Economic Evaluation of Thermal Insulation Materials in the Whole Life Cycle of Enclosure Structure

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Abstract. The thermal performance of building envelope represents a key factor to increase the energy efficiency of the construction sector and to reduce greenhouse gases emissions. This paper provide a calculation of heat losses through building envelope by using two different insulation materials (conventional and energy saving) based on the life cycle economic evaluation theory, the life cycle economic evaluation model of building envelope is established as well as calculates the life-cycle cost after using energy-saving materials on the building enclosure through analyzing the actual project. It is concluded that the application of energy-saving materials in building envelope for a span of 50years can save 910, 0000¥, which cannot only reduce the building energy consumption, but also reduces building life-cycle cost.

1. Introduction
At present, in China buildings are accountable for a significant amount of energy consumption. The number of energy consumption for buildings is increasing in China with the rapid urban development, living standard of people and population growth in recent years. The Chinese government has given greater amount of importance to energy conservation for the new buildings and the existing buildings. By the end of 2010, 95.4% of the new buildings were built on compulsory BEE standards in construction period, the energy-saving renovation and heating measurement reformation for 182 million square meters of existing residential buildings were completed in heating areas of northern China. The objective of saving 100 million tce during“Eleventh five-year plan” was realized [1].

Among different elements of a building, envelopes are one of the important parts for observing the energy consumption. It is the physical separator between the conditioned and the unconditioned environment of a building for resistance to air, heat, noise, light, and water. L.F. Cabeza et al, urges designers to include insulation materials in the building’s envelope to reduce the amount of energy required in the useable stage to maintain the building’s envisaged temperature conditions and to acquire indoor thermal comfort for its occupants. In this context, thermal insulation materials play an important role in the building envelope to reduce the building’s energy demand [2]. Thermal performance of the building envelope is the main factor affecting energy consumption. Therefore, improving the energy efficiency of buildings and reducing building energy consumption are urgent problems for the construction industry [3]. In view of this phenomenon, China improves the awareness of energy conservation, and promotes green building [4]. At the same time, it is also committed to find the ways...
to reduce energy consumption in buildings. The use of new technology, advanced equipment, and new materials helps us to reduce building energy consumption which has become an effective way of building energy conservation [5].

In recent years, China has obtained relevant fees, taxes and fee saved by the research and product development of energy-saving technology and obtained certain achievements, among which the extensive use of insulation materials to envelope structure reduces the policy subsidies for construction. Guo et al. (2012), studied the energy-saving effect of coating exterior walls with heat-reflective insulation and finding an obvious saving in energy with this insulation in Hangzhou [6]. Li and Li (2007), analysed the heat transfer principle of architectural cladding structure in the hot summer and cold winter zone and proposed a new method for calculating the heat load of a building in this area [7]. Xu et al. (2007), analysed the effects of the thermal properties of exterior walls on the annual energy consumption in Shanghai. Their results showed that during transitional seasons, insulation of the walls increased energy consumption [8].

Recent studies have focused to demonstrate the energy saving cost using advanced energy saving materials. However, their environmental analysis and cost effect analysis on building’s life cycle energy demand is an emerging research area promoted by recent changes within the regulatory framework of buildings. The most commonly used insulation material in the construction industry have been widely analysed from different points of views such as glass wool (GW), mineral wool (MW), expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PUR), foam glass (FG), etc., while others can be emerging insulation materials that derive from natural products such as cork (C), sheep wool (SW) or recycled cotton (RC). N. Guo et al.(2010), studied optimal thermal insulation thickness of energy saving building external wall based on life cycle cost analysis about residential building in Changsha region, in Chongqing region, in Nanjing region, and energy-saving renovation for existing residential buildings in Changchun [9]. Previously most of research work regarding energy-saving materials focused on their environmental and cost performance [10, 11].

Regardless of no significant work related to the life cycle energy repercussions of increasing thermal energy efficiency levels in buildings and building energy consumption during heating period. However, due to high cost still thermal insulation materials are not widely used. In view of this problem, this paper from the perspective of whole life cycle, the two schemes of ordinary and energy-saving insulation materials are used for the economic evaluation of the enclosure structure and amongst them the optimal scheme is selected.

