Liang X, Royapoor M, Wang Y, Roskilly T.

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In: 4th Sustainable Thermal Energy Management International Conference (SusTEM2017).

28-30 June 2017, Alkmaar, The Netherlands.

Conference website:

http://research.ncl.ac.uk/thermal_challenge_network/events/sustem2017inthenetherlands/

Date deposited:

11/09/2017

The energy and indoor environmental performance of super-insulated dwellings – A fabric optimisation case study in the UK

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Abstract
The role of high performance fabrics in reducing building energy demand is gaining international significance. With state-of-art building materials, it is feasible to exceed basic regulatory requirements of low energy buildings and create super-insulated fabrics. In this work, a sensor network is imbedded in a three bedroom family house built to Passive House fabric limits and equipped with local electricity generation. First annual compilation of measured data showed the ability of the fabric to maintain indoor thermal comfort within stable performance as the maximum daily temperatures between the warmest and coldest space did not exceed 1.8 °C. The primary energy consumption of the 219 m^2 dwelling was 65 kWh/(m^2a), which was much better than that of the 120 kWh/(m^2a) Passive House target. But the space heating requirement however exceeded the limits of Passive House requirements due to occupant interventions and unfamiliarity with the complex nature of services and relying on the mechanical ventilation with heat recovery (MVHR) and its post heater system to maintain the target indoor temperature. The MVHR limits the CO_2 built-up to an average night time maximum of 700 ppm in bedrooms, an overall indoor average of 528 ppm with an absolute maximum instance of 1750 ppm. It is also found that the temperatures in the office room was overheated to 25 °C for approximately 8.5% of the time in a year, i.e. 747 hours. In order to eliminate this overheating problem and reduce the energy consumption for heating to the limits of Passive House standard, an energy model was developed, validated and used to find out the solutions. The results from the modelling showed that reducing MVHR set-point temperatures was the most effective method; increasing thermal mass and adding cooling load were the second and third effective measures to solve the overheating problem.

Keywords: Passive house; energy performance; indoor environment; DesignBuilder; overheating; optimisation

1 Introduction

Since the 1970s, there were a large amount of attempts to cut down the space heating demand of residential buildings. Some projects reached the goal of significant energy saving for heating demand and achieved "low energy house", which enhanced the thermal mass of the building envelope, contained a mechanical ventilation system for high level indoor air quality, achieved low space heating demand between 50 to 70 kWh/(m^2a) successfully [1]. In the mid-1980s, the "low energy house" energy standard became a legal requirement for new buildings in some Northern Europe countries, e.g. Denmark and Sweden. Further improvements of "low energy house" principle were being considered at that time, for instance, airtightness and insulation materials of the building, a well-controlled mechanical ventilation system and the glazing for windows and doors [2]. Based on the discussions and considerations above, the concept for "Passive House" was launched by Dr. Wolfgang Feist in Germany and Professor Bo Adamson in Sweden in May 1988. The concept was developed through eight research projects and the explanation was given by the two originators: *"Passive Houses" were defined as buildings which have an extremely small heating energy demand even in the Central European climate and therefore need no active heating. Such houses can be kept warm "passively", solely by using the existing internal heat sources and the solar energy entering through the windows as well as by the minimal heating of incoming fresh air* [3].

The first Passive House dwelling was built in Darmstadt-Kranichstein, Germany, in 1990. The house has extremely good performance and was occupied by residents since 1991. This house aimed to reduce the total energy consumption through improving the efficiency of the appliances, lighting and domestic hot water (DHW) system of the building. Focus on the dwelling itself, mechanical ventilation heat recovery, thermal insulation, prevention of thermal bridges, airtightness and high quality glazing were the keys to minimise the Passive House's total energy demand [4]. In general, the building consumed less than 10% of the energy for heating compared to the German new-built building code at that time [5]. The Darmstadt Passive House still functions well as designed after more than twenty years since built: the annual energy consumption of space heating demand was under 15 kWh/m^2 yearly.

Since the first example had been validated in Kranichstein, the standard for Passive House was further elaborated and developed rapidly. The following CEPHEUS (Cost Efficient Passive Houses as EUropean Standards) project funded by the European Union certified the Passive House concept with more than 100 dwellings for 11 cases during 2000 to 2002. These projects presented that, normally, Passive Houses consumed 80 to 90% less energy for space heating than conventional buildings. Additionally, the building costs would increase by 5 to 10% [6, 7]. A building is required to meet these main criteria to obtain the Passive House certification [8-12]:

(a) Primary energy demand: maximum 120 kWh/(m^2a) of usable living space for all domestic applications, including electricity, domestic hot water, heating and cooling.
(b) Space heating/cooling demand: maximum 15 kWh/(m^2a) or 10 W/m^2 for peak demand of usable living space.

(c) Airtightness: maximum 0.6 air changes/h @50 Pa for the pressurisation test.
(d) Thermal Comfort: maximum 10% of the hours over 25 °C for all living areas in a year.

