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Evaluation Method on Energy-Efficient Retrofitting of Wooden Walls of Chinese Traditional Dwelling—A Case Study of Rendetang in Jinhua

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Abstract: Traditional wooden dwellings, which are widely distributed with enormous stocks in China, are of great historical and have obvious cultural value. The walls of such buildings are generally subjected to poor thermal insulation performance, which not only reduces residential thermal comfort but also increases building cooling and heating energy consumption. In addition, buildings of this type have been subjected to all kinds of problems, such as the lack of measures for improving thermal comfort and the shortage of special funds. Consequently, it is very challenging to reutilize Chinese traditional dwellings, many of which are abandoned and even collapsed. All of the above have become major difficulties encountered in the traditional dwelling heritage protection. Hence, investigating the energy-efficient retrofitting strategies for traditional dwellings and giving economical evaluation methods are two keys to solving the reutilization problem of traditional dwellings. Against this background, a set of second-level evaluation methods for the energy-efficient retrofitting of Chinese traditional dwellings are proposed in this research, including the survey on retrofitted dwellings, the retrofitted dwelling modeling and energy consumption analysis, the definition of wall retrofitting scheme, the first-level evaluation of dwelling retrofitting, the second-level evaluation of dwelling retrofitting, and the screening of the wall retrofitting scheme. The first-level evaluation, which took energy efficiency as a reference index, could evaluate the energy conservation effect before and after dwelling retrofitting. With the payback period as the reference index, the second-level evaluation could assess the overall economic efficiency of dwelling wall retrofitting. An appropriate dwelling wall retrofitting scheme could be screened by integrating first-level and second-level evaluation indexes. Then, this scheme was applied to evaluate the wooden wall retrofitting scheme of a typical traditional dwelling in Yapan Village, Zhejiang Province, China. It was discovered through a comparative analysis that if used to reconstruct dwellings in Zhejiang and other places, the combined materials of XPS board and wood-bamboo could not only effectively improve the energy efficiency but also has good economic efficiency. Meanwhile, problems such as the condensation of wooden walls and their construction thickness could be solved by controlling the material thickness. The above research is of guiding significance for the energy-efficient retrofitting of traditional wooden dwellings in the hot-summer and cold-winter zone of China, and moreover, it can provide reference for the energy-efficient retrofitting of traditional wooden dwellings in other climate zones of China.

Keywords: wood structure; traditional dwelling; energy-efficient retrofitting; evaluation method

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1. Introduction

With the rapid growth of building energy consumption in recent years, the green building technology and theory have become a global focus. As reported by the International Energy Agency (IEA), global energy use has doubled since the 1970s [1]. In 2018, the global building energy consumption accounted for 35% [2]. In China, the total commodity energy consumption of domestic buildings in service reached 1000 million tce in 2018, and the carbon emission related to fossil energy consumption was 2100 million tCO2, where the residential building energy consumption accounted for 46% [3]. A lot of energy policies have been released in the international community to reduce building energy consumption and carbon emissions [4].

With great stocks all over the world, residential traditional houses have poorer thermal insulation performance relative to modern houses since they were restricted by the construction technologies and materials and worn down by the years without repair. The indoor thermal environment of residential traditional houses no longer meets the housing needs of contemporary people, so it is imperative to perform their energy-efficient retrofitting. From the perspective of protecting traditional dwellings with historical value, it is urgent to enhance the thermal insulation performance of such dwellings while maintaining the architectural style as much as possible, regarding which global scholars have carried out a lot of energy-efficient retrofitting evaluation and research work. To reduce the energy consumption of historical buildings in Italy with the stock of historical buildings accounting for 46% of the total building stock, Ascione et al. tested the effectiveness of the energy-efficient retrofitting scheme for Italian historical buildings via Energy Plus energy consumption simulation, and verified the feasibility of reconstruction measures from an economic perspective, thus rendering reference for the energy-saving retrofitting of historical buildings [5–7]. In Hungary, Sugáret al. [8] conducted a general survey on traditional dwellings in Budapest, and proposed that the typology-based rapid evaluation method could estimate the heating demand of buildings. In China, the stock of wood structure-dominated traditional dwellings is large, with the main building materials being wood, bricks, and tiles [9]. Traditional wooden dwellings have been investigated in the industry, including seismic performance [10], fireproofness [11], and indoor thermal environment [12]. Against the global double-carbon background, it is especially important to investigate the energy-efficient retrofitting on the premise of respecting the historical values of traditional wooden dwellings, and the research within this field remains to be further perfected.

The existing energy-efficient retrofitting measures for traditional dwellings include active and passive energy-efficient retrofitting. Active energy-efficient retrofitting refers to upgrading the lighting system, heating, ventilation, and air conditioning systems of traditional dwellings, and moreover, solar photovoltaic systems can be introduced and renewable energy sources can be utilized [13]. However, restricted to the considerations of protecting the historical values of traditional dwellings, active energy-efficient retrofitting is not always applicable to traditional dwellings. Passive energy-efficient retrofitting mainly aims to optimize traditional dwellings themselves and further improve indoor thermal environment and reduce building energy consumption. During the evaluation of green buildings, although energy-efficient retrofitting plays a dominant part in active retrofitting, passive energy-efficient retrofitting can provide effective and economic measures to reduce energy consumption to the greatest extent, and moreover, it has aroused increasing attention in the research on the energy-efficient retrofitting of traditional dwellings by virtue of low investments and potential energy-efficient benefits [14].

The present passive energy-efficient retrofitting measures commonly applied to traditional dwellings mainly focus on reducing building energy consumption by improving the thermophysical properties of building envelopes and enhancing their air tightness [14]. The main measures can be divided into two major types, and the first type is window retrofitting in building envelopes of traditional dwellings. In most of the existing studies, attention has been paid to improving the thermal insulation performance by enhancing the air tightness of windows in order not to destruct the traditional residential style and historical values. Han and Yang [15] strengthened heat prevention in summer and thermal insulation in winter by replacing hollow glass and increasing the thermal resistance of external building envelopes, and finally saved the energy consumption by over 50%, which was a considerable energy conservation effect. However, Litti et al. [16] stated that the building energy consumption could be reduced through simply maintaining windows of traditional dwellings and improving the window performance (e.g., replacing double glazing), but the complete replacement of windows would not always bring the highest energy-saving effect. According to the simulation results obtained by Ge et al. [9] by replacing the glass of traditional dwellings, this measure reached a poorer energy-saving effect than other energy-efficient retrofitting measures (such as adding heat-insulating plates on the inner surface of exterior wall). In the other studies on passive energy-efficient retrofitting for traditional dwellings, the attention has been paid to how to improve the thermal insulation performance of building walls, namely the second-type studies, including the utilization of various thermal insulation materials and the improvement of the air tightness of walls. Specific to building thermal insulation materials currently adopted at home and abroad, Jelle [17] expounded their advantages and disadvantages as well as the corresponding solutions, and explored new-type thermal insulation materials for buildings, thus laying a foundation for the follow-up energy-efficient retrofitting. Ge et al. [9] explored external building envelope energy-efficient retrofitting technology commonly applied to traditional wooden dwellings in southern China, and simulation results showed that the energy efficiency of extruded polystyrene boards 10–80 mm in thickness could reach 4.52%. To improve the indoor comfort of traditional dwellings in west Hunan, China, Li et al. [18] added thermal insulating layers and Chinese fir boards in exterior walls, floorboards, and floor slabs to elevate the thermal resistance of building envelopes. Liu expressed that the original boards in traditional wooden dwellings were formed through simple flat seam splicing, thus failing to meet the thermal design and the minimum thermal resistance requirements, and poor thermal insulation and air tightness were important reasons for the low energy efficiency of buildings [19,20]. The thermal insulation effect of building envelopes can be enhanced by reference to the wall construction practice of wooden dwellings in mountainous regions in northern Europe [21]. Based on double-layer “respiratory” wall body, adding polyurethane insulation boards and high-density fiberboards inside it can reach the thermal insulation effect while not destructing the architectural features of the original wooden dwellings. Directing at traditional wooden dwellings in southeast Guizhou, China, Li [22] put forward using new materials and new technologies and fusing traditional wooden dwellings with new materials, modern crafts and construction technologies based on reserving the traditional cultures and styles. With traditional Miao stilted buildings as examples, structural insulated panels (SIPs) are used in exterior walls, while light keel wood walls are used in interior walls, accompanied by brushing of flame-retardant coating. Bianco [23] installed gypsum boards at the inner site of historical building envelopes in Italy, and explored their thermal insulation potential through experiments and field measurements.

In the above studies aiming to improve the thermal insulation performance of walls in traditional wooden dwellings, the condensation phenomenon in humid environment or that caused by thermal insulation materials has not been involved. In some studies, the dampproof problem of walls has been noticed, and the energy-efficient retrofitting idea of traditional wooden dwellings has been extended. Martín-Garín et al. [24] comprehensively analyzed a series of internal insulation-based measures through hygrothermal simulations, and then concluded that waterproof materials were requirements for guaranteeing the air tightness of building envelopes. To facilitate traditional dwellings to adapt to the local humid environment, Liu [19] used raised floors to avoid the direct floor-ground contact, and the results showed that this construction measure could reduce the indoor humidity and reach a certain moisture-proof effect. However, the condensation phenomenon of walls in traditional wooden dwellings has been rarely investigated.

