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Simulation of Indoor Environmental Performance of Dwellings in High-Altitude Cold Regions: A Case Study of Jiuzhaigou

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Abstract

This study takes Jiuzhaigou as a case to investigate the influencing factors and optimization strategies for indoor environmental performance of dwellings in high-altitude cold regions. Based on field surveys, five key factors-plan form, living room orientation, window-to-wall ratio, exterior window material, and climate buffer space-were identified and used to build a prototype model. Computational fluid dynamics (CFD) and other simulation tools were employed to analyze the impact of different factors on indoor wind, thermal, and lighting environments, while range normalization quantified each factor's sensitivity and improvement efficiency. Results show that U-shaped and L-shaped plans with southeast-oriented living rooms significantly enhance winter thermal comfort and ventilation. Controlling window-to-wall ratio within 5%–15% balances daylighting and insulation, and combining low-emissivity (Low-E) glass with south-facing sunrooms as climate buffer spaces notably improves daylighting and passive heating. Sensitivity analysis further indicates that spatial form and orientation are priorities for optimizing wind and thermal environments, while climate buffer space and window-to-wall ratio are key for lighting. The study proposes a "spatial form–climate buffer–high-performance exterior window" layered optimization approach, ultimately providing an optimal scheme for indoor environmental performance in high-altitude cold-region dwellings, and scientific guidance for sustainable improvement of residential comfort in these areas.

Keywords: High-altitude cold regions; Indoor environment simulation; Dwellings; Jiuzhaigou region.
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1. Introduction

The total energy consumption of buildings and the construction sector in China accounted for 44.8% of the country's overall energy use, and carbon emissions reached 48.3% of China's total energy-related carbon emissions,[1] with heating energy consumption accounting for almost 85% of building energy use.[2] More than 60% of China's land area falls within severe cold and cold climate zones, known as "heating regions," where high-altitude cold regions such as the Qinghai-Tibet Plateau are even more dependent on heating due to their extreme climate.[3] Dwellings in these areas typically feature primitive building materials, outdated heating methods, and strong dependence on natural resources. The optimization of environmental performance for such dwellings is urgent, requiring both thermal comfort and reduced energy consumption and environmental impact.[4] Against this background, using building simulation technology to quantitatively analyze the indoor environmental performance of typical dwellings in cold regions can systematically assess the impact of climate change on building thermal environment and energy consumption, revealing their climate adaptability and optimization potential. This is significant for optimizing building structure and envelope performance, promoting adaptive residential design, reducing building energy use, and achieving low-carbon goals.

The rise of environmental issues and the energy crisis in the 1970s prompted the architectural community to reflect on the overreliance on mechanical environmental control. The environmental performance characteristics of traditional dwellings have regained attention and become a research focus. This trend is closely related to the development of building physics, which focuses on the wind, light, and heat properties of buildings and how to optimize these properties through design. Many scholars have begun to comprehensively evaluate the performance of buildings using computer simulation.[5] Anand P used Ecotect software to simulate 14 room orientations in three climate zones in India and found that south-facing bedrooms were comfortable for

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about 79% of the year, and north-facing living rooms had a daytime comfort rate of up to 77.74%, providing quantitative evidence for optimizing room layout and orientation.[6] Gokce Tomrukcu *et al*. systematically evaluated the evolution of building energy consumption and thermal comfort in residential buildings under future climate change scenarios in typical climate regions of Turkey. They proposed regional and hierarchical strategies for building energy retrofit, integrating both active and passive measures. The study found that with global warming, heating energy consumption decreases significantly, while cooling energy consumption increases exponentially, making the risk of summer overheating the main challenge for future indoor environment optimization.[7] Chartchay Chumchan *et al*. investigated the evaporation and transport behavior of cough droplets in indoor environments with quasi-static air through numerical simulation. They found that environmental temperature and relative humidity have a significant impact on the evaporation rate of droplets, highlighting the critical role of indoor ventilation and climate control in creating healthy living spaces.[8] In terms of simulation method validation, Olena Kalyanova Larsen *et al*. systematically evaluated, using the Nordic climate as an example, the effects of model simplification, geometric zoning, and heating system modeling on building energy consumption and indoor thermal comfort performance (such as PMV). By comparing simulation results with actual operational data, they verified the accuracy of the simulation approach. The study found that simplification of spatial zoning has a limited impact on energy consumption simulation results, whereas detailed modeling of heating systems has a significant influence on both energy use and comfort outcomes.[9] In China, researchers have also paid increasing attention to the validation of building simulation methods. Wenjing Li *et al*. systematically reviewed the potential of natural ventilation (NV) for energy conservation and its impact on indoor environmental comfort in the context of the current global trend of energy saving and emission reduction. They pointed out that, during the design performance modeling (DPM) stage, it is necessary to quantify the uncertainties of key parameters and use statistical analysis to identify the most influential factors (such as the thermal capacity of the envelope and relative humidity), in order to maximize the potential of natural ventilation.[10] Wu Zhigang, through data monitoring and software simulation, revealed the spatial construction logic and scale patterns of settlements in southeast Fujian adapting to different climate conditions.[11] Tao Simin, using Ladybug + Honeybee tools, systematically analyzed the internal logical energy flow in architectural language and proposed a new method for studying the environmental performance of traditional dwellings.[12] Xue Qingwen conducted energy consumption simulations for passive residential buildings in severe cold climate zones, selecting insulation thickness, window type, window-to-wall ratio, and building orientation as design variables. By combining parametric simulation, artificial neural networks, and NSGA-II optimization, the study identified optimized variable combinations. The results showed that optimized design can reduce CO_2 emissions by 13.5%–22.4%.[13] Han Fei conducted long-term winter monitoring of a multi-storey passive house, verifying the energy-saving potential of passive houses in cold climate regions. The results indicated that, compared with conventional green buildings, the average space heating demand (SHD) of the passive house was reduced by 86.3%, and total energy consumption decreased by 69.2%.[14] Ren Wenjing, based on field measurements, quantitatively analyzed the coupled effects of geographic and climatic factors on building orientation and form. By introducing concepts such as the orientation-based mean temperature difference (TOMTD) and optimal building width (MITD), the study derived optimal orientation and form design methods. The research pointed out that when horizontal solar radiation is $\leq 6.44\ \mathrm{MJ/m^2 \cdot d}$, the shape coefficient should be prioritized; otherwise, building width becomes the main consideration.[15] Ma Ruihua analyzed the impact of window-to-wall ratio (WWR) changes on air conditioning and heating energy demands in residential buildings across different regions in China (Harbin, Beijing, Chengdu). Through simulation, the study compared the variation of cooling and heating loads with WWR in these three cities, finding that regardless of climate, increasing WWR linearly increases heating and cooling loads, and the sensitivity of energy demand to WWR changes is similar across different cities.[16] It is evident that most current optimization studies employ simulation-optimization coupling methods, using building energy consumption, PMV (Predicted Mean Vote), and CO_2 concentration as typical objective functions, and solving them with various algorithms such as Genetic Algorithm (GA), Non-dominated Sorting Genetic Algorithm II (NSGA-II), and Particle Swarm Optimization (PSO). The optimization variables include not only system parameters such as temperature setpoints and ventilation rates, but also design variables such as building orientation, window parameters, and envelope materials.[17] Furthermore, Yan Haiyan and others found that adaptation of Lhasa residents to the plateau environment mainly manifests in behavioral, physiological, and psychological adaptation, revealing the differentiation mechanism of human thermal sensation under low pressure and cold conditions.[18] Subsequent scholars conducted related studies: for example, Suolang Baimu summarized the climatic adaptability characteristics of traditional dwellings in Lhasa under plateau cold climates, providing ideas for climatic adaptive design for new urbanization in Tibet.[19] Liu Jiaping conducted performance tests on Tibetan dwellings in Tagong Township, Ganzi Tibetan Autonomous Prefecture in winter and summer, aiming to find design optimizations to reduce heating energy consumption and improve living conditions.[20] Despite the extensive research in recent years on optimizing the environmental performance, energy consumption simulation, and climate adaptability of dwellings in cold and high-altitude regions, several issues remain unresolved: (1) Most traditional dwellings are characterized by primitive building materials and outdated heating methods, resulting in significant potential for improving environmental performance, yet there is a lack of systematic, quantitative analyses and regionally adaptive optimization strategies. (2) Although numerous simulation-optimization studies have been conducted, they mainly focus on single elements or urban settings, and comprehensive optimization analyses targeting typical dwellings in extreme climates—such as high-altitude cold regions—are still insufficient, with limited in-depth quantification of the sensitivity and interactions among influencing factors. (3) Against the backdrop of climate change, the structure of heating and cooling energy consumption is undergoing profound shifts, with increasing challenges related to summer overheating and ventilation health, posing new demands for traditional performance optimization approaches. In addition, although advanced simulation tools and multi-objective optimization algorithms are widely used, there remain issues concerning the selection of model parameters, adaptability to different working conditions, and validation of simulation results. In response to these challenges, this study takes the dwellings in Jiuzhaigou—a high-altitude cold region—as its research object. By integrating field surveys, prototype modeling, multi-factor simulation, and sensitivity analysis, this research systematically identifies the key factors and their sensitivities affecting the thermal, wind, and lighting performance of such buildings. The innovation of this work lies in the proposal of a layered optimization path—“spatial form–climate buffer–high-performance envelope”—tailored for extreme climate regions, and the quantitative validation of its effectiveness through simulation. The findings are intended to provide a scientific basis and practical guidance for improving the environmental performance and promoting green, low-carbon design of dwellings in cold plateau areas.