As of 2013, more than 50000 Passive House structures were built worldwide because the standard has been proven to be a reliable scheme to achieve extremely low energy demand dwellings that applicable to several different climates [13]. Most of them were located in Germany, Austria and Scandinavia, while others in various countries worldwide. In 2003, the first North American Passive House was built in Urbana, Illinois [14]. Ireland's first Passive House – Out of the Blue was built by Architect Tomas O'Leary, a Passive house designer, in 2005 [15].

The first batch of certified Passive Houses in the United Kingdom has been built since 2010 [16-18]. Among them, the Camden Passive House was the first new-built dwelling certified to the Passive House standard in London. The case study showed the 12-month monitored thermal and energy performance of the building and aimed to provide standards and reference for UK low energy residential house from the views of energy efficient design and refurbishment, indoor comfort and occupants' health. This study presented that the Camden Passive House was one of the lowest energy dwellings (65 kWh/(m^{2}a)) in the UK. However, summer time overheating was observed in the project even the occupants didn't report it as a problem [19]. Ridley et al. presented the monitored performance of the first two Welsh side by side social Passive Houses in [20]. This two-year monitoring aimed to assess whether the novel building design and the whole systems were performing well as expected and to discover any unexpected building or occupant behaviours. The technical and performing differences resulted in significant discrepancy in space heating demand (one for 9.3 kWh/(m^{2}a) and another one was 25.6 kWh/(m^{2}a)), CO_2 emissions and the indoor environmental performance in summer, even both houses achieved the Passive House certification. The summer overheating in UK homes has been observed and reported in [21, 22]. The studies showed that overheating problem was more likely to happen in the UK houses with extremely high energy efficient than conventional houses. Thus, it is necessary to find out whether overheating occurs in high energy efficient dwelling is the result of higher insulation applied to the building [23].

Although the summer overheating problem for this type of buildings has been discovered in the UK, there are not any effective solutions for it yet. The purpose of this study is to fill the gap of the shortage of feasible solutions for current summer overheating problem happens in these super-insulated dwellings. It aims to investigate the energy and indoor environment performance of a UK Passive House through a 12-month monitoring work and find out the balance between low energy demand in winter and comfort indoor environment in summer; and provide recommendations to prevent the summer overheating problem on the basis of achieving great winter indoor environmental condition with low energy input in this kind of lightweight residential buildings through a case study. The methods used for this study are: 1) evaluate the current energy consumption and indoor environmental condition of a UK Passive House using real-time onsite recorded data gathering by a proprietary monitoring package deployed in the dwelling; 2) set up simulation models for this case study using DesignBuilder software, which was firstly calibrated by the actual energy consumption and indoor thermal performance [24]; and then the models were used to find out where, when and why the overheating is happened; and what the potential solutions for optimisation of the building envelop are to overcome the overheating problem during summer time and further to reduce the overall energy consumption of this house.

2 The case study

A Passive House located in Durham, North East England is selected as the case study target. The house is a new build timber framed detached family house. The two-storey house was designed and built to achieve minimum energy demand and high quality of living environment. The house, as shown in Figure 1, is included in the Passive House database (ID: 4186) of International Passive House Association [25] which meets the Passive House construction standards.

This dwelling benefits from its advanced building envelop design and construction materials (including high performance insulations and triple glazing), a mechanical ventilation with heat recovery system, a photovoltaics array and a high efficiency gas boiler supplied to a thermal store for domestic hot water and space heating. The treated floor area of the house is 219 m^2 based on the calculation of Passive House Planning Package (PHPP). This dwelling consists of three sections from east to west. The first floor (upper level) of this Passive House comprises entrance hall, office, en-suite, living room, dining room and kitchen. And there are three bedrooms, family room, utility room, cloakroom, bathroom in the ground floor (lower level). Due to the personal preferences of the Passive House owner who appreciates outdoor scenery through the openings of the house, there are 4 external doors and 43 windows installed in this dwelling. However, this became one of the biggest challenges for the housing design and construction. Previously, the number of openings in a Passive House dwelling was limited in order to keep the house super-airtight and reduce the windows installation thermal bridges as close to zero as possible. Thus, it took about three years to finish all stages construction works of this contemporary property since 2012. Moreover, high quality but expensive thermal envelope was used for this dwelling. The U-values for basic components of the dwelling are shown in Table 1.

Figure 1: North façade of the Passive House.

Table 1: U-values of the construction envelope.

Components	U-value (W/m^2K)
External wall	0.123
Floor slab	0.09
Roof	0.064
Glazing	0.6

3 The methods

The methods used for this study are:

1) Measurements of the energy performance onsite. For the purpose of understanding the performance of this target property, energy consumption for both main grid electricity and gas and local solar PV electricity generation were recorded by the proprietary monitoring package. Indoor environmental condition of the dwelling including temperature, relative humidity and CO_2 concentration of four different zones have been monitored at the same time.

2) Modelling using DesignBuilder software. DesignBuilder software is used in the study to simulate the house energy consumption and indoor environmental condition. The software is the first comprehensive user interface to the Energy Plus dynamic thermal simulation engine [26, 27], which has been widely audited by the research community and been demonstrated to have high prediction accuracies. Accurate energy consumption and environmental performance data could be generated at any stage for both new and existing buildings.

