Flexible Terraced Passive House Design and Performance Evaluation using Building Simulation

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Abstract

The paper presents design development of a flexible passive housing prototype and its performance evaluation using building simulation. The aim is to plan a row/terraced house that can host a different number of families in the same home utilising a flexible design concept and that can at the same time reduce energy consumption and air pollution significantly with passive design and pay particular attention to materials. Building simulation has been carried out for thermal and energy performance evaluations with DesignBuilder (DB) and a comparison study with Passive House Planning Package (PHPP) to meet the Passivhaus standards using a case study from the UK. Furthermore, differences between PHPP and DB have been discussed to determine pros and cons of both software packages for the simulation of a passive house design.

1 Introduction

A new attention to environment and energy saving has become more and more essential for every kind of planning in the built environment. Air pollution, global warming, waste disposal, and ecological footprint are factors that have negative impact on our planet, and therefore the quality of life are increasingly under pressure year in and year out. As a result, Architecture and Engineering professions are trying to reduce the impact on the built environment and the associated carbon emissions by not only using renewable energy sources, but also considering innovative and environmentally responsive design strategies.

The paper presents design development of a flexible terraced passive house and its performance evaluation using building simulation approach. The aim is to plan a row of terraced houses that can host a different number of families in the same home utilising a flexible design concept, which can at the same time reduce energy consumption and carbon emissions considerably with passive design and pay particular attention to the choice of materials. The study examines the annual energy demand and comfort conditions in the design of a terraced house (also known as terrace or row house) in Bradford, UK. The site used lies at the heart of the city of Bradford, a metropolitan borough of West Yorkshire, in Northern England at a latitude of 53°48’22” North and longitude of 1°43’54” West. The terraced house design is considered as a Passive House (PH) and as a Flexible Home (FH) that can adjust the tenants’ different needs. Again, the purpose of this study was to achieve a sustainable building under certain aspects such as low energy consumption, low carbon, use of renewables and natural materials, with flexibility by design.

The terraced home designed to house 4 to 12 families with only little adjustments in the living spaces to accommodate the number of occupants. Main material is wood, used for the structure as cross laminated timber, and for the insulation as wood wool fibre. The approach was taken to look at the interior design of the houses, the construction type, architectural details and the selection of different materials, starting from an existing case

study in order to incorporate both aspects of flexible and passive housing concepts to achieve a new prototype house/housing. Differences between evaluation and simulation software packages; in this case, Passive House Planning Package (PHPP) and DesignBuilder (DB) have been discussed in order to understand pros and cons of each one, and to also compare in terms of which one is more complete and has the capacity to provide the designers all the instruments required for designing a flexible passive house.

2 Methodology

Early Design Stage

The case study chosen for the studies in this paper goes back to the 'Accent Home' concept, a terraced house design for social housing, developed and situated in the North East of England (Bradford/Leeds region), and designed by Goddard Wybor Architects in conjunction with Building Energy Analysis Unit - University of Sheffield (Altan 2006). This building design was completed in 2005 for Accent Group, one of the UK's largest social housing developers, to achieve low cost and low energy designs for the UK social housing sector.

The idea with this study was to design a new prototype of sustainable building situated in the same area of the Accent Home, starting from the early stages of architectural design together with a vision to develop future housing form with flexibility and adaptability to meet the needs of different tenants or the needs of a single family in the future.

Going back to the drawing board, all dimensions of each apartment have been considered. On an overall plan of 290 m^2, there are 4 apartments; each one included in a rectangular plan of 12 m (north-south direction) x 6 m (east-west direction). The inclination of 19° to east direction is to maximise the sunshine in the morning more than in the afternoon. Moreover, solar analyses have been conducted with thinking of the importance of sun and its directions from different periods in a typical year, and size and length of shading devices to stop the excessive solar gains during the summer period (see Figure 1).

