Economic analysis of expressway building envelope in cold area based on RSM

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Abstract. The DeST-c energy consumption simulation software was used to build the building model based on the toll station and service area building in expressway of Zhangjiakou in the cold area, simulates and calculates the impact of single factor on energy consumption, and carries out economic analysis based on life cycle theory to determine the level of influencing factors. Finally, the BBD test design method and the orthogonal test design method were used to design the test scheme respectively and the economic analysis of the comprehensive thermal performance of the envelope structure, and the optimal energy saving scheme of the comprehensive thermal performance of the building envelope in the cold area was obtained.

1. Introduction

For the past few years, with the rapid development of the economy, the urbanization process is continuously accelerating, building consumption ratio is increasing more and more, and the environmental pollution problem can not be underestimated. In order to improve this situation, the state has issued the "Northern District Winter Clean Heating Plan". On the background, heating system retrofit projects using renewable or clean energy sources such as coal to electricity, coal to gas, become more and more; therefore, the heating system operation needs fine management, however, envelop transformation has a great significance for heating system fine operation, which is very necessary for envelop energy-saving.

By consulting the literature[1]~[5], it can be seen that the global energy conservation for building envelopes has a certain foundation. Of course, there are many shortcomings, and many scholars mainly use the orthogonal test design method to conduct an economic analysis of the comprehensive thermal performance of envelope. However, when we use the orthogonal test design method to conduct economic analysis of comprehensive thermal performance of envelope, there is much work to be done. In this paper, a response surface method and the orthogonal experimental design method are used to analyse the comprehensive thermal performance and economy of envelope. For economic analysis on comprehensive thermal performance of any building envelop, it can be studied as figure 1 below.
2. Materials and methods

2.1. Building model of High-way in cold region

As the study requirement and purpose, this paper selects a toll station in the toll station and service area of the expressway as the building model model. The building is located in Yangyuan County of Zhangjiakou, belonging to the cold area A, 2 floors above ground, is a The building complex, including the office, dormitory, etc., the building plan and the building elevation are shown in figure 2 below. Floor area is 1062.72 m², external wall $K=0.609 \text{W/(m}^2\cdot \text{K})$, interior wall $K=1.308 \text{W/(m}^2\cdot \text{K})$, roof $K=0.284 \text{W/(m}^2\cdot \text{K})$, the exterior window is a general plastic steel hollow glass window. This is simplified, and the DeST-c energy consumption simulation software is used to design the building model.

2.2. Determination of influencing factors

Through reviewing related literature, it is can be seen that main influencing factors of energy consumption of public buildings in cold region include heat transfer coefficient of outer wall, heat transfer coefficient of outer window, heat transfer coefficient of roof, ratio of window to wall, shape coefficient and so on. From the analysis of the influence law and degree of influencing factors on energy consumption, the preconditions for application of response surface method are obtained, that is, reasonable experimental factors are established. The influencing factors are heat transfer coefficient of exterior wall, heat transfer coefficient of exterior window and window-to-wall ratio. In this paper, the incremental net present value is selected as the target value, and the relationship between the thickness of the insulation board, the heat transfer coefficient of the outer window, the window-to-wall ratio and the incremental net present value is established. The thermal performance limit of the envelope
structure in the investment recovery period and standard. The optimal incremental net present value is obtained under equal constraints. The incremental method is a method that can evaluate the incremental effect produced by the post-reconstruction project compared with the pre-reconstruction project. Generally calculated by the following Eq:

\[
NPV_{d} = \sum_{i=0}^{n_i} \left(-K_i + (BK_{2i} - BK_{1i}) + (CI_{2i} - CI_{1i}) + (CO_{2i} - CO_{1i})\right) \left(P/F, i_t, t\right) + S_i \left(P/F, i_t, n_t\right)
\]

\[\sum_{i=0}^{n_i} \left(-K_i + (BK_{2i} - BK_{1i}) + (CI_{2i} - CI_{1i}) + (CO_{2i} - CO_{1i})\right) \left(P/F, IRR_d, t\right) + (S_2 - S_1) \left(P/F, IRR_d, n_1\right) = 0\]