2. Research methodology

2.1 Research subjects

Jiuzhaigou (100°30′–104°27′E, 30°35′–34°19′N) is located in the northern part of Sichuan Province, China,[21] with an average altitude of about 2,500 m and the highest elevation exceeding 4,000 m. It belongs to the plateau cold-temperate–subalpine monsoon climate zone, with obvious vertical zonation characteristics.[22] Locally, the climate is characterized by cold and dry monsoons. According to Jiuzhaigou Meteorological Station data, monthly average temperatures in spring are between 9–18°C, in summer 16–22°C, in autumn 7–18°C, and in winter –4–0°C. July and August are the hottest months, but with large diurnal temperature differences, the average temperature is only 16°C. From September to December, temperatures drop by over 10°C, and January is the coldest month with an average temperature of –4.5°C (Fig. 1).

This study conducted a comprehensive survey of 320 dwellings in four residential villages in Jiuzhaigou, compiling statistics on the basic information and current situation of local dwellings. All of the dwellings are self-built, embodying the ecological wisdom of local ethnic construction, further highlighting the representativeness of the research samples. As of 2024, existing buildings are mainly classified by construction period, main structure, and material use, and can be divided into four types, each with different environmental performance characteristics (Fig. 1):

(1) Traditional period: Dwellings built mainly between

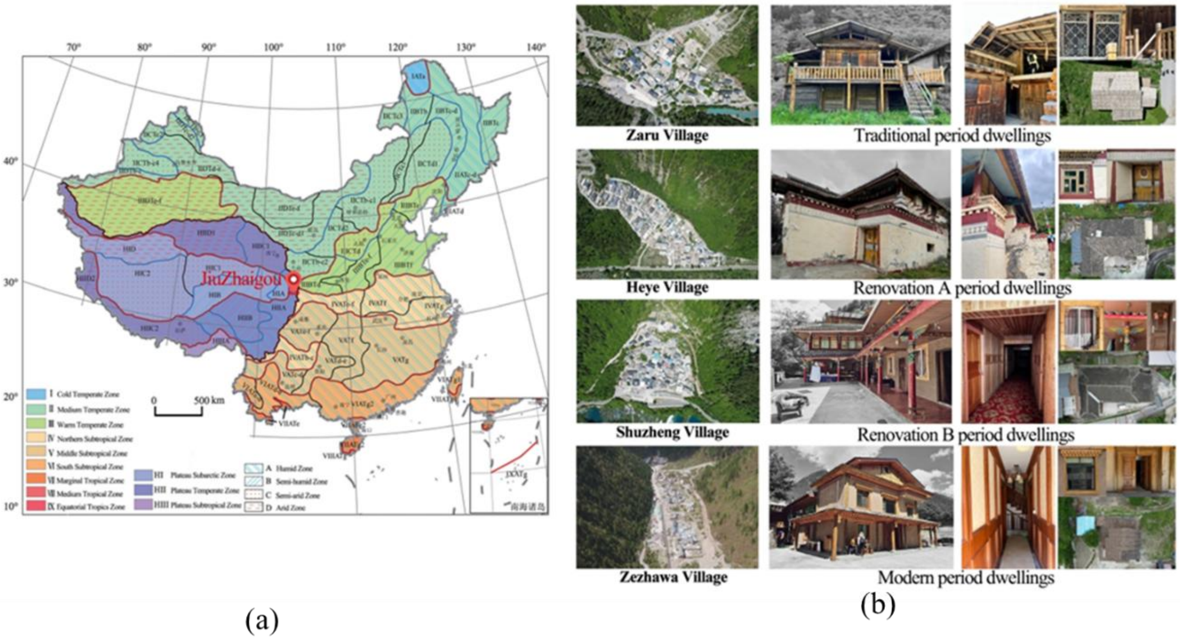


Fig. 1: Overview of the Jiuzhaigou region. (a) Location of Jiuzhaigou in China’s climate zoning. (b) Current status of Jiuzhaigou village dwellings.

1960 and 1983 combine Tibetan diaolou and Han-style timber frame features,[23] mainly using pure timber and earth-wood structures. The ground floor is for livestock, the second floor for living, and the third floor for storage. Emphasis is placed on passive adaptation such as rammed earth wall insulation and "taban" roofs (to cope with concentrated rainy seasons, traditional dwellings use streamlined fir board roofs, called "taban" by locals, about 1.3 m long).[24] However, limited by materials and craftsmanship, comfort is limited despite being cool in summer and cold in winter.

(2) Initial renovation period (A): From 1984 to 1999, local renovations began. After a logging ban, forestry declined, and lifestyles turned mixed, with weakened livestock functions. New materials such as stone-timber, brick-timber, and small blue tiles appeared, and second and third floor spaces were differentiated with preserved religious spaces. Functional zoning improved, but insulation was still unsatisfactory; summer ventilation was good but winter was cold.

(3) Development and renovation period (B): From 2000 to 2016, renovations matured, introducing design techniques such as exterior corridors from Han dwellings. Tourism started, and residential and commercial functions coexisted, with brick-concrete structures becoming mainstream; the ground floor became guest rooms, the second floor for tourist accommodation. Spaces became multifunctional, with improved lighting and ventilation, but more complex thermal loads; winter comfort improved but summer overheating occurred.

(4) Modern period: Since 2017, tourism became the main economy, daily life and tourism operations were highly integrated, spaces were fully functionalized, and modern techniques and materials such as concrete, glass, and color steel roofing were widely used. Mechanical heating and air conditioning are popularized, overall comfort improved but energy consumption is high, and some spaces have obvious shortcomings in insulation and cooling.

2.2 Extraction of influencing factors

Based on the statistical analysis of the spatial and structural information of the dwellings, various influencing factors affecting the indoor environmental performance of the dwellings were extracted. Details on the different manifestations of the impact factor are provided in Supplementary Information Table S1.

(1) Building plan form: The plan form affects the building's shape coefficient. Different plan forms lead to different shape coefficients and, thus, different indoor environmental performance. During the climate adaptation process of Jiuzhaigou dwellings, three plan forms have developed: rectangular, L-shaped, and U-shaped.

(2) Living room orientation: The living room is the main functional space for residents. Local dwellings mainly use its orientation to adapt to the climate, with primary orientations including northwest, northeast, southeast, and southwest.

(3) Window-to-wall ratio (WWR): In the design of Tibetan dwellings in high-altitude regions, careful consideration is required to balance insulation and daylighting in determining the window-to-wall ratio. In Jiuzhaigou, dwellings typically feature three main window-to-wall ratios: 5%, 15%, and 25%.

(4) Exterior window material: The choice of window material plays a decisive role in improving indoor temperature and lighting.[25,26] Jiuzhaigou dwellings use four types: no glass, single glazing, double-glazed units, and double-glazed LOW-E glass.

(5) Climate buffer space: The climate buffer space serves as an intermediary zone between the core indoor space and the outdoor environment and can effectively regulate the building’s indoor climate.[27] Jiuzhaigou dwellings use canopies, exterior corridors, and sunrooms as climate buffer spaces.

2.3 Indoor environment simulation method

2.3.1 Software selection and accuracy verification

This study used computational fluid dynamics (CFD) software to analyze the thermal environment. As a numerical simulation technology, CFD simulation is widely used in fields such as building environments and energy equipment due to its low cost, high efficiency, and repeatability. Using this software, comparative simulation analysis of indoor temperature and air exchange frequency was conducted. Ecotect simulation software (Ecotect) was used for lighting environment analysis. According to the Split Flux method from the Building Research Establishment, Ecotect calculates the daylight factor using an overcast sky model, simulating the least favorable lighting conditions and making it suitable for comprehensive daylighting performance assessment of buildings.[28] The simulation adopted seasonal boundary conditions based on measured data from Jiuzhaigou. Typical outdoor temperatures were set as –4°C (winter), 10°C (transitional season), and 15°C (summer), with corresponding relative humidity values of 70%, 82%, and 84.2%. Prevailing wind speeds were set at 1.14 m/s (winter), 0.42 m/s (transitional), and 0.27 m/s (summer), all from the northeast. Daylighting simulations used the overcast sky model, calculating daylight factor (DF) at 1.2 m height. All other parameters were set according to local climate characteristics and relevant national standards to ensure model reliability.

