Journal of Construction in Developing Countries, 30(Supp. 1), 55–76, 2025

Orthogonal Design Assessments to Improve Energy Efficiency in Rural Residential Buildings

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Published: 31 July 2025

To cite this article: Wang Su Qi, Emma Marinie Ahmad Zawawi and Qie Ji Kwong (2025). Orthogonal design assessments to improve energy efficiency in rural residential buildings. *Journal of Construction in Developing Countries*, 30(Supp. 1): 55–76. https://doi.org/10.21315/jcdc.2025.30.s1.3

To link to this article: https://doi.org/10.21315/jcdc.2025.30.s1.3

Abstract: Rural residential buildings often consume high energy due to inefficient designs that increase heating and cooling demands. This study employed an orthogonal test design method to assess the impact of structural modifications on energy efficiency improvement in rural residences. Key factors tested include wall and roof insulation thickness, heat transfer coefficients of exterior windows, south and north window-to-wall ratios and building shading. The optimal configuration identified involves 120 mm of external wall XPS insulation, a roof heat transfer coefficient of 0.27 (equivalent to 120 mm insulation), a triple-layer insulating glass window with a heat transfer coefficient of 1.20, a south window-wall ratio of 0.3, a north window-wall ratio of 0.1 and a horizontal sunshade length of 0.5 m. This combination resulted in an annual energy consumption of 6,579.72 kWh, compared to 13,036 kWh for the benchmark model. The optimal design achieved a 49.52% energy savings rate, excluding renewable energy and active energy-saving measures. The study concluded that the proposed strategic enhancements to the building envelope, particularly through the use of external wall insulation, can reduce energy consumption in rural residential buildings in Huai'an. The orthogonal design method streamlined the analysis, reducing the number of experimental trials while providing valuable insights into the relative influence of each factor.

Keywords: Energy efficiency, Envelope insulation, Orthogonal test design, Passive design strategies, Rural residential buildings

INTRODUCTION

The energy consumption of rural residential structures is a significant problem. This is mainly caused by the structural integrity of rural buildings, including walls, roofs and windows, which is crucial for energy dynamics (Liu et al., 2022). The outdated construction methods and insufficient thermal insulation increase the need for heating and cooling. For instance, the thermal resistance of traditional materials used in rural constructions, such as brick and untreated wood, is often insufficient when compared to modern insulated materials, leading to significant heat losses during colder months and heat gains during warmer months (Belizario-Quispe et al., 2023). The inefficiency is compounded by suboptimal design choices such as inappropriate orientations,

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inadequate window-to-wall ratios and the lack of integrated shading devices, which are essential for managing solar gains and enhancing natural ventilation (Mahlan et al., 2024).

Recent research has extensively explored multiple dimensions of building energy efficiency. The adaptation of energy-saving measures to specific climatic conditions, as demonstrated by Liu et al. (2022), indicates the need for a regionally tailored approach to optimise energy performance in rural residential buildings. Additionally, empirical studies such as that by Shao, Zheng and Jin (2020) have shown that passive design strategies can effectively modify the thermal environments of rural dwellings, improving their energy performance across diverse climatic scenarios. Despite these advances, the research landscape still lacks a holistic approach that synergistically combines multiple passive design strategies through systematic methodologies such as orthogonal testing to evaluate their cumulative impact on energy consumption (Ke et al., 2024). The urgency for implementing near-zero energy standards in rural settings is compounded by rising global energy prices and the pressing need to mitigate environmental degradation. This context necessitates the integration of innovative energy solutions that respect local architectural traditions while enhancing the affordability and sustainability of rural housing developments (Altan and Ozarisoy, 2022).

In addition, Lin and Yang (2018) utilised a multi-objective genetic algorithm for cost-effective and thermal comfort-focused building design, illustrating advanced computational design approaches. Qin and Zhou (2021) discussed passive low-energy design and practical applications in transitional geographic zones in semi-urbanised rural areas. Jegede and Taki (2022) examined building envelope optimisation by applying indigenous materials in Nigeria, which is relevant for sustainability and local material usage. Liu et al. (2021) used the response surface method to improve building energy efficiency, but it only applies to large-scale energy optimisation projects. Wang, Ge and Xiong (2019) carried out a thermal design optimisation analysis for rural buildings in northern China, focusing on heating demands specific to cold climates. Khan and Bhattacharjee (2021) bridged the gap between energy efficiency and comfort by studying the interaction between thermal and noise insulation in tropical climates. Li et al. (2022) assessed energy-saving retrofits for sunspaces in rural structures by an orthogonal experiment, revealing that the glass type and window-to-wall ratio significantly impact sunspace optimisation, contributing 64.03% and 17.42%, respectively. Jiang et al. (2023) highlighted the cost-effectiveness of traditional construction materials when investigating zero-energy retrofits in rammed-earth buildings. Ozarisoy (2022) assessed passive cooling designs in response to long-term heatwaves in Europe, useful for understanding adaptive strategies in the face of climate change. The study of Li et al. (2021) optimised energy efficiency and thermal comfort in green retrofit projects, blending sustainability with occupant comfort. Lu et al. (2023) conducted a comprehensive study of passive design parameters in traditional dwellings in the Qinba mountains, useful for heritage and rural architecture.