In the Eq: \(NPV_d\) — Incremental net present value; \(IRR_d\) — Incremental internal rate of return; \(BK_{1i}\) — The asset transfer income that can be obtained in the t year before the reconstruction and expansion project; \(BK_{2i}\) — The asset transfer income that can be obtained in the t year after reconstruction and expansion project; \(CI_{1i}\) — Cash inflow in the t year of the project before reconstruction and expansion; \(CI_{2i}\) — The cash inflow of t year after reconstruction and expansion project; \(CO_{1i}\) — Cash outflow in the t year of the project before reconstruction and expansion; \(CO_{2i}\) — Cash outflow of the t year after the reconstruction and expansion project; \(K_i\) — Reconstruction and expansion investment in the t year; \(S_i\) — Residual value of assets at the end of \(n_i\) of the project before reconstruction and expansion; \(S_2\) — Residual value of assets at the end of \(n_2\) of the project after reconstruction and expansion; \(n_i\) — Life span of the project before reconstruction and expansion; \(n_2\) — Life span of the project after reconstruction and expansion; \(i\) — base discount rate.

For the economic analysis of the influencing factors of energy consumption, each unknown quantity in Eq (2) is mainly determined, so that the relationship between single-factor incremental present value and each factor, and the relationship between multi-factor incremental net present value and each factor, is obtained. The specific analysis of the formula is as follows:

\[
NPV_{di} = -C_i + \sum_{i=1}^{\min(n_i, n_2)} \left(C_{Ei} - C_{Ej}\right) \left(P/F, 8\%, t\right) + 0.03C_i \left(P/F, 8\%, \max(n_i, n_2)\right)
\]

In the Eq: \(C_{Ei}\) — Annual energy consumption cost before energy conservation renovation of envelope; \(C_{Ej}\) — Annual energy consumption cost after energy conservation renovation of envelope; \(C_i\) — Cost of energy conservation renovation of envelop.

The larger the incremental net present value, the better the energy conservation renovation plan. The optimal energy conservation scheme is: \(\max(NPV_{d1}, NPV_{d2}, NPV_{d3}, \ldots, NPV_{dn})\).

3. Results and discussion

3.1. Box-Behnken experiment design and response surface analysis.

Through the above calculation and simulation, we defined the appropriate 3 influencing factors and the optimal level of factors. We set scheme is: the three levels of external wall are 70mm, 80mm and 90mm respectively; the three levels of external window is 1.7 W/(m²·K), 1.8 W/(m²·K) and 1.9 respectively W/(m²·K); the three levels of window-wall ratio is 0.3, 0.35 and 0.4. That is, the influence factor of EPS insulation board thickness, heat transfer coefficient of external window and window-
wall ratio is $x_1$, $x_2$, and $x_3$ respectively. On this basis, the Box-Behnken design method is utilized by designing 17 experiment sites with 3 factors and 3 levels, and incremental net present value is the response value, which is denoted as $y$ which is calculated by simulation and analyzed on the basis of life cycle theory. The test plan and results are shown in Table 1 below:

**Table 1. Experiment scheme and response value**

| Experiment scheme | $x_1$ - EPS insulation board thickness/mm | $x_2$ - Heat transfer coefficient of external window /W/(m$^2$·K) | $x_3$ - Window wall ratio | Incremental NPV/Yuan |
|-------------------|------------------------------------------|-------------------------------------------------------------|--------------------------|----------------------|
| 1                 | 0 (80)                                   | -1 (1.7)                                                   | -1 (0.3)                 | 24962.25             |
| 2                 | 0 (80)                                   | 1 (1.9)                                                    | -1 (0.3)                 | 7689.87              |
| 3                 | 1 (90)                                   | -1 (1.7)                                                   | 0 (0.35)                 | 24971.21             |
| 4                 | -1 (70)                                  | 1 (1.9)                                                    | 0 (0.35)                 | 22663.90             |
| 5                 | 0 (80)                                   | 0 (1.8)                                                    | 0 (0.35)                 | 31557.58             |
| 6                 | 0 (80)                                   | 1 (1.9)                                                    | 1 (0.4)                  | 5753.69              |
| 7                 | 0 (80)                                   | 0 (1.8)                                                    | 0 (0.35)                 | 31557.58             |
| 8                 | 0 (80)                                   | 0 (1.8)                                                    | 0 (0.35)                 | 31557.58             |
| 9                 | 1 (90)                                   | 1 (1.9)                                                    | 0 (0.35)                 | 8147.98              |
| 10                | 1 (90)                                   | 0 (1.8)                                                    | -1 (0.3)                 | 32354.41             |
| 11                | -1 (70)                                  | 0 (1.8)                                                    | -1 (0.3)                 | 29867.41             |
| 12                | 0 (80)                                   | -1 (1.7)                                                   | 1 (0.4)                  | 21812.20             |
| 13                | -1 (70)                                  | 0 (1.8)                                                    | 1 (0.4)                  | 29448.64             |
| 14                | 1 (90)                                   | 0 (1.8)                                                    | 1 (0.4)                  | 31604.94             |
| 15                | 0 (80)                                   | 0 (1.8)                                                    | 0 (0.35)                 | 31557.58             |
| 16                | -1 (70)                                  | 1 (1.9)                                                    | 0 (0.35)                 | 5611.16              |
| 17                | 0 (80)                                   | 0 (1.8)                                                    | 0 (0.35)                 | 31557.58             |