The software accuracy verification process was as follows:

1. Monitoring instruments recorded typical daily temperatures and wind speeds in summer, transitional seasons, and winter, and daily averages were calculated;
2. 3D models of surveyed dwellings were established, and software simulations of indoor parameters were performed for typical summer, transitional, and winter days;
3. Actual monitoring data were compared with simulation results (Fig. 2).

In terms of temperature, the difference was 0.21°C in transitional seasons, 0.22°C in winter, and 0.17°C in summer; in terms of wind speed, the difference was 0.013 m/s in transitional seasons, 0.022 m/s in winter, and 0.015 m/s in

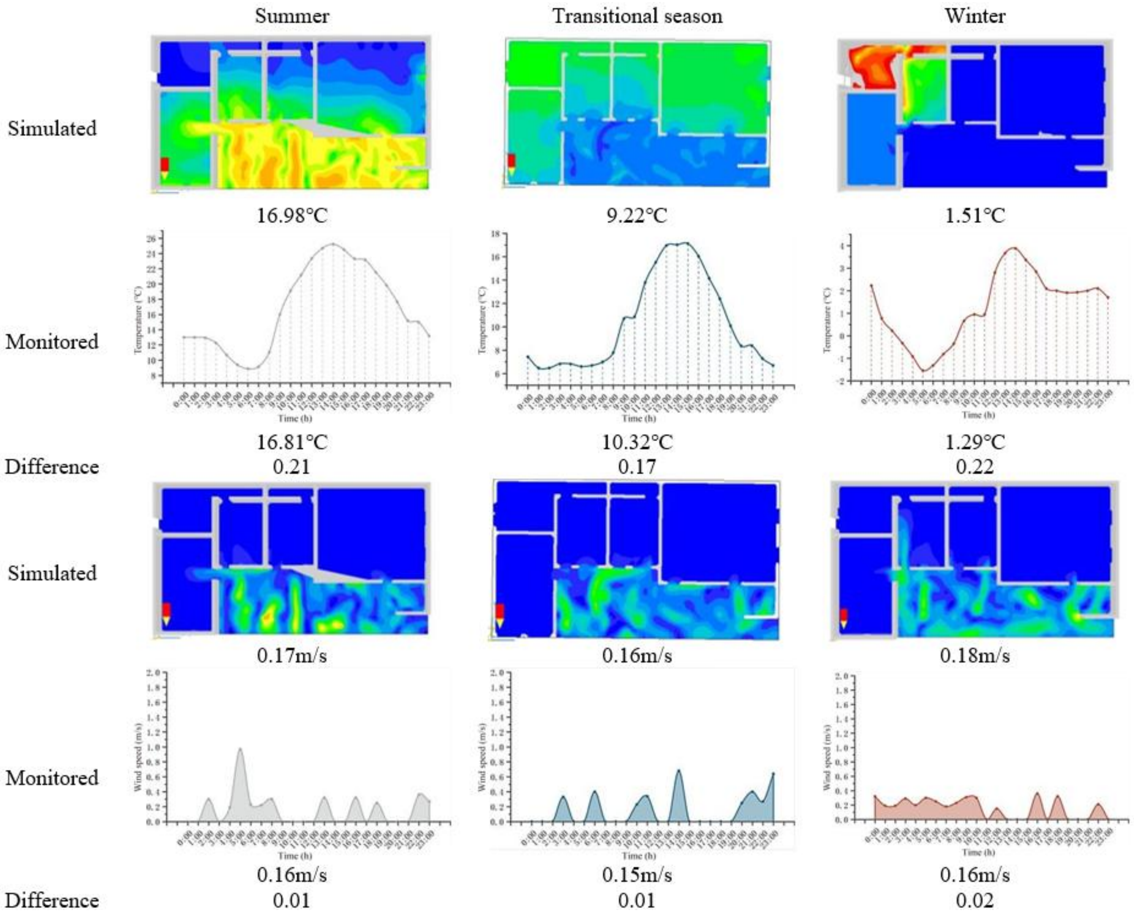
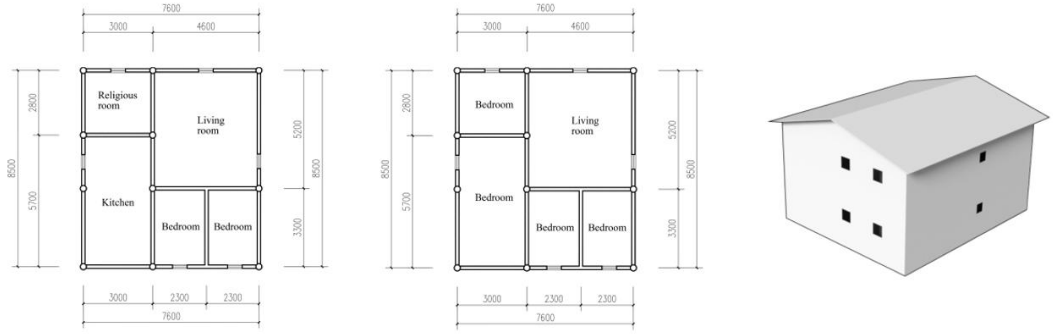


Fig. 2: Calibration of simulation software accuracy.



(a) First floor plan (b) Second floor plan (c) Prototype dwelling model

Fig. 3: Prototype dwelling model.

summer. All differences were within acceptable ranges. According to the "Standard for Energy Efficiency Testing of Residential Buildings" JGJ/T132-2009, these results confirm the accuracy of the simulation software.

2.3.2 Prototype establishment

Based on comprehensive field surveys of 320 dwellings in nine villages in Jiuzhaigou, we systematically identified four typical building structures. Further statistical analysis allowed us to summarize the shared features across these structures—such as plan form, functional layout, window-to-wall ratio, exterior window type, ancillary spaces, heating equipment, and glazing material. The parameters for the prototype building were established by integrating these representative characteristics, ensuring that the simulation model reflects the most prevalent and typical architectural forms in the region. Therefore, the research conclusions are not limited to a single dwelling type, but are generalizable to the main building structures identified in the field survey. The final prototype has the following basic features: north-south orientation, rectangular plan, living room facing northeast, window-to-wall ratio of 5%, casement single-glazed exterior windows, with canopies as auxiliary structures; room depth 8.5 m, width 7.6 m, floor height 2.4 m, double-pitched roof, two stories, with the first standard floor used as the simulation plane in subsequent simulations (Fig. 3).

2.3.3 Selection of simulation influencing factors

This study focuses on two core dimensions of indoor environmental performance—thermal comfort and lighting comfort—following the principle of quantifiability and controllability in selecting influencing factors. Thermal environment factors: Excluding the calculation of envelope thermal performance using energy-saving software (which focuses on load calculation), the CFD fluid simulation captures the effects of building form (plan form), opening distribution (exterior window opening area integrated with window-to-wall ratio), and spatial orientation (functional layout) on thermal comfort under natural ventilation conditions. Lighting environment factors: The daylighting simulation covers geometric optics (plan/layout/window-to-wall ratio), optical properties of materials (glass type), and buffer structures, with all factors included in the Ecotect daylighting analysis. Integration logic of exterior window opening area: Ventilation effects are already represented in the window-to-wall ratio variable through wind speed boundary conditions and are therefore not simulated separately (Table 1).

Table 1: Simulation factor screening table.