While existing research has advanced our understanding of building energy efficiency, there is a gap in studies targeting rural residential buildings with a focus on integrating passive design strategies. This paper aimed to address the gap in building energy efficiency for rural residential buildings using passive design strategies. The current study systematically evaluated the cumulative impact of various structural modifications on energy consumption using an orthogonal design approach. The experimental tests involved simulating different configurations of building envelopes in rural residences, including modifications in external wall insulation thickness (ranging from 40 mm to 120 mm), roof insulation with varying heat transfer coefficients and different window types with optimised heat transfer coefficients. The tests also considered variations in south and north window-to-wall ratios, as well as horizontal shading lengths. Design Builder software was employed to model these parameters, creating a comprehensive analysis of the energy savings potential of combined passive design strategies. Through this detailed assessment, the study attempted to identify the optimal configuration that can significantly reduce energy consumption and guide rural residential buildings towards near-zero energy standards.

FACTORS AFFECTING ENERGY CONSUMPTION

The energy consumption of a building is influenced by a complex interplay of factors associated with the building's physical characteristics and environmental interactions. The key elements in determining energy efficiency include the building's orientation, size coefficient and spatial layout. Additionally, the building envelope comprising walls, roofs and windows plays a pivotal role in thermal performance (Heydarian et al., 2020). Furthermore, the facade's window-to-wall ratio impacts solar heat gain and thermal losses, while natural ventilation and shading devices significantly affect building energy dynamics (Shafaghat and Keyvanfar, 2022). While some factors, like orientation and size coefficient, offer limited post-construction transformation, others, like the building envelope, can be modified to enhance energy efficiency (Nainwal and Sharma, 2023).

Impact of Walls

In non-transparent building envelopes, walls critically influence energy consumption. The thermal performance of walls affects heating and cooling energy requirements, with the heat transfer coefficient being pivotal (Gao et al., 2020). The heat transfer coefficient of exterior walls is stringently regulated under various energy efficiency standards (Abraham et al., 2023). Wall energy consumption is influenced primarily by brick type and insulation practices. In particular, wall materials often include sintered solid bricks and porous bricks in rural residential buildings (Jonnala et al., 2024). Therefore, as a critical component of the building envelope, exterior walls must have good thermal insulation to enhance energy efficiency (Tay et al., 2022). Simulations help understand the combined impact of these elements on energy usage, providing insights for optimising wall construction to meet energy efficiency standards and improve sustainability in new and renovated buildings.

Influence of Roofs

Roof insulation is crucial for reducing heating energy consumption and improving the upper part's thermal environment (Rawat and Singh, 2022). To save costs, typical residential roofs are flat, though these are rare, with double-slope roofs evolving from flat designs (Zhu et al., 2023). Natural vents are seldom used in sloped roofs, impacting natural ventilation's role in energy consumption. Most roofs in the study are double-slope, covered with green tiles, functioning as double-layer roofs. In Huai'an, rural residential roofs are typically constructed with 100 mm-thick reinforced concrete slabs and XPS insulation boards. Tested XPS insulation board thicknesses were 40 mm to 120 mm. A roof without insulation was also simulated for comparison to determine optimal insulation thickness for energy reduction.

Influence of External Windows

Exterior windows, comprising a frame and glass, are the most vulnerable component of a building's outer envelope. Despite covering only 20% to 33% of the outer envelope area, windows significantly influence energy consumption, contributing to about 20% of overall usage (Paulos and Berardi, 2020). Primary factors affecting window energy performance include the thermal transmittance (*U*-value) of the glass and the overall heat transfer coefficient of the window assembly. Improving these factors can reduce energy losses and enhance efficiency (Nourozi et al., 2020).

Effect of Window-Wall Ratio

The window-to-wall ratio is the proportion of windows to exterior walls. Increased window area raises the window-to-wall ratio, impacting illumination and solar radiation (Rana et al., 2022). In summer, windows increase indoor cooling consumption by receiving solar radiation. In winter, they increase indoor temperature, reducing energy consumption. Therefore, optimising the window-to-wall ratio is crucial for managing building energy efficiency (Wang and Wang, 2021).

Influence of Sun-shading Design

High solar radiation intensity necessitates effective sun-shading systems in regions with hot summers and cold winters. Designs like external shading devices, overhangs, louvres, and dynamic shading solutions prevent excessive solar radiation (Barbero-Barrera et al., 2024). These systems reduce cooling demands, enhance comfort, and improve energy efficiency. Without adequate shading, buildings overheat, increasing reliance on air conditioning, which escalates energy consumption and costs (Gupta and Chakraborty, 2021). The lack of sufficient shading in many buildings highlights the need for robust sun-shading systems to optimum thermal performance and reduce greenhouse gas emissions (Lin, Song and Chu, 2022).

Impact of Natural Ventilation

Natural ventilation primarily reduces indoor temperatures during summer by lowering cooling energy consumption (Piselli et al., 2020). In rural areas, split air conditioning systems are commonly used for cooling (Rashad et al., 2021). Natural ventilation, aided by fans, enhances cooling by promoting air exchange and removing indoor heat (Zhang et al., 2021). By promoting air exchange and removing heat from indoor spaces, natural ventilation significantly contributes to reducing the load on air conditioning systems, as illustrated in Figures 1(a) and (b). This synergy between mechanical cooling and natural ventilation not only improves energy efficiency but also enhances occupant comfort.

