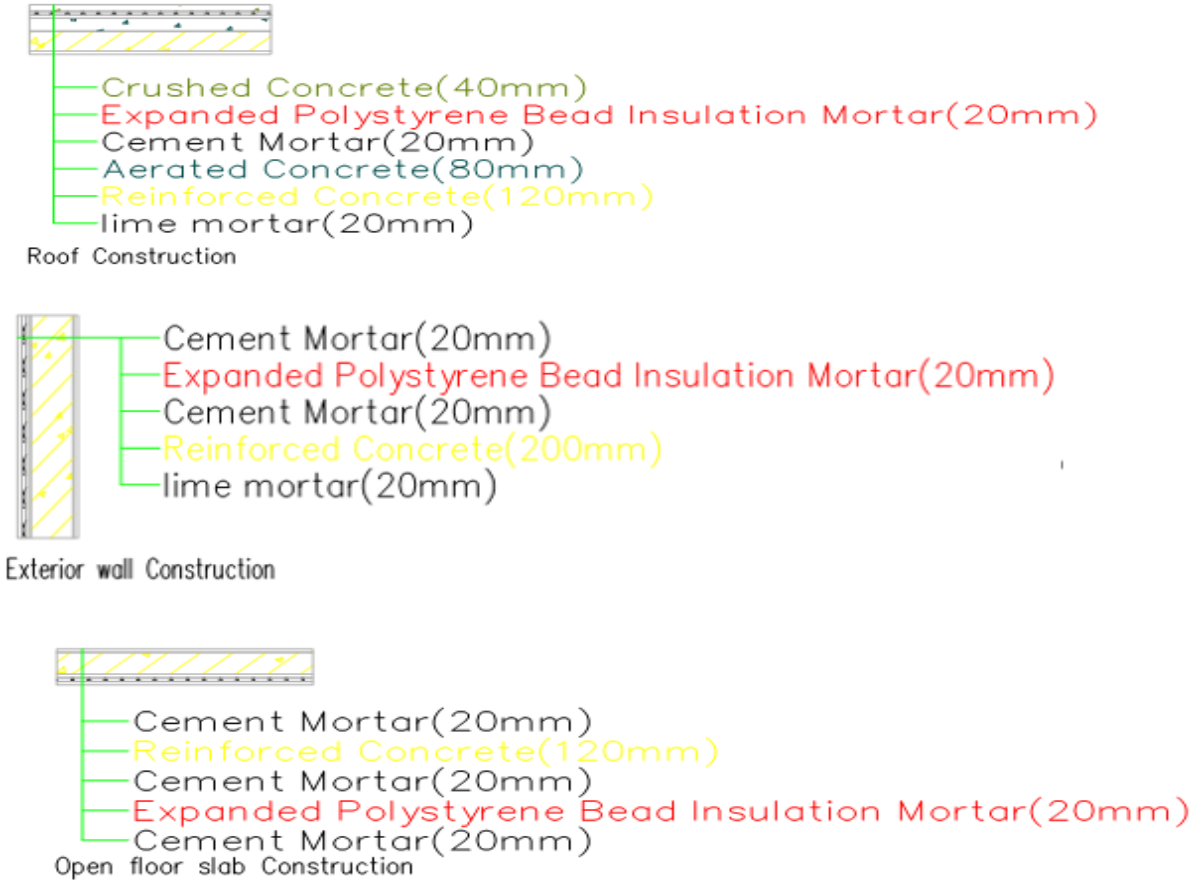

Figure2.3 Main enclosure structure

The thermal performance parameters of building envelope materials are shown in Table 2.2.

Table 2.2 Thermal Performance Table for Building Envelope Materials (Source: "Code for Thermal Design of Civil Buildings" GB50176-2016)

Materials	**Thermal Conductivity (λ)**	**Heat Storage Coefficient(S)**	**Density (ρ)**	**Heat Capacity (Cp)**	**Steam Permeability Coefficient(u)**
	(W/mK)	W/(㎡.K)	kg/m3	J/(kg.K)	g/(m.h.kPa)
Cement mortar	0.930	11.370	1800.0	1050.0	0.0210
Lime mortar	0.810	10.070	1600.0	1050.0	0.0443
Reinforced concrete	1.740	17.200	2500.0	920.0	0.0158
Crushed concrete	1.510	15.360	2300.0	920.0	0.0173

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

Expanded polystyrene bead	0.060	0.950	230.0	900.0	0.0010
Insulation mortar					
Aerated concrete	0.180	3.100	700.0	1050.0	0.0998
Concrete porous brick	0.750	7.490	1450.0	709.4	0.0000

The modeling steps include creating floor elevations, drawing elevation grid lines, laying out the foundation, drawing columns, beams, and slabs, creating stairs, roofs, walls, doors, and windows, and drawing detailed components and ancillary components. The surrounding environment of each floor of the building is free from light obstruction, and the internal areas primarily consist of offices, rest rooms, and activity rooms, with rooms of the same function having consistent floor areas.

The accuracy of the model and the rationality of room parameter settings are critical factors for energy consumption simulation. To enhance the efficiency of factor analysis during parameter-driven simulation, parameters such as building materials, building orientation, building mass, and window-to-wall ratio are selected for building energy consumption simulation to analyze whether these parameters meet energy-saving requirements.

After completing the detailed construction of the BIM building information model on the Autodesk Revit platform, this study exported the model to a gbXML format file compliant with the requirements of the THS-BECS 2022 software, imported it into the energy analysis platform, and generated a BIM energy consumption analysis model. During the import process, the building's spatial structure, envelope structure, floor information, and material thermal performance parameters were retained to ensure consistency between energy consumption simulation and the original design information. Subsequently, the following key parameters related to energy consumption simulation were set in THS-BECS 2022:

First, geographical location and meteorological parameter settings. In the software, select the city where the study object is located (Nanning City), enter its geographical information (latitude 23.00° N, longitude 108.35° E) and elevation, and import the annual hourly meteorological data file to accurately reflect the external thermal environment changes of the building under subtropical climate conditions (Eldamaty, 2024).

Second, building orientation and external environment settings. Verify the actual orientation of the building (90° north) in the software and set the surrounding environmental shading conditions, including the height and spacing of surrounding buildings and whether there are significant shading effects, to improve the accuracy of solar radiation heat gain and cooling load calculations (GB 50176-2016). For exposed roof and facade envelope structures, further check the orientation parameters automatically generated by the software to ensure they are completely consistent with the actual building orientation.

Third, internal usage conditions and operational parameter settings. Based on field survey results and building functional characteristics, set the building's operational hours as 8:00–22:00, with personnel density values taken from standards for office and educational public buildings (DBJ/T45-096-2022). Internal heat loss (human heat loss, equipment heat loss, and lighting heat loss) is entered according to regulations. The lighting power density is set to 10 W/m², and the power density of socket devices is recorded as 7 W/m² to accurately reflect the internal heat load of the building under normal operating conditions (Možina et al., 2024).