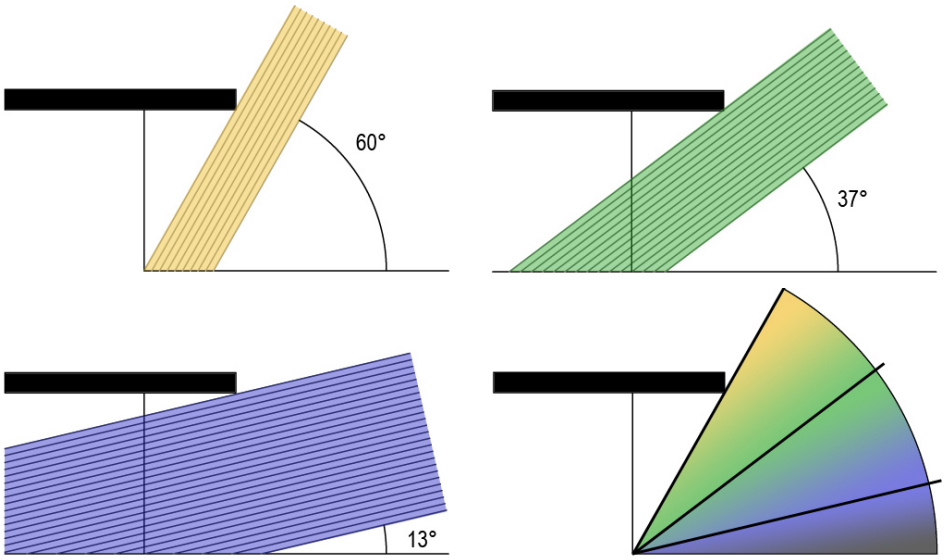


Figure 1: Solar ray inclination: summer, spring-autumn, winter, all year ray spectrum

After studies into the history of terraced houses in England (UK) and flexibility, the design started to shape up into a different kind of configuration that could arrive at the goal of

flexibility and at the same time of energy efficiency before arriving at the final layout (Muthesius 1982; Schneider & Till 2007).

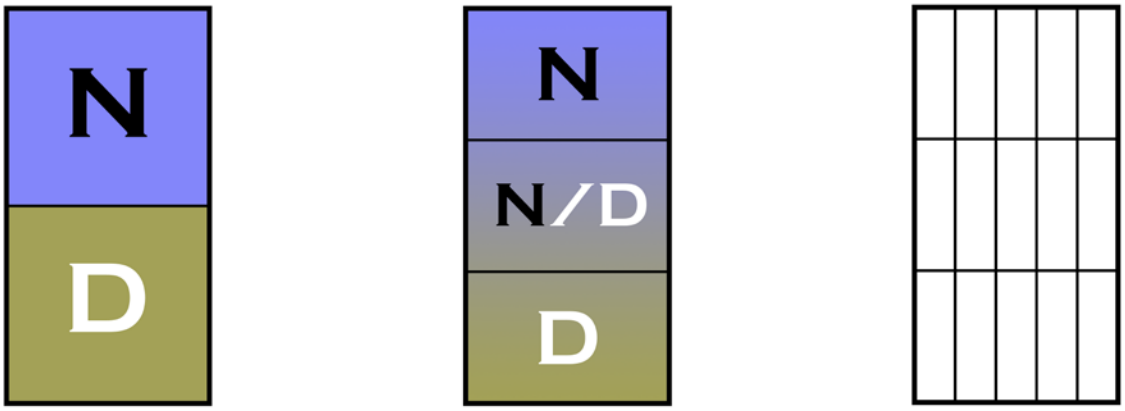


Figure 2: Layout and configuration (N: Night, D: Day)

As mentioned earlier, the main facade of the building is oriented 19° to east and the extended plan is in the shape of a rectangular (12 m x 6 m). Firstly, a decision has been given to divide the plan into two different square areas: Day (D) and Night (N) (see Figure 2a&b). The Day area is suitable for daily activities due to natural light and solar gains coming from the south direction. On the other hand, the Night area situated at the north side of the house, which is perfect for nightly activities that also do not require too much light (see Figure 2a).

The first division of the apartment into two different areas was too straight for future movement of the building interior space. Dividing the length into three different areas allowed defining a third space in between so that this could be used for both daily and nightly activities. This new space can be called “Flexible Space” or “Margin”, also named by a famous Dutch architect, N. John Habraken, who used to call this area during his studies ‘adaptability’ (see Figure 2b) (Habraken 1980).