Equation (1) was used to calculate the errors between actual monitoring data and simulation results. Following the convention of using the measured values as the reference point, percentage error results were generated for energy and indoor climate predictions of the model by Equation (2). CV(RMSE) and MBE between actual and simulated results were calculated by Equation (3) and (4) to validate the building model.

$$\varepsilon_i = M_i - S_i \quad (1)$$

$$\varepsilon_i(\%) = \frac{M_i - S_i}{M_i} \quad (2)$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=0}^{N_i}[(M_i - S_i)^2/N_i]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \quad (3)$$

$$MBE = \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \quad (4)$$

Where M_i and S_i are respective measured and simulated data at time instance i; and ε_i is the error at instance i.

A building model for the Passive House was set up in DesignBuilder. The model is to help find out the accurate energy demand trend and discover the indoor thermal comfort for this selected house. Figure 2 shows the external facade of the detached house modelled in the software.

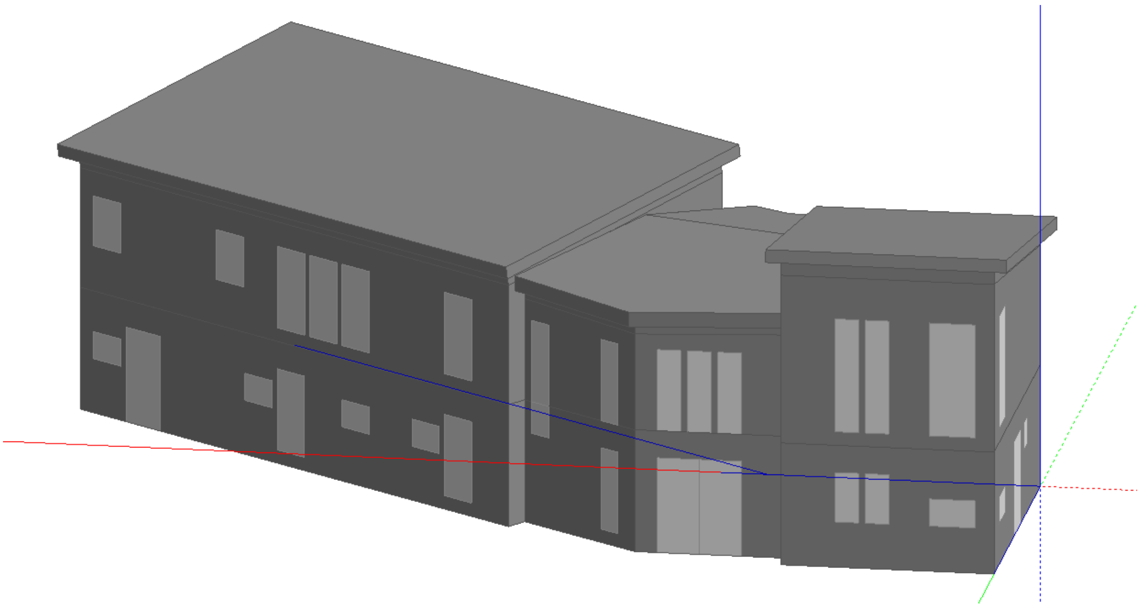


Figure 2: North façade of the Passive House simulated by DesignBuilder.

4 Results and discussion

The first-year monitoring of the Passive House's occupancy performance began since early November 2015. The monitoring intervals for all sensors were 1 minute except the CO_2 concentration detectors, which were 3 minute. Due to the network disruption problem, the energy data for 20th to 30th Jul, 2016 and 29th Oct to 2nd Nov, 2016 has not been recorded by the sensors. However, the remaining monitoring data still represented the features of energy performance of this dwelling. The annual main electricity from grid and gas consumption were 4871.23 kWh and 9169.90 kWh, respectively. Thus, the total energy consumption (excludes the electricity provided by local solar PV) of dwelling was 14041.13 kWh and the primary energy demand was 64.11 kWh/(m^{2}a), which was nearly half value compared to the Passive House standard.

Figure 3 indicates the monthly energy consumption recorded onsite of the Passive House. It shows the differences of energy requirements within summer and winter, especially the gas demand. From the figure, it can be seen that the gas demand increased significantly (approximately 600%) from approximately 200 kWh in summer to 1560 kWh in winter and then began to decrease after January, the coldest month in a year. On the other hand, solar PV electricity generated by onsite station rose from bottom line to the peak since January and dropped down again to the valley value after the hottest summer time. The electricity consumption in a year remained at a stable level except the change of residents' occupancy since September last year. Moreover, because the solar PV electricity would have priority to be used to supply the Passive House directly, the main grid electricity consumption was comparatively lower in summer period compared to winter demand. The increased electricity consumption from September to December was due to the growth of the family members, i.e. changed from two adults to two adults and three children.

