OPTIMIZATION ANALYSIS OF RESIDENTIAL SPACE IN COLD REGION BASED ON BUILDING PERFORMANCE SIMULATION

by

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Purpose-Rural residential buildings in China's cold areas still have large room for improvement in lighting, energy saving and other aspects due to their own development lag. Design/methodology/approach-Taking Zhaoyuan County residential buildings as an example, the spatial elements of residential buildings are quantified, and the variation intervals of each spatial element are determined based on this. Then the standard model of residential buildings is constructed, and the changing trend and related mechanism of heating energy consumption and natural lighting under the change of residential space elements are discussed. Findings-The results show that: in terms of heating energy saving, there is an obvious optimal solution between the window wall ratio of the south facade and the orientation of residential buildings; in indoor natural lighting, all spatial elements show positive and negative correlation without considering glare; building depth, eave height and plane girth area ratio are the key variables affecting heating energy consumption. Window to floor ratio, building eave height, building depth, and plane aspect ratio are the key variables that affect indoor lighting. The research results can provide reference for the energy-saving construction of residential buildings in cold areas.

Key words*: performance simulation, cold regions, spatial optimization, data analysis*

Introduction

At present, the study on energy saving of rural dwellings in China generally has the regional characteristics of farmers. Taking cave dwellings on the Loess Plateau as the research object, Yang *et al*. [1] revealed the scientific mechanism of the *warm in winter and cool in summer* thermal environment of cave dwellings through testing, investigation, analysis, practice and post-evaluation based on green building design principles, *prototype* theory, *level of needs* principle, and *critical regionalism* theory. The *technical prototype* of cave dwelling was constructed and the new kiln dwelling model was proposed on the Loess Plateau. Finally, the construction demonstration was completed. By investigating and testing the envelope structure of rural residential buildings in Beijing, Yang completed an in-depth analysis of the envelope structure and indoor thermal environment. Combined with the results of

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the investigation and test and simulation analysis, he realized a more efficient and accurate energy consumption simulation [2]. In addition, based on factors such as rural architectural characteristics, farmers' lifestyle, and economic level, he realized a more efficient and accurate energy consumption simulation [3]. The methods and principles of solar energy utilization in rural areas of China are discussed. Yang and Gao [4] took the folk houses in Jiangnan water towns as the research object, discussed the current energy-saving problems, sorted out the ecological concepts of the traditional folk houses in Jiangnan water towns from the aspects of climate, geography, local materials, *etc.*, and proposed feasible low-energy technical strategies for modern folk houses in the region. At the same time, ecological technologies such as compound envelope structure and modular PV roof passive solar house are applied in herdsmen's residence in Huangyuan County, Qinghai Province, to explore the design methods and strategies of green ecological residential buildings in Qinghai region under the premise of respecting traditional architectural culture [5]. From the perspective of dealing with extremely cold climate, Jin conducted design research and practice of new residential buildings in Zhalantun, Inner Mongolia based on the principles of climate adaptability, environmental comfort, economic optimization and technical feasibility, and proved that it has achieved remarkable results [6].

Taking *house* as the basic unit of rural living space, Wang and Wang [7] used prototype theory, cell structure principle, passive design strategy and topological morphology principle to establish the design method and construction system of *rural basic unit* with functional structure, prototype menu, cavity space and composite interface from a multi-dimensional perspective and under the guidance of low-carbon. Qin *et al.* [8] took semi-urban rural dwellings in southwest China as his research object, adopted the design principle of *passive priority and active optimization*, and proposed passive design strategies for rural dwellings in aspects such as building orientation, envelope structure and auxiliary temperature regulation PV power generation, which proved to have good results. Chen *et al.* [9] took the traditional houses in the South of the Yangtze River as his research object, studied the design strategies of their courtyards, doors and windows, ventilation and other openings from the perspective of climate adaptability, and applied them to the design of contemporary village and town houses. Yang *et al.* [10] found the respective optimization strategies of raw soil buildings in arid areas in winter and summer. Zhang *et al.* [11] analyzed the wind pressure characteristics of rural dwellings in Luoyang and discussed the optimization strategy for improving the ventilation capacity in summer under the premise of winter wind prevention. Wang ana Zang [12] optimized the size design of the sunroom through the data analysis and software simulation of the residential buildings in Diqing Tibetan area. He *et al.* [13] used orthogonal experimental method to optimize the spatial strategies and apartment types of residential buildings in Hexi Corridor.

