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Comparison of building performance between Conventional House and Passive House in the UK

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Abstract

The building performance monitored over one year of a Conventional House and a Passive House in North East England is presented in this paper. These two houses which differ in building fabric, the type of ventilation and thermal storage, the use of different energy and residents' occupancy result in distinct building energy performance and indoor air quality. According to the measurement data, the primary energy demand of the Conventional House and Passive House were 169.85 kWh/(m^{2}a) and 64.11 kWh/(m^{2}a) while the annual average indoor temperature of the two properties maintained at 17.7°C and 22.0°C, respectively. A simulation study was conducted by DesignBuilder software to improve the Conventional House's energy and indoor environmental performance using passive retrofitting methods, aiming to reduce the primary energy demand, the space heating demand of the property and enhance its general indoor air environmental performance. The DesignBuilder models were validated by monitored data and used to predict the performance of the Conventional House after retrofitting, and then compared it with the Passive House. The results indicate the reduction of space heating demand is by about 80% compared to its current status. The findings showed that there was a huge potential for conventional house retrofitting using passive energy saving methods in northern England.

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Keywords: Building performance; DesignBuilder; Energy demand; Retrofitting; Passive House; Conventional House

1. Introduction

In recent years, building energy conservation has turned into one of the most attractive topic worldwide. In the United Kingdom, the residential building becomes the biggest energy consumer, with nearly 30% of the total energy

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consumption and carbon dioxide emissions [1]. Compare to the energy used in road transport, industry and commercial building, more energy is consumed in the residential sector and it indicates a considerable opportunity to cut down the energy usage and restrict the carbon dioxide emissions. The UK Government has set a number of ambitious targets and taken some steps to achieve 80% reduction of energy consumption and carbon dioxide emissions by 2050 compare to the 1990 levels [2, 3]. According to the statistics data from the Office for National Statistics, the national average usable floor area is 91 m^2 and the average household energy consumption is 16.1 MWh [4, 5]. The Passive House concept was defined as smart buildings with very small heating energy demand but achieve comfortable indoor environmental condition and great indoor air quality. Over 50000 Passive House structures were constructed in the world by 2013 as the Passive House has been proven as one of the most leading energy efficiency residential building and applicable to different climate [6]. A building needs to meet the following criteria in order to achieve Passive House certification [7]:

- Primary energy demand: maximum 120 kWh/(m2a).
- Space heating/cooling demand: maximum 15 kWh/(m^2a) or 10 W/m^2 for peak demand.
- Airtightness: maximum 0.6 h^{-1} @50 Pa in the pressurisation test.
- Thermal Comfort: maximum 10% of the hours for over 25 °C.

The aim of this study is to find out and compare the differences of building energy performance and indoor air quality between the selected Conventional House and Passive House in the North East England and investigate the potential measures to improve the Conventional House’s performance by applying passive energy saving retrofitting methods. To do so, a customized monitoring kit was installed in each house to record their energy consumption and indoor environmental condition, for the purpose of understanding the behaviors for both properties and validate the DesignBuilder models. A simulation study by applying Passive House standard to retrofit the Conventional House was conducted afterwards to improve its performance and intent to achieve effective passive energy saving building with lower energy demand and better indoor environmental condition.

2. The methods

2.1. Case studies: description of the two buildings

The case study properties are shown in Fig. 1: Conventional House and Passive House are, respectively, four and three bedroom two-storey detached family house located in Newcastle upon Tyne and Durham, North East England, the former one was built in 1978 and the second one was 2014. Compare to other British cities, this region is cooler in summer but colder in winter and requires more heating energy during the winter heating season.

Fig. 1. (a) photo of the Conventional House; (b) photo of the Passive House.

The 90 m^2 Conventional House comprises an entrance hall, a living room, a dining room, a kitchen, a toilet, four bedrooms and a bathroom [8]. This dwelling benefits from double glazing windows, 300 mm thickness cavity wall with insulation, and gas central heating for keeping the dwelling warm in winter. But this is a house that without cooling and mechanical ventilation systems. Mains electricity and gas are the two main energy sources supplied to this Conventional House. Electricity is consumed for providing household lighting and appliance while gas is for supplying daily cooking, domestic hot water and winter space heating. Domestic hot water and space heating for this house was provided by a low efficiency non-condensing conventional gas boiler, which discontinued in 2007. The house residents complained about the relative high winter bills but cold indoor temperature.