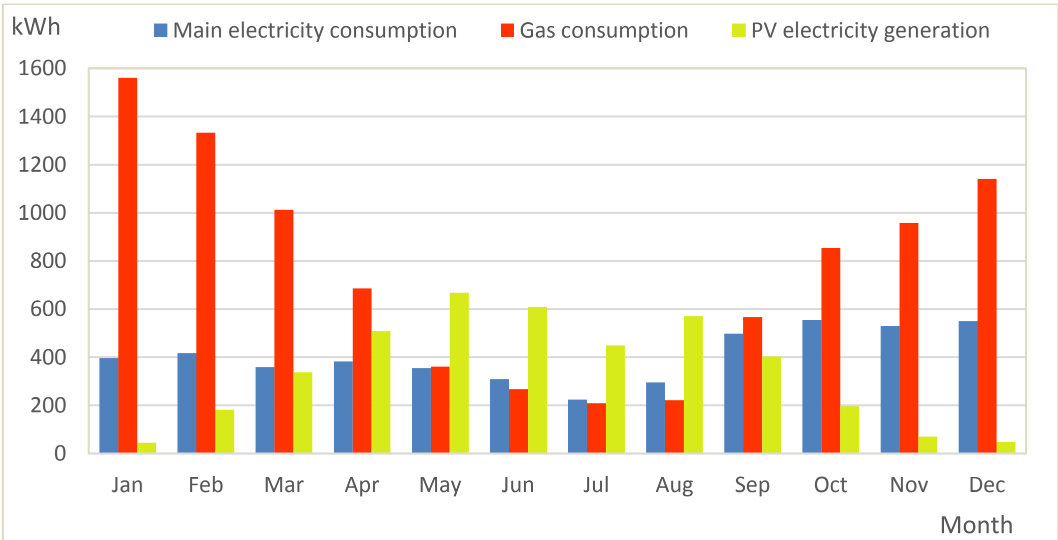


Figure 3: Monthly monitoring energy information of the Passive House.

The monthly gas consumption distribution of space heating and domestic hot water is shown in Figure 4. It can be seen from the figure that the gas consumed of domestic hot water for each month was similar and the average consumption was 414.43 kWh. The space heating demand of this property differed from month to month as the heating requirement in winter was significant. The annual total energy usage for space heating was 5870.8 kWh. Thus, the space heating demand of this dwelling was 26.8 kWh/(m^{2}a), 11.8 kWh/(m^{2}a) beyond the Passive House standard. Because the gas boiler connected with MVHR in the house is to help supply heating to desired indoor temperature. Even in majority of the summer days, the boiler was not turned off and it consumed more energy than expectation due to the demand and preference of the house residents.