At the level of research methods, architects have also contributed a variety of innovative paths. Based on the Xi'an data of Ladybug global climate database, Liu and Yang [14] completed the optimization of residential building layout with Grasshopper platform. Sun and Han [15] analyzed the *top-down* and *bottom-up* building energy conservation design theories with the help of digital technology tools, analyzed their characteristics and limitations, and finally proposed the design process and technology platform under the green building performance-oriented digital energy conservation design theory. Shao *et al.* [16] used the orthogonal test method to evaluate the building heat consumption under the influence of the main design factors of rural residential buildings in cold areas, obtained the influence trend of each factor and the primary and secondary analysis, and finally explored the most favorable combination method.

On the whole, the current energy saving design of buildings is mostly concentrated in urban areas, while the research on energy saving of rural residential buildings is relatively rare, and mainly focuses on traditional residential buildings. The energy saving design of buildings in severe cold areas in northeast China, represented by Zhaoyuan County, still has a high development potential.

Extract argument and construction of standard model

Based on the field investigation and survey of modern residential buildings in Zhaoyuan County, combined with existing relevant studies, this paper summarized 10 indicators, including building orientation, building area, window wall ratio, building eave height, roof slope, body shape coefficient, indoor bedroom space ratio, courtyard planting space ratio, roof form and courtyard section width-height ratio, for later research, fig. 1.

Figure 1. The floor plan and elevation of the residential sample

After comparing various spatial factors, two findings are found: on the one hand, the proportion of planted area, roof form and the ratio of courtyard section width to height have little impact on heating energy consumption and indoor lighting; on the other hand, the roof slope and body shape coefficient of various residential buildings have little difference. Therefore, four spatial elements for feature classification, including building area, window wall ratio, bedroom area ratio and main room orientation, were selected as independent variables in the construction of the simulation model to analyze the mechanism of building performance when independent variables changed.

Materials and methods

Evaluation index

Daylight autonomy

The meaning of the *daylight autonomy* is the percentage of the measurement point in the whole year that exceeds the critical value of artificial lighting, which refers to the total time of the minimum value of natural light illumination in the whole year to meet the needs of visual work at the height of the working plane, reflecting the degree of natural light utilization of the indoor space. Later researchers further perfected the concept, that is, the ratio of the minimum daily illumination required to the total use time of a certain measurement point by natural lighting alone, and the cumulative dynamic evaluation of the instantaneous illumination value, making the evaluation method more effective and practical [17, 18]. However, this method also has a defect, that is, it only considers the minimum light value but ignores the maximum light value, and does not consider the negative uncomfortable effects caused by glare [19].

Energy intensity of heating

Heating energy intensity refers to the energy use intensity (EUI) generated by building heating. The EUI can be used to compare the energy consumption level and efficiency between different types of buildings, usually measured by the number of energy consumed per square meter per year. The heating energy intensity of this study refers to the heating energy consumption per unit area of residential buildings in one year.

Methods

Rhino and grasshopper

Rhinoceros 3D is a 3-D modeling software based on the NURBS modeling method, referred to as Rhino3D, developed by Robert McNeel & Associates in Seattle, USA, in 1992, officially released in 1998. It has been widely used in industrial design, architectural design, jewelry design and other fields, and the latest version has been launched for Rhino7.4.

Grasshopper is a parameterized platform mainly for model construction, and a relatively simple graphical algorithm editor. As an open platform, Grasshopper can be used by users to write algorithms other than the built-in functions of Rhino platform. It has also been promoted from a single form modeling software to a multi-functional experimental platform such as simulation, data analysis, optimization and exploration, with strong flexibility and adaptability, and has been widely used in cutting-edge architectural design. In Grasshopper, LadybugTools series is one of the most frequently downloaded and used open source plug-ins, it integrates the world's mainstream building performance simulation engines such as EnergyPlus, Radiance, OpenFORM, with a low threshold and efficient simulation efficiency. It has been widely used and supported by designers today [20].