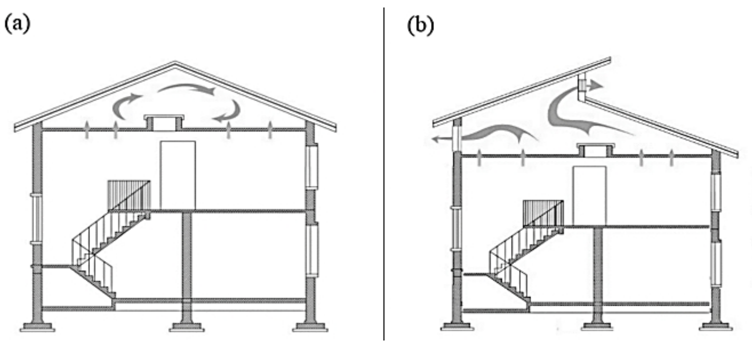

Figure 1. The indoor hot air of roof ventilation cycles: (a) existing roof and (b) renovated roof

PROPOSED METHOD

The methodological framework of the current study utilised the orthogonal method proposed in the work of Li et al. (2022). The statistical method efficiently studies the effects of multiple factors on a particular outcome by systematically varying the factors across a set of controlled experiments. For each combination in the orthogonal array, a simulation is conducted using energy modelling software, Design Builder. The annual energy consumption (in kWh) is recorded as the response variable for each combination. This response is then used to assess the effect of each factor on overall energy consumption. For each factor level, the average energy consumption (W_{ij}) is calculated by summing the energy consumption values across all tests where that particular level appears and dividing by the number of occurrences.

In this study, the average energy consumption for wall insulation thickness (Factor A) at level one (40 mm) was calculated as:

$$W_{ij} = \frac{\sum(\text{Energy consumption for test with A1})}{\text{Number of test A1}} \quad \text{Eq. 1}$$

The range (R) for each factor is determined by subtracting the lowest average energy consumption from the highest average for that factor. This range indicates the influence of that factor on energy consumption. Mathematically, for Factor A, the range is:

$$R_{ij} = \max\{\overline{W_{ij}}\} - \min\{\overline{W_{ij}}\} \quad \text{Eq. 2}$$

The orthogonal test method is calculated as follows (take Factor A as):

$$\overline{W_{11}} = \frac{1}{6} \times (W_1 + W_2 + W_3 + W_4 + W_5)$$

$$\overline{W_{21}} = \frac{1}{6} \times (W_6 + W_7 + W_8 + W_9 + W_{10})$$

$$\overline{W_{31}} = \frac{1}{6} \times (W_{11} + W_{12} + W_{13} + W_{14} + W_{15})$$

$$\overline{W_{41}} = \frac{1}{6} \times (W_{16} + W_{17} + W_{18} + W_{19} + W_{20})$$

$$\overline{W_{31}} = \frac{1}{6} \times (W_{21} + W_{22} + W_{23} + W_{24} + W_{25})$$

where, R_1 is the difference between the maximum and the minimum value of $\overline{W}_{11}$, $\overline{W}_{21}$, $\overline{W}_{31}$, $\overline{W}_{41}$, $\overline{W}_{21}$, $\overline{W}_{11}$ is the average value of the energy consumption of the remaining five schemes when the first level factor of A, $\overline{W}_{21}$ is the average value of the building energy consumption of the remaining five schemes of the second level of A and so on, $\overline{W}_{21}$ is the average value of the building energy consumption of the remaining five schemes of the same factor at the fifth level of factor A. The orthogonal test in the current study selected six factors, which were wall, roof, frame and glasses of windows, south window-to-wall ratio, north window-to-wall ratio and building shading. These factors included the heat transfer coefficients of the wall, roof and frame, and glasses of windows, the window-to-wall ratio and the horizontal length of the building's sun exposure.

In the current study, orthogonal tests examined design factors that influenced a building's energy consumption. This method involves the careful selection and organisation of factors to be tested, minimising the total number of experimental trials. In this study, spatial layout factors were excluded, focusing on five key factors. A total of six sets per factor were employed to construct an orthogonal test table. The wall used 240 mm sintered porous brick and XPS board, with external protection thicknesses of 40/60/80/100/120 mm. The roof's external insulation thickness changed, similarly, with heat transfer coefficients of 0.75/0.55/0.43/0.35/0.30 for 40/60/80/100/120 mm. Levels one to five corresponded to the target window type's heat transfer coefficient, with a glass type median of 1.90 and a window type heat transfer coefficient of 1.20. Specific set factors for the wall, roof and exterior windows are shown in Table 1.

Table 1. Factor combination table and change values

Factor Name	Wall Insulation Thickness (mm)	Roof Heat Transfer Coefficient (W/m²·K)	External Window Heat Transfer Coefficient (W/m²·K)	South Window-to-Wall Ratio	North Window-to-Wall Ratio	Horizontal Visor Length (m)
Horizontal factor 1	40	0.75	3.16	0.2	0.1	0.3
Horizontal factor 2	60	0.55	2.87	0.3	0.2	0.5
Horizontal factor 3	80	0.43	2.74	0.4	0.3	0.8
Horizontal factor 4	100	0.35	1.90	0.5	0.4	1.0
Horizontal factor 5	120	0.30	1.20	0.6	0.5	1.2

RESULTS AND DISCUSSION

In this study, a typical basic residential house in a rural area of Huai'an was selected as the benchmark model to facilitate simulation experiments and renovation (as shown in Figure 2). The benchmark model was set on a homestead area of 198 m^2, with dimensions of 11m by 18m and included buildings and a courtyard that occupy 189 m^2. The primary rural dwellings, which were located in the east measured 10.5 m by 18.0 m and were oriented southward. The main building had dimensions of 10.8 m by 9.0 m, a height of 3.3 m, and a total floor area of 230.69 m^2. Additionally, an auxiliary building was situated on the east side, used for traditional cooking and storage. Some residents used renewable energy sources, such as firewood, in this area. The building size coefficient was 0.56. The window-to-wall ratios were 0.4 for the south side, 0.3 for the north side, no windows on the east side and a small window for a toilet on the west side (as shown in Figure 3).