Influencing factor	Included simulation factor	Screening basis
Thermal environment performance		
Building plan form	Factor 1: Plan form	Directly determines airflow organization and thermal zoning
Building functional layout	Factor 2: Living room orientation	Controls solar gain through spatial orientation
Exterior window opening area	✗ (integrated into window-to-wall ratio)	Defined as the size of the air inlet in CFD by the window-to-wall ratio
Envelope thermal performance	✗	Belongs to energy calculation, little contribution to natural ventilation thermal comfort
Lighting environment performance		
Building plan form	Factor 1: Plan form	Determines room depth and daylighting uniformity
Building functional layout	Factor 2: Living room orientation	Affects duration and angle of sunlight incidence
Window-to-wall ratio	Factor 3: WWR	Controls the physical size of lighting openings
Transparent envelope material	Factor 4: Exterior window material	Determines transmittance and light scattering properties (*e.g.*, Low-E glass τ=0.6 vs. single glazing τ=0.89)
Auxiliary structure	Factor 5: Climate buffer space	Climate buffer space alters the ratio of direct/diffuse light

3 Simulation analysis

3.1 Indoor efficiency of plan forms

3.1.1 Thermal environment and lighting environment analysis

According to the predicted mean vote (PMV) and average adaptive predicted mean vote (APMV) diagram, in winter, the sensation is excessively cold, and the PMV is –3, so the simulation software does not display parameters, and thus mainly the PMV values for transitional seasons and summer are presented, with average winter temperature as a reference. In this study, L-shaped and U-shaped floor plans were established based on the prototype rectangular plan, ensuring that the indoor floor areas of all three plan types were identical. This approach was adopted to eliminate the influence of confounding factors on the simulation results. Simulation results for plan forms show that a rectangular layout allows for smooth indoor airflow, especially when windows are open. This layout shows PMV values in the transitional season biased toward the cold range, indicating a need for additional heat sources or insulation measures to improve thermal comfort. U-shaped and L-shaped layouts provide more complex interior spaces and exterior forms, which influence indoor airflow distribution. The PMV values for U-shaped and L-shaped layouts are relatively better in transitional seasons, indicating that these layouts can more effectively regulate indoor temperature and improve thermal comfort. In summer, the U-shaped layout has weaker indoor airflow, resulting in PMV values closer to the comfortable range, suggesting this layout helps maintain more stable and comfortable indoor temperatures. Winter analysis emphasizes the significant impact of low external temperatures on the indoor environment, with rectangular layouts facing greater challenges in maintaining indoor temperature, while U-shaped and L-shaped layouts are better able to control and adjust indoor airflow through their design, thus providing more comfortable thermal environments for occupants (Fig. 4).

There are certain differences in indoor daylighting performance among the different plan forms. The U-shaped plan, due to its high degree of spatial enclosure and moderate depth, has the highest overall daylight factor (DF), reaching 0.42, which is beneficial for the even distribution of natural light indoors. The DF values for rectangular and L-shaped plans are 0.41 and 0.31, respectively, with the L-shaped plan being slightly inferior, particularly because some spaces are blocked, resulting in insufficient local lighting. Overall, the U-shaped layout not only improves the overall comfort of the

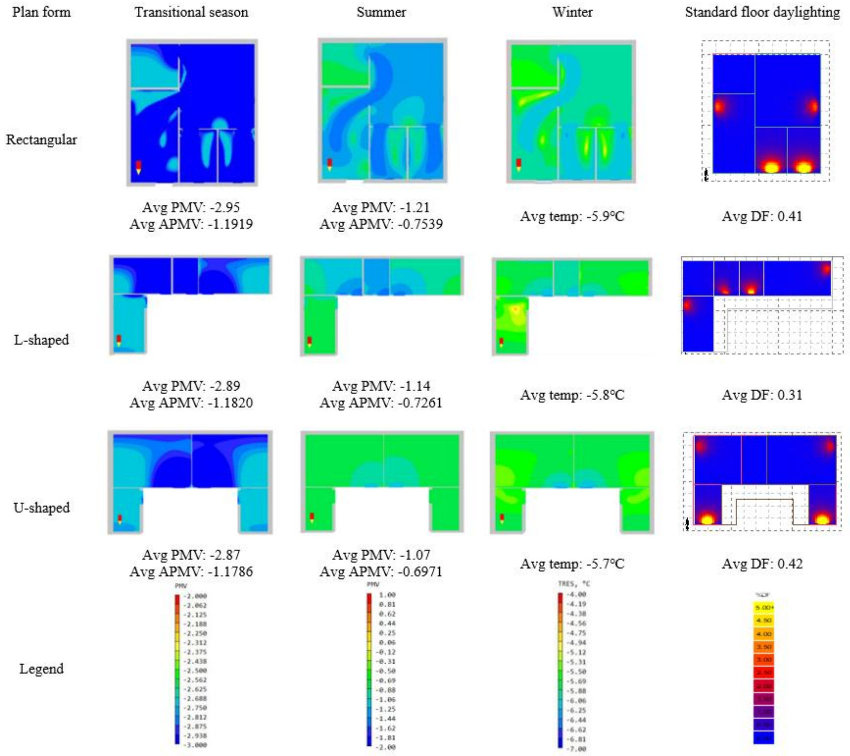


Fig. 4: Simulation results of indoor thermal and lighting environments with plan forms.

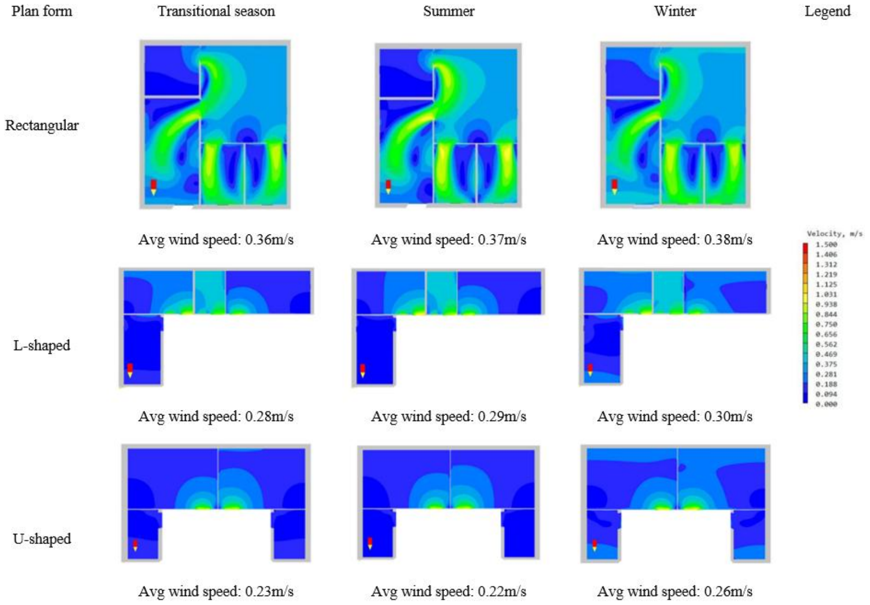


Fig. 5: Simulation results of indoor wind environments with plan forms.

lighting environment but also creates more abundant natural lighting conditions for living spaces, optimizing energy use and living experience in the cold plateau climate (Fig. 4).

3.1.2 Wind environment analysis

Under the influence of prevailing winds in winter, summer, and transitional seasons, air circulation in the standard floor is relatively smooth. The wind speed in each functional room ranges from 0.09 to 0.93 m/s, with an average wind speed of 0.37 m/s. Each functional room has an opening to the outside, meeting the comfort requirements for occupants. Therefore, the wind environment efficiency of different plan forms is relatively similar (Fig. 5).

3.2 Indoor efficiency of living room orientations

3.2.1 Thermal environment and lighting environment analysis

Simulation results of living room orientation indicate that, with smoother indoor airflow in the southwest-facing layout, the PMV falls within the cold sensation range when windows are open. Due to relatively low outdoor temperatures in summer and transitional seasons, the southeast-facing layout, with slightly weaker indoor airflow, exhibits PMV values closer to the "neutral" comfort range; all orientations can achieve good thermal comfort in summer. In winter, with windows open, the average indoor temperatures for northwest, southwest, and northeast orientations are –5.9°C, while that of the southeast orientation is –5.7°C. The southeast orientation, owing to weaker indoor air movement, achieves a slightly higher average indoor temperature than the other orientations (Fig. 6).

3.2.2 Wind environment analysis

Under the influence of prevailing winds in winter, summer, and transitional seasons, air circulation in the standard floor is relatively smooth. The wind speed in each functional room ranges from 0.09 to 1.21 m/s, and each room has an opening to the outside, meeting comfort requirements. Comparatively, spatial orientation has a small impact on the indoor wind environment, and the wind environment of all orientations is basically similar (Fig. 7).