EnergyPlus

EnergyPlus is a building energy simulation engine jointly developed by the American Renewable Energy Laboratory, Lawrence Berkeley National Laboratory and the University of Illinois. While inheriting the advantages of previous energy consumption calculation software, it also adds new functional modules, which can add new functions according to the needs of users. It has high versatility and accuracy [21].

Daysim

Developed in collaboration with the Canadian National Laboratory and the Fraunhofer Institute in Germany, Daysim is a natural lighting analysis software based on Radiance's Monte Carlo reverse ray tracing algorithm [22]. Based on the recorded meteorological data, the software can simulate the light environment throughout the year, and get the percentage of total natural lighting (DA), total natural lighting factor (UDI) and other evaluation indicators.

Parameter presetting

Main atmospheric parameters of Zhaoyuan County

Zhaoyuan County climate belongs to the northern temperate continental climate, four distinct seasons, good lighting conditions, cold and dry winter, wide temperature difference, less diseases and pests. The average annual precipitation is about 600 mm, the water source is abundant, and it is in the upper limit of the first accumulated temperate zone in Heilongjiang Province. The annual effective accumulated temperature is 2900-3100 ℃, the frost-free period can reach 165 days, and the total sunshine in the growing season reaches 1295.6 hours. It is the first accumulative temperate zone in Heilongjiang Province, with an annual effective accumulative temperature of 2900-3100 ℃, suitable temperature, abundant rainfall, and light and heat resources ranking first in Heilongjiang Province, fig. 2.

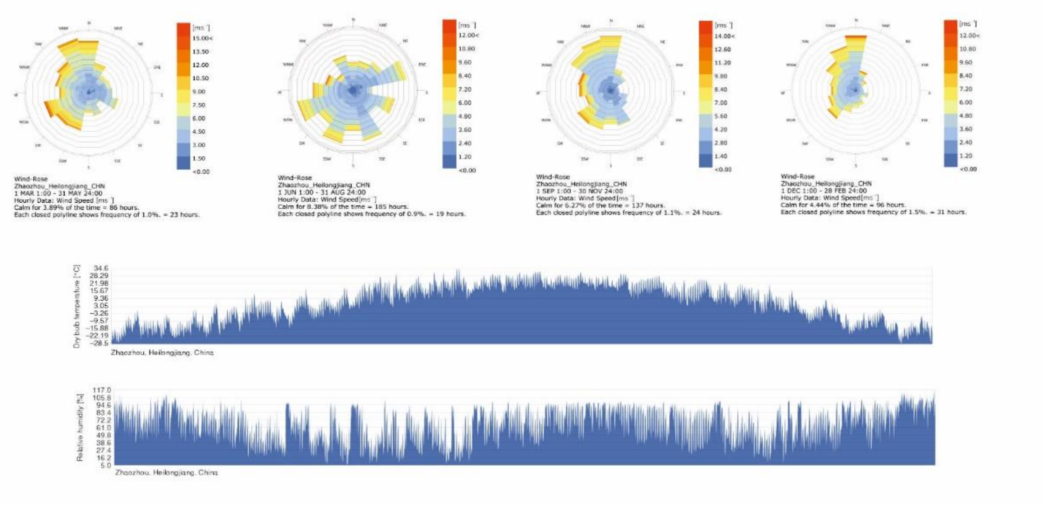

Figure 2. Wind rose, dry bulb temperature, relative humidity of Zhaoyuan County

Material of walls, roof, etc.

The material and thermal parameters of the building model are shown in the tab. 1.