Fourth, HVAC system parameter settings. The cooling and heating modes of the air conditioning system are entered based on the actual measured unit models and operating parameters. The energy efficiency ratio (EER) of the cooling units is set to 3.2, and the coefficient of performance (COP) of the heating system is set to 2.8. Parameters such as supply air temperature difference, supply-to-return air ratio, and heat loss rates of pipes and equipment are taken from the “Energy Conservation Design Standards for Public Buildings” (DBJ/T45-096-2022).The terminal control adopts a zone control strategy to reflect the actual operating characteristics of the multifunctional spaces in the teaching building (Hu et al., 2022).

Finally, simulation accuracy and output parameter settings. The simulation time step is set to 1 hour to obtain the annual cooling load, heating load, and energy consumption data for all systems over 8,760 hours. Output parameters include total building electricity consumption, cooling electricity consumption, heating electricity consumption, air conditioning system load distribution, and the proportion of lighting and equipment energy

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

consumption. These data enable a comprehensive analysis of the building's energy consumption structure and provide a unified baseline for comparing the energy efficiency of different insulation material replacement options in subsequent analyses (ASHRAE, 2002). Figure 2.4 shows the energy model of the building.

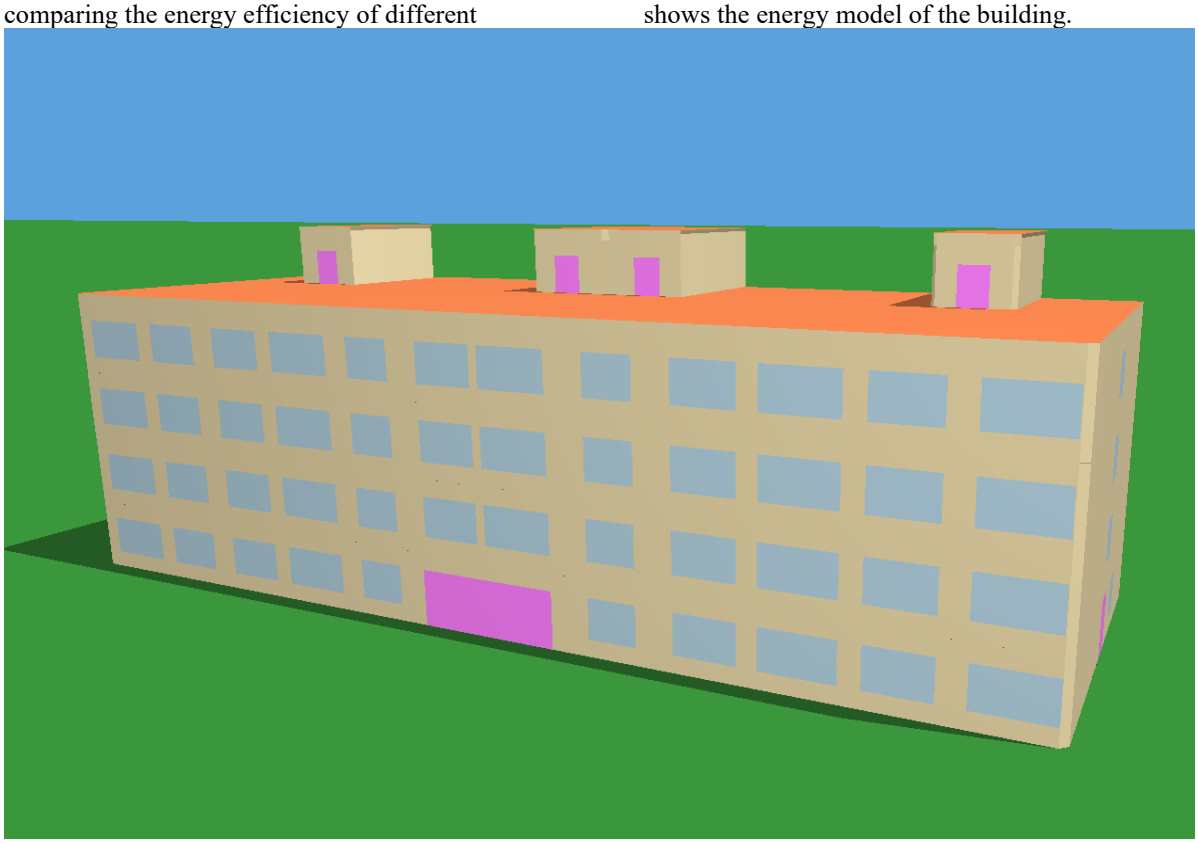

Figure 2.4 BIM energy model of a building

2.5 Model Calibration

To ensure the scientific accuracy and reliability of BIM energy consumption simulation results, this study first established a BIM energy consumption model based on original operating conditions. Subsequently, the annual energy consumption of the building under current conditions was simulated and calculated, and the results were compared and verified in detail with actual measured energy consumption data. The verification process followed ASHRAE Guideline 14 (2002) and relevant building energy consumption simulation accuracy standards (ASHRAE, 2002).

By comparing the simulation results under original operating conditions with actual energy consumption data, the relative error is calculated and the model is evaluated to determine whether it meets the accuracy requirements. The error calculation uses the mean bias error (MBE) (ASHRAE, 2002). According to ASHRAE Guideline 14, the MBE for hourly energy consumption should be controlled within ±10%.

The formula for calculating MBE is derived from ASHRAE Guideline 14-2002, an authoritative standard document published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) for the measurement and verification of building energy consumption and demand savings. According to the standard, the formula for calculating MBE is:

$$\boldsymbol{MBE}(\%) = \frac{\sum_{i=1}^{n}(\boldsymbol{M_i} - \boldsymbol{S_i})}{\sum_{i=1}^{n}\boldsymbol{S_i}}$$

2.5.1 Comparison of hourly outdoor air temperature

This study conducted a one-year field measurement of outdoor air temperature at the research building. Professional equipment was used to collect temperature data once every hour, recording temperature changes at 24 time points from 0:00 to 23:00 each day, thereby achieving continuous 24-hour temperature sampling. A total of 8,760

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

temperature data sets were collected throughout the year, comprehensively covering typical climate fluctuations across all four seasons.

Concurrently, THS-Becs2022 software was run to simulate hourly outdoor temperature distributions for the building over the entire year. The results of the measured data were compared with the simulated data, as shown in Figure 2.5, The blue dashed line represents the actual data, while the orange dashed line represents the simulated data.