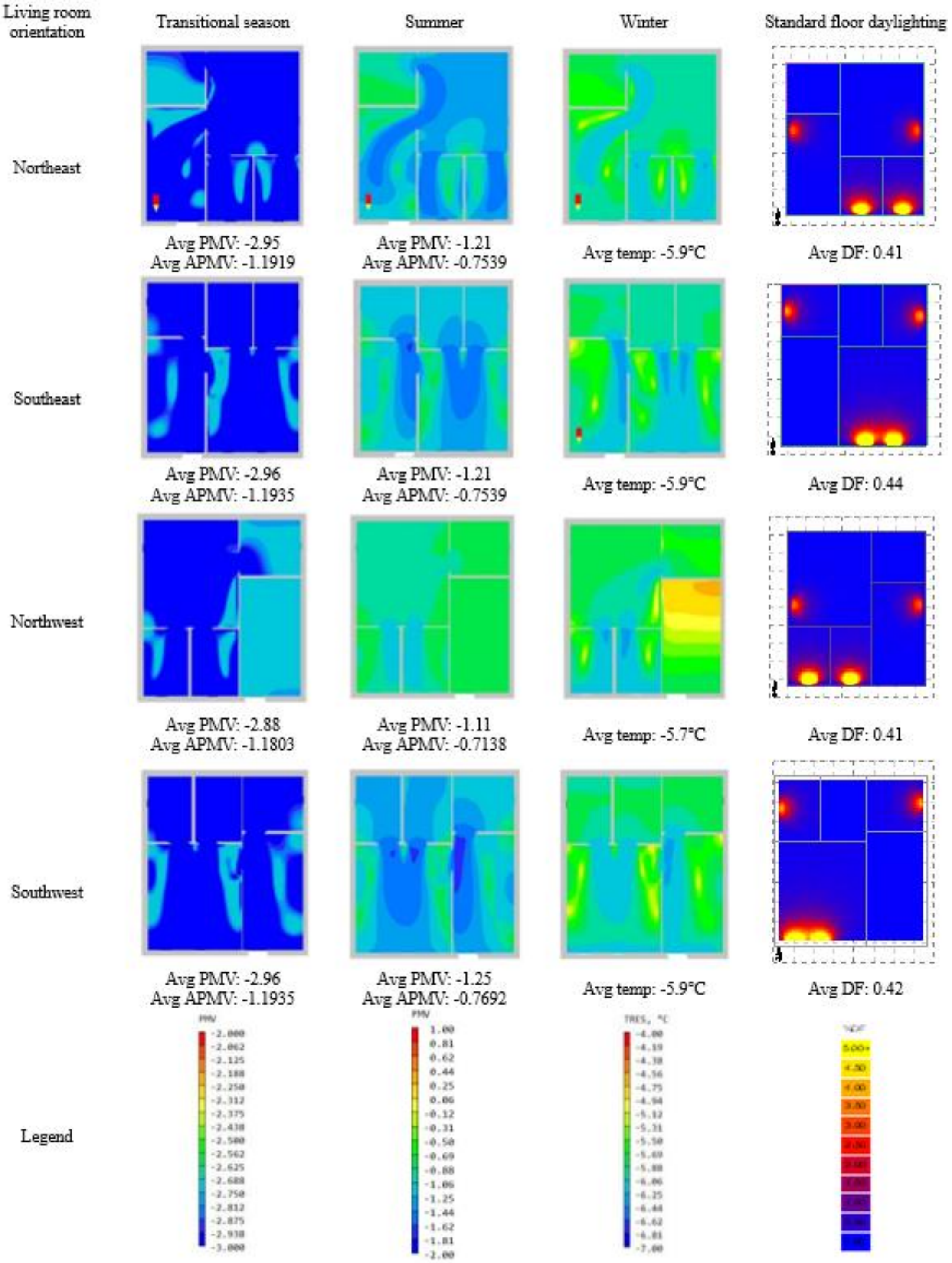


Fig. 6: Simulation results of indoor thermal and lighting environments with living room orientations.

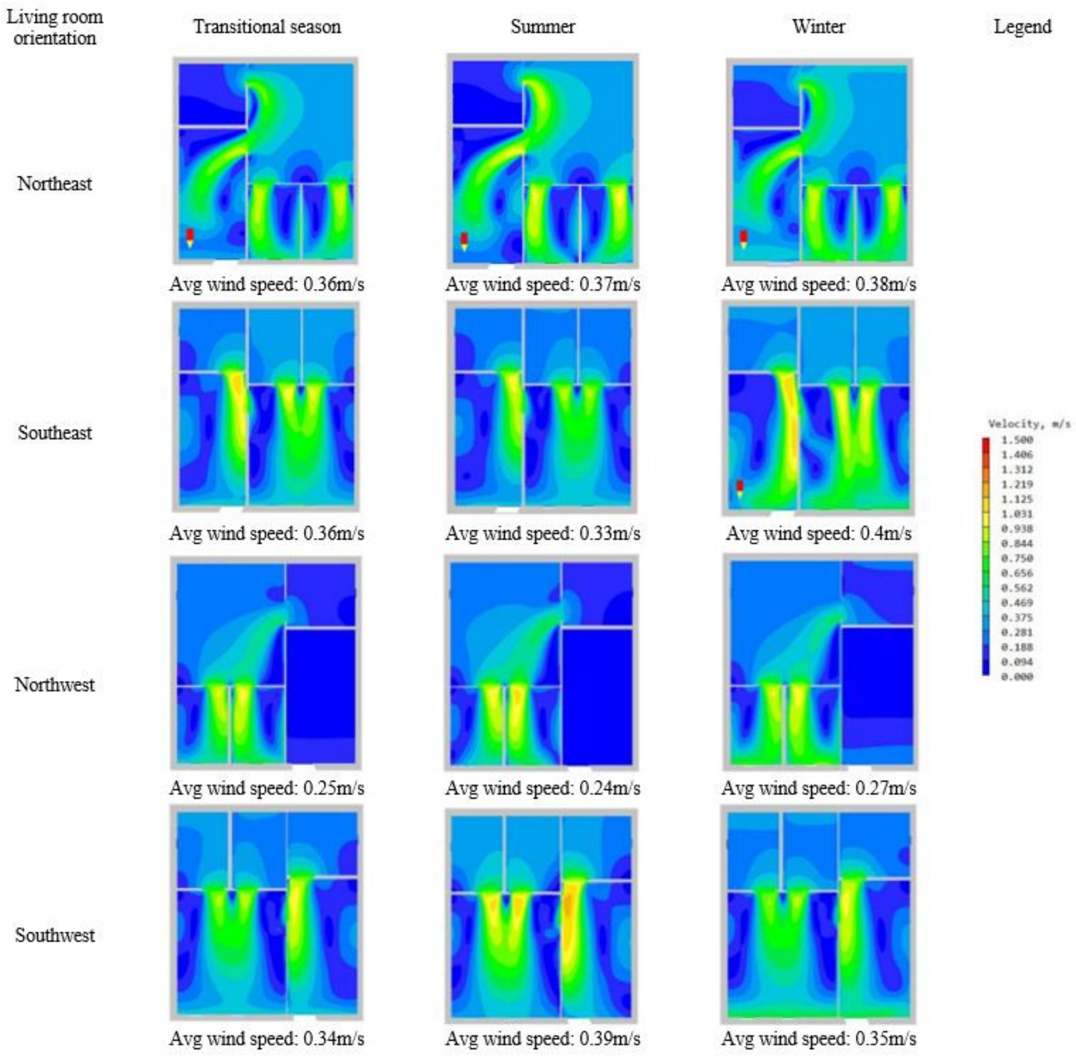


Fig. 7: Simulation results of indoor wind environments with living room orientations.

3.3 Indoor efficiency of window-to-wall ratios

3.3.1 Thermal environment and lighting environment analysis

Data show that a smaller window-to-wall ratio can effectively limit indoor heat loss and provide support for thermal comfort in cold environments. Specifically, in transitional seasons and winter, traditional dwellings with a low window-to-wall ratio (5%) provide a more comfortable indoor environment compared to the local renovation stage (15%) and the modern stage (25%). This is because small window areas help reduce the infiltration of cold outdoor air and the loss of indoor heat, especially at night and in cold seasons. However, although a small window-to-wall ratio improves thermal comfort, it may limit the entry of natural light, thus affecting visual comfort. Field investigations found that local residents, influenced by native culture, do not pursue excessively large window-to-wall ratios, indicating that design should balance the effects of window-to-wall ratio on thermal comfort and natural lighting. Considering the results of the thermal environment, wind environment, and lighting environment, a window-to-wall ratio of 15% is recommended as an optimal choice, which provides both insulation and daylighting, while 5% and 25% can be adjusted according to specific needs for insulation or daylighting (Fig. 8).

The impact of window-to-wall ratio on the indoor lighting environment is significant. When the window-to-wall ratio is 25%, the daylight factor (DF) indoors can reach 1.79, which is significantly better than 15% (DF = 0.99) and 5% (DF = 0.41). A larger window-to-wall ratio can effectively improve the amount of natural light entering the room and increase indoor brightness, but it is also necessary to balance the resulting building heat loss. Taking into account both lighting and thermal performance, a window-to-wall ratio of 15% can meet the requirements for visual comfort and energy conservation in high-altitude dwellings by ensuring daylighting while providing insulation (Fig. 8).

