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Original scientific paper

Thermal Optimization Strategies for Rural Housing in Yulin, China: An Analysis of Current Conditions and Future Improvements

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Abstract: This study investigates strategies to optimize the thermal environment and energy efficiency of rural dwellings in Yulin, China. Temperature, humidity, and solar radiation were monitored in three typical courtyard houses. Standard Deviation analysis revealed issues with indoor comfort and enclosure performance. Renovation approaches were proposed involving layout changes and envelope improvements. Simulations using Ecotect demonstrated the modifications could increase average indoor temperatures by 2.8 °C and reduce fluctuation ranges. This study provides an evidence-based methodology for enhancing rural home thermal comfort through climate-responsive design strategies tailored to the severe cold climate in Yulin, which could serve as a blueprint for similar cold regions around the world.

Keywords: enclosure performance; energy efficiency; indoor thermal comfort; optimization strategy; rural dwellings; thermal environment; Yulin area

1 INTRODUCTION

Accompanying the progression of rural economic development and the elevation of living standards, perceptions of rural living have been undergoing significant transformation [1]. The burgeoning improvements in quality of life and aesthetic appreciation have led to heightened expectations for indoor environmental comfort [2]. Among the indicators of indoor comfort, the thermal environment has emerged as a particularly salient focus of scholarly investigation [3-7].

In this context, several innovative strategies have been proposed. In the study of vernacular architecture, Jorge Fernandes, the different climate response strategies for the development of vernacular architecture in the two regions of Beira Alta and Alentejo are discussed, and it is found that the good thermal performance of passive means alone makes the occupants comfortable [8]. Hailu Haven and GelanEshetu and GirmaYared used subjective and objective measurements to evaluate the indoor thermal comfort of modern and traditional buildings, and to identify the factors that hinder or promote indoor thermal comfort in Semera city, Ethiopia. It is found that traditional building techniques and materials, combined with microclimate considerations, play an important role in regulating the indoor environment [9]. Zhang and Zhong's [10] paper examined the thermal environment of Huizhou folk dwelling houses in China, focusing on interior space layout, and offered insights for the renovation of these traditional buildings.

In the study of modern architecture, Gonzalez-Sanchez and Camaraza-Medina [11] proposed using thermal solar energy in the Four Palms Hotel's hot water system, demonstrating economic and environmental benefits through reduced propane consumption and CO_2 emissions. Bozonnet et al. [12] study cool roofs in French low-rise buildings and explore the passive principle, which helps to better understand the potential and limitations of cool roofs, and helps its development in different climatic regions. Jia et al. [13] examined intelligent building clusters in China, identifying challenges and proposing research directions for improving energy efficiency and information security.

Explorations into region-specific construction techniques and characteristics have also been conducted. Ibrahim et al. [14] investigated traditional residential buildings under the hot and dry climate conditions in North Africa, combined on-site measurement and observation with energy simulation, and proposed targeted passive transformation schemes from the perspective of energy saving. A research team at Xi'an University of Architecture and Technology, through empirical analysis of residential buildings in the Guanzhong area of Shaanxi Province, has found the thermal characteristics of raw soil residential buildings to surpass those of contemporary brick and concrete dwellings [15]. Ding and Chen [16] explored the optimization of the thermal environment and energy-saving in residential buildings under low-carbon operation, developing a heat transfer model, which helps to better understand the potential and practical applications of thermal optimization and energy efficiency. Wang et al. [17] taking the new and old traditional houses in Guangfu Ancient City, Hebei Province as an example, the indoor thermal environment and residents' thermal comfort characteristics were investigated, and it was found that the thermal environment quality of the old traditional houses was poor, but the residents' thermal adaptability was strong. Sun et al. [18] conducted by the authors focuses on urban building thermal comfort, utilizing ArcGIS and building parameters to analyze and propose improvement measures. The study constructs a human thermal comfort model within urban buildings and explores influencing factors through spatial statistics and spatial analysis, providing validation of the effectiveness of the proposed method.

These varied studies highlight the evolving understanding and emerging strategies surrounding the optimization of thermal environments in rural dwellings. However, there remains a need for additional in-depth research, so this article uses Yulin as an example to discuss how thermal comfort and energy efficiency can be further improved in cold regions

2 GEOGRAPHICAL AND CLIMATIC CONDITIONS OF THE YULIN REGION

Situated in the utmost northern region of Shaanxi Province, with latitude and longitude coordinates ranging from 36°57' to 39°35' N and 107°28' to 111°15' E respectively, Yulin acts as the intersecting point of the Loess Plateau and the Mu Us Sandy Land. Furthermore, it functions as the transitional zone between the Loess Plateau and the Inner Mongolia Plateau [19]. The region's ecological sensitivity, stemming from a fragile environment, is manifested in multiple challenges, including land desertification, windborne dust, landslides, and water pollution, compounded by an urban vegetation coverage rate that leaves room for improvement. Consequently, the region lags in urbanization development and exhibits suboptimal habitability.