To sum up, the thermal comfort improvement and energy-efficient retrofitting of traditional dwellings have been extensively investigated, with the focus on the energy efficiency of dwelling retrofitting. However, the economic efficiency has been scarcely evaluated, not to mention the comprehensive evaluation research combining energy efficiency and economic efficiency. “Energy-efficient retrofitting” was taken as a keyword and analyzed via CiteSpace at the time slice threshold of TOP23 to generate a visualized keyword map based on "web of science". It is revealed that the research on energy-efficient retrofitting of traditional dwellings is the most closely related to performance, energy efficiency, consumption, and thermal comfort. However, very few keywords related to economic analysis (cost) have been involved in energy-efficient retrofitting (Figure 1). Qu and Ke et al. [25] pointed out that almost no effort was made to define a sustainable and overall retrofitting strategy from comprehensive perspectives of energy, cost, and thermal comfort in order to solve challenges faced in historical building retrofitting. Therefore, it is crucial to investigate and determine the best energy-efficient retrofitting measures for historical buildings. Moreover, the influences of energy consumption and cost effectiveness on the integrity and thermal comfort of historical buildings should be fully considered. In China, nearly 12,000 villages with traditional village natures are summarized according to the investigation organized by relevant provincial departments, and there are over 2 million natural villages at present, including a lot of historical buildings reserved. Hence, it is nothing negligible to formulate passive energy-efficient retrofitting measures for historical buildings based on protection and reutilization. As for the low-tech energy-efficient retrofitting of traditional wooden dwellings, it is urgent to solve the air tightness and condensation problems while enhancing their thermal insulation performance, and put forward a set of thermal-insulating, dampproof, and economical comprehensive optimization schemes. Given this, passive energy-efficient retrofitting was performed for a traditional dwelling in Jinhua City, Zhejiang Province, China, in accordance with the Heritage Conservation Guidelines, trying to improve the thermal insulation performance while maintaining the architectural style, so as to improve the thermal comfort of houses. Then, a building energy consumption model and an economic model were established through experiments and numerical simulations. Next, the optimal energy-efficient retrofitting scheme was determined, expecting to provide reference for similar research and practice.

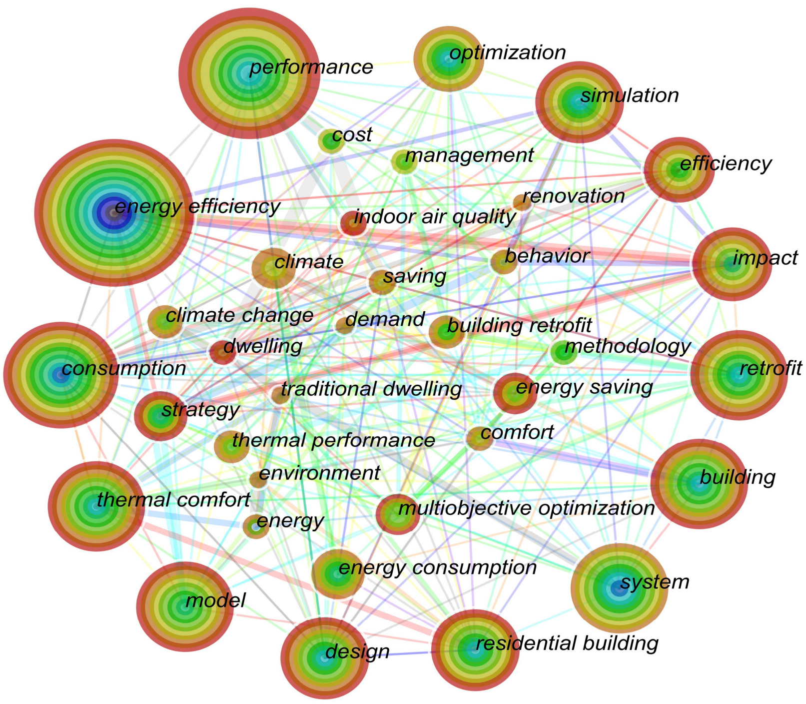


Figure 1. Research knowledge map for "energy-efficient retrofitting of traditional dwelling for thermal comfort" field articles in Web of science.

2. Materials and Methods

2.1. Experimental Materials

To improve the air tightness and thermal insulation performance of traditional wooden dwellings, locally commonly used XPS boards and bamboo-wood composite fiberboards were determined as thermal insulation materials of walls for energy-efficient retrofitting based on the principle of economic applicability (Table 1). With a closed-cell honeycomb structure, XPS boards were characterized by low water absorption, low heat transfer, high crushing resistance, and aging resistance. In this experiment, XPS boards were added between two layers of bamboo-wood composite fiberboards to enhance the thermal insulation performance of the wall. Since the bamboo-wood composite fiberboards were free from formaldehyde, no secondary pollution would be generated, and their service life was long, generally reaching as long as 20 years. In addition, the material surface texture, color, and size could all be customized, which was convenient for the adaptative transformation and promotion of traditional dwellings based on "historic conservation".

Table 1. Selection of retrofitting materials.

	Scope of Application	Advantage	Disadvantage
Bamboo-wood composite fiberboard	Indoor wall materials	Good dampproof effect, convenient installation, and convenient size and pattern customization	Proneness to deformation under humid conditions, relatively fragile material texture, not high hardness, and easy scratching
XPS board	Widely applied to building thermal insulation design and transformation	High-cost performance, superior thermal insulation performance	Thermal resistance of thermal insulation material will be reduced under humid conditions [26]

2.2. Method

2.2.1. Technical Route

Based on the conceptual framework developed by Ozarisoy et al. [27], this paper proposes a set of evaluation methods for evaluating the suitability of energy-saving retrofitting schemes for traditional wooden walls in wooden structures (Figure 2). First, information and data such as indoor thermal environment of the building, the heat transfer coefficient (HTC) of the wall, and personnel activity were acquired by means of field measurement and investigation, which laid a foundation for the follow-up simulation analysis. Second, modeling and simulation were conducted. To be specific, a simulation model was constructed by combining measured data according to the specific retrofitting measures. Then, data such as cooling energy consumption in summer, heating energy consumption in winter, and annual energy consumption were obtained. Third, the energy-efficient retrofitting work was evaluated. The second-level evaluation indexes were acquired according to energy consumption simulation results and the transformed economic indexes, based on which the optimized energy-efficient retrofitting scheme was given.

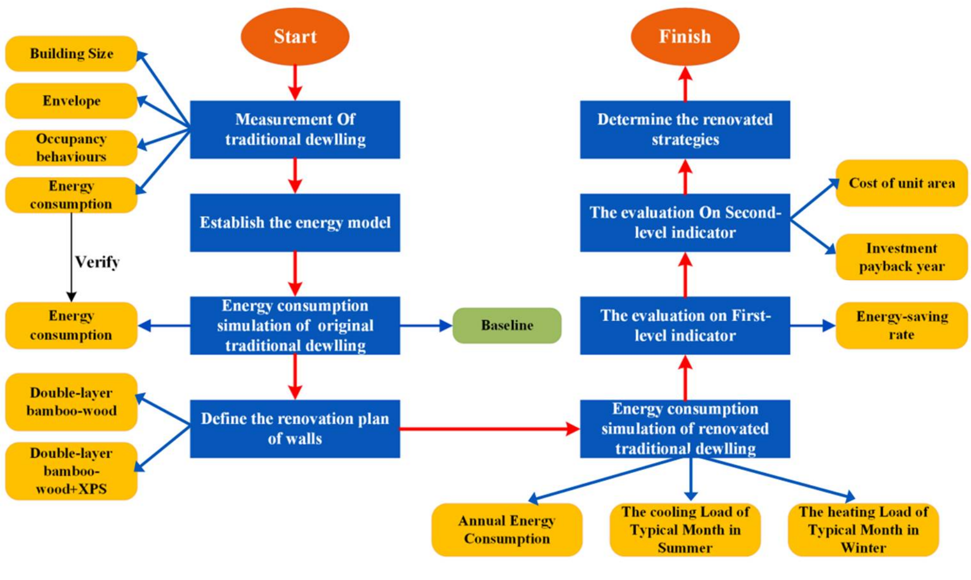


Figure 2. Flow chart for the evaluation method.

2.2.2. Field Measurement and Investigation

To provide related data and information for the follow-up numerical simulation, the to-be-retrofitted traditional dwelling should be measured on the field, with the measurement contents mainly including the building size, the thermal parameters of building envelope, indoor temperature and humidity, and the energy consumption of refrigerating rooms. The measurement instruments and their test precisions are listed in Table 2. Next, an air tightness test was conducted inside the building using the blower door air tightness test system, and the indoor air temperature and humidity of main rooms in the building were measured via temperature and humidity meters. After the to-be-used thermal insulation materials were determined, the JTRG-I wall and glass thermal insulation performance detection device (Figure 3) was used to measure indoor building envelope materials and thermal insulation materials to obtain the corresponding thermophysical parameters. During the field investigation, the electricity utilization conditions of actual air conditioning equipment in the building and the residential work and rest status should also be investigated and recorded.

Table 2. Testing instruments and parameter ranges.