The selected new build timber frame Passive House with 219 m^2 usable floor area was designed to achieve minimum energy demand and high quality of living environment. This dwelling meets the Passive House standard and benefits from its excellent building fabric design (e.g. the application of triple glazing and advanced insulations), a mechanical ventilation with heat recovery system (92% efficiency), a 6 kW photovoltaics array that generates power to a thermal store for providing domestic hot water and space heating, and a high efficiency condensing gas boiler also supplied to the water tank while no power is available from the photovoltaics array [9]. The house residents satisfied with the energy bills paid and the comfort indoor environment achieved during the winter time.

Although 47 external glazing openings exist in the Passive House as a result of the house owner's preference, top-grade construction materials was in use to build this dwelling. The U-values of the four different basic construction elements for the Passive House and the Conventional House are compared in Table 1. From the table, it can be seen that all the U-values of the Passive House basis components are far less than the Conventional House's and it also indicates the potential for applying passive energy saving methods to improve the building performance of the Conventional House.

Table 1. U-values of the basic construction elements.

Elements	Passive House U-values (*W/m²K*)	Conventional House U-values (*W/m²K*)
Walls	0.123	0.54
Floors	0.09	0.25
Roofs	0.064	2.93
Windows (Glazing)	0.60	1.96

2.2. Building modelling and validation

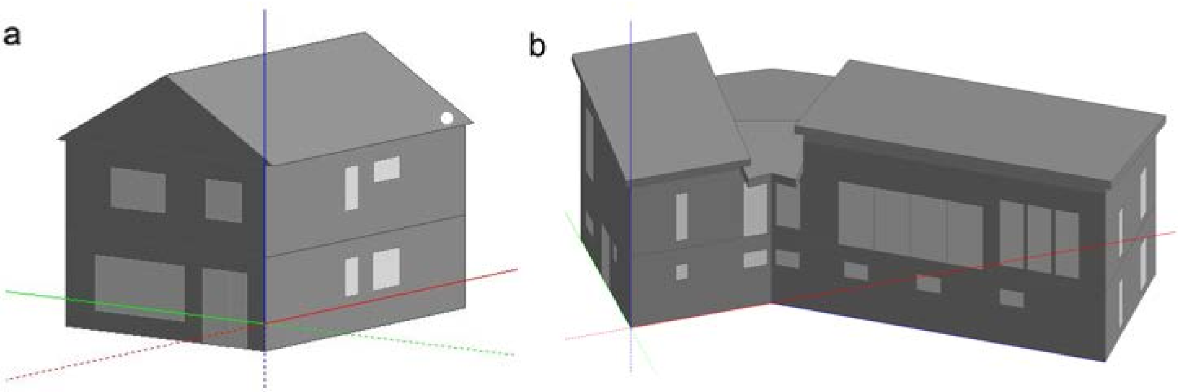

Fig. 2. (a) simulated model of the Conventional House; (b) simulated model of the Passive House.

Nowadays, many different criteria must be balanced in order to provide high quality, comfortable buildings that also comply with building regulations, minimise upfront costs to the client, optimise on-going energy costs and reduce environmental impact. DesignBuilder software has been chosen for this study as it is the first comprehensive user interface to the EnergyPlus dynamic thermal simulation engine and can generate accurate environmental performance data and stunning rendered images or movies at any stage in the design process. One of the methodologies of this study is to develop the DesignBuilder models for both Conventional House and Passive House to simulate the energy consumption and indoor environmental condition of these two dwellings. While the models are validated by actual monitoring data, it would help evaluate the energy performance of these two houses and recommend the most efficient energy saving plan for the Conventional House. Fig. 2 shows the building appearances of the two houses generated by DesignBuilder software.