Climate-wise, Yulin demonstrates a unique pattern. The spring season witnesses a rapid and stable rise in temperature, surpassing the temperature readings observed in autumn. The winter season, predominantly governed by the northern cold air mass with the temperatures averaging between −7.8 to 4.1 °C, markes the region as a cold zone enduring prolonged winters.

These distinct geographical and climatic conditions of Yulin necessitate tailored strategies for thermal environment optimization in rural dwellings, considering not only the harsh winter temperatures but also the ecological challenges of the area. Such strategies would greatly enhance the indoor thermal comfort and energy efficiency in these dwellings, thereby improving the quality of life for rural residents in this ecologically sensitive region.

3 THERMAL ENVIRONMENT EXAMINATION OF RESIDENTIAL STRUCTURES

3.1 Examination Subject

With regard to the residential construction timeline, three characteristic courtyard-style residential buildings from distinct periods within the Yulin area were selected as examination subjects (Fig. 1). Point 1, a south-facing building constructed in 1992, is outfitted with single pane wood windows, displaying suboptimal air tightness. This flat-roofed structure, adorned internally with a vaulted masonry finish, was unoccupied during the period of examination.

Figure 1 Diagrammatic representation of the residential structures at the observational points

Point 2, also facing south, was originally constructed in 1997 and underwent renovation in 2010. It features a single pane steel window with superior air tightness and was unoccupied during the examination.

The most recent of the structures, point 3, was erected in 2017. This south-facing building is equipped with a single pane, double-layered aluminum alloy window, a second-floor sunroom, and a roof insulation layer. It was unoccupied during the examination period. Refer to Table 1 for a detailed overview of the residential buildings at each point.

According to the construction time of residential houses, three typical courtyard-style residential houses in Yulin area in different periods are selected (as shown in Fig. 1). Measuring point 1 was built in 1992, facing south, with single glass wood windows and poor air tightness. The exterior surface of the building is flat-roofed and the interior is vaulted with masonry finishes. Unoccupied during the test. Point 2 was built in 1997 and renovated in 2010. South facing, single glass steel window, good air tightness of the window, unoccupied during the test. The construction time of measuring point 3 is 2017. Facing south, single glassy aluminum alloy window, double layer, sunshine room on the second floor, insulation layer on the roof, unoccupied during the test. See Tab. 1 for the basic information of residential houses at the measuring point.

Table 1 Fundamental information regarding residential structures at the measurement points

Survey station	Building storey	Courtyard type	Architectural orientation	Structural form	Exterior wall practice	Window material
Point 1	A layer of floor	Linear	South	Brick structure	240 mm solid brick wall	Wooden window
Point 2	A layer of floor	Linear	South	Brick structure	240 mm solid brick wall	PVC steel Windows
Point 3	Two layers	Linear	South	Brick structure	240 mm solid brick wall	Aluminium window

3.2 Examination Scheme

The examination spanned from January 16 to January 18, 2021. During this period, the weather remained overcast. The buildings' doors and windows were kept shut throughout the winter examination, and no active heating measures were deployed. Similarly, no individuals resided within the buildings during this period.

The principal content of the examination included the indoor and outdoor air temperature, relative humidity, solar radiation intensity, and outdoor wind speed. The examination tools comprised the HOBO MX2301 temperature/humidity data logger, the JTR04 Black ball radiation temperature tester, the JT2020-4 solar radiation tester, and the TES1341 hot-wire anemometer. The data were logged at half-hourly intervals.

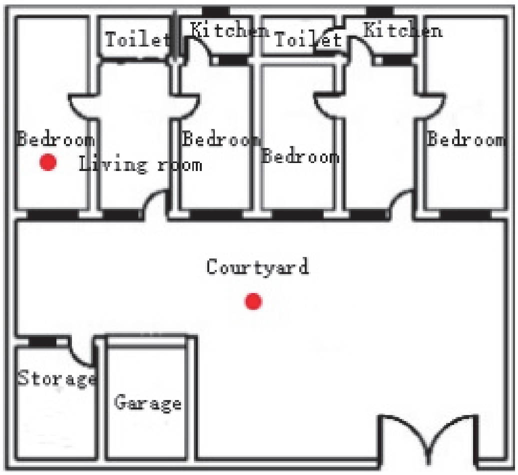
The placement of measurement points, 1.5 m above the ground, aligns with the JGJ/T 347-2014 Standard for Thermal Environment Testing methods of Buildings [20]. The locations of these points are illustrated in Fig. 2.