3.3.2 Wind environment analysis

Under the influence of prevailing winds in winter, summer, and transitional seasons, air circulation in the standard floor of dwellings is relatively smooth. The wind speed in each functional room generally ranges from 0.09 to 1.21 m/s, and each room has an opening to the outside, meeting the comfort requirements for occupants (Fig. 9).

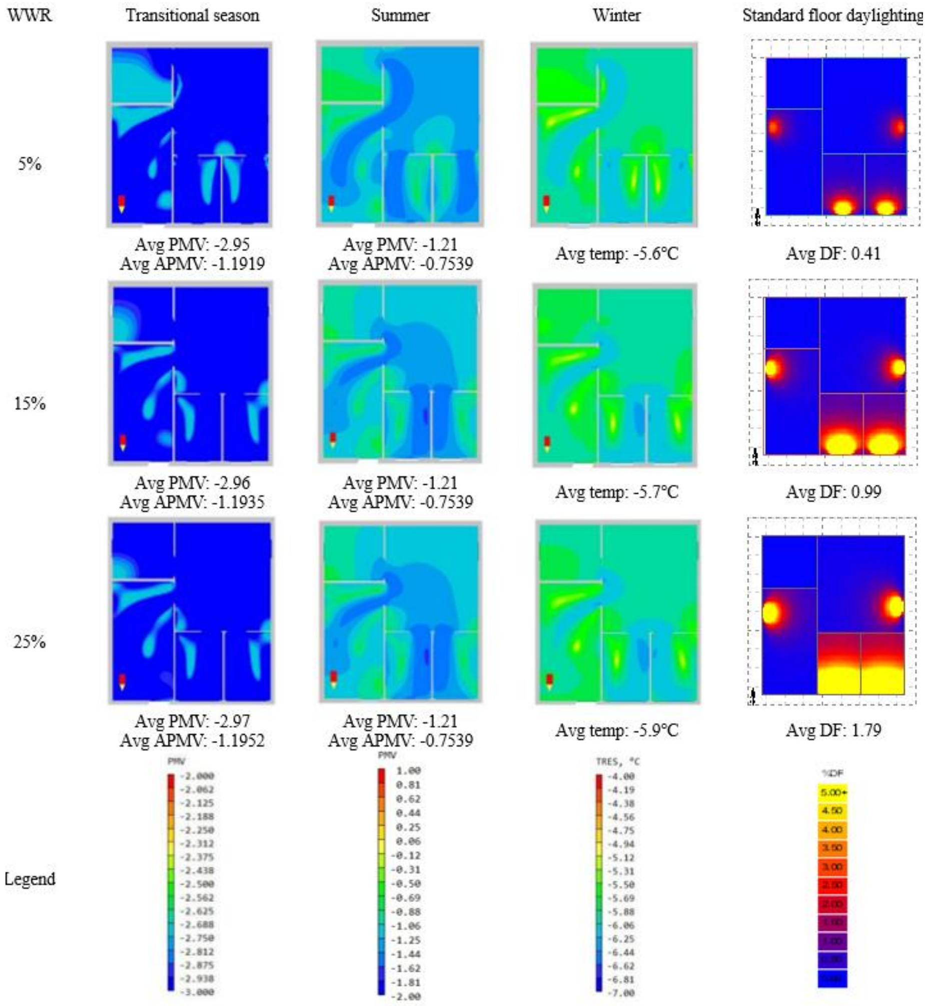


Fig. 8: Simulation results of indoor thermal and lighting environments with window-to-wall ratios.

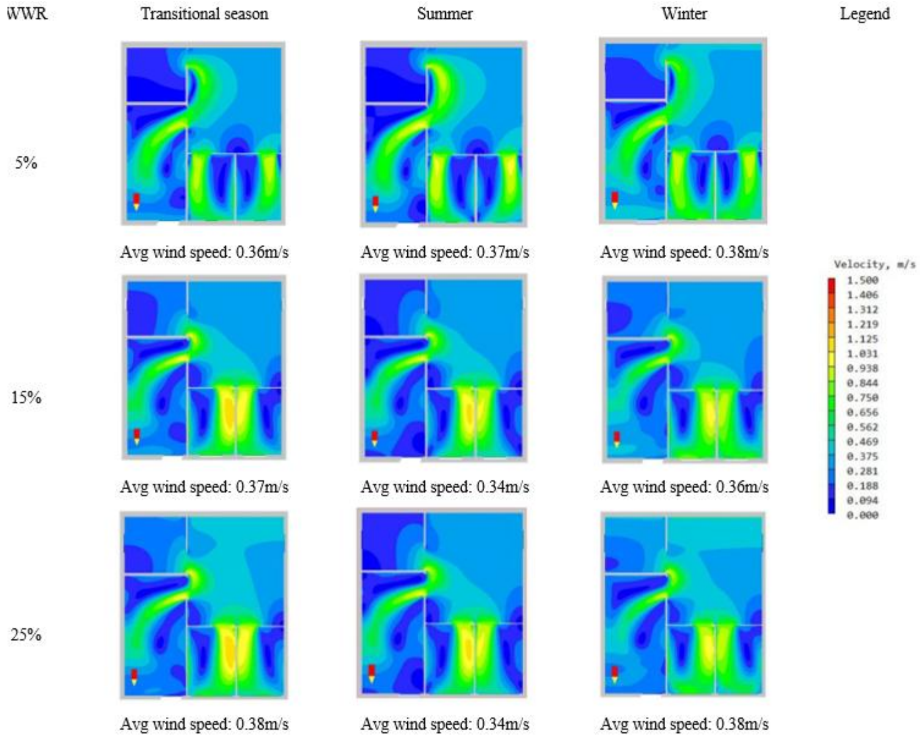


Fig. 9: Simulation results of indoor wind environments with window-to-wall ratios.

3.4 Indoor efficiency of exterior window materials

In high-altitude regions, dwelling design must fully consider the extremity of the climate, especially the cold winters and the large day-night temperature differences in summer. When selecting exterior window materials, it is necessary to comprehensively evaluate their thermal insulation, lighting effects, and cost-effectiveness to ensure dwellings can effectively resist cold while utilizing natural light to create a comfortable indoor environment. Simulation results show that double glazing, with its excellent thermal insulation, can significantly reduce energy loss and improve indoor insulation. However, it may somewhat limit the entry of natural light. By contrast, single glazing is less expensive and provides better light transmittance, but its insulation is poor, leading to greater heat loss in winter. Low-E (Low emissivity) glass is an ideal choice, as it combines good insulation with high transmittance, meeting the dual requirements of energy conservation and comfort in Jiuzhaigou dwellings. Low-E glass can effectively reflect indoor heat, reduce solar overheating, and ensure adequate natural light, thus meeting energy-saving needs while maintaining a bright and warm indoor environment, making it highly suitable for high-altitude dwellings (Fig. 10).

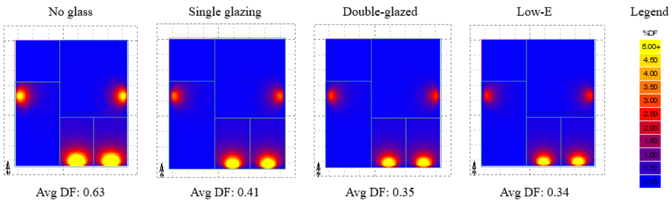


Fig. 10: Simulation results of indoor lighting environments with exterior window materials.

3.5 Indoor efficiency of climate buffer spaces

Analysis of daylighting results for various auxiliary structures shows that exterior corridors and canopies are facilities that reduce indoor lighting intensity, while sunrooms are effective in increasing indoor lighting intensity. The sunroom yields the best results, followed by the exterior corridor; the canopy performs better than the absence of auxiliary structure (Fig. 11).