Test Parameter	Testing Instrument	Measurement Accuracy
Indoor air temperature and humidity	Memory-type hygrometer TES-1361C	Humidity ±3%RH (25 °C, 20–80%RH) Temperature ±0.4 °C (+5–+60 °C)
Surface temperature of building envelope	IR thermometer FLUK F59	±2 °C
Air tightness	Blower door air tightness test system (Blower Door)	±3%
Heat transfer coefficient	JTRG-I wall and glass thermal insulation performance detection device	Cooling/heating box control precision: ±0.2 °C

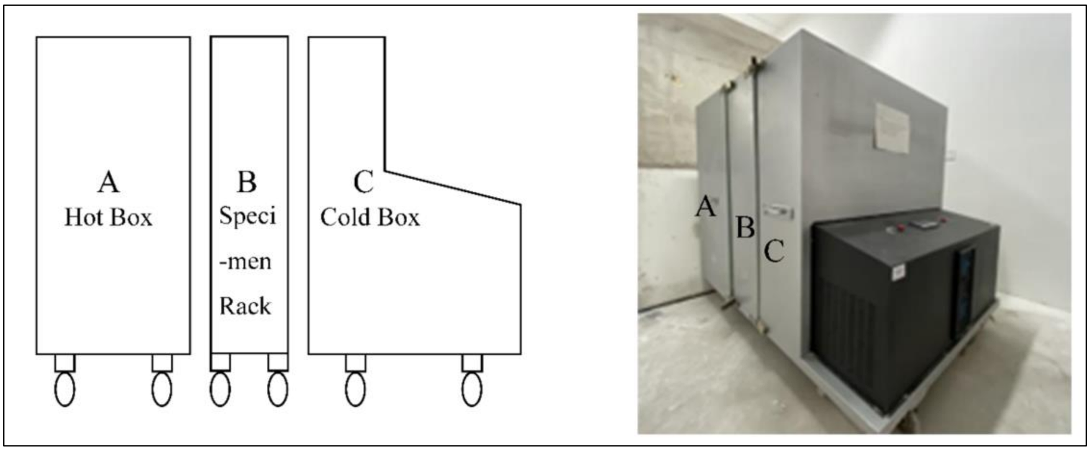


Figure 3. JTRG-I wall and glass thermal insulation performance detection device.

2.2.3. Numerical Simulation

Based on the above measured data, the energy consumption of each room in the traditional dwelling was simulated using energy consumption simulation software (EnergyPlus 9.5.0, the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), The United States) EnergyPlus. First, a 3D parametric model was constructed with the plug-in Grasshopper of Rhinoceros 3D geometric modeling tool. Then, a battery block engine related to parameters such as indoor building envelopes, electrical equipment, and time in Honeybee and Ladybug was built. Finally, the indoor energy consumption value catering to the practical situation was obtained through simulation (Figure 4). The plug-in Honeybee in Grasshopper was an EnergyPlus-based engine tool, which could quantitatively simulate the energy consumption of all kinds of buildings [28]. The parameters of the simulation project included density, set cooling/heating temperature, composition of building elevation, lighting type and time schedule, and HVAC system. In addition, the input parameters were calibrated through field survey and measurement.

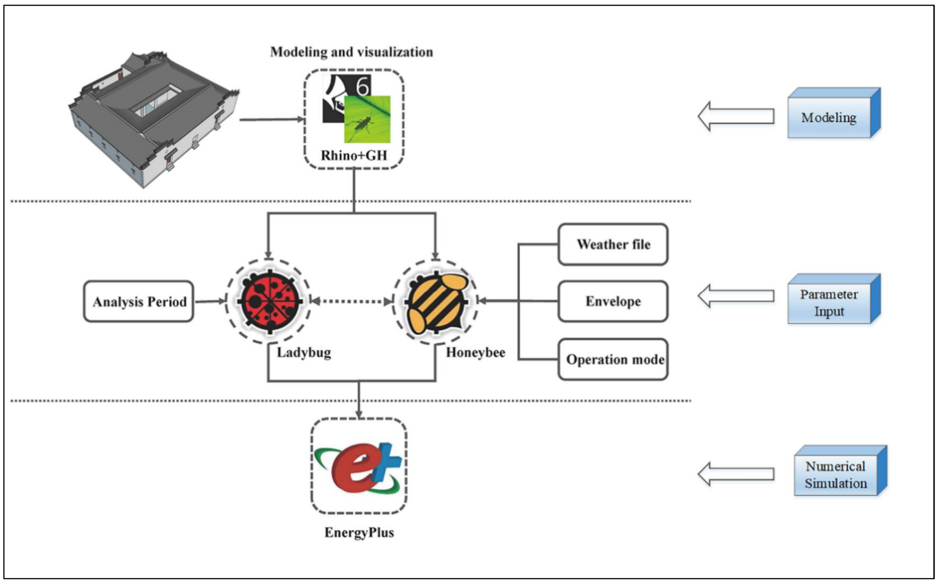


Figure 4. Simulation Flowchart.

2.2.4. Two-Level Index Evaluation Method

(1) First-level index evaluation

Through investigating the ontological features of the traditional dwelling, the geometric information, and the thermophysical parameters of the building envelope were acquired, and a residential building energy consumption analysis model was constructed accordingly via EnergyPlus. Based on the meteorological information of the dwelling place in the typical meteorological year (TMY), the annual and quarterly energy consumptions of each thermal-insulating energy-efficient retrofitting measure were simulated. Based on the energy consumption data of the original building before retrofitting, the evaluation indexes for the energy efficiency of dwelling wall retrofitting were given. On this basis, the energy conservation effects of different energy-efficient retrofitting measures were comparatively analyzed, and the candidate wall retrofitting schemes were preliminarily evaluated and screened.

(2) Second-level index evaluation

When the energy-efficient retrofitting scheme of the traditional wooden dwelling was evaluated, its economic indexes should be considered in addition to its energy-saving effect. Low-cost energy-efficient retrofitting measures are more popular, so it is necessary to perform an economic analysis of energy-efficient retrofitting measures. Ge et al. proposed that the economic analysis should include contents such as incremental cost, net present value, and payback period [9]. When evaluating the economic efficiency of energy-efficient retrofitting of this traditional dwelling, the payback period of construction investment was taken as the evaluation index for the final screening and determination of candidate wall retrofitting schemes for this traditional dwelling. The payback period is calculated as per Equations (1) and (2). Incremental costs refer to direct and indirect cost expenditures arising from retrofitting, including material costs, construction measure costs, mechanical costs, and labor costs. All the data were derived from market surveys and were extracted from relevant research literature, and then the total incremental cost of each retrofitting measure was solved.

$$NPV = \sum_{t=1}^{n} \frac{Ct}{(1+r)^t} - Co \tag{1}$$

$$\Delta P_t = (N-1) + \frac{|A_{N-1}|}{C_N} \quad (2)$$

where NPV, n, r, C_t, C_O, ΔP_t, N, A_{N-1} and C_N stand for the annual net present value, the calculation cycle, the discount rate, the cash flow in the year t, the initial incremental investment cost, the dynamic investment payback period, the year with the cumulative cash flow being positive for the first time, the cumulative net cash flows with the last negative item, and the cumulative cash flow in the year N, respectively.

3. Case Study

3.1. Introduction of Traditional Dwelling Retrofitting Case

Traditional wooden dwellings are one of important buildings in Chinese traditional buildings, with the main entrance generally facing the south, where timber beams and timber columns serve as bearing structures, and bricks, stones, and earth as the main exterior wall materials. From the angle of building layout, the traditional wooden dwellings in northern and southern China are all dominated by a courtyard house layout. In this research, the climate zone of this case was defined as a hot-summer and cold-winter zone. In China, the hot-summer and cold-winter zone mainly refers to the middle and lower reaches of the Yangtze River and surrounding areas, largely in the south of Longhai Railway, the north of Nanling Mountains, and the east of Sichuan Basin. This zone covers all parts of Shanghai, Chongqing, Hubei, Hunan, Jiangxi, Anhui and Zhejiang, the east halves of Sichuan and Guizhou, the south halves of Jiangsu and Henan, the north half of Fujian Province, the south end of Shaanxi and Gansu, and the north end of Guangdong and Guangxi. Therefore, the hot-summer and cold-winter zone gathers the most developed cities and provinces in China, being a zone having an important influence on China's development. In addition, buildings in the hot-summer and cold-winter zone are simultaneously faced with the thermal insulation problem in summer and the heat preservation problem in winter, where the thermal comfort problem is relatively prominent. In the concrete survey, a total of 18 historical villages in Zhejiang Province with the hot-summer and cold-winter zone were randomly investigated (Table 3). The case involved various regions inside Zhejiang Province. Rendetang in Yapan Village, Jinhua City in the middle of Zhejiang Province with all values at median levels was selected as the analysis object through deeply analyzing the traditional dwellings in each investigated village (Figure 5). In Jinhua, the lowest temperature can reach −6 °C in winter, and the highest temperature can reach about 40 °C in summer with a large amount of precipitation and distinct dry and wet seasons, thus belonging to a typical hot-summer and cold-winter zone. Rendetang is a typical two-story courtyard-type brick-wood structured traditional dwelling, and its plane layout and main structure are typical and representative. In this research, the heat preservation and insulation energy-efficient retrofitting of its wooden wall panels was evaluated through measurement and simulation, and an optimal wall retrofitting scheme was given, which could provide a reference for the energy-efficient retrofitting of traditional buildings in other regions within Zhejiang Province. In the building, the three among the four wall surfaces of the enclosure room are plank walls 20 mm in thickness, and the other surface is brick wall 240 mm in thickness. A window is opened on the plank wall and the other window is opened in the opposite brick wall. The ground texture is trinity mixture fill (thickness: 240 mm). The floor slabs in the room on the second story are planks 25 mm in thickness. Chinese-style tiles are paved on the roof, which is structured from up to bottom as Chinese-style tiles (thickness: 10 mm) + mortar (20 mm) + sheathing bricks (18 mm). The first story of the building is a daily living space, and the second story mainly serves as the storage space (Figure 6). Figure 7 shows the 3D models and field photos of Rendetang. Having been long neglected and in disrepair, the interior and exterior walls are both damaged to different degrees, which leads to poor thermal insulation performance and air tightness of the building envelope. A common method used by local residents to meet the needs for thermal comfort is installing air conditioners, but air conditioning energy consumption is large. In this research, the main rooms in the building were measured using temperature and humidity meters. The measurement results (Figures 8 and 9) showed that the indoor real thermal environment still had a way to go to catch up with the energy conservation design standard currently in force.