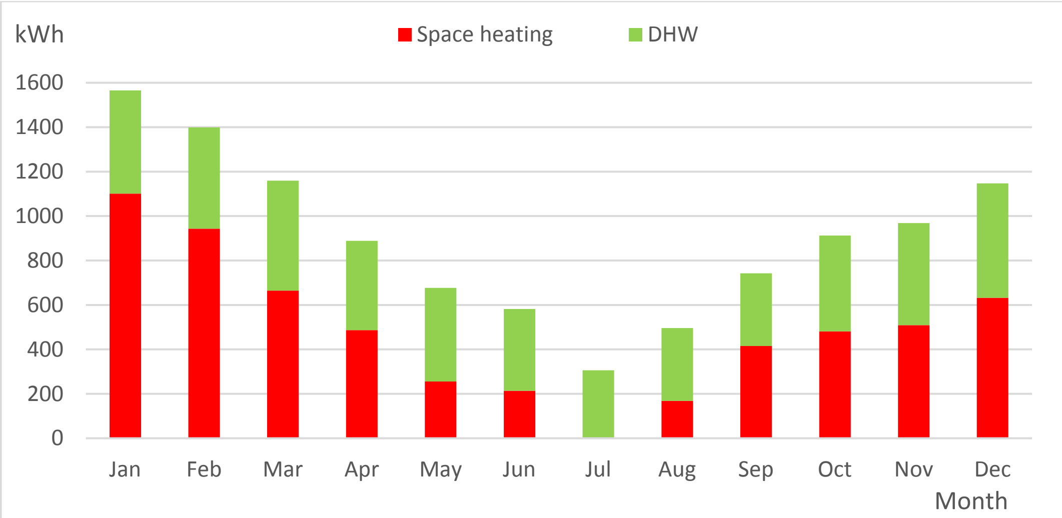
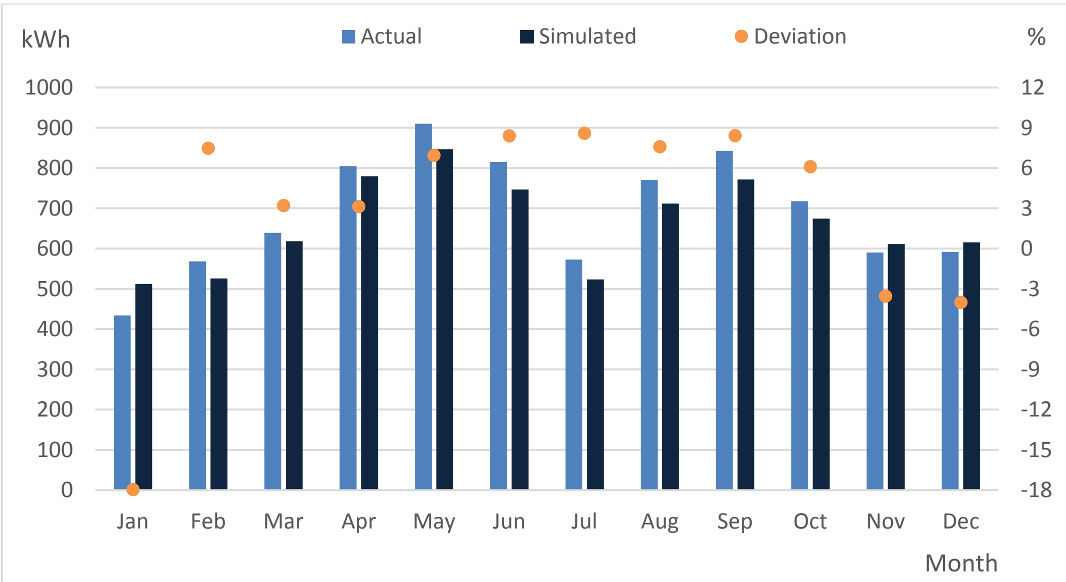
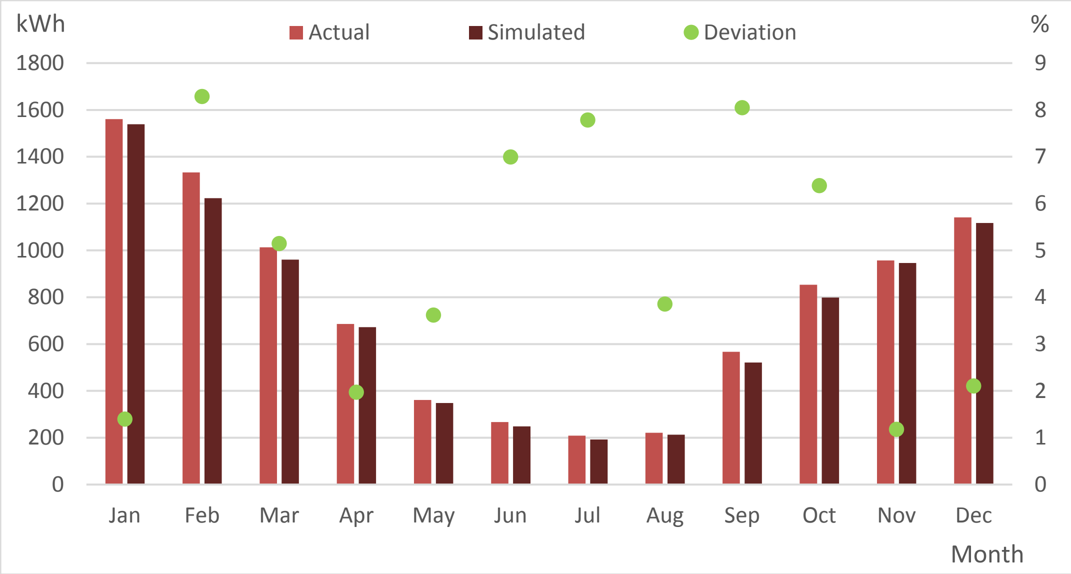


Figure 4: Monthly gas consumption distribution.

According to the measured data, annual solar PV electricity consumed by the dwelling was 3356.11 kWh. Hence, the total dwelling electricity consumption reached 8255.01 kWh. Based on the simulation results, the annual total electricity consumption (including the electricity consumed from the local solar PV generation) was 7936.17 kWh, while the estimated gas consumption was 8733.15 kWh. The annual energy consumption were calibrated using Equation (1) and (2) and the errors between actual usage and simulated results were 3.8% and 5.0% for electricity and gas consumptions respectively, which were within the acceptable range. The comparison of monthly actual total energy consumption and simulated usage and their percentage errors are shown in Figure 5. In addition, Figure 5 (a) indicates the errors comparison for the house electricity consumption while Figure 5 (b) represents the errors analysis for gas consumption. It can be summarised from the two figures that the CV(RMSE) and MBE for electricity consumption were 7.4% (maximum value is 15%) and +3.9% (within the ±5% requirement) , correspondingly according to Equation (3) and (4). For gas consumption, CV(RMSE) was calculated as 5.6% and MBE was 4.2%



(a) electricity consumption



(b) gas consumption

Figure 5: Comparison of monthly actual total energy consumption and simulated usage.

It is clear from the figure that, for electricity consumption, the largest difference appeared in January and the simulated usage was 82 kWh lower than the actual consumption. One of the reasons would be the network disruption happened and the recorded consumption was not for the whole month, so less measured electricity was consumed in that particular month. For gas consumption, all monthly actual consumption were slightly more than the estimated energy. This may due to a slightly lower house temperature was set in the simulation model. The indoor temperature was assumed at 20°C in the DesingBuilder model as it is the standard temperature for Passive House indoor environment. Due to the preference of the house residents, 22°C was the actual house operating temperature. Thus, the 2 °C higher indoor temperature setting increased the gas demand of the house.