The short side of the apartment needed a division that could take into account all the different aspects of the house elements such as stairs, doors, furniture, appliances, etc. The module of 120 cm is used to fit every element in a regular grid. The 1/2 (60 cm) is good for kitchen furniture and appliances, the 2/3 (80 cm) for doors and single bed, and the entire module (120 cm) for stairs and sliding doors (see Figure 2c).

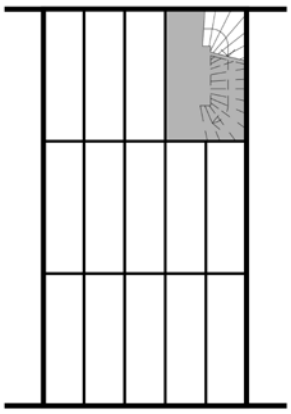


Figure 3: Positioning of toilette

The positioning of staircase and toilette is an important decision that will need to define all the following phases of a flexible design. These are in effect two inflexible elements that once placed they cannot be any more easily moved. For this reason, decision of situating the staircase in the north side of the building, instead of the toilette, needed an accurate analysis. The toilette in the back might have an external window that allows natural ventilation. On the other hand, the stairs in that position creates an independent nucleus and a new entry to the building, and to each independent level of the building. This was the more flexible solution (see Figure 3).

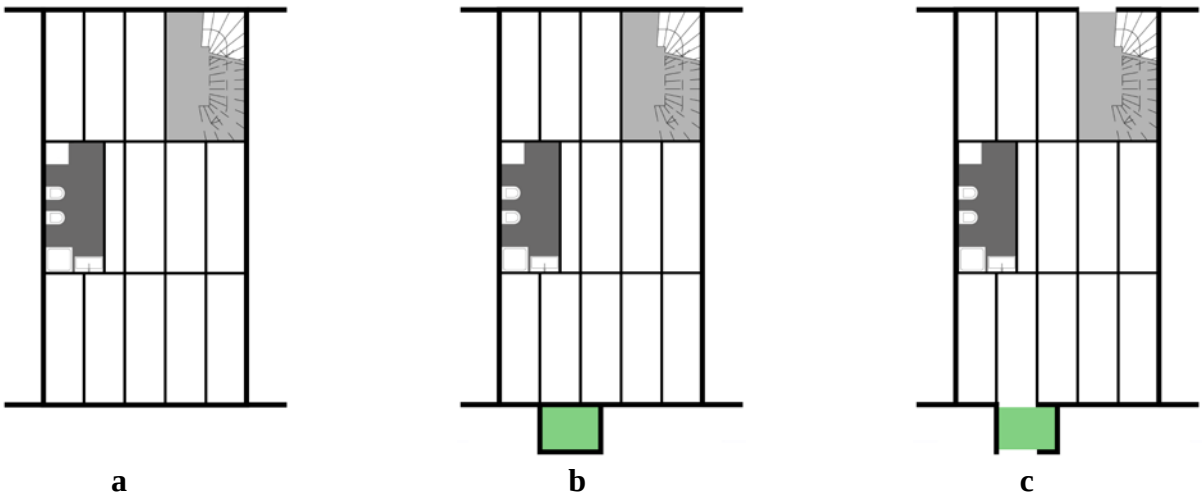


Figure 4: Positioning of staircase and toilette

Furthermore, the stairwell can be used for natural ventilation inside the building and can create a natural solar chimney (see Figure 4a). As a consequence, the bathroom found the right arrangements in the opposite side of the central area. In this particular situation, an inflexible space such as the bathroom, helped to create a distinct division of the apartment in three different areas, and at the same time, the possibility of considering all the remaning spaces as a unique zone (see Figure 4b).

The positioning of the main entry is another important problem to solve in a flexible design and moreover in a terraced home. Firstly, the main entry has a double function, i.e. it is

the way to enter in the apartment from the main street and also is a space that can be used as a temporary deposit, and a small greenhouse in the winter time. Moreover, that off-center position permits the creation of two spaces, for a big and a small window, a solution that allows a division of the interior space in the future. The distance from the partition wall permits the solar ray coming from east to reach the big window of the preceding apartment (see Figure 4c).