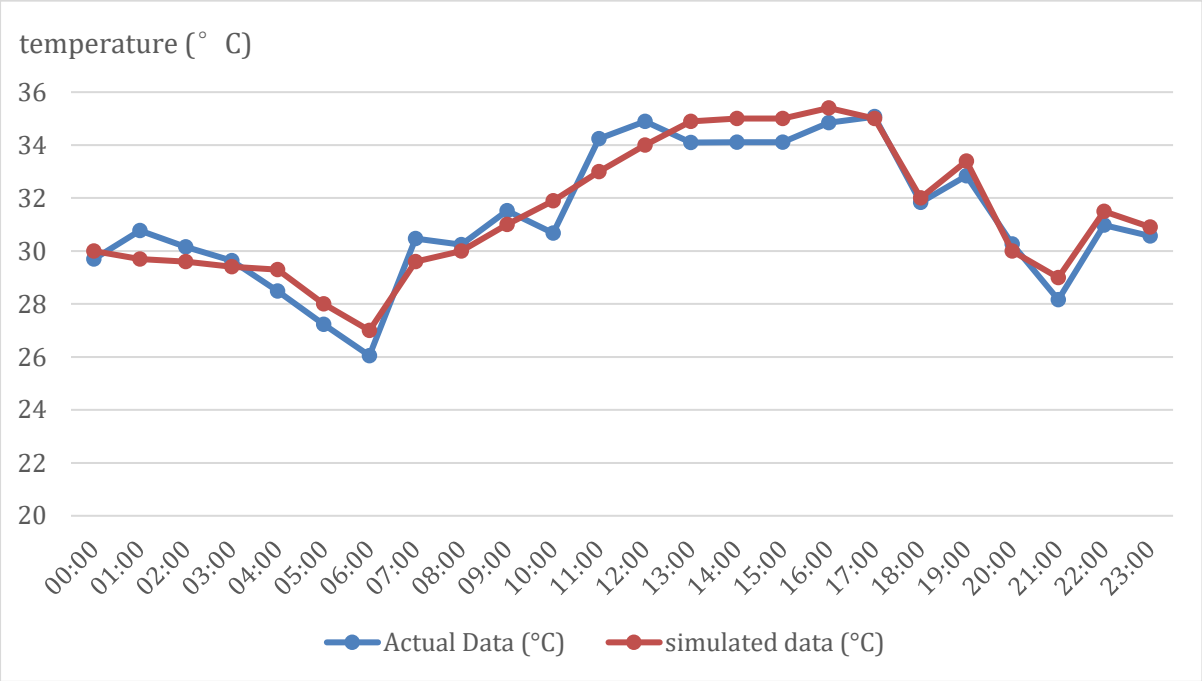

Figure 2.5 Hourly outdoor air temperature data (Comparison of Actual Measurement and Simulation)

Based on actual temperature data, the average daily temperature of the building was calculated to be 31.29°C. According to the Civil Building Thermal Design Code (GB 50176-2016), the typical daily outdoor temperature range for Nanning City, Guangxi Province, is 30.8°C to 34.4°C. The measured data is highly consistent with the standard values, confirming its representativeness and reliability as input parameters for subsequent energy simulation and model calibration.

The comparison of hourly temperatures between simulation and actual measurements shows a high degree of consistency. The simulated daily average temperature was 31.44°C, differing by only 0.15°C from the actual measured value of 31.29°C. The mean bias error (MBE) is approximately 0.48%, far below the ±10% threshold for hourly data specified in ASHRAE Guide 14-2002, indicating that the model has high accuracy and stability. Hourly trend analysis shows that the simulated temperature is slightly lower than the measured value during the early morning hours (1:00–6:00 AM), with the maximum deviation of -1.07°C occurring at 1:00 AM. During the periods from 11:00 AM to 5:00 PM and 7:00 PM to 11:00 PM, the simulated temperatures were highly consistent with the measured temperatures. These results confirm that the BIM-based energy simulation model can accurately reflect the external thermal environment of the subtropical climate in southern Ningxia, providing a reliable basis for subsequent energy analysis and optimisation.

2.5.2 Comparison of annual electricity consumption of buildings

The research team also conducted a year-long on-site measurement of the total electricity consumption of the target building. Data was recorded through daily scheduled meter readings and data export, with actual electricity consumption data collected monthly to ensure data continuity, completeness, and authenticity. To reduce errors, the research team also implemented backup storage and manual verification mechanisms to further enhance the reliability of the measurement results.

Concurrently run the THS-Becs 2022 software. Simulation results display the building's

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

annual energy consumption. Energy parameters comparable to measured data include total annual electricity consumption, annual cooling electricity consumption, and annual heating electricity consumption, as shown in Figure 2.6. The blue bar chart represents actual data, while the orange bar chart represents simulated data.

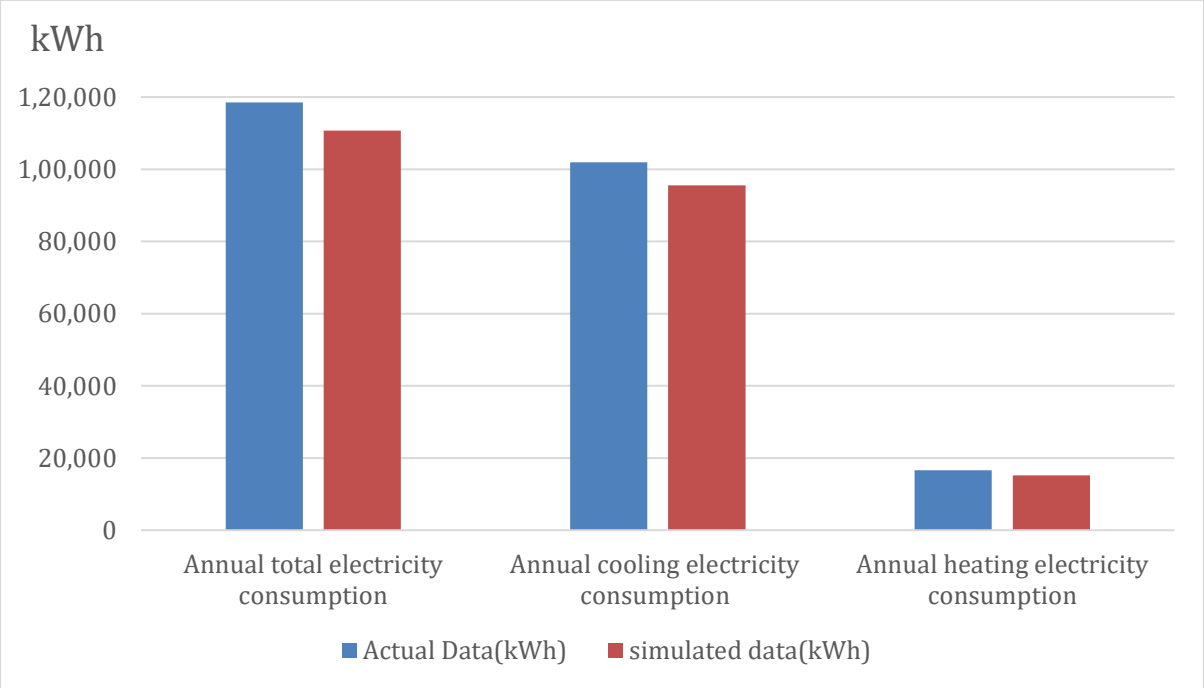

Figure 2.6 Annual electricity consumption of buildings (Comparison of Actual Measurement and Simulation)

The comparison results between simulated energy consumption data and actual measured energy consumption data show that the annual total electricity consumption of the simulated data is 110,679.99 kWh, which is 6.65% lower than the actual measured value of 118,559.68 kWh. Among these, the electricity consumption for cooling in the air conditioning system was 95,515.60 kWh, which is 6.32% lower than the measured value of 101,961.3 kWh; the electricity consumption for heating in the heating system was 15,164.39 kWh, which is 8.64% lower than the measured value of 16,598.38 kWh.