Record the data in the table into Design-Expert software, and the quadratic regression equation of multiple variables was obtained by analysis and fitting.

\[
y = -4.999 \times 10^7 + 428.925 x_1 + 5.645 \times 10^6 x_2 + 32934.385 x_3 + 57.377 x_1 x_2 - 165.348 x_1 x_3 + 60693.4 x_2 x_3 - 2.223 x_1^2 - 1.599 \times 10^6 x_2^2 - 2.066 \times 10^5 x_3^2
\]  

(4)

In the equation: $y$ — Incremental net present value of comprehensive renovation technology, Yuan, $x_1$ — EPS insulation board thickness, mm; $x_2$ — Heat transfer coefficient of external window, W/(m$^2$·K); $x_3$ — Window-wall ratio.

The analysis of variance of the above equations is carried out, and the analysis results are shown in Table 2 below:

**Table 2. Analysis of variance table 1**

| Variance Source | Sum of Squares | Degree of Freedom | Mean Square | F value | P value |
|-----------------|----------------|-------------------|-------------|---------|---------|
| Regression      | 1670526590     | 9                 | 185614065.5 | 662.562121 | < 0.0001 | significant |
| $x_1$, $x_1$    | 11251432.6     | 1                 | 11251432.6  | 40.1627594 | 0.0004 |
| $x_2$, $x_2$    | 564595136      | 1                 | 564595136.3 | 2015.36101 | < 0.0001 |
| $x_3$, $x_3$    | 4889802.5      | 1                 | 4889802.5   | 17.454485  | 0.0041 |
| $x_1$, $x_2$    | 13168.59527    | 1                 | 13168.59527 | 0.0470062  | 0.8345 |
| $x_1$, $x_3$    | 27339.9611     | 1                 | 27339.9611  | 0.09759186 | 0.7638 |
When P value is less than 0.05, it means that it reaches the significant level; when P value is less than 0.01, it means that it reaches the extremely significant level. According to the analysis of table 5 above, the P value of the regression equation is < 0.0001, which indicates that the model is highly significant. The P value of factor \( x_1 \), \( x_2 \), \( x_3 \), and \( x_2^2 \) are respectively 0.0004, < 0.0001, 0.0041, < 0.0001, which means that the thickness of EPS insulation board, heat transfer coefficient of external window and window-wall ratio have a very significant influence on incremental cash value, and the second factor has a very significant influence on incremental cash value.

In order to make sure the optimal incremental net present value and the interaction among the above three influencing factors, the following figure 3 is obtained by the analysis of Design-Expert software. (a) and (b) in figure 3 are steep, which means that the heat transfer coefficient of the external window has the largest influence on the incremental net present value, while the influence of EPS insulation layer thickness and window-wall ratio on the incremental net present value is relatively small. It can be seen from figure 3 below that, incremental net present value increases with the increase of various factors; however, when it is reaches a certain extent, incremental net present value decreases with the increase of various factors, which means that there exists an optimal state, that is, incremental net present value is the largest. The optimal incremental net present value 34042.1 Yuan, is obtained by software design; at this time, the thickness of EPS insulation board is 90mm, the heat transfer coefficient of external window is \( 1.77 \text{ W/(m·K)} \), and the window-wall ratio is 0.3.

| \( x_2x_3 \) | 368368.88 | 1 | 368368.8804 | 1.31491795 | 0.2892 |
| \( x_1^2 \) | 208142.304 | 1 | 208142.3038 | 0.74297821 | 0.4173 |
| \( x_2^2 \) | 1076100941 | 1 | 1076100941 | 3841.21602 | < 0.0001 |
| \( x_3^2 \) | 1122798.74 | 1 | 1122798.736 | 4.00790699 | 0.0854 |
| Residual | 1961021.34 | 7 | 280145.9059 | |
| Lack of Fit | 1961021.34 | 3 | 653673.7805 | |
| Pure Error | 0 | 4 | 0 | |
| Sum Total | 1672487611 | 16 | | |

(a) EPS insulation board thickness and external window heat transfer coefficient
In order to verify the accuracy and reliability of multivariate quadratic regression equation, the incremental NPV 34274 Yuan is obtained by calculating the EPS insulation board thickness 90mm, heat transfer coefficient of external window 1.77 $W/(m^2 \cdot K)$, and the window-wall ratio 0.3. The incremental NPV is 34042.4 Yuan which is predicted by the model; the difference between the former and the latter is 0.7%, which means that the multivariate quadratic regression equation can accurately predict the actual situation and it is relatively reliable.

