Optimization Design Method Based on Energy Balance Calculations for Passive House

Mengyuan Chen¹,³, Caifeng Gao¹, Zhen Yu¹ and Jianghua Wang²

¹ China Academy of Building Research, Beijing, 100020, China
² Tianjin University, Tianjin, 300072, China
³ No. 30, North 3rd Ring East Road, Chaoyang District, Beijing, China
Email: 1335100331@qq.com

Abstract. The Passive House Planning Package (PHPP) is a design tool for energy efficiency for architects and engineers. It uses a quasi-state energy consumption calculation method given by ISO 13790 to calculate the heating, cooling, primary energy demand and renewable energy production of buildings. Based on the technical requirements and energy demand goal of Passive House, this paper analyzes the energy balance calculation model of PHPP software, and developed a Matlab program to find the optimal design parameters. Validated by applying the program to typical projects, the calculation result of the program has acceptable precision, thus can be used for rapid comparison of a large number of passive energy-saving plans, to optimize the design of Passive House based on predicted energy performance.

Keywords. Passive house; energy balance calculations; PHPP; Matlab; optimization.

1. Introduction

Passive House can achieve good indoor environmental quality with very little primary energy. In Germany, Passive Houses allow for space heating and cooling related energy savings of up to 90% compared with typical building stock and over 75% compared to average new builds [1].

For the calculation of the thermal loads and energy consumption of Passive House, the Passive House Institute developed a design software, PHPP. The calculation results of the software are used to verify whether the building meet the certification standards for Passive House [2]. Since the design of the Passive House involves the selection of multiple parameters, the thermal performance parameters and equipment selection of the components of the Passive House need to be optimized during the design phase to achieve good balance between the investment and the energy saving.

To optimize the design of a Passive House, it is important to identify factors that are significantly related to building energy consumption. Some research has already been conducted. Zhou [3] and Yu [4] chose the envelope, HVAC system and lighting system as major elements that can affect building energy consumption. Pu [5] did correlation analysis of the energy consumption of residential buildings. From 29 variables, 4 variables that are significantly related to building energy consumption were identified, which include occupancy density, capacity of air-conditioning system, capacity of electric appliance and the cooling air conditioning way in summer. Li, Bai et al. [6] used orthogonal experiments to analyze the impact of six factors on building energy consumption. They are the external wall heat transfer coefficient, roof heat transfer coefficient, external window heat transfer coefficient, building shading coefficient, building height and Window-wall Ratio.

According to the Passive House Institute, the factors that have a significant impact on the energy consumption of Passive Houses are identified as following five elements: thermal insulation, windows,
fresh air heat recovery, air tightness, and thermal bridges.

In order to make the optimization of the design more efficient, a lot of efforts have been made. Tang [7] applied orthogonal experiment and BP neural networks to establish a quick model for energy consumption prediction. Jin et al. [8] conducted orthogonal experiments on the possible factors affecting Passive House. A multivariate linear regression analysis was used to establish a heating energy consumption prediction model for rural residential house in Inner Mongolia.

Unlike other building energy simulation software, PHPP uses an energy balance calculation method based on the foundation of stable heat transfer theory. It simplifies the complex heat transfer process and reduced the difficulty of energy calculation. This makes it possible to calculate the annual energy consumption in a short period of time using a relatively simple mathematical model.

Some research has investigated the energy balance calculation method of PHPP. Zhang [9] analyzed the sensitivity of different parameters to the heating and cooling demand results using PHPP. Song [2] compared the results produced by PHPP and other building energy simulation tool.

However, the research on the optimization of Passive House design strategies using the energy balance calculation method has not been found in literature.

In this paper, the energy balance calculation method used by PHPP is analyzed. An optimization program was developed on Matlab platform based on the energy balance calculation method. A rural residential house in Northern China was used as a case study to verify the proposed method and program. A multi-parameter optimization is carried out on the case study to obtain the optimal design strategy technologically and economically. The proposed method is simpler, faster and more precise, and can be applied to different types of Passive House projects.

2. Energy Calculation Method of PHPP

PHPP uses a quasi-state energy consumption calculation method given by ISO 13790 based on the foundation of stable heat transfer theory. PHPP treats the indoor environment of the building as a unified space and considers the temperature to be evenly distributed throughout the building [10].