Overall, the simulated data is slightly lower than the measured data, but the deviations are all within the reasonable range of ±10%, meeting the requirements of ASHRAE Guideline 14-2002 for the calibration accuracy of building energy consumption models (annual data deviation $\leqslant \pm 10\%$). Further analysis indicates that cooling accounts for the largest share of total energy consumption, with differences primarily attributable to electricity consumption for cooling. This suggests that the thermal performance of building envelopes and air conditioning operating modes have a significant impact on simulation accuracy.

By comparing and analyzing the measured data with the simulated data, it can be seen that the deviations between the two are all within a reasonable range, meeting the relevant energy consumption model calibration standards. This further validates the reliability and applicability of the BIM energy consumption model constructed, laying a solid foundation for the subsequent development of energy-saving renovation scenario simulations.

Additionally, Analysis using the THS-BECS 2022 energy efficiency verification module showed that the building does not meet the Chinese Standard for Energy Conservation in Public Buildings (DBJ/T45-096-2022), particularly in the thermal conductivity and overall performance of exterior walls and roofs.

As shown in Table 2.3, this indicates weak envelope performance, with significant potential for optimizing summer cooling and winter heating energy use. These findings reveal the existing deficiencies in energy efficiency and provide a foundation for proposing retrofit schemes for exterior wall and roof insulation materials, as well as guiding subsequent simulation scenarios.

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

Table 2.3. Regulatory indicator inspection

Inspection items	Conclusion
Window-to-wall ratio	Suitable
Visible light transmittance ratio	Satisfactory
Skylight type	No roofed light-transmitting parts
Roof construction	Not satisfactory
Exterior wall construction	Not satisfactory
Effective ventilation area	Satisfactory
Non-hollow window area ratio	Not satisfactory
Exterior window air tightness	Satisfactory
Curtain wall air tightness	Satisfactory

2.6 Simulation Scenarios

In recent years, China has strengthened its regulatory framework for building energy efficiency, particularly in the public building sector. The government's 'dual carbon' strategy, announced at the 2020 United Nations General Assembly, aims to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. To this end, central and local governments have introduced mandatory standards to promote the transition of the construction industry towards green and low-carbon development.

As a typical subtropical climate region, Nanning requires all new and renovated public buildings to comply with the latest energy efficiency standards. In 2022, the Guangxi Zhuang Autonomous Region Department of Housing and Urban-Rural Development issued the "Energy Conservation Design Standards for Public Buildings" (DBJ/T45-096-2022), which specifies detailed requirements for thermal performance indicators of building envelopes, energy efficiency of heating, ventilation, and air conditioning systems, renewable energy utilization, as well as thermal conductivity coefficients and thermal capacity limits for walls and roofs.

At the national level, the Ministry of Housing and Urban-Rural Development (MOHURD) issued the "General Specifications for Energy Conservation and Renewable Energy Utilization in Buildings" (GB 55015-2021) in 2021, establishing uniform national requirements for building energy conservation and renewable energy utilization (GB 55015-2021). This standard covers some usable thermal insulation materials, as specified in Table 2.4.

Table 2.4 Material categories listed by MOHURD

Category	Material Name	Thermal Conductivity λ (W/m·K)
Organic	EPS board	0.037–0.043
	XPS board	0.028–0.033
	urethane foam	0.020–0.024
	phenolic board	0.025–0.030
	Expanded polystyrene bead insulation mortar	0.045–0.060
Inorganic	Rock wool	0.040–0.045
	Glass wool	0.040–0.045
	Foam glass	0.045–0.055
	Aerogel blanket	0.018–0.022
	Glass wool	0.040–0.045

According to the standards, this model will simulate four types of thermal insulation materials. Table 3.4 lists the products of thermal insulation materials that meet the energy-saving renovation standards, with material property values based on the thermal conductivity and density specified in the product specifications (GB 55015-2021). Among them, the original thermal insulation materials of the building are expanded polystyrene bead insulation mortar.

Based on the relevant building energy efficiency standards, this model simulates four types

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

of thermal insulation materials. As shown in Table 2.5, the selected insulation materials comply with the retrofit requirements stipulated in the General Code for Energy Efficiency and Renewable Energy Utilization in Buildings (GB 55015-2021). The thermal performance parameters of these materials, including thermal conductivity and density, are referenced from official product specifications. The original insulation material used in the building was expanded polystyrene (EPS) bead insulation mortar. In the simulation process, all parameters except for the insulation material remain consistent with the baseline settings in Table 2.1 and Table 2.2. Only the envelope insulation material is varied to construct four distinct simulation scenarios, aiming to evaluate the energy-saving potential under different material conditions.

Table 2.5 Materials chosen for the simulation scenarios

		Scenario (Original)	Scenario1	Scenario2	Scenario3	Scenario4
Material		Expanded Polystyrene Bead Insulation Mortar	Glass Wool	Rock Wool	XPS Board	Urethane Foam
	Density (kg/m3)	230	140	135	40	63
Properties	Thermal Conductivity (W/mK)	0.060	0.050	0.042	0.030	0.027
	Heat Capacity (J/kgK)	900.0	962.0	1340.0	1488.0	1500.0
	Heat Storage Coefficient W/(㎡.K)	0.950	0.700	0.761	0.360	0.431
	Steam Permeability Coefficient g/(m.h.kPa)	0.0010	0.0013	0.0012	0.0013	0.0010

2.7 Evaluation Indicators

To comprehensively assess the performance of different insulation materials in public building retrofits, this study employs three key evaluation indicators, each aligned with the UN SDGs.

Energy Efficiency Coefficient (%) – This indicator refers to the reduction rate in building energy consumption after material renovation, serving as a key metric for assessing energy-saving potential (Chen et al., 2022). Its core lies in quantitatively reflecting the impact of improved thermal performance of building envelopes on cooling and heating loads, thereby comprehensively evaluating energy-saving effects (Tinarwo et al., 2023). It directly reflects the effectiveness of insulation retrofits in improving building energy efficiency, contributing to SDG 7 (Affordable and Clean Energy).

Cost Analysis – This indicator refers to the process of conducting a systematic economic assessment of the material and construction costs involved in building energy retrofits. It not only includes initial investment costs (such as material procurement and installation costs) but also covers lifecycle costs, i.e., maintenance, operational energy consumption, and replacement costs during the building's service life (Violano & Cannaviello, 2023). Cost analysis can quantitatively reveal the differences between various insulation materials in terms of return on investment, operational energy savings, and sustainable promotion value, making it a core evaluation indicator for assessing the feasibility and economic sustainability of energy retrofits. This ensures that retrofit solutions are not only energy-efficient but also financially sustainable, thereby supporting Sustainable Development Goal 11 (Sustainable Cities and Communities) through the promotion of economically viable and socially inclusive retrofit strategies.

