Optimization Research of Rural House’s Envelope Parameters in Severe Cold Regions of China

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Abstract. The thermal performance of envelope directly restricts the heating energy consumption and indoor thermal environment of rural houses in severe cold regions. However, with the improvement of thermal performance, the construction cost will be greatly affected, which is one of the main factors hindering the implementation of energy saving design for rural houses. The energy saving and economy of whole life cycle should be considered simultaneously when determining the optimal parameters of envelope. This paper, taking the benchmark model of rural houses as research object, the life cycle cost (LCC) as evaluation index, establishes the GenOpt-EnergyPlus optimization platform by coupling EnergyPlus and GenOpt software to carry out the optimization. In the analysis, the insulating layer thickness of exterior wall, roof and ground and the window types are selected as optimization variable. Considering that the length of life span may affect the effective utilization rate of operation and construction cost, three types of life span are set, including 10, 20 and 30 years. Through the analysis, the optimum thickness of insulating layer and the energy saving effect under different conditions were discussed, which provide the basis for the comprehensive optimization of energy saving and economic benefit of rural house’s envelope in severe cold regions of China.

1. Introduction
Rural houses’ area accounts for more than 50% of the total construction area of China [1]. In the year of 2015, the rural houses’ energy consumption reached 197 million tons, accounting for 23% of the total energy consumption of civil buildings [2]. It is an effective way to realize the building energy saving through improving the thermal performance of envelope. Significantly different from urban residences, rural houses mostly adopt self-financing and self-construction based on preference and traditional experience, and lack consideration of overall building performance. In addition, the rural house is single-storey detached building with the characteristics of small in size and scattered in layout. The thermal performance of envelope directly restricts the heating energy consumption and indoor thermal environment. Also, in the construction cost of rural house, the purchase and construction cost of envelope materials account for more than 90%, which directly affects the building cost.
Survey results show that restricted by economic conditions, the thermal performance of rural house’s envelope is poor, such as the bearing materials of external wall is usually solid brick, with the thickness distributed in 370-620mm, among which 370mm wall (U-value is 1.58W/m²·K) account for 68.3%, and only 21.9% with thermal insulation measures. Although 69.1% of roof take insulation measures, but the main use of scattered materials, such as slag, wood ash, insulation performance is poor. External windows are mostly single or double glass window (87.2%). Ground is the most easily ignored part, only 2.0% have thermal insulation measures. There is an obvious contradiction between
the improvement of envelope thermal performance and the demand for low cost construction. Reducing the heating energy consumption will inevitably lead to the increase of construction cost. Economy is one of the important factors restricting the implementation of energy saving design. It’s necessary to determine the optimal thickness of insulation materials from the perspective of life cycle cost (LCC).

Existing studies mainly focus on the plane layout, spatial form, and envelope structure design of rural houses with the goal of reducing energy consumption and improving indoor thermal environment [3-9]. The balance between economy and energy conservation through appropriate control of insulating layer has been investigated in a few studies [10-14], but only focus on the external wall, the interaction between different parts of envelope is not considered. Also, most research focused on the specific climatic conditions. This paper, taking the rural house of severe cold regions in China for example, converts the game between low energy consumption and low cost into LCC as evaluation index, and applies the method of combined performance simulation and optimization algorithm to explore the optimum thickness of insulation layer and the energy saving effect under different conditions.

2. Methods

2.1. Benchmark model

According to the survey results of rural houses, the benchmark mode is obtained, that is the single-storey independent building with three compartments, as shown in figure 1. The building form parameters are shown in table 1. The heat transfer coefficients of external wall, roof, ground, external window and external door are 1.58, 0.93, 3.0, 4.7 and 3.5 W/(m²·K) respectively.

![Figure 1. The schematic diagram of rural house’s benchmark model [15].](image)

| Building orientation | south | 70.06m² (11.3m×6.2m) |
|----------------------|-------|----------------------|
| Area(width × depth)  |       | 2.6m                 |
| Interior height      |       |                      |
| Window-wall ratio    | south | 0.4                  |
|                      | north | 0.3                  |
|                      | C-1   | 1.80m×1.50m          |
|                      | C-2   | 2.60m×1.50m          |
|                      | C-3   | 1.00m×1.50m          |

2.2. Optimization software and algorithms

There is a nonlinear coupling relationship between the envelope parameters and objective function, and it’s impossible to judge whether a parameters combination can achieve the expected effect visually. The method of combining simulation software and optimization algorithm can realize the
cycle calculation and search of "energy consumption simulation—optimized search—result feedback", so as to obtain the optimal parameters combination.