Figure 4 illustrates the modified reference plane. The first floor featured a living room, an elderly room, a kitchen, a toilet, a dining room and an auxiliary room on the east side. There was a living room, master bedroom, guest bedroom and toilet on the second floor. The homestead had a long, strip-like layout, with its specific dimensions outlined in Figure 3. In the benchmark simulation model, a glass sunroom was added to the south, altering the spatial configuration. This addition connected the main house to the auxiliary room and relocated the living room to the east. As a result, the auxiliary room was integrated into the living room, expanding its area and enhancing overall comfort, as shown in Figure 4.

Figure 2. A typical house at Matou County, Huai'an, Jiangsu, China

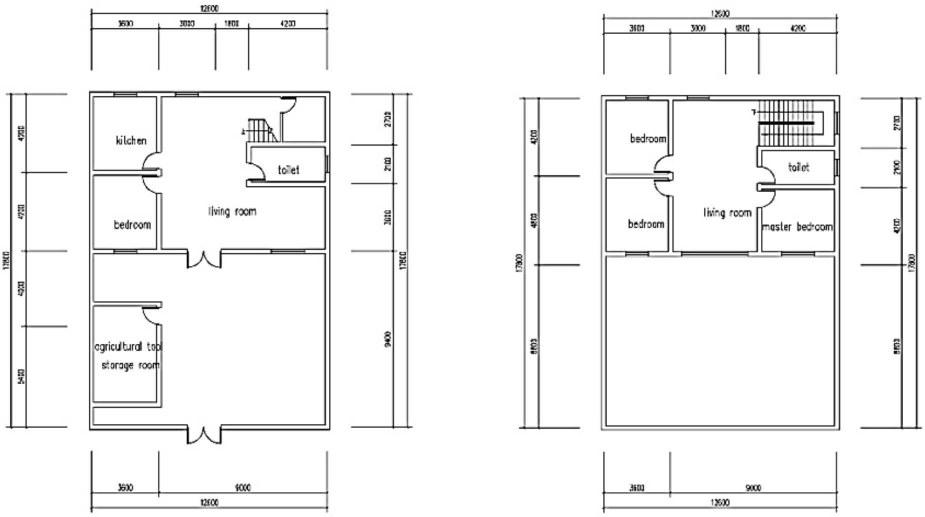

Figure 3. Typical residential model floor plan

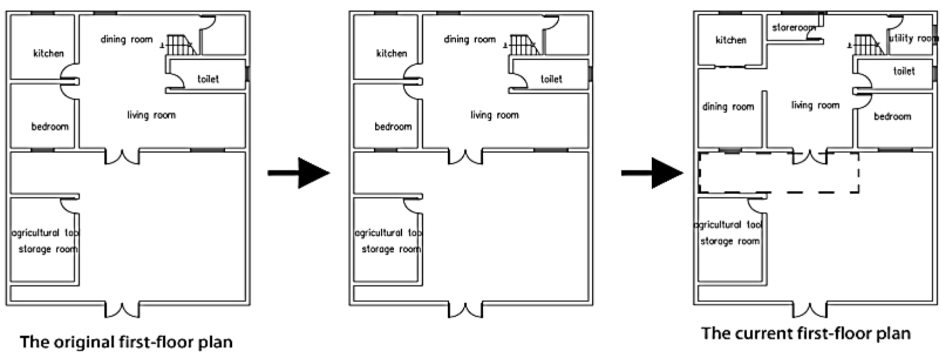

Figure 4. A floor plan of the datum model

The second-floor space directly increased indoor heat and cooling consumption. An effective method was to divide and connect the bedroom and hall, ensuring access to sunlight. This increased indoor solar radiation in winter and heating needs, as well as providing physical isolation in summer to reduce energy use for cooling. The second bedroom was set on the south side, reducing the hall area and converting the original second bedroom to storage or a study. This improved the second bedroom's comfort and reduced overall building energy consumption, as shown in Figure 5.

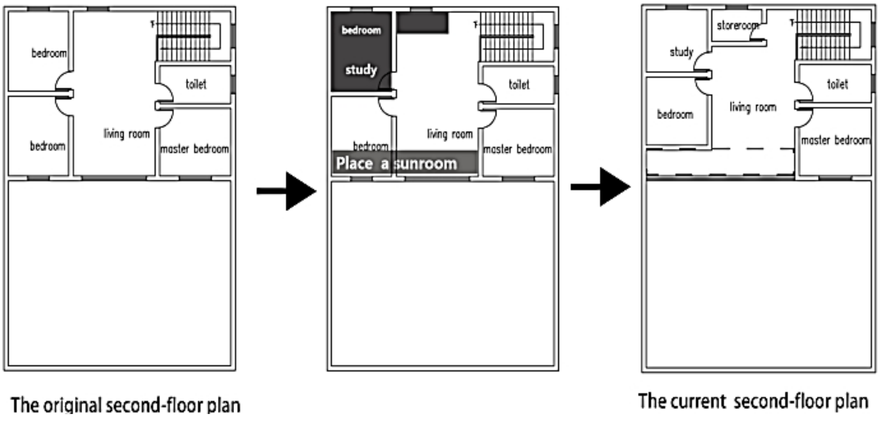

Figure 5. Second-level floor plan of the datum model

Model Parameter Setting

In the simulation process, internal disturbance factors depend on different buildings. Before the simulation, the internal disturbance factors for Huai'an rural housing were standardised. During factor analysis, selected measures must suit the local economic development level and be easily promoted. According to the building thermal division in Code for Civil Building Thermal Design GB50176-2016, Huai'an belongs to the hot summer and cold winter 3B area (700 ≤ HDD18 < 1200). Through the outdoor temperature parameters loaded by the software, the data was measured data in CSWD format collected by the China Meteorological Administration. Figure 6 shows the relative humidity levels in Huai'an.