Life CO_2 Emissions – This indicator refers to the total carbon dioxide emissions throughout the entire life cycle of a building, serving as a key

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

parameter for assessing its environmental impact. It encompasses the entire carbon footprint across all stages, including raw material extraction, processing and manufacturing, transportation, construction and installation, operation and maintenance, renovation and repair, and final disposal (Li et al., 2024). This indicator not only measures the energy efficiency performance of materials during their use phase but also reveals their contribution to greenhouse gas emissions (primarily carbon dioxide) during production and disposal phases, thereby providing a basis for green assessment of the entire life cycle of building design (Balaji et al., 2025). This indicator directly responds to Sustainable Development Goal 13 (Climate Action).

Collectively, these indicators provide an integrated framework for evaluating insulation materials from energy, economic, and environmental perspectives. By linking the assessment directly to

SDG 7, 11, and 13, this study ensures that the optimization of building envelope retrofits contributes simultaneously to energy efficiency, sustainable urban development, and global climate action.

III. RESULTS

3.1 Energy consumption simulation results

Based on Revit2016 and the THS-BECS 2022 energy consumption simulation platform, this paper conducts annual energy consumption simulations for the original building envelope and four different insulation materials (Glass Wool/ Rock Wool/ XPS Board / Urethane Foam). The simulation scenarios are based on climate data from Nanning, Guangxi, ensuring that they comply with the operational characteristics of buildings under subtropical humid climate conditions. The energy consumption results for simulation scenarios 1 to 4 are shown in Table 3.1

Table 3.1 Energy consumption simulation results

	Scenario (Original)	Scenario1	Scenario2	Scenario3	Scenario4
Annual total electricity consumption (kWh)	110679.99	109240.79	108100.42	105890.73	105207.53
Annual cooling electricity consumption (kWh)	95515.60	94698.00	94048.00	92806.80	92426.00
Annual heating electricity consumption (kWh)	15164.39	14542.79	14052.42	13083.93	12781.53
Annual cooling consumption (kWh)	238789.00	236745.00	235120.00	232017.00	231065.00
Annual heating consumption (kWh)	33398.00	32029.00	30949.00	28816.00	28150.00

Simulation results show that different insulation materials have a significant impact on the annual total electricity consumption, annual cooling energy consumption, and annual heating energy consumption of buildings. A comparison of different simulation scenarios with the original building energy consumption is shown in Figure 3.1.

The energy efficiency coefficient is an important indicator for measuring the energy-saving potential of building envelopes. The energy efficiency coefficients for different scenarios are shown in Table 3.2.

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

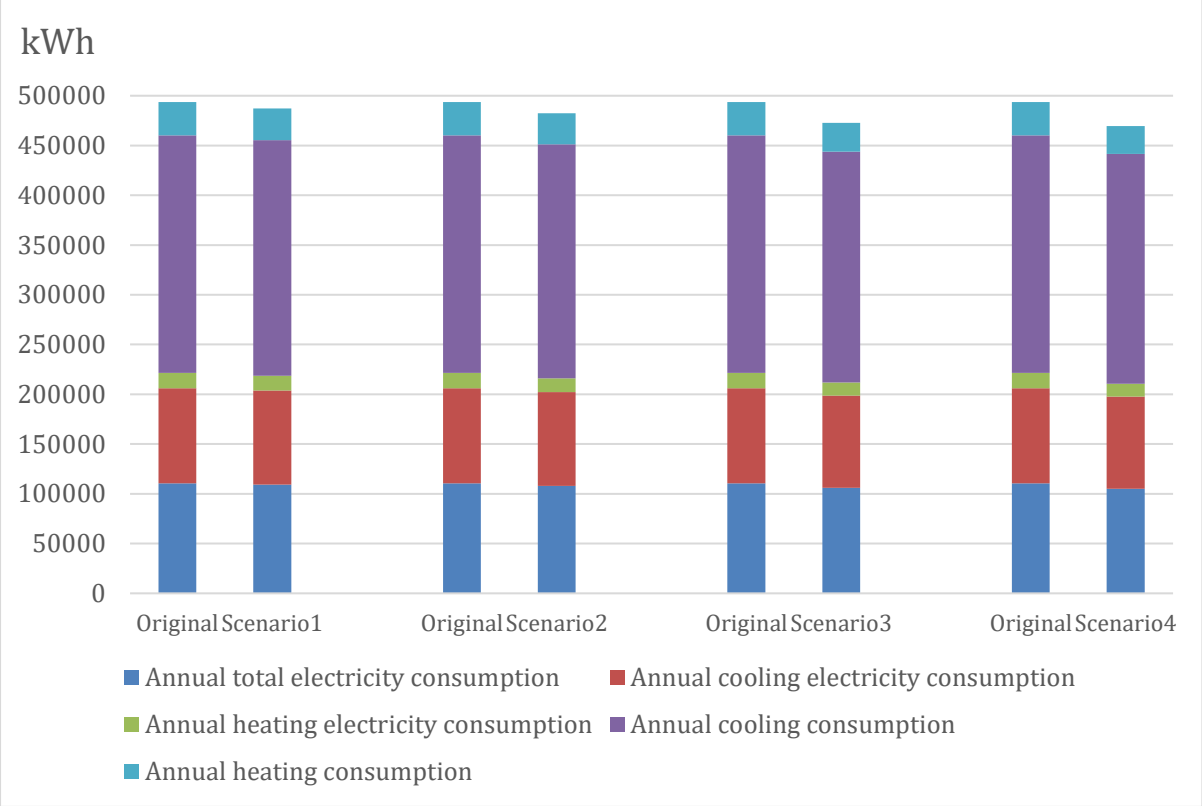

Figure 3.1 Energy Consumption Simulation Results For Scenarios 1 to 4

Table 3.2 Energy efficiency coefficient under different scenarios

	Scenario1	Scenario2	Scenario3	Scenario4
Annual total electricity consumption (kWh)	1.30%	2.33%	4.33%	4.94%
Annual cooling electricity consumption (kWh)	0.86%	1.54%	2.84%	3.23%
Annual heating electricity consumption (kWh)	4.10%	7.33%	13.72%	15.71%
Annual cooling consumption (kWh)	0.86%	1.54%	2.84%	3.23%
Annual heating consumption (kWh)	4.10%	7.33%	13.72%	15.71%
Average	2.24%	4.01%	7.49%	8.57%

3.2 Cost Analysis

Economic cost remains a major constraint in promoting energy-efficient retrofits, especially for public buildings in southern China (Luo, 2025). Effective material selection must balance thermal

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

performance with lifecycle costs—including procurement, installation, maintenance, and replacement—which directly affect project sustainability and scalability (Mohafid & Amoako-Attah, 2024)

According to the simulation results, as a consideration for selecting the best thermal insulation material, urethane foam always performs better than other materials, with a total annual power consumption of 105,207.53 (kWh) and an average energy efficiency of 8.57%. However, urethane foam is considered an expensive material, with high material prices and construction costs (Hateu, 2025.).

Glass wool and XPS board are traditional materials with low unit costs, mature construction techniques, and low initial investment pressure. Although rock wool has superior fire resistance and durability, it has high construction requirements and relatively high labor costs (Chaturvedi et al., 2024).

Table 3.3 presents the unit costs (CNY/m²) and estimated construction costs of four common insulation materials based on data from the Chinese market, tailored for public building exterior walls/roofs, for use in energy-saving simulation economic feasibility comparisons.