According to the principle of energy balance, to maintain a constant internal temperature of the building, the heat loss of the building should be equal to the heat gain. The annual energy balance relationship is shown in figures 1-2.
According to the Passive House Planning Package (2015), the annual energy consumption of Passive Houses is calculated using the following equation [11].

Winter:
\[ Q_H = Q_T + Q_V - \eta_{GW} \times (Q_S + Q_I) \]  
(1)
where \( Q_H \) is the annual heating demand, kWh /\( m^2 \cdot a \); \( Q_T \) is the transmission losses, kWh /\( m^2 \cdot a \); \( Q_V \) is the heat losses of ventilation, kWh /\( m^2 \cdot a \); \( Q_S \) is the solar heat gains, kWh /\( m^2 \cdot a \); \( Q_I \) is the internal heat gains, kWh /\( m^2 \cdot a \); \( \eta_{GW} \) is the free heat utilization factor, which is defined as the fraction of free heat that can be used for space heating.

Summer:
\[ Q_C = Q_S + Q_I - \eta_{GS} \times (Q_T + Q_V) \]  
(2)
where \( Q_C \) is the Annual cooling demand, kWh /\( m^2 \cdot a \); \( Q_T \) is the transmission losses, kWh /\( m^2 \cdot a \); \( Q_V \) is the heat losses of ventilation, kWh /\( m^2 \cdot a \); \( Q_S \) is the solar heat gains, kWh /\( m^2 \cdot a \); \( Q_I \) is the internal heat gains, kWh /\( m^2 \cdot a \); \( \eta_{GS} \) is the free heat utilization factor.

3. Description of the Case Study
In the rural area of China, household boilers use coal or natural gas for heating because the central heating system cannot cover those areas. The household boilers have lower energy efficiency and the emission causes more pollutions. Passive Houses can maintain good indoor thermal comfort and good indoor air quality using much smaller amount of energy, which can be produced by heat pumps efficiently. If Passive House is built in rural areas, it will contribute a lot to reduce the primary energy consumption and better the atmosphere quality.

This paper selects a typical residential house in Northern China as the target of this case study.

3.1. Geometric Parameters
As shown in figure 3, the building consists of five 3.9 m × 4.8 m × 3.3 m rooms arranged in the east-west direction. The main information of the example building is given in table 1.

Figure 3. Plan view of the typical rural residential building.

3.2. Climate and Thermal Performance Parameters
The meteorological data used in the calculation is based on the Tianjin area climate data CN0013a-Tianjin in PHPP. The indoor temperature target is set to 25 °C in summer and 20 °C in winter, and the temperature distribution in each room inside the building is uniform. The occupants are 3 people, and the internal heat gain coefficient \( q_i \) is 2.7 W/m².

External wall in four directions of the example model are solid clay bricks with a thickness of 240 mm. The heat transfer coefficient of the clay bricks is 0.8 W/(m²·k). The roof is a wooden supporting slope roof with a heat transfer coefficient of 1.4 W/(m²·k). The ground is a concrete cement floor with a thickness of 100 mm and a heat transfer coefficient of 0.55 W/(m²·k).
Table 1. Study building main information table.

| Name                  | Unit   | Numerical value | Name                  | Unit   | Numerical value |
|-----------------------|--------|-----------------|-----------------------|--------|-----------------|
| Building footprint    | m²     | 101.46          | Ground area           | m²     | 99.5            |
| Building volume       | m³     | 298.5           | East window area      | m²     | 0               |
| Total external wall   | m³     | 148.6           | West window area      | m²     | 0               |
| East area             | m²     | 15.1            | South window area     | m²     | 35.5            |
| Western area          | m²     | 15.1            | North window area     | m²     | 0               |
| South area            | m²     | 23.7            | Shape coefficient of building | | 0.82 |
| North area            | m²     | 59.2            | Window-wall ratio in south | m² | 0.57 |
| Ceiling area          | m²     | 99.5            | The average air change rate achieved through the ventilation system | 1/h   | 0.4 |

4. Optimization and Discussion

4.1. Optimization Calculation Program

Different parameter combinations are simulated and results are compared to find better design of Passive House technologically and economically. Table 2 provides the variations range of each component.