These detailed examinations and their findings provide valuable insights into the unique challenges posed by the thermal environment of rural dwellings in the Yulin area, enabling the development of optimized strategies for improving indoor thermal comfort and energy efficiency.

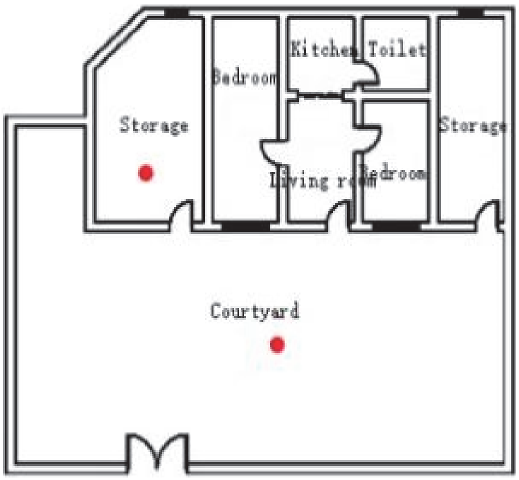
4 EXAMINATION OUTCOMES AND INTERPRETATION

4.1 Solar Radiation Intensity

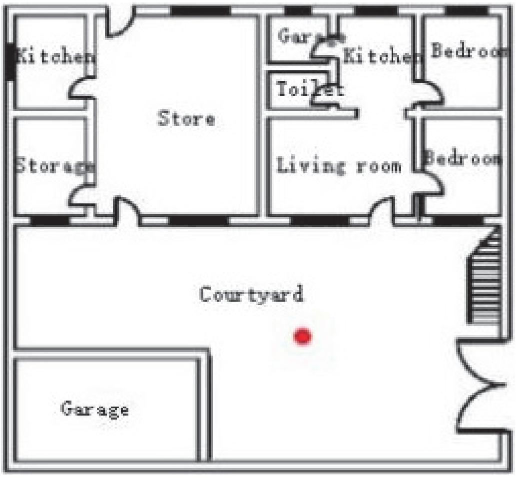
The solar radiation intensity, as displayed in Fig. 3, follows a parabolic trajectory, rising initially before experiencing a decline. The mean solar radiation intensity registers at approximately 270 W/m², with a peak of around 507 W/m² observed at 12:30 PM. Given the relatively short duration of solar radiation in winter, it is crucial to consider the orientation and angle, irrespective of whether passive or active solar heating methods are employed, to optimally utilize radiant heat during the radiation timeframe.



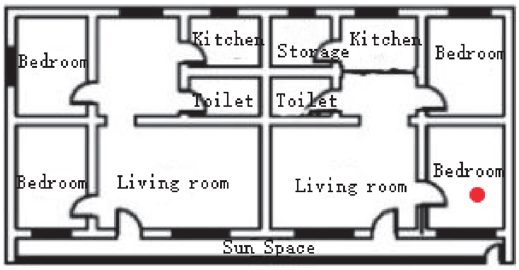
Point 1



Point 2



Point 3 - First floor



Point 3 - Second floor

Figure 2 Layout of the plane and measuring points of the residential buildings

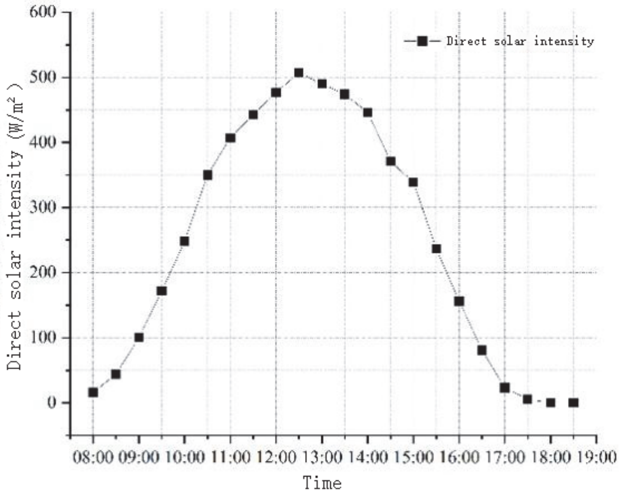


Figure 3 Variation of solar radiation intensity

4.2 Air Temperature

The chilliest day during the winter examination period, January 18, 2021, was selected to represent a typical winter day. The indoor airflow rate during the examination was virtually non-existent, and the airtightness was well-maintained, effectively reducing the incursion of cold air. Indoor and outdoor air temperatures, as well as extreme values, mean values and variances are presented in Fig. 4 and Tab. 2, respectively.