Thanks to the main entry and the staircase disposition, the apartment is provided with two independent entry doors. The first one in the south facade and connected directly with the main street, and the second one on the north side that can be used as a service door or an independent door to arrive at the apartments of the first and second floors. The internal space resulting from this division is a long and dynamic space of 48 m^2 that can meet the needs of different tenants (see Figure 5a).

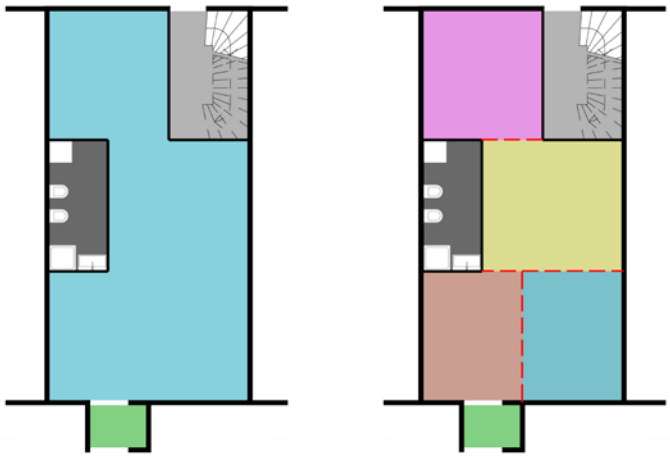


Figure 5: Space with possible divisions

The same space is shown here in its possible divisions (see Figure 5a&b). Different zones can be converted by tenants through sliding walls; i.e. sliding walls for daily changing or through more or less flexible kind of walls (see Figure 5b).

The longitudinal section (see Figure 6) helps to understand the way in which the house can grow. Starting from a configuration with one nucleus (first and second apartments starting from the left of Figure 6) in which one family occupy three stories, it is possible to transform the same apartment dividing it in more flats for example two or three, as we can see in the section in which every colour represent a family unit (see Figure 6).

Figure 6: Section with growing nucleus

Passive House Planning

Energy efficiency in housing is an important factor that has to be considered in order to achieve the aim of sustainable housing. Thus in the recent years, the applications of renewable energy in buildings rapidly increased, sometimes also supported by national subsidies. Nevertheless high costs of the energy systems and their complex integration coupled with expensive refurbishment attempts discouraged many people to invest in this sector. On the one hand, it is important to design flexible houses in order to move forward with the new technologies, then again it is equally necessary to reduce the use of energy systems and to maximise the advantages of sun, location and materials. This is a passive method that allows comfort with few energy systems. Passive design is not an attachment or supplement to architectural design, but it is rather a design process that is integrated within architectural design (Brophy & Lewis 2011; Keeler & Burke 2009).

Sustainable building through the Passivhaus standard can be achieved at any location in the world. Passive houses are very well insulated and draught proofed buildings whose annual space heat demand is so low that the conventional heating system can be omitted. The small amount of heat still required can be delivered to the individual rooms by heating the air supplied by the ventilation system. This will work, when the space heating energy demand is up to 15 kWh/m^2 per annum.

Super insulation, isolated thermal bridges and airtightness are three important principles of the Passivhaus standard that have to be considered during every design step. In this flexible and passive housing study, there are low u-value windows; (0.77 W/m^2K) external walls with u-value of 0.11 W/m^2K, roof with u-value of 0.11 W/m^2K and ground floor with u-value of 0.12 W/m^2K that reduce noticeably the heat transfer.

In the case study home, a combination of the planning principles from the “plotter pen” and the cross laminated timber structure to avoid thermal bridges through the building boundary have been considered (see Figure 7).