Table 2. The variation range of the parameters for each component.

| Name                                | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-------------------------------------|---|---|---|---|---|---|---|---|---|----|
| External wall insulation thickness (mm) | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 |
| Ceiling insulation thickness (mm)    | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 |
| Floor insulation thickness (mm)      | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 |
| External window U value (W/m²·K)     | 2.3 | 2.1 | 1.9 | 1.7 | 1.5 | 1.3 | 1.1 | 0.9 | 0.7 | 0.5 |
| External window SHGC value           | 0.35 | 0.4 | 0.45 | 0.5 | 0.55 | 0.6 | 0.65 | 0.7 | 0.75 | 0.8 |
| Exterior window shading coefficient   | 0.55 | 0.5 | 0.45 | 0.4 | 0.35 | 0.3 | 0.25 | 0.2 | 0.15 | 0.1 |
| Heat recovery efficiency of the heat recovery system | 0.95 | 0.90 | 0.85 | 0.80 | 0.75 | 0.70 | 0.65 | 0.60 | 0.55 | 0.50 |
| Air tightness (time/h)               | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |

4.2. Validation

This paper developed a Matlab program using the energy calculation method described in Chapter 2 to carry out energy simulation of buildings. The program using same methods as the PHPP but is much faster and can be easily embedded by optimization tools. For this case study, the heat transfer coefficient of the insulation materials is set to 0.033 W/(m²·k). Different combinations of the parameters of components given in table 2 form the possible sets of design decisions. The Total number of options is 10⁴. 50 random sets are selected from all 100,000,000 options to validate the Matlab program against PHPP. As shown in figure 4, the light color part in the figure is the distribution range of the solution set, and the dark part is the distribution of the randomly selected solution.

The selected 50 sets are used both by the PHPP and the proposed Matlab program for energy consumption calculation. The results are compared in figures 5 and 6.
The correlation coefficient of winter heating is 0.9947; the correlation coefficient of summer cooling error is 0.9849. It can be seen that the error between the calculation program and the PHPP simulation result is small, and the program is suitable for the design optimization.

4.3. Optimization

According to the Passive House standard, the required cumulative heating load limit is 15 kWh/(m²·a), and the required sensible heat cumulative load limit is 15 kWh/(m²·a). The cooling and dehumidification demand limit in Tianjin are 22 kWh/(m²·a). This section takes this as a constraint. The minimum incremental cost is used as the cost function, and the performance parameters and cost parameters of each component are used as design variables.

The cost information of commonly used energy-saving products in Passive Houses is listed in table 3. The number of air changes (N50) is set at 0.6 times/h according to the requirements of the Passive House Standard. The cost of airtight construction and thermal bridge treatment is estimated to be 80 yuan/m².

171 possible sets of parameters can meet the heating and cooling load requirement. The cost range is shown in figure 7.

Because the shape coefficient of the building and the Window-wall ratio of the south façade are relatively large, the incremental cost is 1242RMB/m². The possible design options that can meet the Passive House requirements are sorted by incremental cost, and the design parameters of the preferred set are input back into the PHPP verification. The results of PHPP calculation are shown in table 4.
Table 3. Performance and cost of relevant products.

| Parameter Name          | Value             | Vacuum Insulation Panel | Rigid Polyurethane Foam board | Extruded Polystyrene board | Graphite Polystyrene board | Polystyrene foam board |
|-------------------------|-------------------|--------------------------|-------------------------------|-----------------------------|---------------------------|-----------------------|
| Insulation Materials    |                   |                          |                               |                             |                           |                       |
| Heat transfer coefficient / (W/m²·K) | 0.008             | 0.024                    | 0.029                         | 0.033                       | 0.039                     |
| Cost / (RMB/m³)         | 4 000             | 1 000                    | 700                           | 600                         | 320                       |
| External window        |                   |                          |                               |                             |                           |                       |
| Material               | Wooden window     | Aluminum wood composite window | Plastic window               | Plastic window             |
| Heat transfer coefficient / (W/m²·K) | 0.5              | 0.7                      | 0.8                           | 1.0                         | 1.2                       |
| Cost / (RMB/m²)         | 4 000             | 3 100                    | 2 500                         | 1 500                       | 1 300                     |
| Heat recovery system    |                   |                          |                               |                             |                           |                       |
| Heat transfer coefficient / (%) | 55               | 60                      | 75                            | 77                         | 83                       |
| Cost / (RMB/unit)       | 5 000             | 8 000                    | 10 000                        | 12 000                     | 24 000                    |
| Manual shading products |                   |                          |                               |                             |                           |                       |
| Kind                   | Louver            | Louver                   | Roller blind                  | Roller blind               | Cloth curtain             |
| SHGC value             | 0.1               | 0.2                      | 0.3                           | 0.4                         | 0.5                       |
| Cost / (RMB/m²)         | 650               | 500                      | 350                           | 200                         | 100                       |