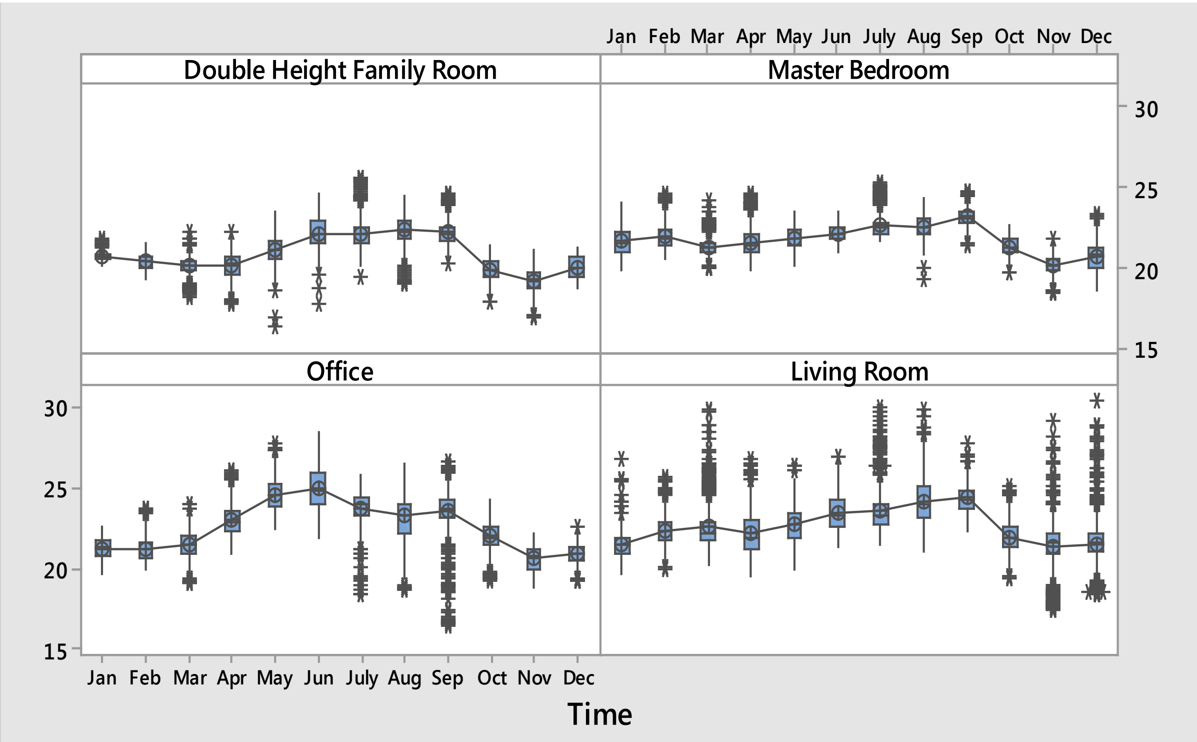


Figure 6: Boxplot of monthly indoor temperature of four different rooms in the dwelling.

The monitored indoor temperature, relative humidity and CO_2 concentration of four different zones (Double Height Family Room, Office, Master Bedroom and Living Room) in this house represented its great indoor environmental performance. The differences between highest and lowest values for monthly indoor temperature, relative humidity and CO_2 concentration were 2.5 °C, 20.2% and 177 ppm, respectively. The annual average indoor temperature of the whole property was 22 °C which was very comfortable and even 2 °C beyond the Passive House standard. In terms of relative humidity, 45.5% represented the annual average level. Monthly indoor temperature trends of these four different rooms in the dwelling during the monitoring period is shown in Figure 6. In the boxplot figure, the tiny blue boxes represent the middle 50% of all the data. The upper and lower whisker represent the upper and lower 25% of the distribution, respectively. The observations beyond the upper or lower whisker are the outliers. It can be seen from the figure that the temperature trend in lower floor was more stable and was about 2 °C lower compared to the upper floor. During the winter heating season, the average indoor temperature for all zones were beyond 20 °C, which was great performance with satisfied thermal comfort. But the indoor temperature in summer time was obviously around 3 °C beyond the temperature in winter time, especially for the Office and Living Room in upper floor. This super-insulated dwelling may experience the summer overheating problem.

Table 2 represents the assessment of indoor air quality in the Passive House., The monitored indoor temperature and relative humidity has been classified to several categories based on the CIBSE Guide A – Environmental design shown in the table to assess the thermal performance of the dwelling. The four different categories of the indoor CO_2 concentration (IDA) in the dwelling was classified according to the standard of EN 13779. And the average level of indoor CO_2 concentration for this dwelling was only 529 ppm. All the indoor environmental condition demonstrate the dwelling is under the best performance for more than 90% hours of monitoring.

Table 2: Assessment of indoor air quality in the Passive House.