In this study, MBE and CV(RMSE) between actual and simulated results were used to validate the building models and they were calculated by Eq. (1) and Eq. (2), where M_i and S_i were respective measured and simulated data at time instance i. Following the convention of using the measured values as the reference point, percentage error results were generated for energy consumption and indoor environmental condition of the models by Eq. (3) [10].

$$MBE = \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \quad (1)$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=0}^{N_i}[(M_i - S_i)^2/N_i]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \quad (2)$$

$$\varepsilon_i(\%) = \frac{M_i - S_i}{M_i} \quad (3)$$

3. Results and discussion

The first detailed performance monitoring year for the Conventional House conducted by the sensors and data loggers started in July 2015. Real time electricity consumption, 5 minute interval indoor temperature and relative humidity were recorded by the proprietary monitoring kit. The annual monitored electricity and gas consumption were 2646.35 kWh and 10436.92 kWh, respectively. As the conditioned space of this Conventional House is calculated as 90 m^2 according to the actual measured data, the total energy consumption of dwelling was 13083.27 kWh and the primary energy demand was 145.37 kWh/(m^2a). The measured average indoor temperature for the whole house was 17.7°C in the first monitoring year while the average indoor temperature during the winter heating season (Nov-15 to Apr-16) was 16.1°C. 64.2% represented the average indoor relative humidity of this Conventional House for the whole monitoring year.

The first 12-month monitoring of the Passive House's performance began since November 2015. Ten sensors were installed in the property to record the building performance including 1 minute interval energy consumption, indoor temperature and relative humidity, and 3 minute interval indoor CO_2 concentration measurement. The annual recorded electricity and gas consumption were 4871.23 kWh and 9169.90 kWh, respectively. Thus, the total energy demand of the dwelling was 14041.13 kWh. Because the treated floor area of this Passive House is 219 m^2 based on the simulation of PHPP, the primary energy demand was only 64.11 kWh/(m^2a), which was 47% lower than the requirement set in the Passive House standard. The space heating demand was 26.8 kWh/(m^2a), higher than the 15 kWh/(m^2a) Passive House standard requirement due to the house residents' dependency on heating even in the summer. During the monitoring period, the annual average indoor temperature of the whole dwelling was 22 °C and 45.5% represented the annual average relative humidity level, which were very comfortable for the living environment.

Both DesignBuilder models for the Conventional House and the Passive House have been validated by their actual energy demand and indoor environmental condition. For the Conventional House, the simulation results generated by the model indicated that the annual electricity and gas consumption were 2457.21 kWh and 10348.53 kWh, respectively. And the simulated average indoor temperature was 17.6°C. Thus, the total energy consumption error between actual measurement and simulation was 2.12% according to Eq. (3), which was within the acceptable range. The MBE was calculated as +2.12% (within the ±5% requirement) and the CV(RMSE)was 7.14% (maximum value is 15%) according to Eq. (1) and Eq. (2). Analogously, the indoor temperature error between actual measurement and simulation was 0.56%. The MBE and CV(RMSE) for the annual indoor temperature could be calculated as 1.76% and

5.15%. For the Passive House, the simulation results estimated by the DesignBuilder model indicated that the annual electricity and gas consumption were 4680.06 kWh and 8733.15 kWh. And the simulated average indoor temperature was also 22°C. Hence, the total energy consumption error between actual measurement and simulation was 4.47% according to Eq. (3), which was within the acceptable range. Based on Eq. (1) and Eq. (2), the MBE and CV(RMSE) for the energy consumption were +4.47% and 6.5%, respectively. It can be seen from the evaluation above that the Passive House is excellent to minimize the energy demand and receive comfortable indoor environmental condition and there is a huge gap for the house performance between Passive House and Conventional House.

From the view of passive methods of building energy saving, advanced building construction technologies and materials can enhance the thermal mass of building envelop and reducing the energy consumption for heating of the building by utilising the existing internal heat effectively. From the simulation, it is found that the external wall, roof, floor and glazed windows were the four main parts, which resulted in internal heat lost. To improve the house performance, a house retrofitting simulation using advanced materials certified by Passive House standard conduced in the DesignBuilder software, which is one of the most effective and rigid passive energy saving regulations applied to this Conventional House. In the simulation, 150 mm thickness expanded polyurethane board was chosen to add to the outer surface of external wall, and inner surface of floor slab and roof level; the double glazing for windows and doors have been replaced by good quality triple glazing. The estimated U-values of the four fabric elements are listed in Table 2. The new U-values are compared with the current ones and they are all within the limitation restricted in the Passive House standard. As an example, the comparison of external wall structure for current construction and recommended retrofitting construction is shown in Fig. 3.

Table 2. Comparison of U-values for different envelop elements.