Table 1. Multiple linear regression model summary table

Position	Construction practice	Heat transfer coefficient [$Wm^{-2}K^{-1}$]
Wall	20 mm cement mortar +370 mm brick wall +20 mm mixed mortar	1.58
Roofing	Ceiling + wooden keel (shed board) +150 mm wood ash + wooden frame + watchboard + coil waterproof layer + tile roof	0.93
Exterior window	Single wooden window	4.70
External door	Single wooden door	3.50
Ground	20 mm cement mortar + concrete cushion + plain earth rammed	–

Indoor natural lighting simulation

Since this study focuses on the influence of building or room shape on lighting performance, and does not focus on building materials, the model shape and window opening of natural lighting simulation are constructed in proportion to the current situation, and the meteorological data is the same as the wind environment.

Heat source and schedule setting in the building

According to the current (JGJ 26-2018) *Design Standards for Energy Conservation of Residential Buildings in Cold and Cold Areas* and other relevant national standards [23], the calculated indoor temperature is set to 18 ℃, the number of air exchange is set to 0.5 per hour, the running time of the heating system is from 0:00 to 24:00, and the lighting power density is 5 W/m^2. The power density of the equipment is 3.8 W/m^2. According to the field survey, the heating period of the residential buildings is set to be from October 20 to April 20.

Results

According to the accumulated data of standard model performance simulation, correlation analysis is carried out to analyze the correlation between various spatial elements and performance indicators, and the key variables affecting building performance are screened by statistical analysis. In order to facilitate data collation and statistics, the names of independent variables of spatial elements and dependent variables of performance indicators were all shortened to uppercase first letters of English names. Please see the tab. 2 for details.

Table 2. Abbreviations and units of the main parameters

Full name	Abbreviation	Unit	Full name	Abbreviation	Unit
Facade wide	FW	m	Building depth	BD	m
Eave height	EH	m	Bedroom width	BW	%
Glazing ratio	GLZ	–	Orientation	O	°
Building area	A	m^2	Aspect ratio	AR	–
Perimeter area ratio	PAR	–	Window to ground ratio	WGR	–
Form factor	F	–	Bedroom area proportion	BAP	%
Energy use intensity	EUI	kWh/m^2·per year	Daylight autonomy	DA	%

Heating energy consumption

According to SPSS26's Spearman correlation analysis, fig. 3, when spatial elements are controlled within a specific interval, facade wide, building depth, eave height, area, aspect ratio, perimeter area ratio, form factor, and window to ground ratio all show significant correlation with heating energy consumption per unit area. Building depth, building area and unit area heating energy intensity showed a significant negative correlation. The eaves height, length-to-width ratio, girth-to-area ratio, window-to-ground ratio, and body type coefficient have significant positive correlation with the heating energy intensity per unit area. Because the ratio of window to wall and the orientation of the building are in the best range and the change is small, there is no significant correlation with the heating energy consumption per unit area. In addition to the influence on dependent variables, there are some correlations between independent variables. For example, there is a significant correlation between building space and building area, plane aspect ratio, plane perimeter area ratio, and body type coefficient.

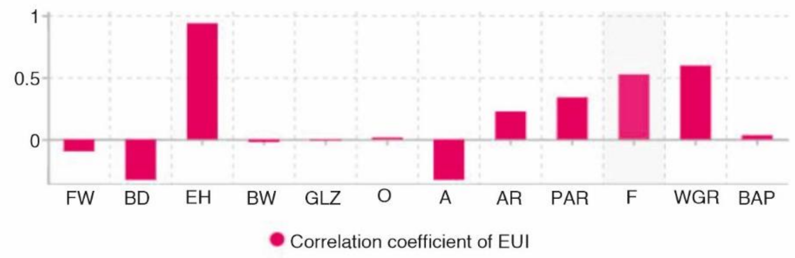

Figure 3. Correlation between spatial factors and EUI

Natural lighting

When the spatial elements are controlled within a specific interval, all the spatial elements, except for the bedroom width and bedroom area proportion, show a significant correlation with the average percentage of natural lighting in the room. There were significant positive correlations between the average percentage of natural lighting in the room, the height of eaves, the ratio of window to wall, the ratio of length to width, the ratio of perimeter area and the ratio of window to floor. Building depth, building orientation, building area, body size coefficient and the average percentage of indoor natural lighting showed a significant negative correlation, fig. 4.