	% hours	Double Height Family Room	Master Bedroom	Office	Living Room
Temperature	< 17°C	0.03	0	0.16	0
	17°C < T < 25°C	99.86	99.92	90.48	92.44
	> 25°C	0.11	0.08	9.36	7.56
	> 28°C	0	0	0.05	0.40
Relative humidity	< 30%	0.01	0.37	5.00	0.23
	30% < H < 70%	99.99	99.62	94.99	99.77
	> 70%	0	0.01	0.01	0
Carbon dioxide	< 800 ppm	99.44	91.81	95.77	95.09
	800ppm < CO_2 < 1000ppm	0.54	7.95	3.16	4.09
	1000ppm < CO_2 < 1400ppm	0.02	0.24	0.87	0.82
	> 1400 ppm	0	0	0.20	0

Table 3: Overheating criterion analysis.

Zone	Criterion	May	June	July	August	September
Office	C1 (% ΔT)	17.6	8.9	0	0	0
	C2 (Count of days when We>6)	9	3	0	0	0
	C3 (Instances when ΔT>4)	0	0	0	0	0
Master Bedroom	C1 (% ΔT)	0	0	0	0	0
	C2 (Count of days when We>6)	0	0	0	0	0
	C3 (ΔT>4)	0	0	0	0	0
Living Room	C1 (% ΔT)	0.3	0.3	6.3	1.3	0.3
	C2 (Count of days when We>6)	0	0	3	1	0
	C3 (ΔT>4)	0	0	0	0	0
Double Height Family Room	C1 (% ΔT)	0	0	0	0	0
	C2 (Count of days when We>6)	0	0	0	0	0
	C3 (ΔT>4)	0	0	0	0	0

From the analysis above we know that the performance of this Passive House is fabulous. The super insulated dwelling keeps the energy consumption of this house under the requirement for one of the most rigorous building standard worldwide. Simultaneously, the indoor environmental condition including temperature, relative humidity and CO_2 concentrations of the dwelling are maintained at high quality level because of the advanced fabric construction, especially in winter time. However, the percentage hours for over 25°C in the Office and Living Room were closed to 10% and this indicated there would be a risk of overheating during summer time happened in the upper level of the property. An annual overheating analysis carried out by three criteria set out within CIBSE Technical Manual 52 was shown in Table 3. There were three criterions to evaluate if a zone existed overheating problem using the onsite monitored temperature data from May to September. The temperature percentage hour for over 25 °C of Office and Living Room were closed to 10%, which is restricted by the Passive House standard. Overheating problem existed in May due to the super-fabric design.

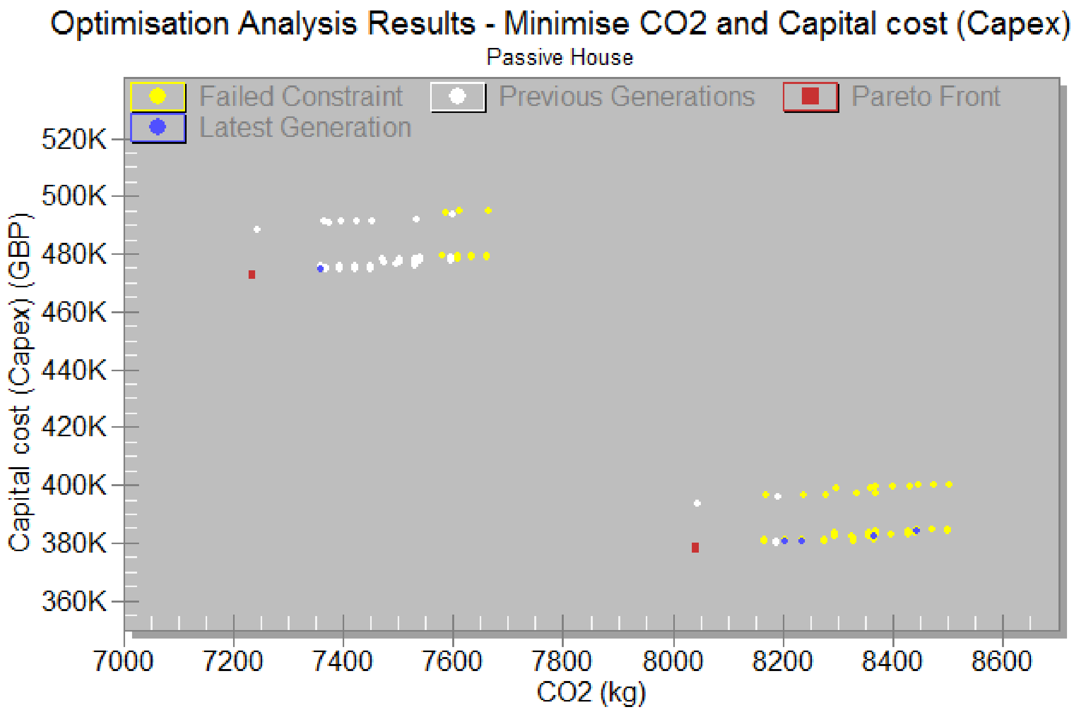


Figure 7: Optimisation of the Passive House.