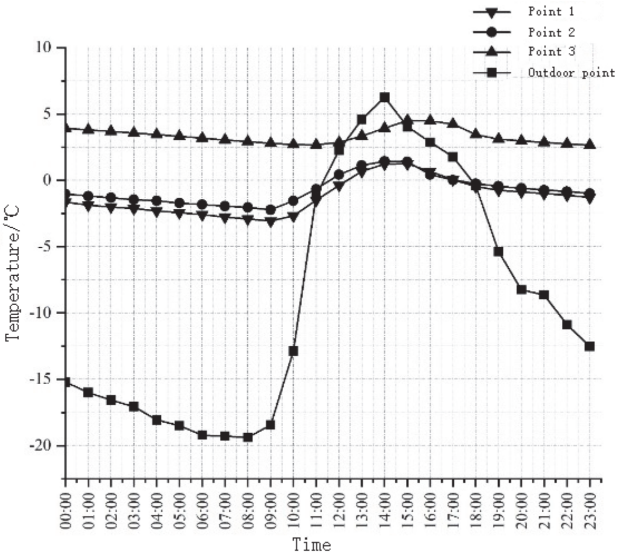


Figure 4 Variation of indoor and outdoor temperatures on a typical winter day

A closer analysis of the recorded temperatures unveils the benefits of incorporating a sunroom, as evidenced by the higher average temperature and more stable temperature fluctuations in measuring Point 3. This finding suggests that a sunroom is a viable strategy to improve the indoor thermal environment during winter [21].

Table 2 Details of residential temperature at each measurement point

	The maximum / ℃	The minimum / ℃	The average / ℃	Variance / ℃²
Point 1	1.24	−3.07	−1.25	1.73
Point 2	1.43	−2.22	−0.73	1.15
Point 3	4.51	2.66	3.34	0.32

However, the recorded indoor temperatures across all residential houses, without the implementation of any heating measures, were significantly below the required 18 ℃ winter indoor calculation temperature as prescribed by DBJ61-65-2011 "Shaanxi Province Residential Building Energy Conservation Design Standard".

4.3 Relative Humidity

The relative humidity fluctuation at each measuring point is presented in Fig. 5, with extremes, averages, and variances detailed in Tab. 3. The relative humidity demonstrates a soft trend of initial decrease, followed by an increase. The wall envelope structure material of the residential houses exhibits commendable thermal insulation and moisture retention properties, as indicated by the relatively steady indoor humidity, which is less affected by outdoor humidity fluctuations.

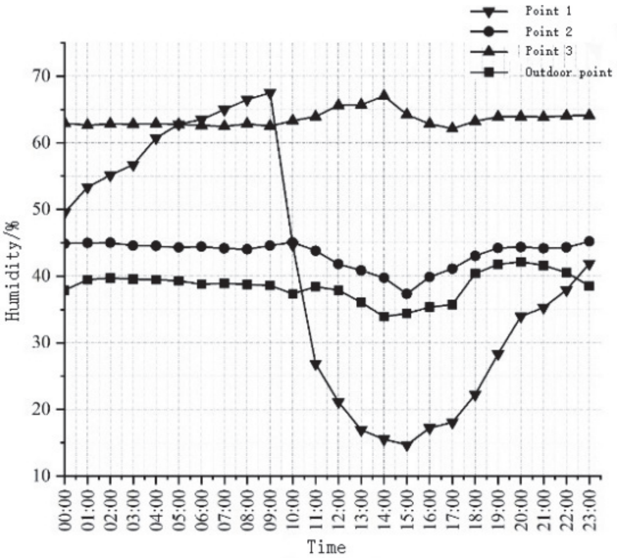


Figure 5 Variation of indoor and outdoor relative humidity on a typical winter day

Table 3 Details of relative humidity of dwellings at each measurement point

	The maximum / %	The minimum / %	The average / %	Variance / %²
Point 1	42.15	33.93	38.52	4.77
Point 2	45.18	37.33	43.35	4.35
Point 3	67.01	62.13	63.55	1.39

Despite this, the observed relative humidity did not reach the required 30%-60% as mandated by GB50176-2016 Code for Thermal Design of Civil Buildings [22]. Hence, it is advised to adopt suitable active and passive transformation strategies to enhance the indoor thermal and humidity comfort of rural dwellings in the Yulin area.

These examination results contribute to an understanding of the unique thermal environment challenges faced in the Yulin area. The findings offer practical implications for enhancing thermal comfort in rural dwellings and form a foundation for further studies investigating specific interventions for climate-responsive design strategies.