EnergyPlus was used as the energy consumption simulation engine, which has passed the envelope performance and energy consumption test of ASHRAE Standard 140-200, and the simulation results were reliable. Taking CSWD data of Harbin as the boundary conditions, and according to the "Design Standard for Energy Efficiency of Rural Residential Buildings" (GB/T 50824), the indoor calculated temperature is set as 14°C, and the ventilation rate is 0.5 h⁻¹. People density, human metabolism rate and clothing, indoor lighting and other parameters are set uniformly.

GenOpt was selected as the optimization software, which is a general optimization program developed by LBNL [16] and able to couple simulation programs with digital input and output. There are many optimization algorithms inherent in the software. Hooke-Jeeves algorithm was selected to carry out optimizing calculation, which can deal with multivariable and nonlinear problems and is suitable for optimizing the output results of simulation software [17]. Java language was used to write related programs to complete the coupling of EnergyPlus and GenOpt. During the optimization process, EnergyPlus performs the energy consumption simulation, GenOpt automatically writes the input files for simulation program, then starts the simulation program, analyses the value from simulation result file and performs optimizing search.

2.3. Variables setting
The structural design scheme of exterior wall, roof and ground is shown in Table 2. Compared with the benchmark model, the insulation layer is added, which is also the main factor affecting the heat transfer coefficient and construction cost. Therefore, the insulation layer thickness of each part is set as a continuous variable. Considering the impact of building orientation on energy consumption, the external wall’s insulating layer thickness of four orientation (east, west, south, north) were denominated as different variables. The extruded polystyrene foam insulation board (XPS board), with the heat conductivity coefficient of 0.03 W/m·K and the price of ¥480/m³, was selected as the insulation material. The variable name, symbol and parameter values of building envelope is shown in Table 3. Since the external window is stereotyped product, it’s set as a discrete variable. Four types of window are selected, and their performance parameters & prices are shown in Table 4.

Table 2. The structural design scheme of exterior wall, roof and ground.

| Name          | wall                      | roof          | ground                |
|---------------|---------------------------|---------------|-----------------------|
| **Diagram**   |                           |               |                       |
| indoor        |                           | outdoor       |                       |
| **Structure** | 1-interior surface        | 1-tile        | 1-surface course      |
|               | 2-370mm solid brick       | 2-waterproof layer | 2-protective layer   |
|               | 3-20mm cement mortar      | 3-plank       | 3-XPS board           |
|               | 4-cementing compound      | 4-wood roof truss | 4-damp proof course |
|               | 5-XPS board               | 5-XPS board   | 5-20mm cement mortar |
|               | 6-alkali resistant glass fiber mesh cloth (8mm, double layer) | 6-vapor barrier (plastic film) | 5-20mm cement mortar |
|               | 7-exterior surface        | 7-wood joist  | 6-concrete cushion    |
|               |                           | 8-suspended ceiling | 7-rammed earth       |
Table 3. The variable name, symbol and parameter values of building envelope.

| Name       | Symbol | Min value (m) | Step (m) | Max value (m) | Initial value (m) |
|------------|--------|---------------|----------|---------------|------------------|
| East wall  | e      | 0.01          | 0.01     | 0.30          | 0.01             |
| West wall  | w      | 0.01          | 0.01     | 0.30          | 0.01             |
| South wall | s      | 0.01          | 0.01     | 0.30          | 0.01             |
| North wall | n      | 0.01          | 0.01     | 0.30          | 0.01             |
| Roof       | r      | 0.01          | 0.01     | 0.30          | 0.01             |
| Ground     | g      | 0.01          | 0.01     | 0.30          | 0.01             |

Table 4. The types of external window and performance parameters.

| Symbol | Window type                              | U-value (W/m²·K) | Shading coefficient | Price (¥/m²) |
|--------|------------------------------------------|------------------|---------------------|--------------|
| A      | single glass wooden window (benchmark)   | 4.70             | 0.93                | 70           |
| B      | double glass plastic-steel window (6mm)  | 3.10             | 0.78                | 270          |
| C      | double low-e glass plastic-steel window (6mm) | 2.40         | 0.45                | 350          |
| D      | three glass plastic-steel window (6mm)   | 2.10             | 0.81                | 400          |
| E      | two double glass plastic-steel window    | 1.48             | 0.78                | 540          |

2.4. Objective function

If the goal is only to reduce energy consumption, it can be achieved by increasing the thickness of insulation layer, but it will inevitably increase the construction cost, which is uneconomic for rural housing. So, in order to minimize the total building cost during its lifetime, the life cycle cost (LCC) of rural house is to be studied. LCC is the sum of present values of investment cost (IC), operation cost (OC), maintenance or replacement cost (MC) minus the present value of recovery cost (RC) for buildings. The purpose of this study is to analyse which parameters combination has the lowest LCC, therefore there is no need to include cost data for all components of the building but only the differences produced by the variation of specified parameters, such as the thickness of insulation layer, between the benchmark model and any other case. When the difference value reaches minimum, the optimized parameters combination will be obtained. The difference value of LCC is calculated from: $dLCC = dIC + dOC + dMC - dRC$, and the calculation method of each parameter is as follows [18]:

$dIC$, the sum of the differences in the initial investment cost (IC) between rural house that adopt energy-saving measures and benchmark model, is calculated from:

$$dIC = \gamma \sum_{i=1}^{n} dIC_i = \gamma \sum_{i=1}^{n} S_i \times dP_i$$  \hspace{1cm} (1)

where $dIC_i$ is the difference value of construction cost for each component of envelop; $S_i$ is the area where energy-saving measures are taken; $dP_i$ is the difference value of material price; $\gamma$ is the cost change rate during construction period, $\gamma=100\%$.

$dOC$, the difference in the operating cost (OC) arising from the reduction in heating energy consumption, is calculated to present value from:

$$dOC = a e_p dE/e$$  \hspace{1cm} (2)

where $a$ is the discount factor which takes into account the effect of inflation and escalation of energy price. Refer to related research, when the nominal interest rate $i=7\%$, the inflation rate $f=2\%$, and the escalation in energy price $e=1\%$, it can be obtained that $a=8.17, 13.76$ and $17.59$, when life span $n=10$, 20 and 30, respectively. $e_p$ is the energy price, the price of standard coal is set as ¥600/ton; $dE$ is the difference value of annual coal consumption; $e$ is the operating efficiency of heating equipment, and set as 0.6.

$dMC$, the sum of the differences due to added maintenance or replacement cost (MC) for the components, is calculated to present value from:

$$dMC = \sum_{i=1}^{n} dMC_i = dMi(l+r)^k$$  \hspace{1cm} (3)
where $dM_i$ is the difference value of maintenance or replacement cost for each component; $r$ is the discount rate, $r = (i-f)/(1+f)$; $k$ is the number of years in which maintenance fund flows begin to occur. Once replacement is assumed to take place, the window’s life cycle is set as 20 years, when life span $n=30$, the window needs to be replaced, $dMC \neq 0$; when $n=10$ or $n=20$, no replacement cost is considered, $dMC=0$.

$dRC$: the difference value of RC. The insulation material basically has no recovery value, $dRC=0$.

According to the establishment method of objective function, combining with the benchmark model’s form parameters and the envelope optimization variables, the life cycle cost function of rural house’s envelope is established.

3. Results and discussions

In order to improve the optimization efficiency and accuracy, the optimization calculation was carried out for four types of external window respectively. Through the calculation of GenOpt-EnergyPlus optimization platform, the optimal parameter combinations of building envelope under different conditions are obtained. Taking life span $n=20$ as an example, the optimization process was analysed in details, as shown in figure 2-figure 5.

**Figure 2.** The iteration curves of optimization variables and objective function (B type window).

Based on B type window, the iteration curves are shown in figure 2. At the beginning of iteration, the value of objective function decreased significantly and reached the minimum after a long period of fluctuation. After 231 iterations, the optimal solution was obtained. The minimum value of $dLCC$ is ¥9696.69, and the values of $e$, $w$, $s$, $n$, $r$, $g$ are 0.07m, 0.06m, 0.06m, 0.07m, 0.09m, 0.05m respectively. The corresponding heating energy consumption of rural house is 8569.37KWh, and the heat loss index is 29.12W/m². Compared with benchmark model, the energy saving rate is 57.44%. The initial investment cost increased by ¥9940.34, while the operation cost can be saved ¥19,637.02.

**Figure 3.** The iteration curves of optimization variables and objective function (C type window).
Based on C type window, the iteration curves are shown in figure 3. After 210 iterations, the optimal solution is reached. The minimum value of dLCC is ¥-8575.13, and the values of e, w, s, n, r, g are 0.07m, 0.06m, 0.06m, 0.07m, 0.09m, 0.05m respectively. The heating energy consumption is 8380.08KWh, and the heat loss index is 28.48W/m², with the energy saving rate of 57.44%. The initial investment cost increased by ¥11380.71, while the operation cost can be saved ¥19955.83.

Figure 4. The iteration curves of optimization variables and objective function (D type window).

Based on D type window, the iteration curves are shown in figure 4. After 185 iterations, the optimal solution is reached. The minimum value of dLCC is ¥-8373.26, and the values of e, w, s, n, r, g are 0.08m, 0.09m, 0.08m, 0.08m, 0.09m, 0.05m respectively. The heating energy consumption is 7555.26 KWh, and the heat loss index is 25.68W/m², with the energy saving rate of 62.47%. The initial investment cost increased by ¥12971.75, while the operation cost can be saved ¥21345.01.