Table 3. Survey table of traditional dwellings in some historical and cultural villages in Zhejiang.

S/N	Village Name	Region	Quantity of Traditional Dwellings	Proportion of Wooden Structures	Proportion of Wooden Structures
1	Chuijia Tian Village	Lishui, Zhejiang	16	75.3%	4.2
2	Yapan Village	Jinhua, Zhejiang	25	95.8%	4.1
3	Boutou Village	Xianju, Zhejiang	23	95.7%	4.3
4	Andian Village	Qingtian, Zhejiang	24	100%	3.8
5	Xiapu Village	Tiantai, Zhejiang	37	86.5%	4.2
6	Ha Shi Zhuang Village	Wencheng, Zhejiang	13	46.2%	4.1
7	Yuxi Village	Shengzhou, Zhejiang	8	100%	3.7
8	Baheyang	Shengzhou, Zhejiang	12	75%	3.8
9	Shangwu Village	Shengzhou, Zhejiang	16	100%	4.1
10	Lakeside Village	Suichang, Zhejiang	21	76.1%	4.4
11	Cao Ling Village	Qingyuan, Zhejiang	46	78.3%	3.6
12	Daji Village	Qingyuan, Zhejiang	34	94.1%	4.2
13	Arrow Ridge Village	Fenghua, Zhejiang	47	55.3%	3.9
14	Gaoqian Village	Xianju, Zhejiang	52	98.1%	4.3
15	Hongtang Village	Dongyang, Zhejiang	26	87.6%	4.2
16	Po Tong Village	Jinhua, Zhejiang	11	89.6%	4.6
17	Pak Fuk Yan Village	Taishun, Zhejiang	15	100%	3.5
18	Tuan Shi Village	Longyou, Zhejiang	13	97.8%	3.7

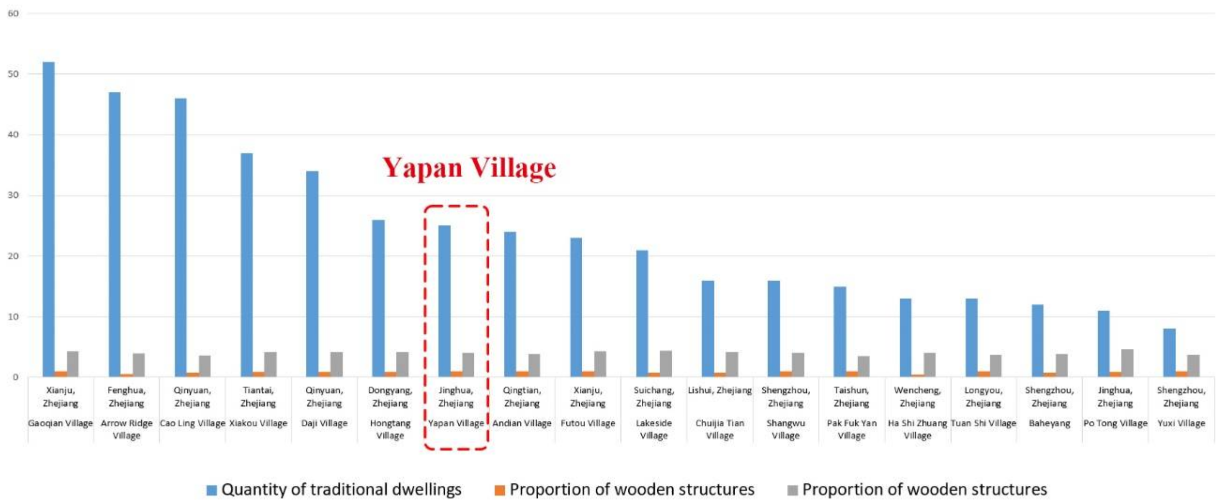
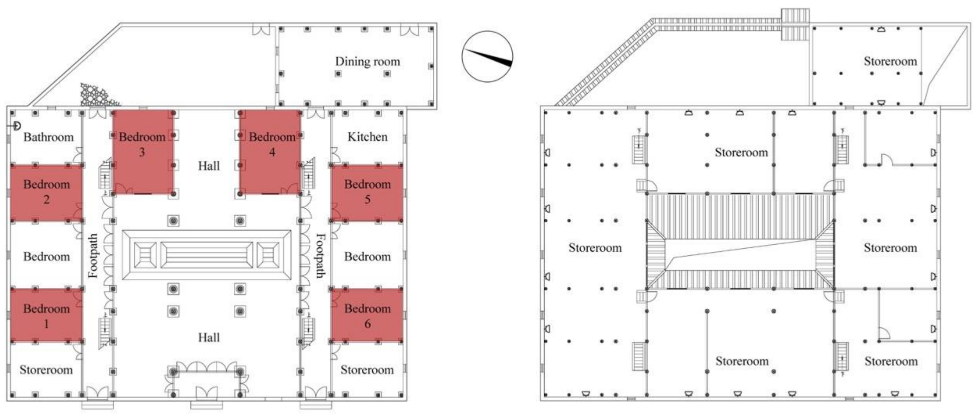
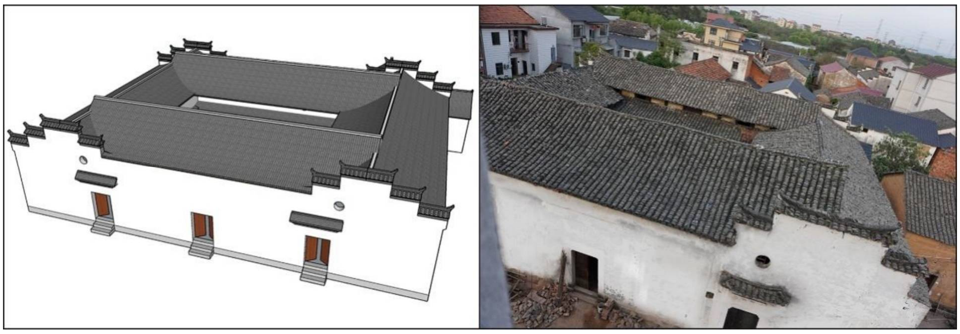


Figure 5. The data comparison histogram for the villages surveyed.



(**a**) (**b**)

Figure 6. Planar graph of Rendetang. (**a**) First-story plan; (**b**) Second-story plan.



(**a**) (**b**)

Figure 7. Residential building models and field photo. (**a**) Residential building models; (**b**) field photo.

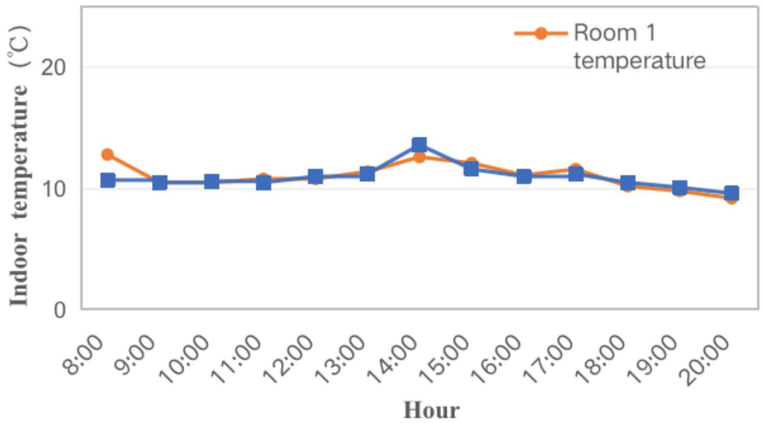


Figure 8. Indoor temperature measurement of Rendetang (20 January 2021).

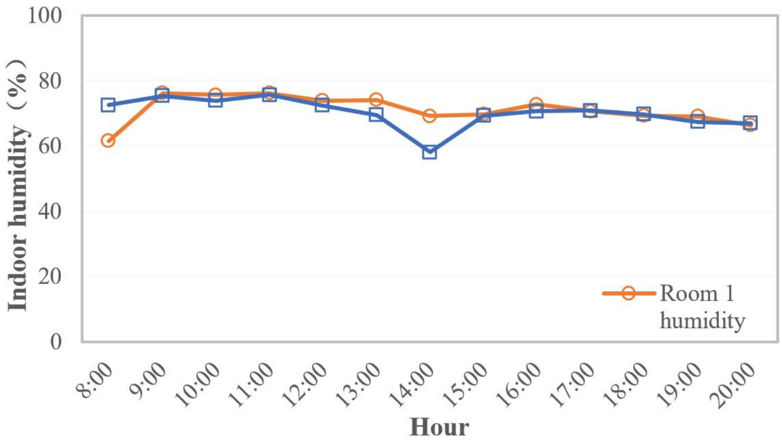


Figure 9. Indoor humidity measurement of Rendetang (20 January 2021).