5 THE SEMANTIC DIFFERENTIAL METHOD-BASED QUANTITATIVE ANALYSIS

The optimization of rural dwellings mandates the incorporation of the diverse renovation desires and requirements of local inhabitants. Owing to subjective deviations rooted in individual disparities, a direct quantitative comparison is unachievable. As a result, there exists a necessity to execute quantitative analyses on multifarious qualitative challenges and establish suitable decision-making methodologies [23]. Factor analysis of given scales is employed to quantitatively convey the relative weight value of each element.

In this context, the Semantic Differential (SD) method, a technique of architectural planning proposed by Charles Egerton Osgood in 1957 [24], proves useful. It has since been extensively applied in architectural space research. The SD method is a quantitative analysis method for the psychological feelings of the participants. In recent years, various new psychological research methods have emerged one after another, but due to its own technical limitations in the field of psychology, it has shined in the fields of architecture, planning management, product research and development, and has been gradually withdrawn from the field of psychology. The semantic difference method is a relatively mature psychological scale for scholars at home and abroad, which has the characteristics of simplicity, easy to grasp. The relevant studies on the application of the SD method in the field of architecture are as follows:

Xia Sun and other researchers used scientific methods to objectively assess human perception of traditional and modern neighborhoods, and applied EEG tests and SD method to assess the perception of external space in traditional and modern commercial districts [25]; Wang De and other researchers used the semantic difference method to study the spatial perception characteristics of eight representative streets in Shanghai and their relationship with the street's object indicators, providing a reference for the humanized design of street space [26].

There is no specific provision in the literature on the number of adjective pairs in the evaluation of SD method, and when selecting adjective pairs, we should try to choose familiar words and adjectives with clearer positive and negative meanings, so this paper selects 10 pairs of adjectives as evaluation factors for the main research elements to construct a semantic difference scale or SD curve [27].

Table 4 SD method evaluation factors

Serial number	Evaluation scale (score)
1	Layout is not reasonable – Well-laid out (−2, −1, 0, 1, 2)
2	Area is not appropriate - Area is suitable (−2, −1, 0, 1, 2)
3	Improper height - Suitable height (−2, −1, 0, 1, 2)
4	Poor light - Better light (−2, −1, 0, 1, 2)
5	Poor ventilation - Good ventilation (−2, −1, 0, 1, 2)
6	Poor heating effect - Good heating effect (−2, −1, 0, 1, 2)
7	Poor moisture resistance - Good moisture resistance (−2, −1, 0, 1, 2)
8	Low energy efficiency - High energy efficiency (−2, −1, 0, 1, 2)
9	Poor insulation performance - Good insulation performance (−2, −1, 0, 1, 2)
10	Poor comfort - Higher comfort level (−2, −1, 0, 1, 2)

Following the "second-order" principle, these pairs of evaluation factors were segmented into positive and antonymous adjective pairs. A five-level evaluation scale was established, ranging from poor to good, corresponding successively to scores of −2, −1, 0, 1, and 2 (See Tab. 4).

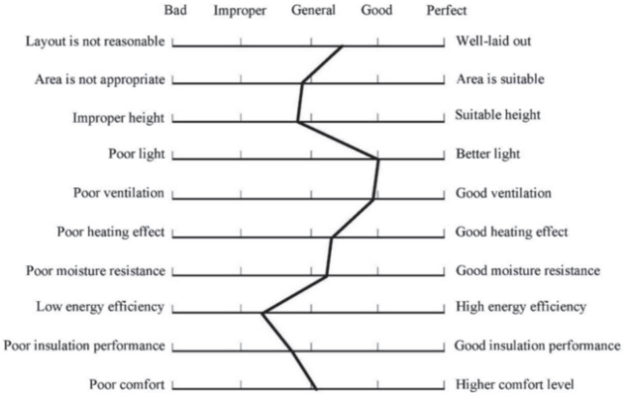


Figure 6 SD method broken line chart

Then the mean value of the original data $\left(\overline{x}=\frac{\sum_{i=1}^{n}x_i}{n}\right)$ is calculated and the SD mean curve is plotted. From Fig. 6, it is observed that the mean score of a majority of the evaluation factors is more significant than 0. Elements such as residential area, storey height, energy consumption efficiency, and thermal insulation efficiency register score near to or even less than 0, necessitating further improvement to meet residents' needs.

On the basis of SD data, it is analyzed in SPSS statistical analysis software. Total variance interpretation pertains to the contribution of factors towards variable explanation (see Tab. 5). In this case, the necessity for at least four factors to express the variable to over 90% is evident. This necessity confirms the effectiveness of the factor representation. Moreover, Fig. 7 supports the selection of four common factors, as the slope of the first four factors is notably steep, and the curve flattens from the fifth factor onwards.