Table 3.3 Material Costs

Materials	Unit Cost (CNY/m^2)	Construction cost (CNY/m^2)	Note
Glass Wool	30-45	20-30	Low cost，High moisture absorption, performance decreases after compression
Rock Wool	60-80	25-35	Class A fire resistance, excellent stability
XPS board	60-85	25-35	Low thermal conductivity, good moisture resistance
urethane foam	100-130	30-50	Significant energy savings relatively high costs.

3.3 Lifecycle CO_2 Emissions

In the process of achieving sustainable building goals, the thermal insulation materials selected for building envelopes must not only possess excellent thermal performance and economic viability but also consider their carbon emissions throughout their entire lifecycle (ISO,2006.).

This study not only systematically analyzed the energy consumption performance of different thermal insulation materials during the building operation phase using BIM energy consumption simulation tools, but also introduced a life cycle assessment perspective to quantify the economic costs and carbon emission levels of each material during use. By comprehensively comparing the operating electricity consumption per unit area of the building, the unit material cost, and the unit life cycle carbon emissions (kg CO_2/m^2).

Figure3.2 and Table 3.4 show a comparison between building costs and CO2 emissions. In Figure 3.2, the blue bar chart represents the annual total operating cost per square meter (including building material costs, construction costs, operating costs, and material costs), while the red curve indicates the annual CO2 emissions per square meter. Table 3.4 provides detailed values for each item.

Table 3.4 Total unit cost and unit life cycle CO2 emissions under different scenarios

	Scenario (Original)	**Scenario1**	**Scenario2**	**Scenario3**	**Scenario4**
Material cost (CNY/m^2)	150	125	175	210	245
Construction cost (CNY/m^2)	60	30	35	40	60
operating cost (CNY/m^2)	26.3	25.9	25.2	25.1	24.1
Fuel cost (CNY/m^2)	1421	1357	1235	1020	890

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

Total cost (CNY/m²)	1657.3	1537.9	1470.2	1295.1	1219.1
CO2 emissions (kg/m²)	9.34	8.93	8.65	8.47	8.13

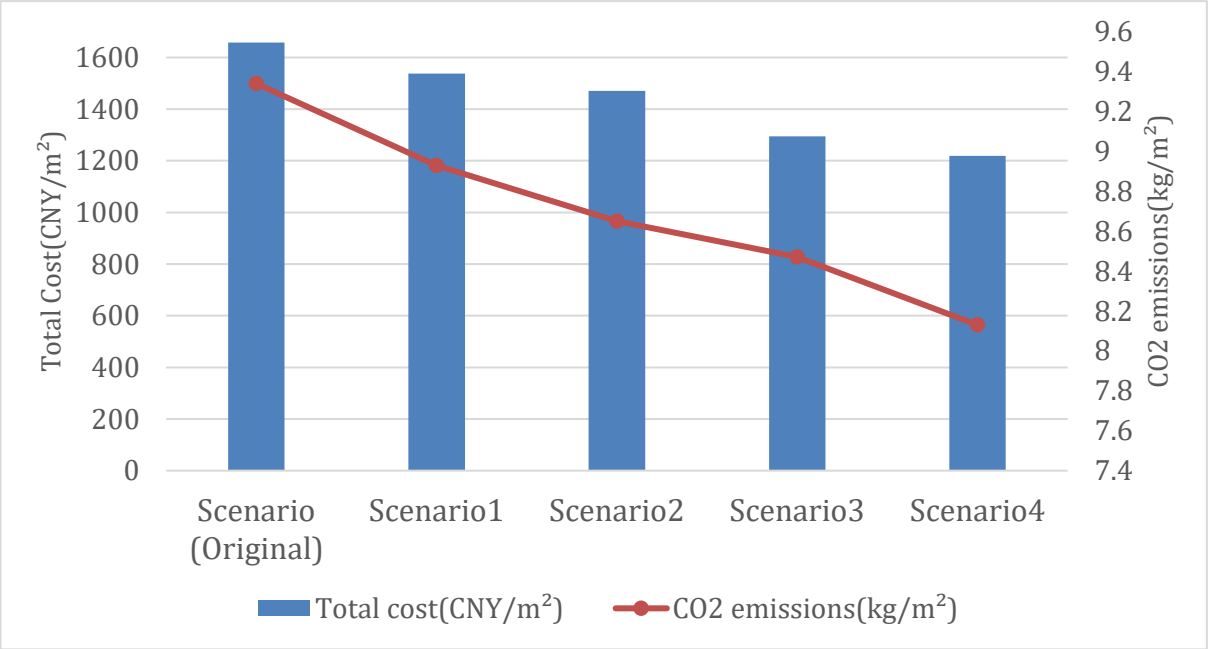

Figure 3.2 Cost-benefit analysis and CO2 emissions comparison for all scenarios

IV. DISCUSSION

4.1 Interpretation of Results

A comparison of the simulation results shows that urethane foam consistently outperforms other insulation materials in terms of energy savings and CO2 emissions over its life cycle. This excellent performance is related to the material's thermal conductivity, density, fire resistance, structural properties, and the climatic conditions in subtropical regions.

According to the simulation results, compared with the original conditions, the four types of insulation materials exhibit varying degrees of energy-saving effects across five energy consumption indicators. The average energy savings rates are as follows: glass wool at 2.24%, rock wool at 4.01%, XPS board at 7.49%, and urethane foam reaching a maximum of 8.57%.

This indicates that urethane foam is the most energy-efficient among these materials. The reason for this result is that thermal conductivity is the most direct factor determining thermal insulation performance. Among all materials, urethane foam has the lowest λ value (0.027 W/m·K), XPS board (0.030 W/m·K), rock wool (0.042 W/m·K), and glass wool (0.050 W/m·K) . The lower the λ value, the higher the thermal resistance, which directly reduces heat transfer through the building envelope.

Comprehensive BIM energy consumption simulation results indicate that annual energy consumption is highly correlated with cooling load. This trend reflects the high positive correlation between the thermal performance of insulation materials and energy efficiency, particularly in subtropical climates where summer cooling load dominates annual energy consumption. The ability of insulation materials to suppress cooling load has become a key factor in evaluating energy-saving performance.

Secondly, urethane foam has a moderate density (63 kg/m³) and relatively high specific heat capacity (1500 J/kg·K), enabling it to strike a balance between lightweight properties and good thermal inertia. This ensures that urethane foam can slow down indoor temperature fluctuations, reduce peak cooling loads, and improve thermal comfort. In

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

contrast, glass wool and rock wool are lightweight but have higher thermal conductivity, while XPS borad is highly efficient, its lower specific heat capacity limits its thermal buffering effect.

Although rock wool and glass wool are Class A fire-resistant materials with excellent fire resistance and breathability, making them suitable for public buildings with high durability and safety requirements, their overall energy efficiency is slightly lower. Urethane foam can be sprayed on-site to form a continuous insulation layer, reducing thermal bridging caused by construction joints, improving building airtightness and energy efficiency stability, and demonstrating more durable and consistent thermal performance throughout the building's lifecycle.