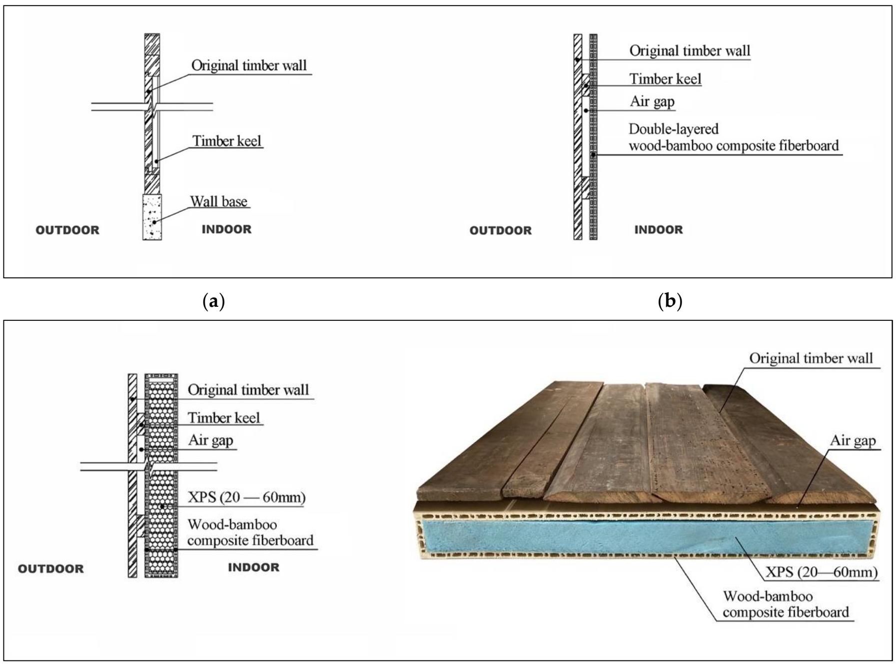
To further figure out the actual indoor thermal environment of Rendetang and the thermophysical properties of its building envelope, measurement was repeated, and the measurement data on 20 January 2011, were finally used for the simulation. The data showed that the indoor temperature and humidity of the measured rooms were 10–14 °C and 60–80%, respectively, from 06:00 to 08:00 in the morning. Fu et al. [29] proposed that the thermal comfort temperature in winter was 21.1 °C, the indoor relative humidity should be kept within 30–40% in winter, and thus neither the temperature nor humidity in the rooms reached the thermal comfort requirements of human body. Next, the JTRG-I wall and glass thermal insulation performance detection device was utilized to measure the original indoor plank walls, bamboo-wood composite fiberboards and XPS boards, thus to obtain the corresponding thermophysical parameters (Table 4).

Table 4. Measured thermal parameters of thermal insulation materials.

Structure	Heat Transfer Coefficient W/(m^2·K)	Heat Conductivity Coefficient W/(m·K)	Thickness/(mm)
Original wooden wall panel	2.78	0.15	20
Bamboo-wood composite fiberboard	15.63	0.14	9
XPS board	1.73	0.03	20~60

3.2. Retrofitting Measures

To improve the thermal insulation performance of wooden wall panels in each bedroom on the first story of Rendetang, the bamboo-wood composite fiberboard and XPS board combined retrofitting scheme was adopted in this research to add an internal thermal insulation layer in the wall body, namely, two bamboo-wood composite fiberboards (thickness: 9 mm) were combined with XPS boards to form composite thermal insulation materials (Figure 10c). XPS boards were embedded into the double-layer bamboo-wood boards for the following reasons: The two materials are of good properties; the synthetic material can be produced by mature technologies at present, and the XPS boards sealed in the bamboo-wood composite fiberboards are relatively dampproof, thus giving full play to the thermal insulation effect of the thermal insulation layer; the construction is fast and convenient. In this research, comparative simulation experiments on the original plank wall (Figure 10a), the double-layer bamboo-wood fiberboard scheme (XPS boards not added) (Figure 10b), and the double-layer bamboo-wood composite fiberboard and XPS board combined thermal insulation material (Figure 10c) were set to verify the thermal insulation effect of the composite thermal insulation materials. As for the installation of composite thermal insulation materials, metal components were arranged on the external surface of thermal insulation materials and the timber keel of the original plank wall by flexible means of bolt hanging. The real photos of composite thermal insulation materials are displayed in Figure 10d.



(c) (d)

Figure 10. Wall structure chart. (**a**) Original wall; (**b**) double-layer bamboo-wood composite fiberboard; (**c**) double-layer bamboo-wood composite fiberboard-XPS board; (**d**) real photos of composite thermal insulation layers.

In Jinhua, which belongs to a hot-summer and cold-winter zone, the internal thermal insulation mode can very easily trigger condensation especially in summer, thus leading to wall cracking, indoor temperature and humidity imbalance, etc., but the condensation can be effective relieved through effective ventilation. Hence, a critical detail remaining to be handled during wall retrofitting, that is, ventilation using the gaps between the planks of the original plank wall. A 20 mm of air space is reserved between the internal thermal insulation layer and the original plank wall, and the air permeating into the air space carries away the water vapor adhered on the outer layer of the internal thermal insulation layer via the gaps in the original plank wall. In this way, the condensation phenomenon of the internal thermal insulation layer can be effectively mitigated, its service life is lengthened, and meanwhile, the planks in the original plank wall are protected from decay due to water accumulation.

The original window of the building is fixed lattice window without glass. As for window retrofitting, the following aspects are mainly considered: the antique beauty of windows is reserved; the air tightness and thermal insulation performance of windows are enhanced; windows are openable, which is convenient for ventilation. Therefore, the timber lattice is reserved in the window retrofitting, double glazing is installed at the side close to the indoor space, and the thermal insulation effect is reached through the vacuum layer in the double glazing. In addition, a ring of sealing strips is fixed at the outer edge of double glazing to enhance the air tightness of windows (Figure 11). The whole window is transformed into two openable windows, which are connected to mullions using hinges.

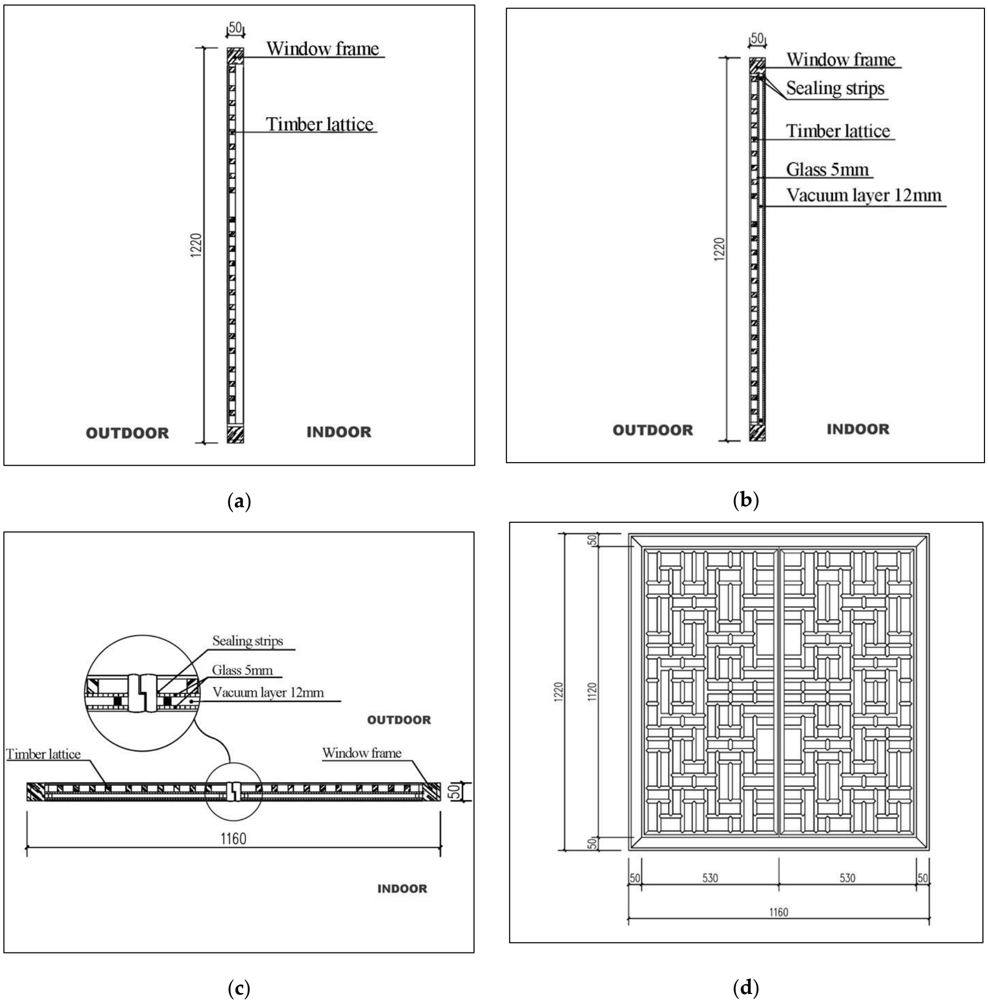


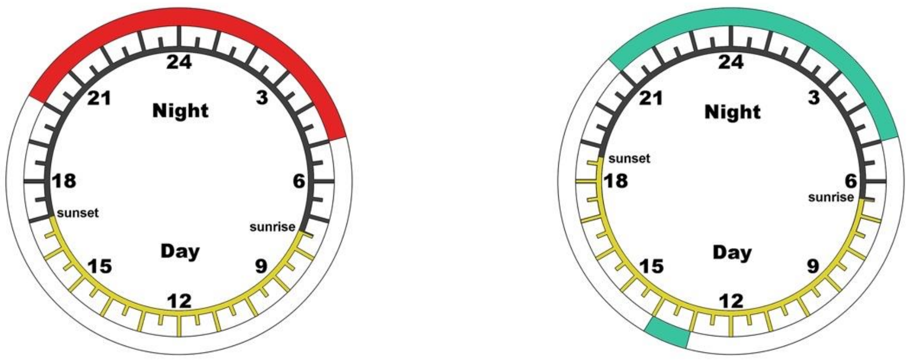
Figure 11. Window retrofitting diagram. (**a**) Longitudinal sectional graph of original window; (**b**) longitudinal sectional graph of window after retrofitting; (**c**) transverse sectional graph of window after retrofitting; (**d**) vertical view of window after retrofitting.