Table 5 Explanation of total variance (Table source: IBM SPSS Statistics software)

Serial number	Initial eigenvalue			Extract the sum of squares of loads			Sum of squares of rotational loads		
	Total sum	Percentage of variance	Cumulate %	Total sum	Percentage of variance	Cumulate %	Total sum	Percentage of variance	Cumulate %
1	2.630	26.298	26.298	2.630	26.298	26.298	2.399	23.993	23.993
2	2.387	23.867	50.165	2.387	23.867	50.165	2.185	21.847	45.840
3	2.043	20.431	70.596	2.043	20.431	70.596	2.096	20.962	66.802
4	1.687	16.874	87.470	1.687	16.874	87.470	2.067	20.668	87.470
5	.492	4.917	92.387						
6	.402	4.019	96.406						
7	.262	2.621	99.027						
8	.091	.911	99.938						
9	.006	.062	100.000						
10	1.582E-16	1.582E-15	100.000						
Extraction method: principal component analysis									

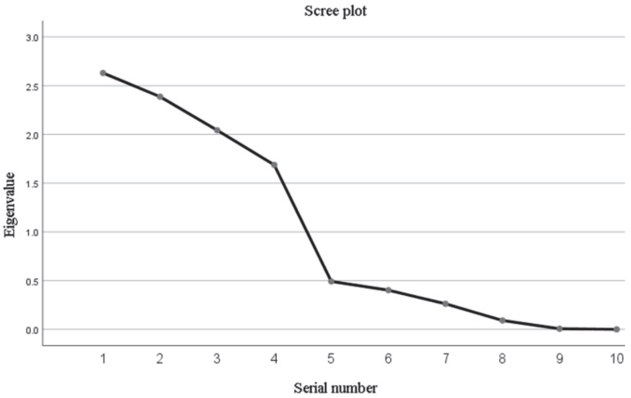


Figure 7 Scree plot (Image source: IBM SPSS Statistics software)

In conclusion, two dimensions can be extracted from these factors - Dimension 1 as the spatial function factor, and Dimension 2 as the maintenance structure factor. These dimensions suggest directions for the optimization of rural dwellings in the Yulin suburbs.

This SD method-based quantitative analysis offers a robust tool for tackling the inherently subjective nature of architectural planning. The method's utility extends beyond providing a data-driven strategy for rural dwelling optimization, as it forms a basis for an inclusive renovation process that addresses individual needs and collective residential requirements.

6 RESIDENTIAL BUILDING OPTIMIZATION STRATEGIES

A quantitative examination of winter test data reveals an intimate connection between the quality of the indoor thermal environment in residential dwellings and two key factors - spatial functional layout and thermal performance of the building envelope [28]. Consequently, potential improvements to the indoor thermal comfort of rural dwellings in the Yulin region during winter can be addressed via spatial layout and maintenance structure.

6.1 Layout Optimization

In the optimized layout, a northern arrangement of the kitchen and dining room functions as a thermal buffer, mitigating cold wind intrusion during winter. Southern-oriented bedrooms and living rooms ensure adequate sunshine absorption. An "additional sunshine room" is introduced to the traditional local layout (see Fig. 8), providing solar energy heat storage and insulation during winter and a cooling effect during summer [29]. A garage addition, livestock area, plantation section, and crop stack area segregation contribute to the overall layout. Deciduous trees planted in the yard offer sun and wind protection, fostering a beneficial microclimate environment.

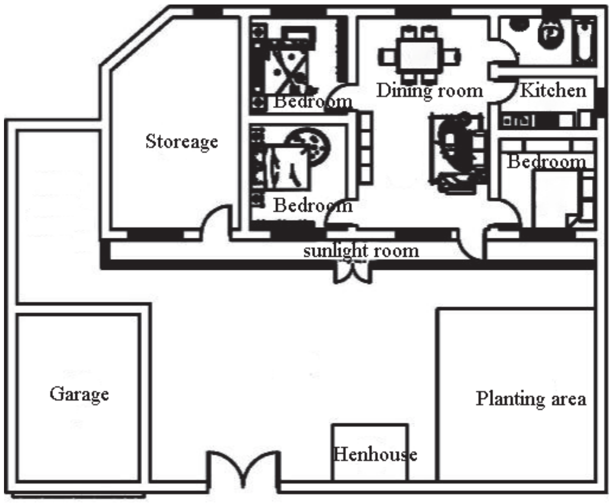


Figure 8 Optimized plane layout

6.2 Wall Insulation Measures

Wall energy consumption significantly contributes to the total energy consumption of the outer envelope structure, accounting for roughly 25% of total heat loss in winter. The existing 240 mm thick solid clay brick walls possess a relatively high heat transfer coefficient of 2.0 W/(m²·K). Upon transformation to a 370 mm thick sintered porous brick wall, an insulation layer and vapor barrier are added between the exterior wall brick and plaster surface. Optimal insulation material selection involves materials with low thermal conductivity coefficients and low densities, such as polystyrene plastic or extruded polystyrene foam boards, positioned laterally in the insulation layer to prevent moisture damage from rain (see Fig. 9).