2. Economic evaluation theory and model of life cycle

2.1. Economic evaluation theory of the whole life cycle of building energy conservation

The cost of energy saving and consumption reduction in the whole life cycle of a building should be considered from two aspects: first, it is a direct benefit. The use of energy saving materials in parts such as the enclosure structure can achieve the effect of heat insulation from the whole building and reduce the cold and heat load of the building. From the perspective of the whole life cycle, although the initial investment is increased, the energy consumption in the use of building is reduced, thus saving the energy consumption in the operation process. Second, the indirect benefit, that is because of the adoption of the new energy saving technologies to obtain social benefits.

In this paper, the cost calculation and economic evaluation of the new energy saving materials are made from the point of direct benefit.

2.2. Economic evaluation model of the whole life cycle of enclosure structure

Life cycle cost of envelope = construction cost + operation cost + removal cost

Considering the time value of capital, the present value of the total life cycle cost is:

\[ PC = C_i + C_i\left( \frac{P}{A,i,n} \right) + C_i\left( \frac{P}{F,i,n} \right) \]  \hspace{1cm} (1)
Where,
\( C_1 \) is the construction cost; \( C_2 \) is the cost of operation and maintenance; \( C_3 \) is the demolish cost; \( i \) is the discount rate; \( n \) is the life (year) of the construction project.

2.3. Comparison and selection of energy saving schemes for enclosure structure
In order to compare the advantages of the energy saving scheme for the building envelope, the present value comparison method is used to compare the two different schemes with the same engineering example EPS and XPS. Insulation board is adopted for the enclosure structure of scheme 1. The enclosure structure of scheme 2 adopts Phenolic insulation board.

3. Calculation of heat consumption index of building envelope:
Heat consumption index of building envelope is calculated according to the “standard for energy design of residential and residential construction in severe cold areas.

3.1. Heat consumption index of the designed building should be calculated according to the formula

\[
q_H = q_{HT} + q_{INF} - q_{IH}
\]

Where, 
\( q_H \) — Index of heat loss of building (W/ m²)
\( q_{HT} \) — heat transfer capacity of building and building enclosure converted to unit building area in unit time (W/ m²)
\( q_{INF} \) — heat loss due to building air penetration converted to unit building area in unit time (W/m²)
\( q_{IH} \) — heat quantity of building interior converted to unit building area in unit time, adopted 3.8W/m²

3.2. Heat transfer capacity of building and building enclosure converted to unit building area in unit time

\[
q_{HT} = q_{Hq} + q_{Hw} + q_{Hd}
\]

Where, 
\( q_{Hq} \) — heat transferred through wall converted to unit building area in unit time (W/m²)
\( q_{Hw} \) — heat transferred through roof converted to unit building area in unit time (W/m²)
\( q_{Hd} \) — heat transferred through floor converted to unit building area in unit time (W/m²)

3.3. Heat transferred through external wall converted to unit building area in unit time

\[
q_{Hq} = \sum q_{Hqi} = \sum_{A_0} \frac{\epsilon_{qi} K_{mqi} F_{qi} (t_n - t_e)}{A_0}
\]

Where, 
\( t_n \) — indoor calculated temperature, adopting 18°C
\( t_e \) — outdoor mean temperature in heating period (°C)
\( \epsilon_{qi} \) — correction factor of external wall heat transfer coefficient
\( K_{mqi} \) — External wall average heat transfer Coefficient [W/ (m² K)]
\( F_{qi} \) — area of external wall (m²)
$A_o$——building area (m$^2$)

Similarly, in terms of unit building area the heat transfer through roof and floor in unit time can be calculated as follow:

$$q_{Hi} = \frac{\sum q_{Hi}}{A_o} = \frac{\sum e_{Hi} K_{Hi} F_{Hi} (t_i - t_e)}{A_o}$$

$$q_{Hi} = \frac{\sum q_{Hi}}{A_o} = \frac{\sum K_{Hi} F_{Hi} (t_i - t_e)}{A_o}$$

3.4. Heat consumption for building air exchange in unit time converted to unit building area shall be calculated according to formula

$$q_{INF} = \frac{(t_e - t_i) C_p \rho N V}{A_o}$$

Where,

$C_p$——the specific heat capacity of air, 0.28 Wh / (kg. K)

$\rho$——the density of air (kg/m$^3$) is taken as the value under the average outdoor temperature $t_e$ in the heating period

$N$——the number of air changes is (0.5times/h)

$V$——volume of air ventilation (m$^3$) when the staircase is not heated $v= 0.6V_0$, when the staircase is heated $v= 0.65V_0$, where $V_0$ is the volume enclosed by the outer surface and the bottom layer.