Figure 5. The iteration curves of optimization variables and objective function (E type window).

Based on E type window, the iteration curves are shown in figure 5. After 240 iterations, the optimal solution is reached. The minimum value of dLCC is ¥-6656.31, and the values of e, w, s, n, r, g are 0.09m, 0.07m, 0.07m, 0.07m, 0.09m, 0.05m respectively. The heating energy consumption is 7118.06 KWh, and the heat loss index is 24.19W/m², with the energy saving rate of 64.64%. The initial investment cost increased by ¥15425.05, while the operation cost can be saved ¥22081.36.

Limited by the length of article, summary of the optimization results is shown in table 5, which can provide the basis for determining the thickness of insulation layer.

Table 5. Summary of optimization results under different conditions.

| Window type | n   | dLCC   | e   | w   | s   | n   | r   | g   | dIC | dOC | dMC | Energy saving rate (%) |
|-------------|-----|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------------------------|
| B           | 10  | -2114.9| 0.06| 0.04| 0.04| 0.05| 0.07| 0.03| 8275.6 | -10390.5 | — | 51.1 |
| B           | 20  | -9696.7| 0.07| 0.06| 0.06| 0.07| 0.09| 0.05| 9940.3 | -19637.0 | — | 57.4 |
| B           | 30  | -13285.7| 0.09| 0.07| 0.07| 0.10| 0.10| 0.06| 11073.7 | -26353.0 | 1993.6 | 60.3 |
As shown in table 5, for the same kind of window, the longer the life span is, the thickness of insulation layer will increase correspondingly when LCC reaches the lowest value. Although the initial investment cost increased, the energy saving rate improved, and the operation cost decreased due to the reduction of energy consumption, which can be reflected from the increasing trend of $|d\text{LCC}|$.

Comprehensive analysis shows that, when life span $n=10$, the values of $d\text{LCC}$ are negative for B, C, D type window, while the $d\text{LCC}>0$ when adopting E type window. It means that when the life span is short, although the thermal performance of E type window better than others, the initial investment cost is obviously increased, and the short-term energy saving benefit is not enough to make up for the added investment cost. When $n=20$ and $n=30$, the values of $d\text{LCC}$ are negative for four types of window, indicating that even if the initial investment cost is high, it can be made up by the operation cost saved when the life span is long. All design schemes are economical and feasible.

As long as $d\text{LCC}<0$, the design scheme is feasible. The selection of better scheme only needs to compare the value of $d\text{LCC}$, that is, the smaller the value of $d\text{LCC}$, the better the economy of design scheme. As shown in figure 6, the $d\text{LCC}$ is minimum with B type window. when life span $n=10$, 20 and 30 years, the values of $d\text{LCC}$ are -2114.84, -9696.69 and -13285.64 respectively. From the perspective of annual average, the annual average of $d\text{LCC}$ is -263.5, -278.3 and -255.7. It can be seen that the overall effect is optimal when life cycle is 20 years, and the difference of energy saving rate is small between $n=20$ and $n=30$ years. The following are C and D type windows, which have little difference in $d\text{LCC}$. The $d\text{LCC}$ is maximum with E type window, but the energy saving rate is the highest. Due to the uneven economic level of different regions or families, the thickness of insulation layer can be determined according to the results in table 4 based on the actual economic situation.

![Figure 6. The dLCC of four types of external window.](image)

**4. Conclusions**

Through the calculation of Genopt-Energyplus optimization platform, the optimal parameter combinations and energy saving effect of rural house’s envelope under different conditions are obtained, which can provide the basis for selection of the envelope’s insulating layer thickness. The results show that for the same kind of window, the longer the life span is, the thickness of insulation layer will increase correspondingly when LCC reaches the lowest value. As long as $d\text{LCC}<0$, the design scheme is feasible. When the life span $n=10$ years, the design schemes based on B, C, D type windows are feasible, the $d\text{LCC}>0$ with E type window. When the life span $n=20$ or $n=30$ years, the
design schemes based on four types of window are feasible, and the sequence as follows: single-frame double glass plastic-steel window (B type), single-frame double low-e glass plastic-steel window (C type), single-frame three glass plastic-steel window (D type) and two single-frame double glass plastic-steel window (E type). But in terms of energy saving rate, the order is the opposite. Sometimes although the energy saving rate is higher, due to the investment cost is too high, also cause uneconomic. From the view of annual average, the overall effect is optimal when the life span is 20 years, and the difference of energy saving rate is small between n=20 and n=30 years.

It should be noted that if the insulation material or economic parameters are changed, the results will change as well, which can be recalculated according to the method in this paper. In addition, the automatic optimization method adopted can solve the problem of incomplete parameters caused by manual screening and realize the real optimization.

5. References
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