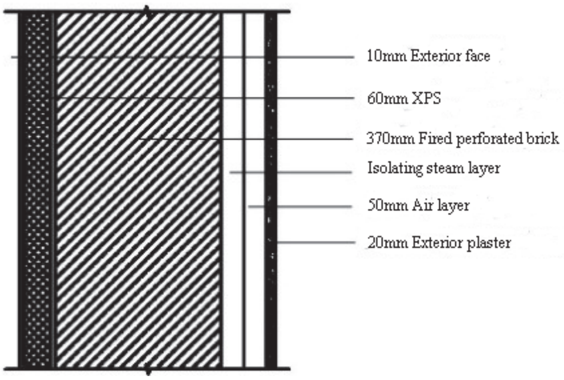


Figure 9 Wall insulation optimal structure diagram

6.3 Roof Insulation Measures

The direct exposure of residential roofs to the sun necessitates thermal performance enhancement due to their contribution to the total energy consumption of the maintenance structure. According to the climatic environment and residential situation of the Yulin region, the following measures are proposed: (1) Addition of a thermal insulation layer to flat roof buildings on the roof waterproof layer to increase roofing insulation. The incorporation of a heat insulation suspended ceiling not only reduces the height of indoor space but also reinforces the heat preservation and insulation ability of the roof area, thereby reducing heat exchange (see Fig. 10). (2) A thermal insulation slope roof addition on top of the existing flat roof can avoid direct sunlight, forming a temperature buffer zone between the indoors and outdoors and playing a crucial role in maintaining indoor temperature stability [30].

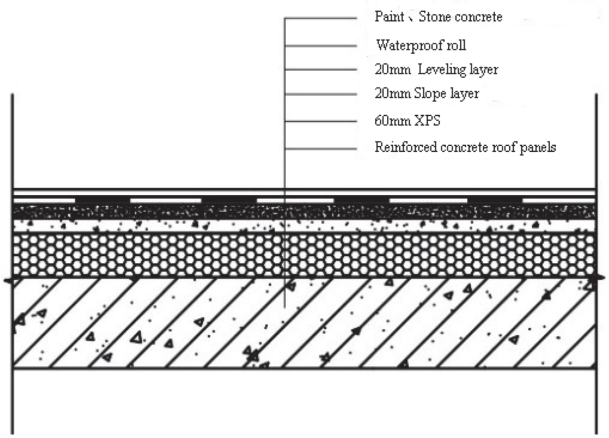


Figure 10 Roof optimization structure diagram

6.4 Window Insulation Measures

The thermal insulation performance of doors and windows typically constitutes the least efficient aspect of the outer envelope. Therefore, special attention should be given to the thermal insulation performance of doors and windows in building energy-saving design. The doors and windows of Yulin rural residential houses generally feature a single-layer design, with some even having wood-framed doors and windows. However, deformations and opening-closing gaps often lead to door and window crevices. An upgrade to plastic steel windows with superior air tightness and economic value can improve door and window air tightness. Further, the use of a double-layer hollow glass air spacer can augment window heat transfer resistance. Given the cold regional location of Yulin, it is recommended to add an extra layer to the original glass, employing a double-layer plastic steel window to boost indoor thermal comfort during winter (see Fig. 11).

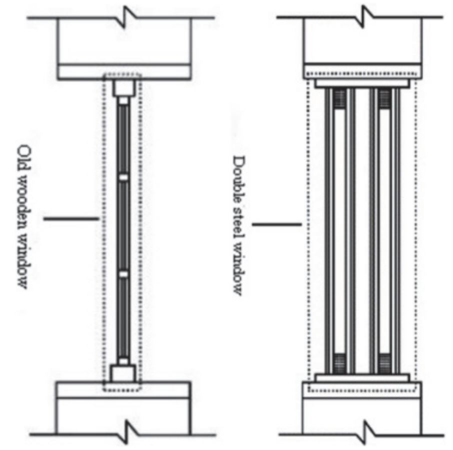


Figure 11 Window optimization structure diagram

7 COMPARATIVE ANALYSIS

An analysis was conducted by constructing a typical rural residential building model in Yulin, using the simulation software, Ecotect. Thermal performance parameters of the residential building model were adjusted to reflect changes suggested in the optimization strategy, taking into account the local meteorological data of Yulin. A comparative analysis of the indoor thermal comfort of rural residential buildings, pre and post-optimization, was subsequently performed.