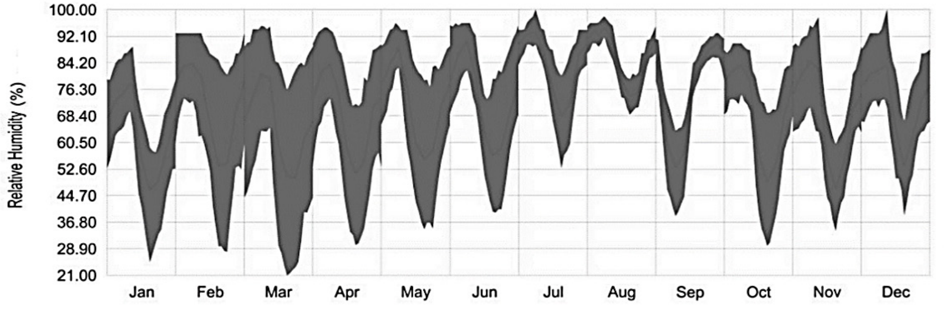

Figure 6. Outdoor relative humidity: Huai'an, China

Interior design parameters adhered to the provisions in the Code for Thermal Design of Civil Buildings (GB 50176-2016). As shown in Table 2, the indoor temperature limit for heating rooms in winter was 18°C and the air conditioning temperature in summer was 26°C, with an average relative humidity of 64%. In this simulation, all rooms were heated and cooled, except for the stairwell. According to the 2018 Energy Saving Design Standard (JGJ 26-1481), the occupancy level was set at two people in the bedroom, three in the living room and one in other rooms. The work and rest settings reflected immediate changes inside the house, divided into early summer and autumn-winter stages for peasant residents. Table 3 shows the living, work and rest schedules. The average lighting power density was set to 5W/m² per specification requirements.

Table 2. Heating and cooling room indoor heat and humidity environment parameters

Indoor Heat and Humidity Environment Parameters	Winter	Summer
Temperature (°C)	≥ 18	≤ 26
Relative humidity (%)	30 to 60	≤ 60

Table 3. Farmers' living schedules

Schedule	Spring/Summer (April to September)	Autumn/Winter (October to Next March)
Breakfast	6:00 a.m.	7:00 a.m.
Lunch	11:30 a.m.	12:00 p.m.
Dinner	5:30 p.m.	5:30 p.m.
Sleep	10:00 p.m.	9:30 p.m.

Model Validation

After modelling, a typical residential model was simulated through Design Builder (as shown in Figure 7). The annual building energy consumption of the quasi-model was 13,036 kWh, the annual cooling consumption was 6,886 kWh and the annual heating consumption was 6,150 kWh. These energy consumptions were to meet the annual total heating after the indoor heating comfort of the cooling and heating season. Heating and cooling equipment was open according to the indoor parameter standards. To compare simulated energy consumption, the study examined the effect of changing the width of the sunroom in rural Huai'an. The sunroom's glass had the same thermal parameters as the south window, with other parameters matching the original model, controlling relevant variables as shown in Figure 8.