4. Analysis of engineering examples

This paper takes different insulation materials as an example to calculate the building material and heat consumption indexes of the two schemes respectively, to obtain the coal consumption and heating period operation cost of building

4.1. Engineering background

During the first-phase, high-rise apartment of ocean university city project located in, Dalian city, with a construction area of 5,994m$^2$, a building height of 54.8m, a base area of 330.1m$^2$,a shape coefficient of 0.3, and a design service life of 50 years. Dalian city is a cold region, days of the heating period are 131 days, and heating period indoor temperature remains at 18$^\circ$C, the average outdoor temperature remain intact at -1.6$^\circ$C. See table 1 for the quantities of each part of the enclosure structure of this project:

| Number | Enclosure structure | Quantity(m$^2$) | Thickness(mm) |
|--------|---------------------|----------------|--------------|
| 1      | Outer wall          | 4744.36        | 80           |
| 2      | Roof covering       | 604.08         | 70           |
| 3      | flooring            | 4167.51        | 20           |
| 4      | Floor (only for first floor) | 280.77 | 50          |

Scheme 1. EPS insulation is used for exterior wall and floor where as XPS insulation board is used for roof.

Scheme 2. Phenolic resin foaming materials with better insulation are used in the enclosure structure.
Thermal conductivity and correction coefficient of thermal insulation material are shown in table 2.

Table 2. Thermal conductivity and correction coefficient of insulation materials:

| Number | Name of material | Heat conductivity coefficient [W/(m².K)] | Correction factor |
|--------|------------------|------------------------------------------|------------------|
| 1      | EPS              | 0.042                                    | 1                |
| 2      | XPS              | 0.03                                     | 1.2              |
| 3      | Phenolic foam    | 0.022                                    | 1.15             |

4.2. Comparison of heat consumption index

4.2.1. Calculate the thermal resistance $R$. Where,

$$ R = \frac{\delta}{\lambda \mu} \quad (8) $$

$R$—single layer structure thermal resistance (m².k)
$\delta$—thickness of material layer (m)
$\lambda$—material thermal conductivity (W/ m.k)
$\mu$—correction factor

Therefore, the thermal resistance of EPS with a thickness of 80mm (here in after referred to as 80 thickness as well) was $R = 0.08/0.042.1 = 1.905$ (m².k).

Similarly, the thermal resistance of EPS and XPS with different thickness is shown in table 3.

Table 3. Thermal resistance of EPS and XPS (m². k)

|        | 80mm | 70mm | 50mm | 20mm |
|--------|------|------|------|------|
| EPS    | 1.905| 1.667| 1.190| 0.476|
| XPS    | 2.222| 1.994| 1.389| 0.556|

4.2.2. Calculate the heat transfer coefficient $k$

$$ k = \frac{1}{(R + 0.15)} \quad (9) $$

Where,
$K$—heat transfer coefficient [W/ (m² K)]

The heat transfer of each material with different thickness is calculated shown in table 4

Table 4. Heat transfer coefficient of EPS and XPS K [W/ (m² K)]

|        | 80mm | 70mm | 50mm | 20mm |
|--------|------|------|------|------|
| EPS    | 0.487| 0.550| 0.746| 1.597|
| XPS    | 0.422| 0.477| 0.650| 1.417|

4.2.3. Calculate the heat consumption index. Putting the values in equation 2 we get,

$$ q_{m_0} = \frac{0.905 \times 0.487 \times 4744.36 \times \left[18 - (-1.6)\right]}{5994.5} = 6.836 \text{(W/m²)} $$