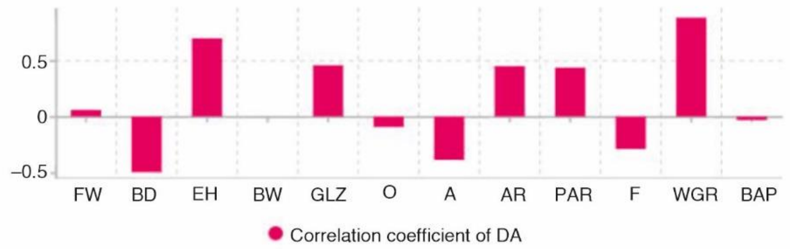

Figure 4. Correlation between spatial factors and DA

Discussion

Although correlation analysis is used to determine the mechanism of action of various spatial factors on heating energy consumption intensity and natural lighting quality, correlation analysis can obviously show that there are serious autocorrelations among various independent variables. For example, the absolute values of correlation coefficients between depth, aspect ratio and body type coefficient all exceed 0.8, and serious collinearity exists among multiple groups of spatial factors. The absolute value of the correlation coefficient between building area and perimeter area ratio and body type coefficient is also large, which also has collinearity problem. If we want to further explore the impact of various spatial factors on residential heating energy consumption intensity and natural lighting level, it is also necessary to screen spatial factors to determine key variables.

Using MATLAB to drive Lasso regression analysis to screen key variables affecting heating energy consumption and natural lighting, MATLAB was first used to read all the collected variable data, and then correct dependent variables and all independent variables were set, and gradient descent method was selected as the way to determine λ value. By running Lasso regression program to complete further screening, the spatial elements with non-zero regression coefficient can be obtained, that is, the selected key variables, fig. 5. Finally, three key variables affecting residential heating energy consumption intensity are obtained: building depth, building eave height, and building girth area ratio. Building depth, building eave height, plane aspect ratio, and window to ground ratio are the key variables that affect the average percentage of indoor natural lighting.

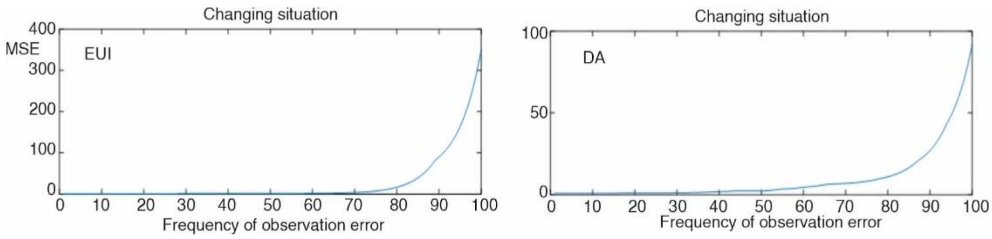

Figure 5. Lasso regression driven by gradient descent method

Heating energy intensity

With key variables of heating energy intensity screened by Lasso regression as independent variables and heating energy intensity as dependent variables, a multiple linear regression model was constructed with the help of SPSS.

Table 3. Multiple linear regression model summary table

Model	R	R^2	Adjusted R^2	Standard estimates error	Durbin-Watson
1	0.998a	0.997	0.997	1.097565323	1.400

a. (constant), BD, EH, PAR b. EUI

According to the abstract of the multiple regression model of unit area heating energy consumption, tab. 3, it can be seen that R^2 is 0.997, which is very close to 1, indicating that independent variables such as building depth, building eae height, and building girth area ratio can explain 99.7% of the variation of dependent variable unit area heating energy consumption. Generally speaking, if R^2 is above 0.3, it can be considered that the regression equation has a good fitting effect. In addition, the Durbin-Watson coefficient is 1.4, which is between 0 and 4 and close to 2, indicating that the independent variables are relatively independent and will not affect the accuracy of the results.