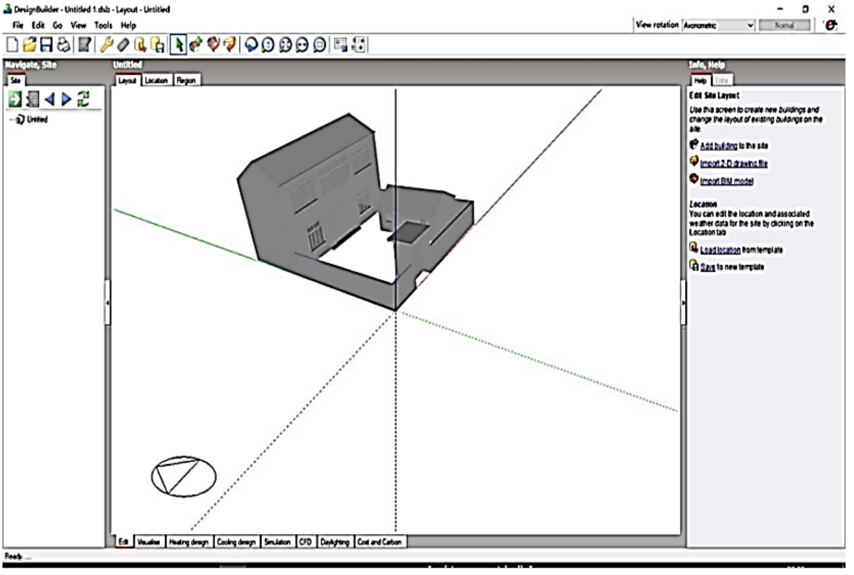

Figure 7. Simulation of schematic model

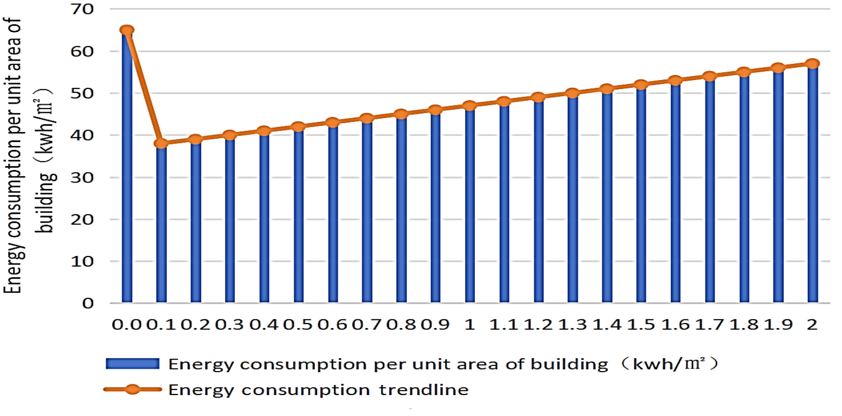

Figure 8. Comparison of annual energy consumption under different sunroom widths

Figure 9 presents simulation results using three different brick materials. The simulation results showed that the annual energy consumption of 240 mm sintered solid brick was the largest, reaching 13,036k Wh/a, the energy consumption of concrete porous brick and sintered porous brick decreased significantly, to 12,251 kWh/year and 11,568 kWh/year, due to the similar energy consumption of sintered porous brick and concrete porous brick and found in the actual research where sintered porous brick was more affordable, so sintered porous brick adopted as the wall material.

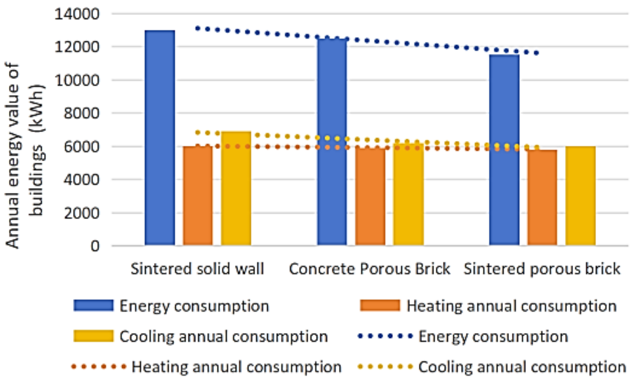

Figure 9. Comparison of annual energy consumption of buildings with different wall materials

According to the analysis of total heating and cooling energy consumption, the influence of the south window-to-wall ratio is shown in Figure 10. As the ratio increased from 0.1 to 0.8, heating energy consumption decreased, while cooling energy consumption increased. The increase in cooling energy consumption in summer was significantly greater than the decrease in heating energy consumption in winter. This was because increased solar radiation in summer raised cooling needs, while increased solar radiation in winter decreased heating needs. Large window areas are not conducive to winter insulation, as they lead to faster heat dissipation. According to Dagher Akhozheya and Slimani (2022), considering heating and cooling energy consumption and natural lighting and ventilation, the optimal south-facing window-to-wall ratio was about 0.3.

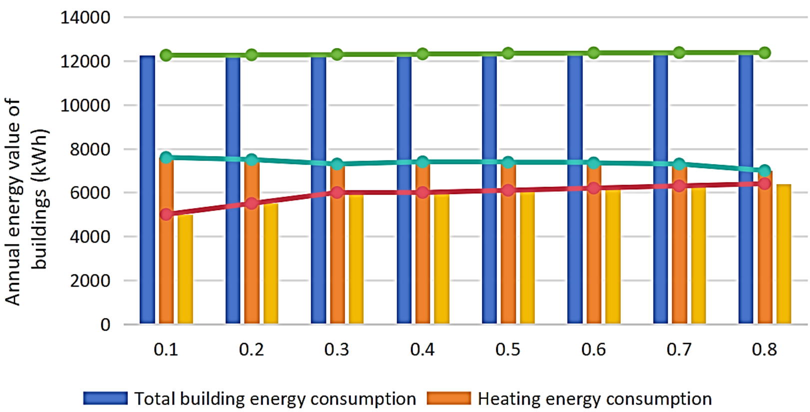

Figure 10. The impact of south-facing window-to-wall

The impact of insulation layer thickness (Factor A) on building energy consumption is illustrated in Figure 11. The orthogonal test revealed that energy consumption decreases with increased insulation thickness. While energy savings increased with insulation up to 100 mm, the rate of savings slowed beyond this point. The most rapid decline was between 60 mm and 80 mm. With an energy consumption reduction of 11,302.72 kWh, wall insulation was the most crucial factor in reducing overall energy consumption. Therefore, for near-zero energy buildings, the use of a 100 mm XPS insulation layer was the most suitable.

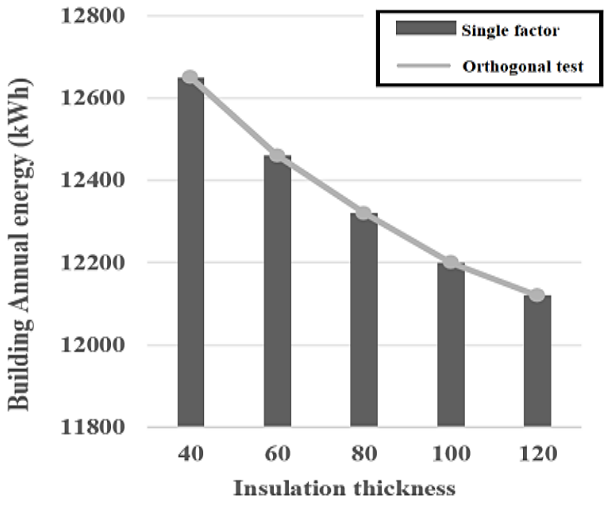

Figure 11. Comparison of the impact of insulation thickness

The impact of the roof's heat transfer coefficient (Factor B) on the building's overall energy consumption is shown in Figure 12. In Figure 12(a), under single-factor conditions, energy consumption decreased as the insulation thickness increased. The orthogonal test results revealed that energy consumption decreased most rapidly when the roof heat transfer coefficient was 0.37 or 0.31, which corresponded to XPS insulation layer thicknesses of 80 mm and 100 mm, respectively. As illustrated in Figure 12(b), the roof heat transfer coefficient was mainly influenced by the insulation layer's thickness. However, beyond a certain point, further increasing the insulation thickness led to diminishing returns in energy reduction. Based on the multi-factor orthogonal test, a 100 mm roof insulation layer was identified as the optimal choice.