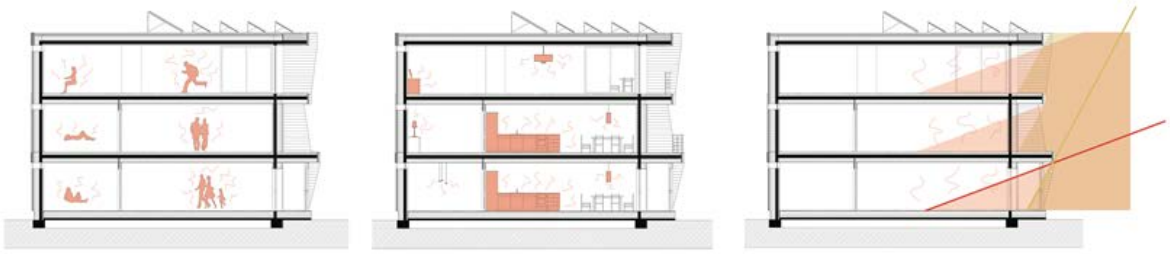
Figure 7: Planning principle from the "plotter pen" in East-West section

PHPP could be easily used as a design tool. It provides the architect and the engineer with instruments that are necessary for the design of a well-performing passive house (PHI 2010). Thus, the definition of PHPP needs some more clarification.

In the PHPP calculations, not only the heat losses but also the heat gains and the thermal inertia can be determined. Through the PHPP worksheets, it is possible to define every heat gain coming from sun, appliances, domestic hot water (DHW) distribution and people as the users of the building. This last internal gain is not a constant value in a flexible housing and has to be considered in a different kind of occupancy.

The first thing noticed working with the PHPP worksheet is the straight forward organisation of Microsoft Excel based spreadsheet. It may be easy to insert all the different values for a building that is regular in plan or in elevation, but this cannot be the same way for a building that has an irregular shape or such as in this case, a prototype that needs little adjustments in architectural design in order to find the best shape for a good inside comfort.

Another aspect that did not help in the design of a flexible home is the calculation of PHPP on a treated floor area. One of the aims of this project was to understand the difference in terms of inside comfort between the different kinds of configurations that a flexible design would allow but with PHPP, only the comfort for the overall treated area of the whole building can be calculated. This aspect, for example, has importance for studying the overheating hours. The PHPP verification worksheet gives the frequency of overheating (see Figure 9, central column, 7th row) that is the hour percentage per year in which the temperature exceeds the 25°C. Despite this result gives an idea with a good approximation of the average temperature, it does not give any information about the temperature distribution because there is no distinction between spaces on north, south or between utilisation of every room.



a **b** **c**

Figure 8: Internal gain model (a, b, c)

Passive House Verification

Building:	Flex PH Housing				
Location and Climate:		Leed Monthly Mean			
Street:	Barnby Pl				
Postcode/City:	BD2 4RB				
Country:	England				
Building Type:	Terraced House				
Year of Construction:	2013				
Number of Dwelling Units:	1		Interior Temperature:	20,0	°C
Enclosed Volume V_e:	714,0	m³	Internal Heat Gains:	2,1	W/m²
Number of Occupants:	4,2				

Specific Demands with Reference to the Treated Floor Area

Treated Floor Area: 147,5 m²

	Applied:	Annual Method	PH Certificate:	Fulfilled?
Specific Space Heat Demand:	14	kWh/(m²a)	15 kWh/(m²a)	Yes
Pressurization Test Result:	0,2	h⁻¹	0,6 h⁻¹	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	110	kWh/(m²a)	120 kWh/(m²a)	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	68	kWh/(m²a)		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:	34	kWh/(m²a)		
Heating Load:	9	W/m²		
Frequency of Overheating:	0	%	over 25 °C	
Specific Useful Cooling Energy Demand:		kWh/(m²a)	15 kWh/(m²a)	
Cooling Load:	2	W/m²		

Figure 9: PHPP verification worksheet

Building Simulation

In the study, DesignBuilder (DB) software has been used for conducting building simulation (DB, 2013). The DB software is an advanced graphical user interface that has been specially developed to run EnergyPlus simulations. EnergyPlus is the US Departments of Energy's 3rd generation dynamic building energy simulation engine for modelling building, heating, cooling, lighting, ventilating and other energy flows. EnergyPlus is integrated within DB's environment which also allows the user to carry out complete simulations without leaving the interface.