3.2. Design and analysis of orthogonal experimental design

Apply the orthogonal test design method, select the appropriate orthogonal table, design and analyze the test plan, see Table 3.

| Experiment Scheme | Influence Factor | Incremental NPV (Yuan) |
|-------------------|------------------|------------------------|
|                   | EPS insulation board thickness (mm) | Heat Transfer Coefficient of External Window($W/(m^2 \cdot K)$) | Window-wall Ratio | |
| 1                 | 1 (70)           | 1 (1.7)                | 1 (0.3)           | 23532.28 |
| 2                 | 1 (70)           | 2 (1.8)                | 2 (0.35)          | 30217.45 |
| 3                 | 1 (70)           | 3 (1.9)                | 3 (0.4)           | 4388.65  |
| 4                 | 2 (80)           | 1 (1.7)                | 2 (0.35)          | 23975.34 |
| 5                 | 2 (80)           | 2 (1.8)                | 3 (0.4)           | 30670.23 |
| 6                 | 2 (80)           | 3 (1.9)                | 1 (0.3)           | 7689.87  |
| 7                 | 3 (90)           | 1 (1.7)                | 3 (0.4)           | 22746.90 |
According to the table, the heat transfer coefficient of the outer window has the largest value of $R_j$, followed by the window-to-wall ratio, and finally the thickness of the EPS insulation board. $R_j$ is larger, which indicates the greater the influence of this factor on the incremental NPV. The order of importance of influencing factors is: the heat transfer coefficient >Window-wall ratio >EPS insulation thickness, which is consistent with the analysis results in the above section.

Due to the larger the incremental NPV, the better; when the corresponding level of each influencing factor is $\{K_{j1}, K_{j2}, K_{j3}\}$, it is the best level when heat transfer coefficient of external window is $1.8 \text{ W/(m}^2\text{K)}$, window-wall ratio is 0.3, and EPS insulation board is 90mm, the incremental NPV is the largest, it is 32354.41 Yuan.

4. Conclusions
This paper uses DeST-c software to set up a building model for a highway toll station and service area building in Zhangjiakou, and the influence of exterior wall, exterior window and window-wall ratio on energy consumption is simulated and analyzed respectively, and conducts economic analysis. On the basis of the economic analysis of the individual influencing factors, the response scheme and the orthogonal experimental design method were used to design the experimental scheme, and the simulation analysis was carried out according to the experimental scheme. The optimal schemes under the two methods were obtained respectively. The results are as follows:

a. Using the response surface method to analyze the economics of the integrated thermal performance of the envelope structure, the optimal increase is obtained when the thickness of the EPS insulation board is 90 mm, the heat transfer coefficient of the outer window is 1.77, and the window-to-wall ratio is 0.3. Net present value, 34042.1 yuan. That is to say, the thermal performance of the best integrated enclosure structure is: the external wall heat transfer coefficient is $0.282 \text{ W/(m}^2\text{K)}$, the outer window heat transfer coefficient is $1.77 \text{ W/(m}^2\text{K)}$, and the window to wall ratio is 0.3.

b. When the economy of comprehensive thermal performance of envelop is analyzed by orthogonal experiment, the order of importance of the three factors is: Heat transfer coefficient of external window >window-wall ratio >EPS insulation thickness, which is consistent with the results analyzed in the above section. When the heat transfer coefficient of external window is $1.8 \text{ W/(m}^2\text{K)}$, window-wall ratio is 0.3, and EPS insulation thickness is 90mm, the incremental NPV is the largest, that is 32354.41 Yuan.

c. Compare the optimal incremental NPV obtained by the two method, we can learn that the result obtained by response surface method is 1687.69 Yuan more than that obtained by orthogonal experiment method, which is an increase of 5.2%. It also shows that the response surface method is better than the orthogonal experiment method when analyzing the economy of the comprehensive thermal performance of the envelop.

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