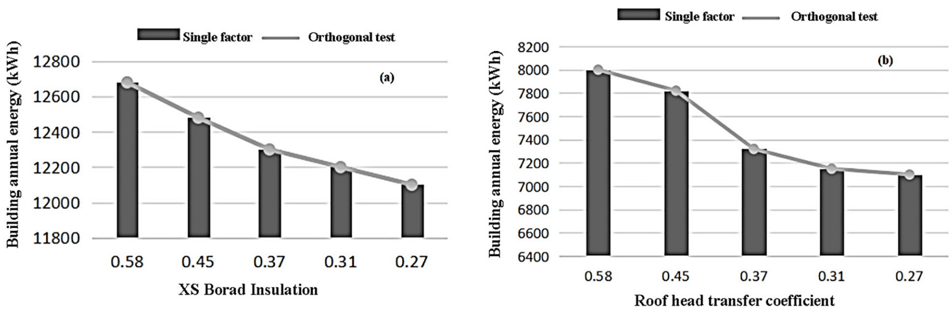

Figure 12. Comparison of the building energy consumption: (a) XPS insulation and (b) roof heat transfer coefficient

The impact of the external windows' heat transfer coefficient (Factor C) on the building's overall energy consumption is depicted in Figure 13. This figure illustrates the influence of six factors in the orthogonal test. The results confirmed that energy consumption decreased as the window heat transfer coefficient decreased. The most rapid and significant reduction in energy consumption occurred with a coefficient of 1.2, achieved using 5 + 12A + 5Low-E + 12A+ 5Low-E glass. Consequently, this glass type was considered the most suitable for rural housing in Huai'an.

Optimal Design Factors

In studying the energy consumption factors of rural housing in Huai'an, all evaluation criteria are based on energy consumption levels. Lower index levels indicate lower energy consumption, while higher levels indicate higher consumption. Table 4 presents the results of the orthogonal test, examining the impact of six key factors on the building's energy consumption.

Table 4. Orthogonal test table calculation results

Energy Consumption Average	Horizontal Factor					
	Wall Insulation Thickness (mm)	Roof Heat Transfer Coefficient (W/m²·K)	Window Heat Transfer Coefficient (W/m²·K)	South Window-to-Wall Ratio	North Window-to-Wall Ratio	Shading Length (mm)
\`W1j	8,106.36	8,015.37	7,836.21	7,425.96	7,436.23	7,499.23
\`W2j	7,751.42	7,821.59	7,735.24	7,302.12	7,429.36	7,210.41
\`W3j	7,212.32	7,799.27	7,496.45	7,388.65	7,469.49	7,438.15
\`W4j	6,903.19	7,309.63	7,410.36	7,428.32	7,499.28	7,392.65
\`W5j	6,803.64	6,987.24	7,219.54	7,509.15	7,512.61	7,601.63
R1	1,302.72	1,028.13	616.46	207.03	96.38	391.22
Influence factor weight	A-1	B-2	C-3	D-5	E-6	F-4

Table 4 lists the average energy consumption for five levels of each factor. The table indicates the variation in energy use across different configurations. The range (R1R_1R1) values highlighted the influence of each factor, with wall insulation thickness having the most significant impact (R1 = 1,302.72), followed by the roof heat transfer coefficient with a range of 1,028.13. The window heat transfer coefficient and shading length exhibited moderate influences, while the south and north window-to-wall ratios gave relatively minimal effects. These results helped prioritise structural modifications, revealing that improving wall and roof insulation provides the most substantial energy savings in rural residential buildings. Consequently, the factors' influence weights ranked A-1, B-2, C-3, F-4, D-5 and E-6, guiding the design focus for energy-efficient building envelopes.

Table 5 presents the configurations used in the orthogonal tests to analyse the impact of different design parameters on the annual energy consumption of rural residential buildings. The model and other design parameters aligned with the benchmark model, ensuring consistency across all 25 test cases. Each test represented a unique combination of six factors: wall insulation thickness (ranging from 40 mm to 120 mm), roof heat transfer coefficient (from 0.75 $W/m^2{\cdot}K$ to 0.30 $W/m^2{\cdot}K$), window heat transfer coefficient (from 3.16 $W/m^2{\cdot}K$ to 1.20 $W/m^2{\cdot}K$), south window-to-wall ratio (0.2 to 0.6), north window-to-wall ratio (0.1 to 0.5) and shading length (0.3 m to 1.2 m). The table records the annual energy consumption for each combination, labelled W1 to W25, with values ranging from 6,659.42 kWh to 8,535.19 kWh. This systematic variation in design factors provides insights into how changes in wall and roof insulation, window specifications, window-to-wall ratios and shading length affect overall energy performance. For instance, Test 1 with minimal insulation resulted in the highest energy consumption, while Test 19, featuring increased insulation and optimised heat transfer coefficients, achieved significantly lower consumption. These results helped identify the most effective strategies for improving energy efficiency in rural residential buildings.