In the proposed flexible PH housing design, the amount of heat required for the internal comfort is delivered to the individual rooms using a mechanical ventilation system. The efficiency of a passive house depends largely on the HVAC choice and on right management of natural and mechanical ventilation. During the simulations, the inside comfort levels widely changed because of the HVAC settings. The following parameters have been considered and used as input data for HVAC, DHW, activity and construction:

- **Compact HVAC:** HVAC systems is defined parametrically and modelled within EnergyPlus using Compact HVAC descriptions with a cav (constant air volume).
- **Natural ventilation:** Natural Ventilation and infiltration air flow rates is calculated based on opening and crack, sizes, buoyancy, wind pressure and the activity schedules.
- **Mechanical ventilation:** The mechanical ventilation utilised in the flexible PH housing design has an ac/h (air change per hour) of 0.4 as required by the PassivHaus standard with an outside air definition method set for zone.
- **Fans:** See table 1.

Table 1: Fans

Night cycle control	Cycle on control zone
Fan placement	Blow through
Part-load power coefficients	Variable speed motor
Fan type	Intake
Pressure rise (pa)	1000.0
Total efficiency (%)	85.0
Fan motor in air (%)	100.0
Outside air definition method	Minimum fresh air (Per area)
Outside air mixing	Recirculation
Outside air control minimum flow type	Proportional

- **Heat recovery:** See table 2.

Table 2: Heat recovery

Heat recovery type	Sensible
Sensible Heat Recovery Effectiveness	0.800
Heating setpoint temperature	15.00

- **DHW:** See table 3.

Table 3: Domestic Hot Water

Type	Dedicated DHW boiler
DHW CoP	0.85
Fuel	Biomass

- **Water temperatures:** See table 4.

Table 4: Water temperatures

Delivery temperature (°C)	65.00
Mains supply temperature (°C)	10.00

- **Activity:** Compact schedule has been used for occupancy, metabolic activity, openings of windows and doors, lighting. The schedules are based on data published in the UK's National Calculation Methodology (NCM). The NCM for the EU's Energy Performance of Buildings Directive (EPBD) is defined by the Department for Communities and Local Government (DCLG) (BRE 2013). The procedure for demonstrating compliance with the Building Regulations for buildings other than dwellings is by calculating the annual energy use for a proposed building and comparing it with the energy use of a comparable 'notional' building. Both calculations make use of standard sets of data for different activity areas and call on common databases of construction and service elements. A similar process is used to produce an 'asset rating' in accordance with the EPBD. The NCM therefore comprises the underlying method plus the standard data sets.
- **Construction:** DesignBuilder uses construction components to model the conduction of heat through walls, roofs, ground and other opaque parts of the building envelope. Constructions can be selected on the Constructions model data tab to define the thermophysical and visual properties of the various internal and external surface elements in the building. Using the construction data the physical properties of each elements have been defined of the building (e.g. external wall, party wall, interior wall, roof, floors and ground floor). In DB software, there is a complete library of material that can be used to define every layer of the building elements. Every material is defined by thermodynamic properties (DB 2013). The same is for windows and doors that can be selected from a well-provided library. Since this project is a row of 4 identical blocks, with the exception of internal changes depending of utilisation and flexibility design.