As revealed by the Ecotect simulation analysis (Fig. 12), the average indoor temperature of optimized dwellings during winter displayed an enhancement, being 2.8 °C higher than that of the original configuration. The indoor temperature fluctuation range of optimized dwellings was measured to be 3.7 °C, smaller in comparison to the 4.3 °C observed in the original dwellings. Prior to optimization, it was observed that the fluctuation in indoor temperature was significantly influenced by the outdoor environment, and thus exhibited poor thermal stability. However, post-optimization, the temperature curve of the residential houses was characterized by mild fluctuations, demonstrating improved thermal insulation performance, and a markedly better indoor thermal environment.

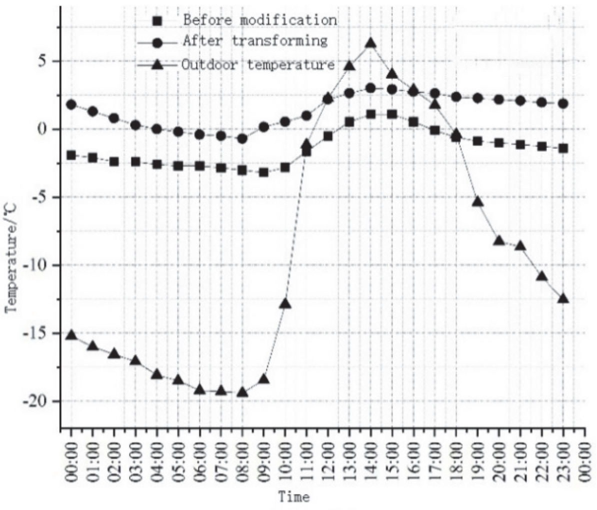


Figure 12 Comparative analysis of pre and post-renovation residential building temperatures

The aforementioned results from the Ecotect simulation indicate that the proposed optimization strategy can substantially enhance the thermal performance of rural residential buildings in Yulin. Specifically, it appears to significantly increase the average indoor temperature during winter, while simultaneously reducing the fluctuation range, thus leading to a more stable indoor thermal environment. These findings highlight the potential of such targeted optimization strategies to significantly contribute to the energy efficiency and thermal comfort of residential buildings, particularly in regions with comparable climatic conditions.

8 CONCLUSION

In the present era, a significant proportion of the Chinese population continues to reside in rural areas, where a vast number of rural buildings exist. Enhancing the quality of life and comfort within these rural residential buildings bears considerable practical importance. This study sought to address this challenge, with a focus on improving the comfort level of rural dwellings. Field tests were conducted on rural dwellings in the Yulin area, and the SD method was utilized to carry out a quantitative analysis of various qualitative problems, facilitating the extraction of relative weight values of the contributing factors.

Aiming to enhance the indoor thermal comfort of rural residential houses in Yulin during the winter season, an optimization strategy was put forth. The key findings were:

(1) Environmental monitoring showed sub-optimal indoor temperatures, humidity, and thermal stability in typical Yulin rural houses.

(2) Proposed modification strategies involving layout, roof, wall, and window enhancements were estimated to increase average indoor temperatures by 2.8 °C and decrease fluctuation ranges.

(3) Simulation-based analysis demonstrated the potential of tailored interventions to significantly enhance energy efficiency and thermal comfort.

(4) The study provides a methodology and blueprint for climate-responsive optimization of rural dwellings in severe cold regions.

(5) Future work could expand this approach through long-term in situ testing of implemented strategies in Yulin and comparative studies in other cold climate contexts.

Although the semantic difference method is simple and effective, it is widely used, but it also has flaws. For example, usually an adjective can have different understandings, but in order to capture the psychology of the subjects, subjects with different experience backgrounds will pay attention to different problems, which is also the main bottleneck of sd method, so some errors will inevitably occur.

In conclusion, this study highlights the significant benefits simple encapsulation and design strategies can offer for improving sustainability and comfort of rural homes in cold climates. It brings to light that even small-scale changes, like layout and structural modifications, can yield noteworthy improvements in indoor thermal comfort. Therefore, for future research, not only the study of individual buildings, but also the study of streets, green spaces or overall residential communities. It is imperative that future initiatives continue to focus on these optimization strategies, considering local climatic and cultural factors, in order to promote sustainable and comfortable rural living environments in China and potentially other similar contexts globally.

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