3.3. Simulation Process

The simulation scheme was formulated according to the concrete energy-efficient retrofitting measures via EnergyPlus. Then, an initial building energy consumption model (without using any energy-efficient retrofitting technology) was established by combining the field measurement and the actual construction drawings. To better evaluate the energy consumption of this dwelling, the authenticity and reliability of energy consumption simulation were improved under the following four scenarios. First, a total of six representative bedrooms (Figure 6a) on the first story of the dwelling were chosen as the research objects. To concretely display the influence of each energy-efficient retrofitting measure on the building energy consumption, it was assumed that all the six bedrooms were equipped with air conditioners of the same power. Second, the textures and dimensions of the building envelope and windows of the analysis object were defined and modeled according to the original conditions and measured parameters (Table 5). Third, the building components outside the analysis object were defined and modeled based on the original conditions. Fourth, the most real energy consumption of indoor electrical equipment was reproduced by introducing the work-rest schedule (Figure 12) of residents and the concrete power parameters of indoor electrical equipment. The parameter settings of simulated conditions are listed in Table 6. With the cooling, heating, lighting, and equipment energy consumption of the original building as the benchmark, the energy consumption in winter and that in summer as well as annual energy consumption under different energy-efficient retrofitting schemes were simulated.

Table 5. Measured thermal parameters of Rendetang.

Retrofitted Part	Structure and Thickness (mm)	Heat Transfer Coefficient (W/m^2·K)	Thermal Resistance R (m^2·K/W)
Roof	Chinese-style tile (10 mm) + lime mortar (20 mm) + sheathing brick (18 mm)	0.58	0.47
Window	Wooden frame 20 mm	/	/
Exterior wall	Brick wall 240 mm	2.04	0.04
	Thin plank wall 20 mm	1.11	0.62
Foundation	Triple-combined soil (240 mm)	3.62	0.03
Floor slab	Plank (25 mm)	0.74	0.62



(**a**) (**b**)

Figure 12. Work-rest schedule of residents. (**a**) Conditioning schedule of residents in summer; (**b**) air conditioning schedule of residents in winter.

Table 6. Simulation scenarios and parameter settings.

Working Condition Parameter		Value
Indoor temperature setting	Summer	26 °C
	Winter	18 °C
Heating period		From December 12 to 28 February in the next year
Cooling period		From 15 June to 31 August
Air conditioning schedule		See Table 7
Meteorological data		Annual data of local typical climate
Air tightness		2.3 h^{-1}

Table 7. Energy-saving effects of different retrofitting measures.

Retrofitting Measure	Summer kWh/Mon.	Winter kWh/Mon.	Annual kWh/Year	Energy-Saving Rate
-	2221	5460	30,377	-
Double-layer bamboo-wood composite fiberboard	1809	4537	25,033	17.6%
Double-layer bamboo-wood composite fiberboard + XPS board (2 cm)	1056	2827	15,270	49.7%
Double-layer bamboo-wood composite fiberboard + XPS board (3 cm)	907	2481	13,317	56.2%
Double-layer bamboo-wood composite fiberboard + XPS board (4 cm)	807	2250	12,027	60.4%
Double-layer bamboo-wood composite fiberboard + XPS board (5 cm)	735	2085	11,099	63.5%
Double-layer bamboo-wood composite fiberboard + XPS board (6 cm)	679	1963	10,404	65.8%

3.4. Simulation Results

Table 7 presents the average monthly energy consumption in winter and summer and the annual energy consumption of the original building and the building retrofitted through different energy-efficient retrofitting measures. To specify the relationship between each retrofitting measure and the energy consumption under the original status more intuitively, the energy-saving effects of different retrofitting measures were included into the table for comparisons, with the energy efficiency expressed by Formula (3). In the control experiment, a certain energy-saving effect was already achieved by adding the double-layer bamboo-wood composite fiberboards compared with that before retrofitting, but the energy-saving effect was poorer than that harvested by the scheme adding XPS boards. Since the bamboo-wood composite fiberboards reduced the energy consumption in rooms by enhancing the air tightness of plank walls, but its heat transfer coefficient was relatively approximate to that of the original plank wall, then the thermal insulation effect was not ideal enough.

$$R = \frac{\Delta E}{E} * 100\% \tag{3}$$

where R stands for the energy efficiency, is the difference value between the annual energy consumption after retrofitting and that under the original status, and E refers to the annual energy consumption under the original status.

It could be observed from the energy consumption data in Table 7 that after the double-layer bamboo-wood composite fiberboards were added to the original building, the energy-saving effect was improved by 17.6%, which was further enhanced after XPS boards were installed. With the increase in the thickness of XPS boards, the energy-saving effect was also gradually strengthened. In comparison to the scheme only installing the double-layer bamboo-wood composite fiberboards, the energy-saving effect achieved by the retrofitting scheme with the addition of 2 cm XPS boards was elevated by 32.1%. Nevertheless, the increase rate of energy-saving effect was slowed down with the increase in the thickness of XPS boards. Restricted by the structural thickness of the thermal insulation layer, the maximum thickness of XPS boards was 6 cm, corresponding to the energy-saving effect of 65.8%. The experimental results showed that the bamboo-wood composite fiberboard vs. XPS board retrofitting scheme could significantly improve the energy-saving effect of traditional wooden dwellings.

4. Evaluation and Discussion

4.1. First-Level Index Evaluation (Energy-Saving Effect)

Through the accuracy verification of this simulation scheme, the energy consumption of No. 3 room installed with an air conditioner before dwelling retrofitting was simulated (Table 8). The simulation results showed that the annual energy consumption of this room was 5062.83 kWh, and the monthly average energy consumption in summer was 370.17 kWh and that in winter was 910 kWh. Since the electricity consumption in No. 3 room was independently measured with an ammeter, the actual energy consumption of this room could be independently extracted and compared with the simulation result. It was discovered that the error rate of annual energy consumption was 6.94%, where the error rate of single-month energy consumption in summer was 3.26% and that in winter was 21.02%. Through analysis, the reason for the large error in winter was that the energy consumption part by warming with coal and timber was also included, and thus the heating energy consumption simulated was greater than the actual heating energy consumption. As revealed by the above comparative analysis, the energy consumption simulated by EnergyPlus was basically accurate and reliable.

Table 8. Comparison of real electricity consumption and simulated energy consumption of No. 3 room.

	Simulated Energy Consumption (kWh)	Actual Electricity Consumption (kWh)	Error Rate
Annual	5062.8	4734.2	6.94%
Each month in summer	370.1	358.4	3.26%
Each month in winter	910.0	751.9	21.03%

4.2. Second-Level Index Evaluation (Economic Efficiency)

In practical engineering, both energy efficiency and economic cost should be considered, including the labor cost added after energy-efficient retrofitting and the later-stage maintenance cost. Therefore, the research group has fully mastered information such as the price of thermal insulation materials through looking up relevant literature, consulting manufacturers, and conducting market surveys. On this basis, the total cost of each retrofitting measure and the cost of unit area (Table 9) could be further calculated. In actual projects, the total cost of each retrofitting measure is about 1.2–1.5 times that of energy-saving materials [30]. With Tables 6 and 8 combined, it could be seen that with the increase in the thickness of XPS boards, the energy-saving effect was enhanced accordingly, but the cost of unit area was also increasing. Investment payback period can quantify the returns of each energy-efficient retrofitting measure, and moreover, it can intuitively display the estimated time when the positive returns are reached. Therefore, the investment payback period could be used as a second-level index to comprehensively evaluate the energy-saving effect and the economy of each energy-efficient retrofitting scheme. According to Formula (2), the annual return of each energy-efficient retrofitting measure could be calculated, which was namely the product between the annual energy saved in comparison to the initial energy consumption and the local electricity price. According to surveys, the present electricity price is 0.508 ¥/kwh in Jinhua. Figure 13 displays the annual returns of different energy-efficient retrofitting measures. It could be observed that all the 5 composite thermal insulation materials would begin to generate returns after 5 years. For local villagers, the most suitable retrofitting scheme could be selected according to the energy-saving effect and the investment payback period.

The formulation of energy-efficient retrofitting measures is restricted by factors such as energy-saving effect, retrofitting cost, and investment payback period. To optimize and screen energy-efficient retrofitting measures combining various factors, the direct influencing factors (energy efficiency, cost of unit area, and investment payback year) were firstly listed (Table 10). The analysis results showed that although energy efficiency and cost of unit area were positively correlated with the thickness of XPS boards, the investment payback period could be reached the earliest when the thickness of XPS boards was 5 cm.

Table 9. Economic costs of different energy-efficient retrofitting measures.