Table 5. Factors under orthogonal tests

Test Number	Factors						Annual Energy Consumption (kWh)
	A	B	C	D	E	F	
1	40	0.75	3.16	0.2	0.1	0.3	W1 = 8,535.19
2	40	0.55	2.87	0.3	0.2	0.5	W2 = 8,136.49
3	40	0.43	2.74	0.4	0.3	0.8	W3 = 8,041.60
4	40	0.35	1.90	0.5	0.4	1.0	W4 = 7,992.18
5	40	0.30	1.20	0.6	0.5	1.2	W5 = 7,826.34

(*Continued on next page*)

Table 5. *Continued*

Test Number	Factors						Annual Energy Consumption (kWh)
	A	B	C	D	E	F	
6	60	0.75	2.87	0.4	0.4	1.2	W6 = 7,999.61
7	60	0.55	2.74	0.5	0.4	0.3	W7 = 7,739.18
8	60	0.43	1.90	0.6	0.1	0.5	W8 = 7,710.94
9	60	0.35	1.20	0.2	0.2	0.8	W9 = 7,609.16
10	60	0.30	3.16	0.3	0.3	1.0	W10 = 7,698.21
11	80	0.75	2.74	0.6	0.2	1.0	W11 = 7,632.18
12	80	0.55	1.90	0.2	0.3	1.2	W12 = 7,419.25
13	80	0.43	1.20	0.3	0.4	0.3	W13 = 7,219.16
14	80	0.35	3.16	0.4	0.5	0.5	W14 = 6,928.43
15	80	0.30	2.87	0.5	0.1	0.8	W15 = 6,862.58
16	100	0.75	1.90	0.3	0.5	0.8	W16 = 7,223.59
17	100	0.55	1.20	0.4	0.1	1.0	W17 = 7,091.37
18	100	0.43	3.16	0.5	0.2	1.2	W18 = 6,869.71
19	100	0.35	2.87	0.6	0.3	0.3	W19 = 6,659.42
20	100	0.30	2.74	0.2	0.4	0.5	W20 = 6,671.86
21	120	0.75	1.20	0.5	0.3	0.5	W21 = 7,080.94
22	120	0.55	3.16	0.6	0.4	0.8	W22 = 6,854.19
23	120	0.43	2.87	0.2	0.5	1.0	W23 = 6,719.54
24	120	0.35	2.74	0.3	0.1	1.2	W24 = 6,701.91
25	120	0.30	1.90	0.4	0.1	0.3	W25 = 6,661.62

Notes: A = Wall insulation thickness (mm); B = Roof heat transfer coefficient ($W/m^2 \cdot K$); C = Window heat transfer coefficient ($W/m^2 \cdot K$); D = South window-to-wall ratio; E = North window-to-wall ratio; F = Shading length (mm).

Table 6 compares the optimal scheme with configurations suitable for Huai'an's actual conditions. The optimal combination was A5 + B5 + C5 + D3 + E2 + F2, which included 120 mm external wall XPS insulation, a roof heat transfer coefficient of 0.27 (120 mm insulation thickness), an outer window heat transfer coefficient of 2.34 (5 + 12A + 5Low-E + 12A + 5 Low-E triple-layer insulating glass), a south window-wall ratio of 0.3, a north window-to-wall ratio of 0.1 and a horizontal sunshade length of 0.5 m. Design Builder simulation results showed that the optimal matching of annual building energy consumption was 6,579.72 kWh, compared to 13,036 kWh for the benchmark model. Excluding renewable energy and active energy-saving measures, the optimal building configuration achieved an energy-saving rate of 49.52%.

Table 6. Optimal matching of level factors

	Horizontal Factor	A	B	C	D	E	F	Annual Energy Consumption (kWh)
Optimal collocation	Horizontal label	A5	B5	C5	D2	E1	F2	6,761.72
	Horizontal data	120	0.27	1.20	0.3	0.1	0.5	

Notes: A = Wall insulation thickness (mm); B = Roof heat transfer coefficient (W/m²·K); C = Window heat transfer coefficient (W/m²·K); D = South window-to-wall ratio; E = North window-to-wall ratio; F = Shading length (mm).

CONCLUSIONS

Rural residential buildings in Huai'an face significant challenges in energy efficiency due to outdated structural designs. This study used the Design Builder simulation software to evaluate the impact of various structural improvements on energy consumption. The research investigated enhancements such as increased insulation, optimal window heat transfer coefficients and adjusted window-wall ratios. In general, the results of the current study identified external wall insulation as the most impactful modification, with increased insulation thickness directly correlating with reduced energy usage.

The study's findings on external wall insulation was that increasing external wall insulation thickness significantly reduces energy consumption. Using XPS insulation materials and increasing the insulation thickness up to 100mm effectively reduced the walls' heat transfer coefficient, lowering heating energy requirements in winter. Similar to wall insulation, improving roof insulation decreases energy usage. Simulations indicated that adding up to 100mm of XPS insulation on roofs reduces the heat transfer coefficient, leading to a reduction in total energy consumption. In terms of window specifications, optimising the thermal properties of windows enhances energy efficiency. Using windows with lower heat transfer coefficients, such as triple-glazed Low-E glass (5 + 12A + 5Low-E + 12A + 5Low-E), minimised energy loss. This balances energy savings with installation considerations, suiting Huai'an's climate.

Future research should explore integrating renewable energy sources, such as solar panels and geothermal systems, to further reduce the energy footprint of rural residential buildings. Investigating the long-term performance and maintenance of insulation materials under varying climatic conditions could provide deeper insights into sustainable building practices. Expanding the study to different rural regions with diverse climates would help validate the findings and tailor energy efficiency strategies to specific environments.

ACKNOWLEDGEMENTS

All authors are very grateful to Institut Pengajian Siswazah, Universiti Teknologi MARA, for partially financing this research.

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