Finally, while urethane foam has the highest initial material and construction costs (245 CNY/ m^2 and 60 CNY/ m^2, respectively), its excellent thermal performance reduces operational energy costs to 24.1 CNY/ m^2 per year, the lowest among all materials. Additionally, urethane foam achieves the lowest lifecycle CO_2 emissions (8.13 kg/m^2), highlighting its environmental advantages in long-term renovation strategies. This balance between higher initial investment and significant lifecycle savings makes Urethane foam the optimal choice for energy-efficient renovations in subtropical climates.

Consequently, The superiority of urethane foam is therefore the result of a synergistic combination of very low thermal conductivity, moderate density with good heat capacity, enhanced airtightness from spray application, and strong lifecycle carbon performance. While mineral wools remain advantageous for fire safety, and XPS offers a balanced economic option, PU provides the most effective overall solution for reducing cooling energy demand, lowering lifecycle costs, and aligning with climate action objectives.

4.2 Comparison with Literature

This study focuses on the No. 5 Teaching Building of Guangxi University in Nanning, China. The building's geometric shape, climatic boundary conditions, and operational parameters remain unchanged, with only the exterior wall insulation material being replaced. The original material was Expanded Polystyrene Bead Insulation Mortar. Four common building insulation materials were selected for simulation: Urethane Foam, XPS Board, Rock wool, and Glass wool. The results show that all four materials can reduce the building's total electricity consumption, cooling energy consumption, and comprehensive energy consumption to varying degrees. Among them, Urethane Foam performed the best, reducing annual total energy consumption by nearly 5%, cooling load by over 3%, and average energy consumption by 8.57%. XPS board were slightly less effective, while rock wool and glass wool had relatively weaker energy-saving effects.

The case study most closely related to this research is the energy consumption simulation study conducted by Yu et al. (2023) on office buildings in the Shenzhen, China. In this study, the building geometry remained unchanged, with only the exterior wall insulation material being replaced, substituting ordinary mortar walls with XPS board insulation walls. The annual total electricity consumption decreased by 6.2%, and cooling energy consumption decreased by 4.5%. In contrast, the energy savings achieved in this study using XPS board were 4.33% (total electricity consumption) and 2.84% (cooling energy consumption), slightly lower than the results reported by Yu et al. The primary difference lies in the differing baseline conditions: Yu et al.'s baseline walls lacked insulation layers, with thermal conductivity coefficients exceeding 1.0 W/m·K, whereas the EPS mortar used in this study already possessed some insulation properties (thermal conductivity coefficient approximately 0.055 W/m·K), leaving limited room for further reduction in heat flux density.

Zhao et al. (20250) conducted a study in Chongqing, China, where they replaced the insulation material in traditional brick walls with Urethane foam and optimized shading and window-to-wall ratios, achieving a significant 7.5% reduction in annual electricity consumption. Although this study also used Urethane foam as the primary material, its higher energy savings rate compared to this study is primarily due to the broader scope of intervention, which not only involved replacing wall materials but also optimizing building design parameters. This study, however, is more aligned with real-world renovation scenarios involving a single variable. While the energy savings are smaller, they better reflect the inherent performance differences of insulation materials.

Additionally, Ali et al. (2024) noted in their systematic review of the energy-saving effects of insulation materials in different climate zones that, in subtropical humid climates, Urethane foam and XPS board superior energy-saving potential in buildings dominated by cooling loads due to their low thermal conductivity, high density, and high closed-cell content. This study validated this view, with Urethane foam and XPS board both outperforming rock wool and glass wool, and the energy-saving differences being highly correlated with the thermal

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

performance of the materials.

Consequently, the results of this study are consistent with previous research in terms of trends, namely that materials with low thermal conductivity and high closed-cell content exhibit superior operational energy efficiency in subtropical climates. However, since the basic walls in this study already possess a certain level of thermal insulation capability and the intervention measures are limited to material replacement, the energy-saving potential is slightly lower compared to some comprehensive optimization cases. Nevertheless, the results are more closely aligned with the assessment of energy-saving potential under realistic renovation conditions.

4.3 Practical Implications for Industry

The findings of this study provide practical guidance for energy-saving renovations of public buildings in subtropical climates. The selection of insulation materials for building envelopes not only affects energy efficiency improvements but also directly impacts renovation costs and carbon emissions. Therefore, in actual engineering projects, a comprehensive balance should be struck between 'energy efficiency performance, economic costs, and lifecycle CO_2 emissions to avoid the imbalance between technical and economic sustainability caused by a single-indicator approach.

Firstly, shifting from performance-driven to integrated trade-offs is the new trend in material selection. In this study, urethane foam was identified as the optimal insulation material due to its excellent thermal insulation properties, good structural stability, and long-term economic efficiency. Material selection should not be limited to initial investment considerations, but should be guided by the principle of 'optimal life cycle performance.'

Secondly, the suitability of material properties must be closely aligned with regional climate characteristics and building usage patterns. In the hot and humid regions of southern China, materials must combine thermal insulation, moisture resistance, and structural stability. In the cold regions of northern China, freeze expansion resistance and wind resistance are preferred characteristics. Therefore, future material selection should not be fixed on 'universal standards,' but rather a diversified material selection system should be established based on regional building climate characteristics.

Finally, in the context of increasingly stringent building energy efficiency policies and green certification systems, environmental footprint assessments of materials (such as carbon emissions over the entire life cycle and recyclability) should be incorporated into standard evaluation frameworks. Although urethane foam performs well in terms of carbon emission reduction, it will further enhance its 'green' label if it is combined with environmentally friendly blowing agents and recyclable designs. This also presents a new direction for the development of building material manufacturers, namely, the evolution from 'energy-saving materials' to 'sustainable materials.'

4.4 Policy and Sustainability Implications

Building energy consumption accounts for a significant share of global energy consumption and greenhouse gas emissions, making it a core component of achieving the United Nations Sustainable Development Goals (SDGs).Among the 17 SDGs, those most closely related to building energy efficiency and green retrofits include SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), with their relevance particularly evident in the simulation results of this study. Table 4.1 illustrates the relationship between the simulation results of this study and specific Sustainable Development Goal (SDG) indicators.

Table 4.1 Comparison of Research Findings with UN SDGs

Research findings	Result	UN SDGs supported
Reduced operational energy	Electricity: − 4.94% efficiency coefficient: 8.57%	SDG 7.3
Lower life-cycle cost	Total cost: − 10664 CNY/m^2	SDG 11.1
Lower carbon intensity	CO_2 emissions: −13%	SDG 13.2
Replicable BIM workflow	Calibrated BIM + THS-BECS multi-scenario materials	SDG 7.3, 11.1, 13.2

4.4.1 SDG 7 Relevance

SDG 7 aims to ensure access to affordable, reliable, sustainable and modern energy for all. Sub-goal SDG 7.3 further emphasizes: 'By 2030, double the global rate of improvement in energy efficiency'

International Journal of Engineering, Management and Humanities (IJEMH)
Volume 6, Issue 5, Sep.-Oct., 2025 pp: 22-47 ISSN: 2584-2145 www.ijemh.com

(UN, 2015). To measure the effectiveness of SDG 7.3 implementation, the United Nations Statistics Division has set core indicator 7.3.1: Energy intensity measured in terms of primary energy and GDP.