Retrofitting Measure	Material Cost ¥/m^2	Total Cost ¥	Cost of Unit ¥/m^2
Double-layer bamboo-wood composite fiberboard	68.8	32,758.8	82.6
Double-layer bamboo-wood composite fiberboard + XPS board (2 cm)	83.4	39,710.5	100.1
Double-layer bamboo-wood composite fiberboard + XPS board (3 cm)	92.1	43,853.1	110.5
Double-layer bamboo-wood composite fiberboard + XPS board (4 cm)	95.1	45,281.4	114.1
Double-layer bamboo-wood composite fiberboard + XPS board (5 cm)	99.1	47,186.1	118.9
Double-layer bamboo-wood composite fiberboard + XPS board (6 cm)	103.1	49,090.6	123.7

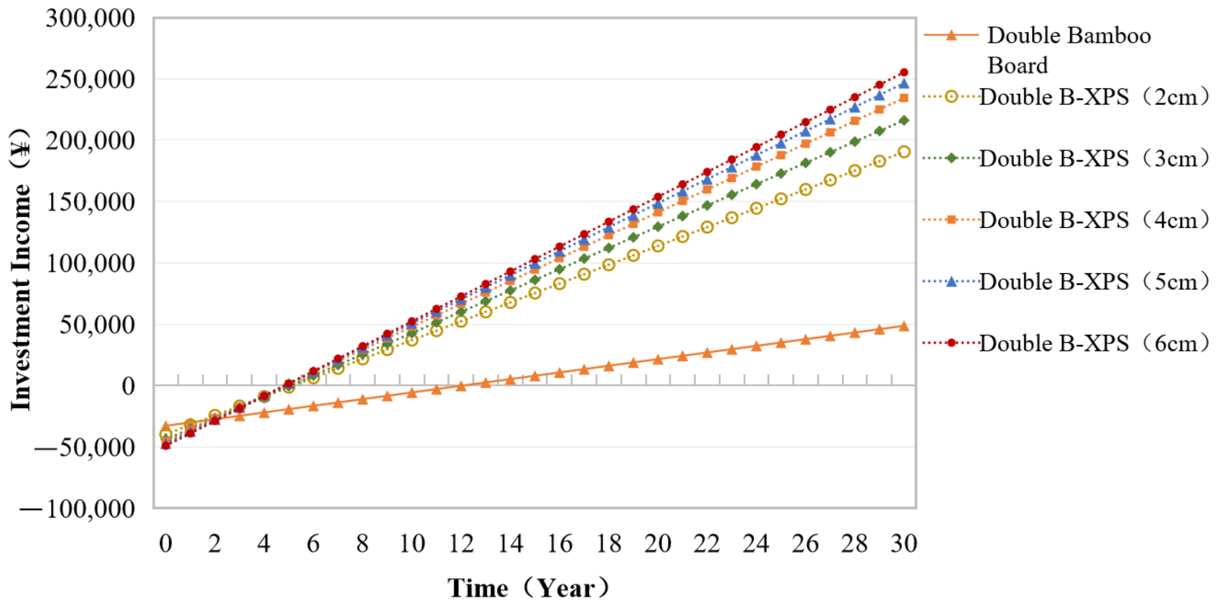


Figure 13. Investment payback periods of different retrofitting measures.

Table 10. Evaluation parameters under different energy-efficient retrofitting schemes in this case.

Retrofitting Measure	Energy Efficiency	Cost of Unit Area (¥/m^2)	Investment Payback Year
Double-layer bamboo-wood composite fiberboard	17.6%	82	13.07
Double-layer bamboo-wood composite fiberboard + XPS board (2 cm)	49.7%	100	6.17
Double-layer bamboo-wood composite fiberboard + XPS board (3 cm)	56.2%	110	6.06
Double-layer bamboo-wood composite fiberboard + XPS board (4 cm)	60.4%	114	5.86
Double-layer bamboo-wood composite fiberboard + XPS board (5 cm)	63.5%	118	5.82
Double-layer bamboo-wood composite fiberboard + XPS board (6 cm)	65.8%	123	5.84

4.3. Relationship between Wall Thickness and Energy-Efficient Retrofitting

During the wooden wall retrofitting of dwellings, the wall thickness allowed to be added for the thermal insulation wall retrofitting is restricted by a lot of factors, remaining to be reasonably evaluated and set according to the wall structure. In addition to improving the energy-saving effect and the indoor thermal comfort, it is also necessary to minimize the impacts of wall retrofitting on the actual indoor use area. In this case, the original planks of this dwelling were arranged along the center line of columns, which were 200 mm in diameter, and a total of three columns were distributed along each wall surface in each room. The internal surface of the plank showed a maximum vertical distance of 80 cm from the structural wooden column, which could be fully utilized in retrofitting, and bamboo-wood composite fiberboard and XPS board composites could be added. Although some indoor area would be occupied in this case, this part of area was not fully utilized in actual use since the locating place of indoor furniture was limited due to the columns protruding out of the wall under the original use status, while the indoor wall surface became smoother after retrofitting. Except the column base, furniture could be located along edges, so the actual spatial use was not impacted. Therefore, the maximum thickness of composites was chosen as 78 mm, with a mounting clearance of 2 mm reserved (Figure 14). During installation, the outer edge of the composite was flush with the outer edge of the wooden column, and rubber beads were used to fill in the joint between the composite and wooden column to prevent water vapor from permeating the room. The retrofitted wall was flat, and its thermal insulation performance was substantially improved. The construction of Chinese traditional dwellings is usually influenced by local construction technologies as well as the construction materials. Since the timber diameter directly decides the column diameter, the thickness of thermal insulation material should be reasonably adjusted according to the wall thickness during wall retrofitting.

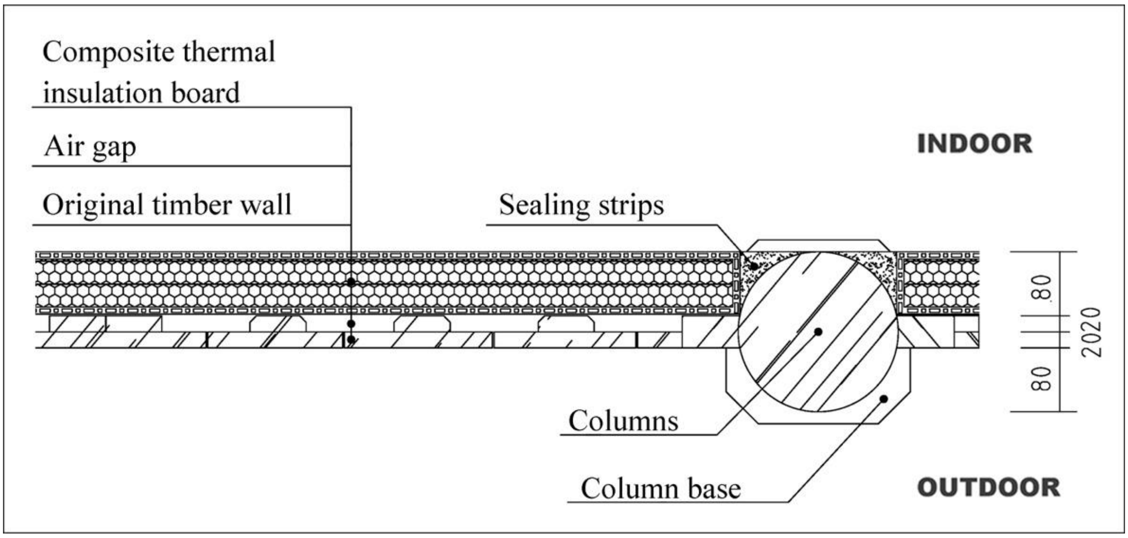


Figure 14. Cross section of thermal insulation wall retrofitting (maximum thickness).

4.4. Limitations and Further Research

This research is also subjected to some limitations, specifically manifested as follows: First, the error between the actual energy conservation effect of retrofitting measures and the simulation result needs to be further verified through the practical retrofitting and measurement of concrete cases, thus giving the actual energy consumption after retrofitting and obtain more accurate energy efficiency; second, the energy-efficient retrofitting of the most common courtyard-type traditional dwelling (sample selection) was analyzed, but the energy-efficient retrofitting of multi-courtyard and courtyard-free traditional dwellings was not analyzed. In the follow-up research, the sample size can be further expanded so that the retrofitting scheme is of broader application prospects. Meanwhile, this research mainly aims to propose an evaluation method for the energy-efficient retrofitting of traditional dwellings. The case conclusions drawn are not universally applicable but only applicable to traditional wooden dwellings in the hot-summer and cold-winter zone of China. Hence, this method should be reused to screen and determine suitable wall retrofitting schemes for traditional dwellings in other climate zones or other different types of traditional dwellings.

The research on the energy-efficient retrofitting methods for Chinese traditional wood walls and their evaluation further aims to guide the retrofitting and reutilization of Chinese traditional dwellings so as to realize the sustainable development. Therefore, more empirical researches should be carried out to further verify the applicability and energy efficiency of this energy-efficient retrofitting method. In the meanwhile, multiple types of thermal insulation materials should be comparatively analyzed to deeply verify the energy conservation effect that can be reached by thermal insulation materials for walls. More importantly, appropriate construction processes should be screened out to handle problems such as the wall construction thickness and the condensation of traditional wooden dwellings, expecting to keep the historical features of traditional dwellings to the greatest extent while improving the thermal comfort of buildings. Meanwhile, the research group will extend the research on different types of traditional dwellings in different climate zones, thus providing a reference for the energy-efficient wall retrofitting of more diversified traditional dwellings in more regions.