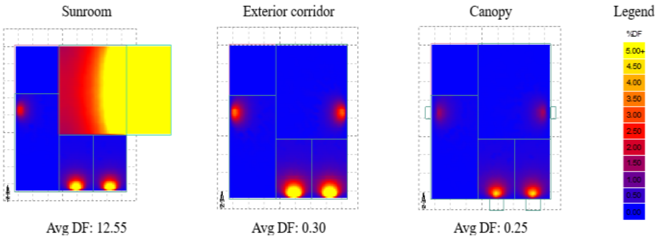


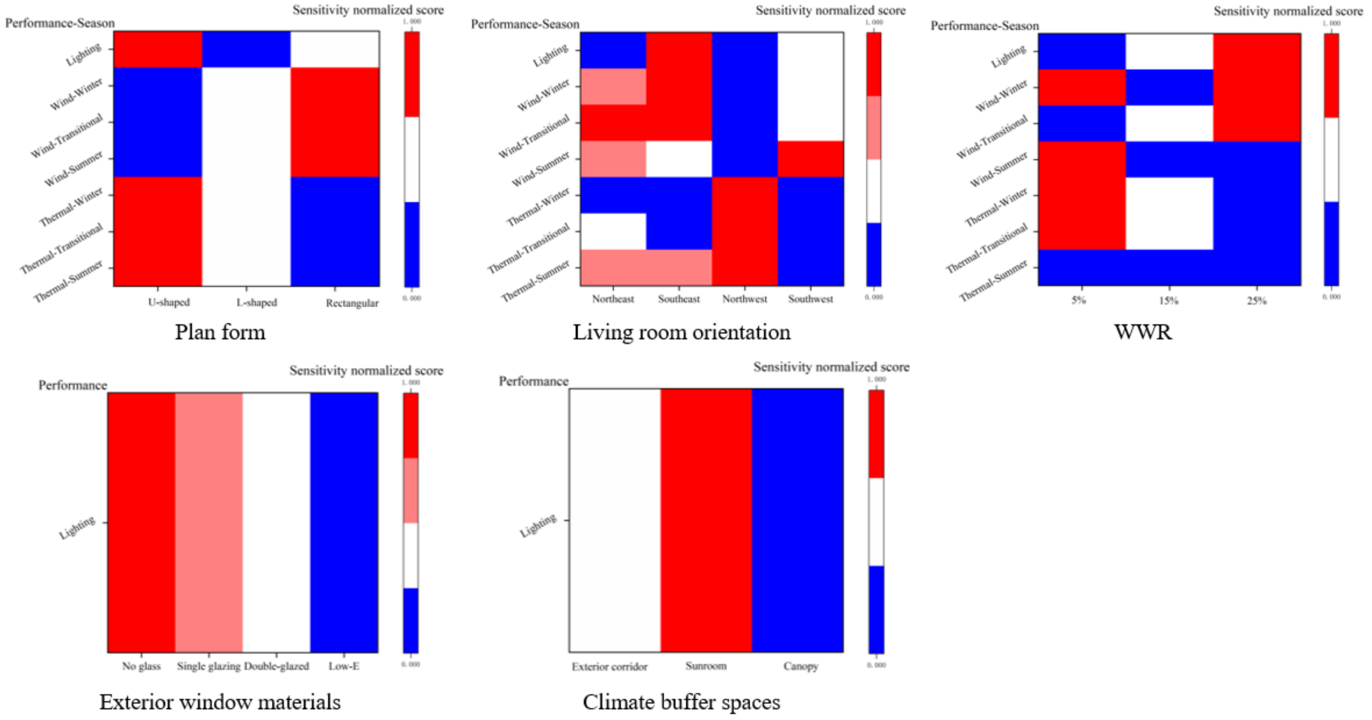
Fig. 11: Simulation results of indoor lighting environments with climate buffer spaces.

4. Discussion

4.1 Single-factor efficiency analysis

4.1.1 Ranking of efficiency of different environmental performance elements

Based on the direct results of the efficiency matrix analysis for different environmental performance elements, the impact efficiency of each major design factor on environmental performance is ranked and comparatively analyzed. The heatmap uses normalization in the range of 0–1, with multi-color segments reflecting the relative merits of each factor for wind, lighting, and thermal environmental performance (Fig. 12).



Plan form

Living room orientation

WWR

Exterior window materials

Climate buffer spaces

Fig. 12: Matrix analysis of the efficiency of different environmental performance factors.

(1) Plan form

Simulation results show that the U-shaped layout creates milder indoor airflow, with transitional season APMV and winter temperature both superior to other forms; in summer, it also achieves Level II thermal comfort, showing better comprehensive thermal environment advantages. The L-shaped plan is second-best, while the rectangular plan, due to smooth airflow, is more prone to cold sensation in the transitional season and has the lowest winter temperature, resulting in relatively poorer thermal comfort. Therefore, the U-shaped plan is optimal, the L-shaped plan is intermediate, and the rectangular plan is least favorable.

(2) Living room orientation

For living room orientation, southeast orientation performs best in terms of both winter insulation and natural daylighting, meeting the dual requirements for daylighting and thermal environment in high-altitude regions and making it the preferred orientation. The southwest orientation ranks second; although summer temperatures are higher, this can be regulated by shading and ventilation. Northwest and northeast orientations have average overall performance and are recommended as alternatives.

(3) WWR

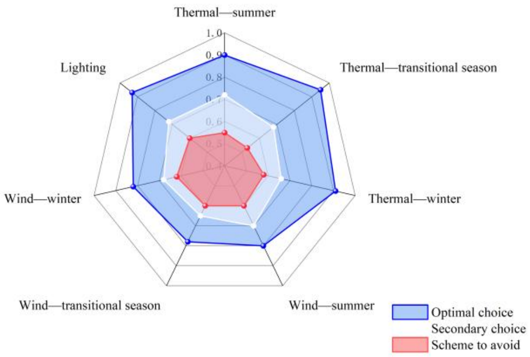
For window-to-wall ratio, simulations show that a smaller ratio is more favorable for improving thermal comfort; a 15% window-to-wall ratio performs best in terms of APMV in the transitional season. Considering the climate and culture of Jiuzhaigou, a window-to-wall ratio range of 5% < r ≤ 15% is recommended over 15% < r ≤ 25%; ratios above 25% are not recommended.

4.1.2 Optimal factor combination model

Based on the results of single-factor sensitivity analysis, this study integrates thermal and lighting performance objectives and proposes an optimal factor combination model for dwellings in the cold regions of Jiuzhaigou (Table 2). The optimization strategy is primarily guided by thermal environment considerations, prioritizing a U-shaped plan (raising winter indoor temperature by about 3°C compared to a rectangular layout) and a southeast-oriented living room to maximize solar heat gain; this is supplemented by a 5%–15% window-to-wall ratio (average daylight factor 1.35 ± 0.1) combined with Low-E glass (increasing DF by 0.3 compared to single glazing), which together limit heat loss while ensuring lighting requirements; furthermore, replacing canopies/exterior corridors with a south-facing sunroom (raising DF by 0.5–0.8 and passive heating efficiency by 25%) eliminates daylight obstructions. Practice shows that this system can bring APMV close to neutral in the transitional season (|APMV| < 0.5), raise the base winter indoor temperature to above 12°C without heating, and meet the requirements for Class III light climate zones (DF ≥ 1.2) according to the "Standard for Daylighting Design of Buildings."

The core advantage of this scheme lies in the strengthening of indoor environmental performance—U-shaped plan and southeast orientation form a "dual insulation core," significantly improving extreme cold resistance (winter heat load reduced by 18% compared to traditional rectangular dwellings), and a window-to-wall ratio limit (r ≤ 15%) reduces exterior window heat loss by up to 37%, solving the contradiction between window opening and heat loss in cold regions; the synergy of lighting and insulation depends on Low-E glass's unique transmission–reflection balance, optimizing both daylighting and insulation performance. Potential drawbacks include restrictions on plot length-to-width ratio (>1.5) imposed by the U-shaped plan, leading to reduced spatial flexibility, increased initial construction costs by about 25% due to advanced materials, and the risk of summer overheating in the sunroom (up to 32°C+). It is recommended to use a zoning control strategy: maintain the optimal combination for core areas, use L-shaped layouts in auxiliary areas to ease space constraints, and integrate operable windows (opening rate ≥30%) and movable shading devices in the sunroom to switch between summer and winter modes, balancing initial investment with long-term

Table 2: Optimal factor combination model.

Factors	Optimal choice	Secondary choice	Scheme to avoid	Radar chart of indoor environmental performance for different combinations
Plan form	U-shaped	L-shaped	Rectangular	
Living room orientation	Southeast	Southwest	Northeast/Northwest	
WWR	5%<r≤15%	15%<r≤25%	r>25%	
Exterior window material	Low-E	Double-glazed	Single glazing	
Climate buffer space	Sunroom	No buffer space	Exterior corridor	

adaptability.

4.2 Multi-factors sensitivity analysis

To scientifically evaluate the contribution of different influencing factors to the improvement of indoor environmental performance, the range normalization method was adopted to carry out normalized sensitivity analysis on the simulation data for thermal, wind, and lighting environments. By comparing the normalized improvement efficiency of each factor, priorities for environmental renovation were extracted to provide a quantitative basis for optimization design of dwellings.