In the field of building energy efficiency research, this macro indicator can typically be quantified and mapped through a series of building energy efficiency parameters, including annual total electricity consumption of the building (kWh) (ASHRAE, 2002) and energy efficiency coefficient (%) (ASHRAE, 2002) and so on.

This study replaced the thermal insulation material of the building envelope with urethane foam has significantly changed the overall energy efficiency of the building. specifically manifested as follows: Compared to the original building scenario, the annual total electricity consumption decreased from 110,679.99 kWh to 105,207.53 kWh, with an annual reduction of 5,472.46 kWh, representing a decrease of 4.94%. The average energy consumption coefficient (energy savings rate) is 8.57%.

The above quantitative results indicate that significant energy savings can be achieved simply by optimising the insulation materials used in the building envelope, without altering the main structure of the building or relying on large-scale equipment investment. This not only demonstrates the enormous potential of materials to improve building energy efficiency, but also directly aligns with the United Nations Sustainable Development Goal SDG 7.3, which aims to 'double global energy efficiency by 2030.'

4.4.2 SDG 11 Relevance

SDG11 is dedicated to 'making cities and human settlements inclusive, safe, resilient and sustainable.' Sub-goal SDG 11.1 explicitly states: 'By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums' (UN, 2015). The United Nations Statistics Division has established the measurement indicator 11.1.1 as: 'Proportion of urban population living in slums, informal settlements or inadequate housing.' Improvements in this indicator urgently need to be achieved by providing affordable, efficient, and quality-assured housing solutions.

In the field of building energy efficiency and green housing research, reducing the total life cycle cost of buildings is key to improving housing affordability and achieving sustainability goals. This study quantifies the impact of optimizing insulation materials in building envelopes on total life cycle economic benefits, from initial material costs during construction to energy savings during use, and assesses its alignment with SDG 11.1 sub-targets.

The building under study after replacing the original material with urethane foam insulation, the annual electricity savings amounted to 5,472.46 kWh. According to the Guangxi Development and Reform Commission (2024), the average electricity price for general industrial and commercial use is 0.80 CNY/kWh. Therefore, the annual operating electricity costs can be reduced by approximately 4,377.97 CNY. Based on the common building lifecycle of 20 years (ISO 15686), the total electricity cost savings for the building amount to 87,559.4 CNY.

Although the unit cost of urethane foam is slightly higher than that of traditional insulation materials (such as glass wool, EPS, and XPS board), this study estimates that the additional unit cost is approximately 95 CNY/m², but its excellent thermal performance brings higher energy efficiency. Quantitative simulation results show that under working conditions using urethane foam, electricity consumption during the building operation phase is significantly reduced, thereby driving down electricity, fuel and other daily operation and maintenance costs. Compared with the original plan, this reduces costs by 533.2CNY/m², and based on a 20-year life cycle, the cumulative total cost savings are 10,664 CNY/m², which can effectively offset the initial investment. Good cost-benefit ratio.

Starting from the objectives of SDG 11.1, energy-efficient building design not only reduces residents' long-term operating costs and improves thermal comfort but also reduces the financial burden on public buildings and affordable housing through effective material selection. This achieves true 'affordable housing' while ensuring residential safety and functionality. Especially in the context of China's rural revitalization and urbanization development, such energy-saving optimization schemes provide policymakers and developers with practical, low-carbon, low-investment, high-return green building pathways.

4.4.3 SDG 13 Relevance

SDG 13 is dedicated to 'Take urgent action to combat climate change and its impacts,' with a particular emphasis on global efforts to reduce greenhouse gas emissions through policy and technological measures, thereby advancing the achievement of carbon neutrality goals. Sub-target SDG 13.2 explicitly states: 'Integrate climate change measures into national policies, strategies and planning' (UN, 2015). To this end, the core

measurement indicator set by the United Nations Statistics Division is 13.2.2: 'Total greenhouse gas emissions per year.' The construction sector's reduction of carbon dioxide emissions through material optimization is a key component in implementing this policy objective.

After conducting a simulation analysis of the research building and replacing the original materials with urethane foam insulation, the unit carbon dioxide emissions decreased significantly. According to the quantitative analysis results, the CO_2 emissions per square metre of the building decreased from 9.34 kg/m² in the original plan to 8.13 kg/m² in the optimized plan, a reduction of 1.21 kg/m² or 13%. Based on the total floor area of the study building being 4,271 m², the annual CO_2 emissions reduction is approximately 5.18 tonnes, demonstrating a significant greenhouse gas mitigation effect.

Consequently, optimising the thermal insulation materials used in building envelopes not only improves energy efficiency but also significantly reduces CO2 emissions per unit of building area. This is highly consistent with SDG 13, which aims to combat climate change and its impacts, and provides a feasible path and empirical data support for promoting the low-carbon transformation of the construction industry.

4.5 Policy Recommendations

In order to promote green transformation and low-carbon development in the construction industry and improve building energy efficiency, the following policy recommendations are put forward to provide reference for relevant decision-makers and contribute to the achievement of sustainable development goals:

1. Promote high-efficiency insulation materials to improve building energy performance. (Aligning with SDG 7)
2. Support green retrofitting to reduce life-cycle costs and improve housing affordability (Aligning with SDG 11)
3. Establish carbon emission assessment mechanisms for buildings (Aligning with SDG 13)

V. CONCLUSION

This study conducted a comprehensive comparative analysis of four types of insulation materials using BIM, taking public buildings at Nanning University in Guangxi, China, under a subtropical climate as an example. The analysis focused on energy consumption, cost-effectiveness, and CO2 emissions, aligning with the UN SDGs. The main research finding that replacing the original insulation material with urethane foam can achieve the highest energy efficiency, with an average energy saving rate of 8.57%, a total electricity consumption reduction of 4.94%, and the lowest CO2 emissions of 8.13 kg/m² (a 13% reduction). Extruded polystyrene (XPS) follows closely behind, while rock wool and glass wool perform moderately. Despite the higher initial cost, urethane foam performed better in terms of life cycle cost savings and carbon emissions reduction. This study proposes a comprehensive analytical framework that integrates BIM, energy consumption simulation and SDG evaluation under subtropical climate conditions. By quantitatively correlating material performance with SDG7, 11 and 13, it contributes to academic and practical knowledge.

However, this study also has certain limitations. This study is based on a single case building, and the simulation data and parameters have regional and building type specificity, making it difficult to fully generalize to all climate zones or building types. Additionally, the material carbon footprint analysis did not break down the material's entire life cycle into specific stages (such as manufacturing, transportation, and waste disposal). Future research should extend the framework to other building types (such as hospitals and residential buildings) and diverse climate zones (including cold or arid regions), incorporate renewable energy systems and user behavior modeling, and implement sensitivity analyses. Integrating Life Cycle Assessment (LCA) and Environmental Product Declaration (EPD) data will significantly enhance the accuracy of carbon impact assessments, providing robust support for broader policy formulation and planning efforts.

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