Table 4. Economic optimal design parameters and energy consumption indicators.

| Name                              | Unit          | Parameter value |
|-----------------------------------|---------------|-----------------|
| External wall insulation thickness| mm            | 0.30            |
| Floor insulation thickness        | mm            | 0.03            |
| Ceiling insulation thickness      | mm            | 0.21            |
| Insulation material heat transfer coefficient | W/m²·K | 0.039          |
| External window U value           | W/m²·K       | 1.2             |
| External window SHGC value        | %             | 0.7             |
| Heat recovery efficiency of the heat recovery system | % | 0.55          |
| Exterior window shading coefficient|               | 0.1             |
| Heating demand                    | kW·h/m²·a    | 15.04           |
| cooling demand                    | kW·h/m²·a    | 12.13           |
| cooling and dehumidification demand | kW·h/m²·a | 20.68           |
| Incremental cost per unit of building area | RMB / m² | 1242.70         |

Applying the proposed method to a case study in the rural area of the Northern China, the optimal design that can meet Passive House criteria and with lower construction can be found within limited time and efforts. The tool developed in Matlab platform can be easily used by architects and engineers for engineering practice.

5. Conclusion
The basis for the PHPP software is the energy balance calculation method. Based on this calculation method, this paper developed a program based on Matlab to find the optimal set of design parameters.
from a large number of possible options. The proposed method is simple to use, clear in principle and not time-consuming. It can help designers to optimize the design of Passive House in a short period of time.

**Acknowledgments**

This work was supported by National Key Research and Development Project of China (No. 2017YFC0702610 entitled Research on Core Technologies for Nearly Zero Energy Buildings).

**References**

[1] http://www.passiv.de/en/02_informations/01_whatisapassivehouse/01_whatisapassivehouse.htm.
[2] Song AY, Wu J L, Gao C F and Yu Z 2016 Design optimization of Tianjin Sino-Singapore eco-city passive house project using PHPP Building Science 32 (4) 38-43.
[3] Zhou X R 2009 *Study on Building Energy-Saving Design Method Based on Total Energy Demand in Scheme Stage* (Tsinghua University).
[4] Yu Q 2011 Study on Building Energy-Saving Parametric Design Method in Schematic Stage (Tsinghua University).
[5] Pu Q P 2012 *Research on Prediction Model and Influencing Factors of Urban Residential Building Energy Consumption* (Chongqing University).
[6] Li A Q and Bai X L 2007 Study on predication of energy consumption in residential buildings Building Science 23 (8).
[7] Tang S L 2017 *Research on Evaluation of Suitable Technical System of Passive Ultra-Low Energy Residential Buildings in Hot Summer and Cold Winter Area*.
[8] Jin G H, Zhang D J, Li Y Z, et al. 2018 Structural optimization of passive residential in agricultural and pastoral areas of western Inner Mongolia Science Technology and Engineering 18 (7) 223-227.
[9] Zhang Z R, Xie F, Cai Q et al. 2015 Application and implementation of energy balance in passive house Construction Science and Technology (15) 52-56.
[10] Zhou A J, Hu Y H, Liu Y L, et al. 2017 Comparative study on energy consumption calculation software of passive ultra-low energy buildings Building Science 2017 (12) 177-181.
[11] Passive House Planning Package (PHPP) *The energy balance and planning tool for efficient buildings and refurbishments* http://passiv.de/en/04_phpp/04_PHPP.htm.