5. Conclusions

To solve the poor indoor thermal comfort problem of traditional wooden dwellings in hot-summer and cold-winter zone of China, a set of evaluation method for wooden wall energy-efficient retrofitting was proposed in this research by combining the requirements for energy conservation, and economic and historical value protection. With a traditional wooden dwelling in Jinhua, Zhejiang, as the analysis object, the proposed evaluation method was used to comparatively analyze several feasible wooden wall retrofitting schemes by means of field measurement and numerical simulation, and optimization suggestions over wooden wall retrofitting of this dwelling were given. The study found that, for traditional wooden dwellings in China's hot summer and cold winter regions, first of all, the bamboo-wood composite fiberboard + XPS board combined materials, if applied to indoor wall retrofitting of bedrooms, can enhance the airtightness and thermal insulation capacity of rooms, and the thermal insulation performance of the wall is further strengthened with the increase in the thickness of XPS boards. Secondly, the condensation problem and plank decay during interior thermal insulation retrofitting of the wall can be solved by reasonably utilizing the original structure of the wooden wall in this historical building (e.g., forming an air layer through the structural distance). Lastly, considering the retrofitting cost and the actual structural wall thickness, the thickness of XPS thermal insulation boards should be reasonably selected, so as to reach the comprehensive benefits of saving energy sources and reducing the retrofitting cost. The poor thermal comfort has become a common problem faced in the reutilization of Chinese traditional wooden dwellings. From the analysis results, however, the heat preservation and thermal insulation effect of dwellings can be substantially improved through appropriate wall retrofitting, so as to reach the goal of energy conservation and emission reduction. More importantly, a lot of traditional dwellings have not been effectively protected and utilized in China, and such type of retrofitting is featured by a low cost and not great construction technology difficulties. Therefore, this retrofitting scheme is expected to be widely applied in the protection and reutilization of traditional dwellings and further realize the sustainable development of historical heritages. This research provides an evaluation basis for optimizing and screening the energy-efficient retrofitting schemes of traditional wooden dwellings in hot-summer and cold-winter zone of China, and the research results are of scientific significance for promoting the research on the energy conservation and carbon emission reduction of traditional buildings.

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Nomenclature

HTC	Heat transfer coefficient
XPS	Extruded polystyrene board
SIPs	Structural insulated panels
TMY	Typical meteorological year
NPV	Net Present Value
r	Discount rate
Ct	Cash flow in year t
CO	Initial incremental investment cost
ΔPt	The dynamic investment payback period
A_{N-1}	The cumulative net cash flows with the last negative item
C_N	the cumulative net cash flow of year N

References

1. IEA. Key world energy statistics. *Int. Energy Agency* **2014**, *2011*, 3.
2. 2019 Global Status Report for Buildings and Construction. Available online: https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019 (accessed on 15 June 2022).
3. Building Energy Efficiency Research Center of Tsinghua University. *2020 Annual Report on China Building Energy Efficiency*; China Architecture & Building Press: Beijing, China, 2020.
4. Martínez-Molina, A.; Tort-Ausina, I.; Cho, S.; Vivancos, J.-L. Energy efficiency and thermal comfort in historic buildings: A review. *Renew. Sustain. Energy Rev.* **2016**, *61*, 70–85. [CrossRef]
5. Galatioto, A.; Ciulla, G.; Ricciu, R. An overview of energy retrofit actions feasibility on Italian historical buildings. *Energy* **2017**, *137*, 991–1000. [CrossRef]
6. Ascione, F.; De Rossi, F.; Vanoli, G.P. Energy retrofit of historical buildings: Theoretical and experimental investigations for the modelling of reliable performance scenarios. *Energy Build.* **2011**, *43*, 1925–1936. [CrossRef]
7. Ascione, F.; Bianco, N.; De Masi, R.F.; de'Rossi, F.; Vanoli, G.P. Energy retrofit of an educational building in the ancient center of Benevento. Feasibility study of energy savings and respect of the historical value. *Energy Build.* **2015**, *95*, 172–183. [CrossRef]
8. Sugár, V.; Talamon, A.; Horkai, A.; Kita, M. Energy saving retrofit in a heritage district: The case of the Budapest. *J. Build. Eng.* **2020**, *27*, 100982. [CrossRef]
9. Ge, J.; Lu, J.; Wu, J.; Luo, X.; Shen, F. Suitable and energy-saving retrofit technology research in traditional wooden houses in Jiangnan, South China. *J. Build. Eng.* **2022**, *45*, 103550. [CrossRef]
10. Shen, Y.; Yan, X.; Yu, P.; Liu, H.; Wu, G.; He, W. Seismic resistance of timber frames with mud and stone infill walls in a Chinese traditional village dwelling. *Buildings* **2021**, *11*, 580. [CrossRef]
11. Yuan, C.; He, Y.; Feng, Y.; Wang, P. Fire hazards in heritage villages: A case study on Dangjia Village in China. *Int. J. Disaster Risk Reduct.* **2018**, *28*, 748–757. [CrossRef]
12. Song, L.; Lin, B.; Zhu, Y. Simulation of the summer indoor thermal condition of a traditional Chinese residential building in Anhui. *Qinghua Daxue Xuebao/J. Tsinghua Univ. (China)* **2003**, *43*, 826–828.
13. Ma, Z.; Cooper, P.; Daly, D.; Ledo, L. Existing building retrofits: Methodology and state-of-the-art. *Energy Build.* **2012**, *55*, 889–902. [CrossRef]
14. Chen, X.; Yang, H.; Lu, L. A comprehensive review on passive design approaches in green building rating tools. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1425–1436. [CrossRef]
15. Han, J.; Yang, X. Analysis of passive energy-saving retrofitting of rural residential houses in southern Anhui Province-A case in Hongcun. *Energy Procedia* **2018**, *152*, 470–474. [CrossRef]
16. Litti, G.; Audenaert, A.; Lavagna, M. Life cycle operating energy saving from windows retrofitting in heritage buildings accounting for technical performance decay. *J. Build. Eng.* **2018**, *17*, 135–153. [CrossRef]
17. Jelle, B.P. Traditional, state-of-the-art and future thermal building insulation materials and solutions–Properties, requirements and possibilities. *Energy Build.* **2011**, *43*, 2549–2563. [CrossRef]
18. Li, Z.; Yang, H.; Chen, Y. The improvement of thermal insulation performance of traditional houses of Miao nationality in western Hu'nan province. *Huazhong Archit.* **2021**, *39*, 30–34.
19. Liu, S.H. Chunhua, Analysis of the thermal environment and energy-saving retrofitting of a traditional dwelling in western Hunan. *Build. Sci.* **2016**, *32*, 27–32.
20. Code for Thermal Design of Civil Building. In State Administration for Market Regulation of China: Beijing, China, 2016; Vol. GB 50176-2016. Available online: https://www.chinesestandard.net/PDF/English.aspx/GB50176-2016 (accessed on 15 June 2022).
21. Xu, H.; Li, S.; Wu, J. Natural expression of modern wood buildings in Nordic Region. *Urban. Archit.* **2013**, *15*, 42–45.
22. Li, Q.; Peng, K.; Wang, X.; Yang, J.; Bin, T. Renovation of Chinese ethnic structural wooden buildings in Qiandongnan Miao and Dong autonomous prefectures in Guizhou province. *Chin. J. Wood Sci. Technol.* **2018**, *32*, 38–41.
23. Bianco, L.; Serra, V.; Fantucci, S.; Dutto, M.; Massolino, M. Thermal insulating plaster as a solution for refurbishing historic building envelopes: First experimental results. *Energy Build.* **2015**, *95*, 86–91. [CrossRef]

24. Martín-Garín, A.; Millán-García, J.A.; Terés-Zubiaga, J.; Oregi, X.; Rodríguez-Vidal, I.; Baïri, A. Improving energy performance of historic buildings through hygrothermal assessment of the envelope. *Buildings* **2021**, *11*, 410. [CrossRef]
25. Qu, K.; Chen, X.; Wang, Y.; Calautit, J.; Riffat, S.; Cui, X. Comprehensive energy, economic and thermal comfort assessments for the passive energy retrofit of historical buildings-A case study of a late nineteenth-century Victorian house renovation in the UK. *Energy* **2021**, *220*, 119646. [CrossRef]
26. Cai, S.; Zhang, B.; Cremaschi, L. Review of moisture behavior and thermal performance of polystyrene insulation in building applications. *Build. Environ.* **2017**, *123*, 50–65. [CrossRef]
27. Ozarisoy, B.; Altan, H. Developing an evidence-based energy-policy framework to assess robust energy-performance evaluation and certification schemes in the South-eastern Mediterranean countries. *Energy Sustain. Dev.* **2021**, *64*, 65–102. [CrossRef]
28. Eltaweel, A.; Su, Y. Controlling venetian blinds based on parametric design; via implementing Grasshopper's plugins: A case study of an office building in Cairo. *Energy Build.* **2017**, *139*, 31–43. [CrossRef]
29. Fu, C.; Mak, C.M.; Fang, Z.; Oladokun, M.O.; Zhang, Y.; Tang, T. Thermal comfort study in prefab construction site office in subtropical China. *Energy Build.* **2020**, *217*, 109958. [CrossRef]
30. Zhu, L.; Wang, Z.; Sun, Y.; Shao, Z. Economic evaluation of energy saving technology for building envelope: Taking a residential building in Henan as an example. *Build. Energy Effic.* **2017**, *45*, 123–126.