Table 4. Table of multiple linear regression coefficients

Model		Un-normalized coefficient		Standardization coefficient	t	Significance	Collinearity statistics	
		B	Standard error	Beta			Allowance	VIF
1	(constant)	1.930	1.294		1.492	0.136		
	BD	–1.809	0.075	–0.079	–24.226	0.000	0.143	6.987
	EH	42.995	0.057	0.938	760.599	0.000	1.000	1.000
	PAR	135.791	1.658	0.267	81.899	0.000	0.143	6.987

a. EUI

According to the multiple linear regression coefficient table, tab. 4, B represents the regression coefficient, and Beta is the regression coefficient after standardization. By comparing the absolute value of Beta, we can determine the influence degree of each key variable on the dependent variable. Therefore, the ranking is based on the influence degree of heating energy consumption per unit area: Building eave height > building girth area ratio > building depth, in which the ratio of eave height to girth area has a positive effect on the growth of building heating energy consumption, and the depth has a negative effect on the growth of building heating energy consumption. The significance of the three independent variables is less than 0.01, the variance expansion factor of the cornice height is 1, and the variance expansion factor of the depth and perimeter area ratio is close to 5. Generally speaking, VIF less than 10 indicates that the regression model basically does not have collinearity problems, so it can be considered that the regression model has a good effect.

According to the regression coefficient, the regression equation is established:

$$\mathrm{EUIy} = 1.930 - 1.809\mathrm{BD} + 42.995\mathrm{EH} + 135.791\mathrm{PAR} \tag{1}$$

where EUIy [kWhm^{-2}] is the heating energy consumption of residential units, that is, the total heating energy intensity of residential units, BD [m] – the building depth, EH [m] – the building eaves height, and PAR – the building plan perimeter area ratio.

Table 5. Multiple linear regression equation test of heating energy intensity

No.	BD	EH	PAR	Simulated value	Predicted value	Difference value
1	6.2	2.7	0.504399	175.611573	175.293545	0.318028
2	6.9	3	0.471673	183.042004	182.481848	0.560156
3	7.8	2.5	0.438228	156.078991	154.814718	1.264273
4	7.6	3.5	0.444976	198.890836	199.087836	–0.197
5	6.8	2.7	0.494118	173.531598	172.812077	0.719521
6	6.3	2.9	0.51746	185.973808	185.485211	0.488597
7	7.1	3.2	0.48169	192.575325	192.079267	0.496058
8	7.4	2.6	0.436937	160.855084	159.662512	1.192572
9	7.6	2.8	0.429825	168.024203	166.933967	1.090236
10	8	2.9	0.416667	169.710972	168.723129	0.987843

In order to verify the validity of the regression equation, the author randomly selected 10 groups of three spatial elements including building depth, eave height and plane perimeter area ratio in the value interval of the independent variable, and calculated the heating energy consumption intensity by using the form of software simulation and regression equation prediction respectively, and found through comparison, tab. 5. The difference between the simulated value and the predicted value is basically controlled below 1 kWh/m^2. Which proves that the regression equation is more effective and reliable.

Daylight autonomy

The key variables of natural lighting screened by Lasso regression were taken as independent variables, and the daylight autonomy was taken as dependent variable. A multiple linear regression model was constructed with SPSS.

Table 6. Multiple linear regression model summary table

Model	R	R^2	Adjusted R^2	Standard estimates error	Durbin-Watson
1	0.959a	0.920	0.920	2.710573095	0.738

a. (constant), BD, EH, PAR, WGR b. DA

According to the abstract table of the multivariate regression model of the DaylightAutonomy, tab. 6, it is found that R^2 is 0.920, indicating that the four independent spatial factors of building depth, building eave height, plane aspect ratio, and window to ground ratio can explain 92% of the variation of the daylight autonomy of the dependent variable. Therefore, it is confirmed that the regression model has a good fitting effect. Durbin-Watson coefficient is between 0 and 4, indicating that the variables are relatively independent.