Elements	Passive House standard U-values (*W/m²K*)	Conventional House current U-values (*W/m²K*)	Conventional House retrofitted U-values (*W/m²K*)
Walls	0.15	0.54	0.12
Floors	0.15	0.25	0.10
Roofs	0.15	2.93	0.13
Windows (Glazing)	0.85	1.96	0.78

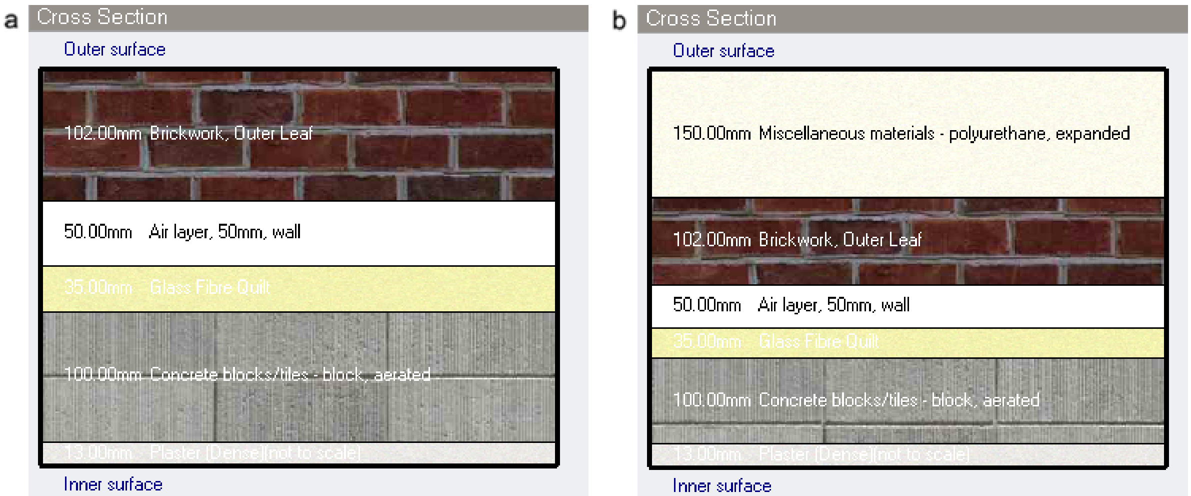

Fig. 3. (a) current external wall of the Conventional House; (b) estimated retrofitted external wall of the Conventional House.

To compare the house performance for current status and after retrofitting, indoor temperature was set at 16°C in the model and the annual heating gas consumption is 812.30 kWh while the annual heating consumption of current status is 3641.85 kWh from the simulation. Thus, at 16°C indoor environmental condition level, the heating demand of this conventional house can reduce about 77.7% because of the building fabric retrofitting. By retrofitting the building fabrics, this conventional house is able to be heated to 20°C, which is the average indoor temperature during heating season based on the DesignBuilder model simulation. The house electricity consumption after retrofitting is not different compares to current status, but the annual gas consumption grows up from 10348.53 kWh to 11267.74 kWh, leading by the rising heating demand.

4. Conclusions

This study shows the energy performance and indoor environmental condition between Conventional House and Passive House are very different. For the Passive House, the building performance was remarkable. It provided relatively stable 22°C indoor temperature during the first monitoring year with only 64.11 kWh/(m^2a) primary energy demand. For the Conventional House, although the 145.37 kWh/(m^2a) primary energy demand was 17.8% lower than the national average level, the 16.1°C winter indoor average temperature cannot make the house reach the comfort standard within the whole heating season. Thus, a retrofitting to the Conventional House by using passive methods is essential to improve its performance for reducing the energy demand and increasing the indoor temperature. For the Conventional House, retrofitting simulation was conducted by the validated DesignBuilder models. Through the improvement of building fabrics, the primary energy demand reduced approximately 23.7% to 110.85 kWh/(m^2a) at 16°C indoor temperature level. Moreover, the heating energy decreased from 3641.85 kWh to 812.30 kWh, with 77.7% reduction. On the other hand, after retrofitting, the house temperature could be enhanced to comfortable level (e.g. 20°C) to satisfy the residents' requirement. Hence, the primary energy demand is 154.60 kWh/(m^2a) after retrofitting. Compare to the Passive House, the high efficiency mechanical ventilation with heat recovery and the condensing boiler also play an important role in energy saving. The future work for further study is to explore the impact from house utility from the view of energy saving. Overall, the results from this study indicates the advantage of house retrofitting by using passive energy methods in achieving lower energy consumption and good thermal comfort. The results from the study may be used as a reference for the future UK Conventional household retrofitting.

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