A feasibility study of optimisation to reduce the house heating demand and overheating risk was conducted by the DesignBuilder model. Figure 7 indicates the optimisation results for the Passive House. The simulation model was set up to restrict the annual total energy consumption for space heating and discomfort hours during summer of the dwelling. These were the two constrains for the optimisation. Design variables, for instance, window to wall ratio, window blind, local shading, external wall, thermal mass, insulations and mechanical ventilation set-point temperature were considered to meet the requirements. All the scatter points (4 different types of Generations dots) in the figure represent the estimated optimisation results. The Pareto Fronts (red dots) mean the best practical results calculated according to the model settings and satisfied with the limitations of energy usage and CO_2 emission. Fail Constraints (yellow dots) indicate the results that fail to meet the assumed constrains stated above. Within them, results from top left corner were generated by applying advanced construction building materials and components. They required comparatively higher investment cost but produced less CO_2. On the contrary, results from bottom right corner showed the low capital cost invested in the building fabric would lead to higher heating demand and carbon dioxide emissions. From Figure 7, it is found that in most cases, the conventional fabric conditions couldn't make the dwelling meet the requirements for both winter low space heating energy consumption and discomfort hours during summer time. The fabric construction of the dwelling is already one of the best patterns for space heating energy saving and indoor environment condition. It performs very well no matter in winter or summer, although it demands higher investment for the building fabric and construction. But there is still the possibility to reduce the MVHR set-point temperature from 20 °C to 18 °C and adding thermal mass of the dwelling for achieving better house performance. Taking into account the methods, it is predicted by the model that 18.9% space heating energy savings can be implemented. In addition, over 200 discomfort (overheating) hours could be eliminated and the carbon dioxide emissions saving would reach 13.4% under simulation.

For this case, over-insulated in a lightweight building is one of the reasons for leading house overheating because fixed glazing windows design and highest standard's construction materials are not beneficial for internal heat release. Coupled with the fact the office room is immediately above the plant room and the DHW distribution then the office is prone to run at a slightly higher temperature than the rest if the house under normal conditions. So it was realised that not having an opening window in the office room and vents of the MVHR system caused the trouble of summer overheating. The result is that the room temperature cannot be purged by opening a window and forcing air through, particularly at night time. Thus, adding cooling load to the office room is one of the scheme to reduce the overheating risk and achieve the desired objective with minimal compromise to the integrity of the airtightness and thermal efficiency. As expectation, a small wall mounted split unit powered by the solar PV electricity generation was installed in the office room since late June 2016, and no overheating hours from July to September after adding the cooling system. The problem was weakened and the temperature in that room dropped down to normal level. However, the room temperature does not remain down for very long if the air conditioner has been turned off. This is a factor of having little thermal mass in the upstairs rooms.

5 Conclusions

The energy performance and indoor environment condition of this Passive House is outstanding. According to the measured data, the primary energy demand was only 65 kWh/(m^2a), which is approximately half of the Passive House standard. The annual average indoor temperature, relative humidity and CO_2 concentration of the whole property were 22 °C, 45.5% and 529 ppm, respectively. However, the daily working gas boiler leads to higher energy consumption for heating in winter and warmer indoor temperature in summer. The space heating demand was 26.8 kWh/(m^2a), higher than the 15 kWh/(m^2a) Passive House standard requirement. The house performance was great in winter but approximately 8.5% of the time in a year (747 hours in total) of temperature exceeded 25 °C in the Office room during summer, which indicated the risk of house overheating. To prevent summer overheating problem for this Passive House, measures could be used are: turning off the gas boiler in summer months; lower the fabric standard under the required range; increase thermal mass, unfixed all openings and improve the vents positions for MVHR system to force air through the house. Moreover, adding cooling system and reduce the mechanical ventilation set-point temperature were recommended to these type of super-insulated Passive House. This has been validated by installing a small wall mounted split unit in the Office room. As appropriate cooling load was added to the Office room, the room temperature has been dropped down significantly and it reduced the risk of overheating in summer time. Based on the analysis in this study, it shows the advantages of Passive House in achieving high thermal comfort, low energy consumed and low carbon emissions. It also provides high quality indoor environment for living. The initial optimisation study indicated that 18.9% heating energy saving achieved by reducing the MVHR set-point temperature from 20 °C to 18 °C and adding thermal mass of the dwelling, while it met the requirements for comfortable indoor temperature during a whole year. 204 hours for house overheating (23.3%) could be decreased and the carbon dioxide emissions saving would reach 13.4% to make it a sustainable dwelling with better performance. A further specify optimisation of fabric design to reduce the risk of house overheating is recommended and will be conducted in the future.

Acknowledgement

The author would like to express acknowledgement of the financial supports by Sir Joseph Swan Centre for Energy Research, Newcastle University and China Scholarship Council for this study. Special appreciation and thanks are also delivered to the owners of the Passive House, Mr Roger Lindley and Mrs Hilary Lindley, for their kind co-operation and supports during the whole research period.

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