Similarly, according to the formula
\( q_{H\text{w}} = 0.853 \text{W/m}^2; \ q_{H\text{d}} = 22.446 \text{ (W/ m}^2) \)

So it is concluded that:

\[ q_{H} = q_{H\text{w}} + q_{H\text{d}} + q_{H\text{w}} = 30.136 \text{(W/ m}^2) \]

\[ q_{\text{INF}} = \frac{19.6 \times 0.28 \times 1.293 \times 0.5 \times 10854}{5994.5} = 6.424 \text{(W/ m}^2) \]

So,

\[ q_{H} = q_{H\text{d}} + q_{\text{INF}} - q_{H\text{w}} = 30.13 + 6.424 - 3.8 = 32.760 \text{(W/ m}^2) \]

Similarly, the heat consumption index of scheme 2 is 22.396(W/ m²)

### 4.3. Calculation of coal consumption for heating

\[ q_c = \frac{24 \times Z \times q_H}{H_c \times \eta_1 \times \eta_2} \quad (10) \]

- \( q_c \) — heating coal consumption index (kg/ m²)
- \( Z \) — days of heating period (D)
- \( H_c \) — standard coal calorific value 8.14103(W.H/kg)
- \( \eta_1 \) — external pipe network transmission efficiency, 0.85 before energy saving measure, 0.90 after energy saving measures
- \( \eta_2 \) — external pipe network transmission efficiency, 0.85 before energy saving measure, 0.90 after energy saving measures

By subsidizing scheme 1 and scheme 2 into the calculation formula of heating coal consumption index respectively, it can be concluded that the heating coaling consumption of engineering envelope using EPS and XPS is 27.066kg/m². The heating consumption of Phenolic material is 14.134kg/m².

If Phenolic insulation material is used, the whole project will save 77.521 tons of standard coal in each year’s heating period. The unit market price of coal is 1300yuan/ton. So annual coal consumption cost of plan 1 is 210,000 Yuan, while that of plan 2 is only 110,000 Yuan, which can save 100,000 Yuan per year

### 4.4. Economic evaluation and program comparison

According to the market price, the cost of plan 1 is about 670,000 Yuan, and the cost of plan 2 is about 750,000. The demolish costs of the two schemes are very low to consider so they are neglected. With a calculation period of 50 years and a discount rate of 10%, the economic evaluation model of the whole life cycle of the envelope can be obtained:

- Scheme 1:
  \[ PC_1 = 67 + 21( P / A, 10, 50 ) = 275.2¥ \]
- Scheme 2:
  \[ PC_2 = 75 + 11(P / A, 10, 50) = 184¥ \]

Because of PC1 > PC2 scheme 2 is optimal scheme

### 5. Discussion

After comparing both conventional and energy-saving insulation materials from the life cycle perspective it is proved that if we use energy-saving insulation materials instead of conventional material although the initial construction cost of energy-saving material which is 750,000¥ is high comparing with conventional material which is 670,000¥. As we know that the whole life cycle perspective is 50 years. It can save 910, 000¥.
Additionally, if we consider two main stakeholders who will be affected from economic evaluation using energy saving materials that are contractors and owners. From contractor point of view, it is slightly unfair with contractor because the advantages from the insulation materials are in fever of owner as he uses the building for whole life cycle, as well as the market rate and demand of building will also be high as compare to conventional building. On the other hand the contractor pay more for Energy saving building’s by using insulation materials, skilled labor, advanced equipment and working overtime but in result get nothing.

To make balance between the contractor and owner, the government needs to make some policies consider material and design-related changes in order to improve energy efficiency as well as a combination of both to make a balance. Our future research direction will specifically specify the imbalance between the contractor and owner.

6. Conclusion
In this paper, the cash flow method is used to calculate the life cycle cost of building envelope, and the present value method is used to choose the optimal scheme. Economic impacts from life cycle perspective are considered in this study, for two insulation materials and the results are compared with each other. It’s concluded that although the construction cost is more but the cost can be minimized using the whole life cycle consideration. In addition the government encourages the adoption of energy-saving technologies and products. Energy-saving buildings can save relevant fee, taxes and obtain policy subsidies.

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