Table 7. Table of multiple linear regression coefficients

Model		Unnormalized coefficient		Standardization coefficient	t	Significance	Collinearity statistics	
		B	Standard error	Beta			Allowance	VIF
1	(constant)	30.801	1.493		20.634	0.000		
	BD	–1.983	0.120	–0.169	–16.469	0.000	0.269	3.723
	EH	9.638	0.148	0.411	64.926	0.000	0.707	1.414
	PAR	4.255	0.425	0.099	10.020	0.000	0.292	3.426
	WGR	104.006	1.264	0.575	82.265	0.000	0.580	1.725

a. DA

According to the multiple linear regression coefficient table, tab. 7, the influence degree of each variable on the dependent variable can be determined according to the absolute value of the standardized coefficient Beta. The specific influence degree is sorted from high to low as follows: Window to floor ratio > building eave height > building depth > plane aspect ratio, in which eave height, plane aspect ratio and window to floor ratio have a positive effect on the increase of average percentage of natural lighting, while building depth has a side effect on the increase of average percentage of natural lighting. The significance of the four independent variables is all less than 0.01, and the variance inflation factor is all less than 5, so it can be considered that the regression model does not have collinearity problem. In summary, the regression effect is good.

According to the regression coefficient, the regression equation is established:

$$\mathrm{DAy} = 30.801 - 1.983\mathrm{BD} + 9.638\mathrm{EH} + 4.255\mathrm{AR} + 104.006\mathrm{WGR} \tag{2}$$

where DA is the Daylight Autonomy in residential buildings, BD [m] – the building depth, EH [m] – the building eaves height, AR – the plane aspect ratio, and WGR – the window to ground ratio.

Table 8. Regression model test of DA

No.	BD	EH	AR	WGR	Simulated value	Predicted value	Difference value
1	7.7	3.1	1.441558	0.231799	77.215152	75.652016	1.563136
2	7.5	2.8	1.506667	0.113131	60.487013	61.092071	–0.605058
3	6.5	3.2	1.584615	0.149184	70.5625	71.011668	–0.449168
4	7.3	2.6	1.383562	0.156496	64.051793	63.547479	0.504314
5	6.3	3.4	1.84127	0.237133	82.807971	83.575159	–0.767188
6	6.9	3.2	1.637681	0.203777	77.34657	76.122263	1.224307
7	7.2	3.4	1.472222	0.207492	76.395604	77.137318	–0.741714
8	7.9	2.5	1.291139	0.139049	58.286667	59.186027	–0.89936
9	6.8	2.7	1.588235	0.174465	70.190476	68.242547	1.947929
10	6.7	3.5	1.552239	0.229534	79.9875	81.72559	–1.73809

In order to verify the validity of the day lighting regression equation, the author also randomly selected 10 groups, tab. 8, of four form factors including building depth, building eave height, plane aspect ratio and window to ground ratio in the value interval of the independent variable, and calculated the average percentage of indoor natural day lighting through software simulation and regression equation prediction respectively, and conducted a comparative study on the two. It is found that the difference between the simulated value and the measured value is basically controlled at about 1%, which confirms the validity of the regression equation.

Conclusions

In terms of heating energy saving, facade wide, building depth, eave height, area, aspect ratio, perimeter area ratio, form factor, and window to ground ratio all show significant correlation with heating energy consumption per unit area. The proportion of bedroom area is negatively correlated with the overall heating energy consumption.

At the level of indoor natural lighting, without considering glare, all the form factors show positive and negative correlation, and there is no optimal solution in the middle area. There was a negative correlation between the building area and the average percentage of total natural lighting. In the building orientation, the south and southwest orientation of the main room is better than the southeast orientation, and the average percentage of natural lighting is higher. The ratio of window to wall was positively correlated with the average percentage of natural lighting in the room. In terms of bedroom area, the area of the south bedroom was positively correlated with the average percentage of natural lighting in the room, while that of the north bedroom was roughly negatively correlated.

Lasso regression shows that when each spatial element is controlled in the corresponding interval, building depth, eave height and plane girth area ratio are the key variables affecting the total heating energy consumption intensity. The spatial factors are sorted according to the degree of influence: building eave height, plane girth area ratio, and building depth. Window to ground ratio, building eave height, building depth, and plane aspect ratio are the key variables that affect the percentage of average indoor natural lighting. The spatial factors are ranked according to the degree of influence: window to ground ratio, building eave height, building depth, and plane aspect ratio.

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