4.2.1 Normalized sensitivity results

Thermal and wind environment performance are mainly affected by three factors: plan form, living room orientation, and window-to-wall ratio. For the thermal environment, the absolute change in APMV during the transitional season for each factor is used as the basis; for the wind environment, the simulated data of average indoor wind speed is used; for the lighting environment, five factors—plan form, living room orientation, window-to-wall ratio, exterior window material, and climate buffer space—are analyzed based on the improvement in daylight factor (DF). The results are as follows (Table 3):

Table 3: Results of multi-factor sensitivity normalization.

Environment	Factors	Optimal choice	Worst option	Maximum improvement	Sensitivity normalized score
Thermal（APMV）	Plan form	U-shaped	Rectangular	0.0133	1.00
	Living room orientation	Northwest	Southeast	0.0132	0.99
	WWR	5%	25%	0.0033	0.25
Wind (Wind speed)	Plan form	U-shaped	Rectangular	0.15	1.00
	Living room orientation	Northwest	Southeast	0.09	0.60
	WWR	25%	5%	0.08	0.53
Lighting（DF）	Plan form	U-shaped	Rectangular	0.11	0.009
	Living room orientation	Southeast	Northwest	0.03	0.002
	WWR	25%	5%	1.38	0.11
	Exterior window material	Single glazing	Low-E	0.07	0.006
	Climate buffer space	Sunroom	Canopy	12.30	1.00

4.2.2 Comprehensive sensitivity ranking

Through normalized sensitivity analysis of each major influencing factor, the actual contributions of different factors to the improvement of thermal, wind, and lighting performance of dwellings in high-altitude cold regions can be clarified, thus providing a scientific priority ranking for indoor environmental renovation and optimization:

1. Thermal environment sensitivity: plan form > living room orientation > window-to-wall ratio;
2. Wind environment sensitivity: plan form > living room orientation > window-to-wall ratio;
3. Lighting environment sensitivity: climate buffer space > window-to-wall ratio > plan form > exterior window material > living room orientation.

4.2.3 Recommendations for prioritizing renovation

Based on the results of normalized sensitivity analysis, improvements to the indoor environmental performance of dwellings in high-altitude cold regions should be implemented in a hierarchical manner according to environmental type, with the following recommended sequence:

1. Priority for improving thermal environment: first, optimize the building plan form (recommend U-shaped, L-shaped, or other spatial forms with a high degree of enclosure) to enhance overall insulation and thermal comfort; second, adjust living room orientation (recommend southeast or southwest) to make full use of solar resources; finally, control the window-to-wall ratio reasonably (preferably 5%–15%) to reduce heat loss, while ensuring lighting needs.
2. Priority for wind environment optimization: focus on optimizing plan form to ensure smooth natural ventilation paths and avoid dead corners. Supplement this with adjustments in living room orientation (to facilitate prevailing wind access), improving ventilation efficiency. Appropriately increase window-to-wall ratio and operable areas, but balance with thermal environment needs.
3. Priority for lighting environment optimization: first, add climate buffer spaces (such as sunrooms) to significantly improve indoor daylighting while also providing passive heating. Appropriately increase window-to-wall ratio (15%–25%) to enhance natural lighting. In practice, prioritize the use of high-performance exterior windows such as Low-E glass to improve insulation while ensuring daylighting and comfort. Optimization of space layout (plan form, orientation) has relatively limited impact on lighting, but can serve as an auxiliary measure for overall improvement.

In practice, it is recommended to adopt a layered optimization path of "spatial form–climate buffer–high-performance exterior window," flexibly combining plot and economic conditions, and to gradually promote optimization of highly sensitive factors, forming a climate-adaptive environmental improvement strategy system suitable for cold plateau regions.

5. Conclusion

(1) Dominant role of spatial form and functional layout in plateau adaptation.

U-shaped, L-shaped, and other highly enclosed spatial forms, combined with southeast and west-oriented living room layouts that fully utilize the long-duration solar resources of the plateau, are key to achieving winter thermal comfort in Jiuzhaigou and other high-altitude cold regions. By optimizing spatial enclosure and orientation, the base indoor temperature can be effectively increased, with APMV approaching thermal neutrality, and the wind environment more easily achieves effective natural ventilation. This alleviates the threat of extreme cold to residents' health on the plateau, while also utilizing intense solar resources to improve the indoor thermal environment. Compared to plains and urban areas, this type of enclosed space and orientation design is better suited to the unique climate of large diurnal temperature differences and long sunshine hours on the plateau.

(2) Plateau-environment balancing strategy for window-to-wall ratio.

Under conditions of high altitude, low atmospheric pressure, and high radiation, the design of the window-to-wall ratio must balance insulation and daylighting. Empirical studies show that controlling the window-to-wall ratio within the range of 5%–15% not only resists extreme night cooling, but also ensures necessary natural lighting during the day. This approach is well-suited to the traditional wisdom of plateau dwellings, which emphasizes both energy conservation and daylighting. Compared with the preference for larger window sizes in low-altitude cold regions to enhance daylighting, high-altitude regions should give priority to smaller window sizes for better thermal insulation.

(3) Synergistic enhancement from high-performance exterior windows and climate buffer space.

Low-E glass exterior windows and climate buffer spaces such as south-facing sunrooms play a important role in improving the light and thermal environment of dwellings in cold plateau regions. Sunrooms not only significantly increase the daylight factor (DF up to 12.55), but also provide passive heating during the day to counteract extreme night cold, which is especially suitable for plateau environments with large day-night temperature differences such as Jiuzhaigou. Such passive techniques are preferable to single mechanical heating, more in line with the plateau's requirements for low energy consumption and ecological sustainability, and represent an organic combination of traditional plateau dwelling experience with modern technology.

(4) Optimal factor combination model for the environmental performance of plateau dwellings.

Combining the single-factor efficiency ranking, this study proposes an optimal configuration of factors suitable for dwellings in high-altitude cold regions: U-shaped or L-shaped high-enclosure spaces as the foundation; living rooms arranged in the southeast or southwest; window-to-wall ratio controlled at 5%–15%; exterior windows preferably using Low-E glass; and south-facing sunrooms or other climate buffer spaces added. This combination maximally coordinates the multi-dimensional needs of thermal comfort, lighting environment, and natural ventilation for plateau dwellings, achieving simultaneous improvements in winter indoor temperature, daylighting, and energy conservation. It is a new pathway integrating the ecological wisdom of traditional plateau dwellings with modern green building technology.

(5) Sensitivity prioritization and the layered optimization path for plateau regions.

Sensitivity analysis shows that the improvement of thermal and wind environments is dominated by spatial form and orientation, while the optimization of the lighting environment is primarily determined by climate buffer space and window-to-wall ratio. In plateau villages with limited space and financial resources, it is recommended to gradually implement a layered optimization system of "spatial form–climate buffer–high-performance exterior window," prioritizing highly sensitive measures to drive the overall synergistic enhancement of the indoor environment. The strategy of first optimizing spatial form, then window openings, and finally applying high-performance materials is particularly adapted to the conditions of high-altitude regions, where land for housing is limited, financial resources are constrained, and geographic resources are scattered.

In summary, through systematic simulation and sensitivity quantification analysis of indoor environmental performance in dwellings in high-altitude cold regions, this study highlights the integration of plateau climate response and ethnic construction wisdom, and the unique value of enclosed spaces, orientation to utilize plateau sunlight, and climate buffer such as sunrooms, and proposes a "layered–stepwise–zoned" optimization path more suitable for improving the environmental performance of plateau dwellings. With an emphasis on localization, applicability, and replicability, this research forms a low-carbon comfort improvement solution that fits the actual situation of plateau dwellings, providing scientific support for specific implementations in various plateau villages. Based on the climatic characteristics of Jiuzhaigou, which are representative of high-altitude cold and humid regions in western Sichuan and southern Tibet, the findings and optimization strategies proposed in this study can be extended to similar high-altitude cold regions in China, particularly the eastern Qinghai-Tibet Plateau and western Sichuan. These results provide valuable guidance for the design and renovation of residential buildings in such climates, aiming to improve thermal comfort and energy efficiency.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

CRediT Statement

All authors contributed to the study conception and design. **Shanshan Zhu:** Computer simulation and proofreading were performed; **Zuxin Xia:** Data collection and analysis were performed; **Xianmin Mai and Ziwei Li:** The manuscript structure and the conclusion sections were prepared; **Shanshan Zhu and Zuxin Xia:** The first draft of the manuscript was written and all authors commented on previous versions of the manuscript; All authors read and approved the final manuscript.

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