3 Results

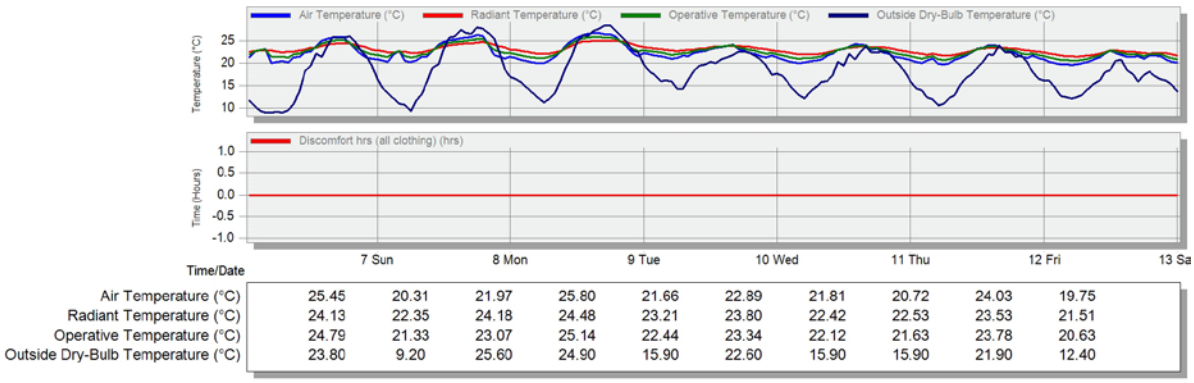
In the study, a specific attention has been paid to the comfort of each space of the house design by not only observing changes during both the day and the year, but also trying to get more information about the changes of temperature in rooms that PHPP did not consider/recommend. Thanks to the activity schedule tab, it was possible to set every house zone for a specific use so to make the model more close to reality. Unlike PHPP, in DB every room can be set to have a specific use and the model takes into account the position, in relation to the sun, of every space inside the building, and the effect of windows and appliances for inside comfort. Within DB, different kind of configuration and disposition of walls, doors and rooms have been tested to determine whether a new way of living in the house could change the inside comfort or could achieve the Passivhaus standard. The following are some the examples of analyses carried out.

Typical summer week – ground floor living room simulation

With the simulation for a typical summer week, DB allowed to study the internal comfort during one of the warmest weeks of the year. One of the problems that were observed simulating a passive house is a variable percentage of overheating during the summer time. Responsibility for such an internal temperature increase has to be related to the super

insulation, the airtightness and the large glazed south facade of the house. Nevertheless with some easy expedients like shading using trees or other shading devices for windows, it is possible to avoid overheating during the summer.

In this example, the hourly internal comfort and temperature distribution of the living room in the ground floor from 29 June to 5 July are shown (see Figures 10 & 11).



Air Temperature (°C)	25.45	20.31	21.97	25.80	21.66	22.89	21.81	20.72	24.03	19.75
Radiant Temperature (°C)	24.13	22.35	24.18	24.48	23.21	23.80	22.42	22.53	23.53	21.51
Operative Temperature (°C)	24.79	21.33	23.07	25.14	22.44	23.34	22.12	21.63	23.78	20.63
Outside Dry-Bulb Temperature (°C)	23.80	9.20	25.60	24.90	15.90	22.60	15.90	15.90	21.90	12.40

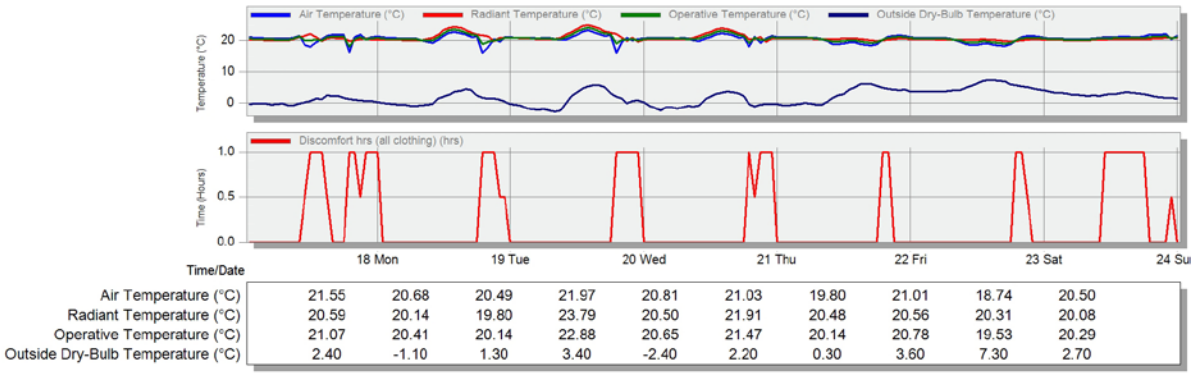
Figure 10: Typical summer week – temperature and discomfort hours (all clothing)

Hours at or below	10.0	58.5	109.5	141.0	153.0	168.0
Hours at	10.0	48.5	51.0	31.5	12.0	15.0
Hours at or above	168.0	158.0	109.5	58.5	27.0	15.0

Figure 11: Typical summer week – temperature distribution

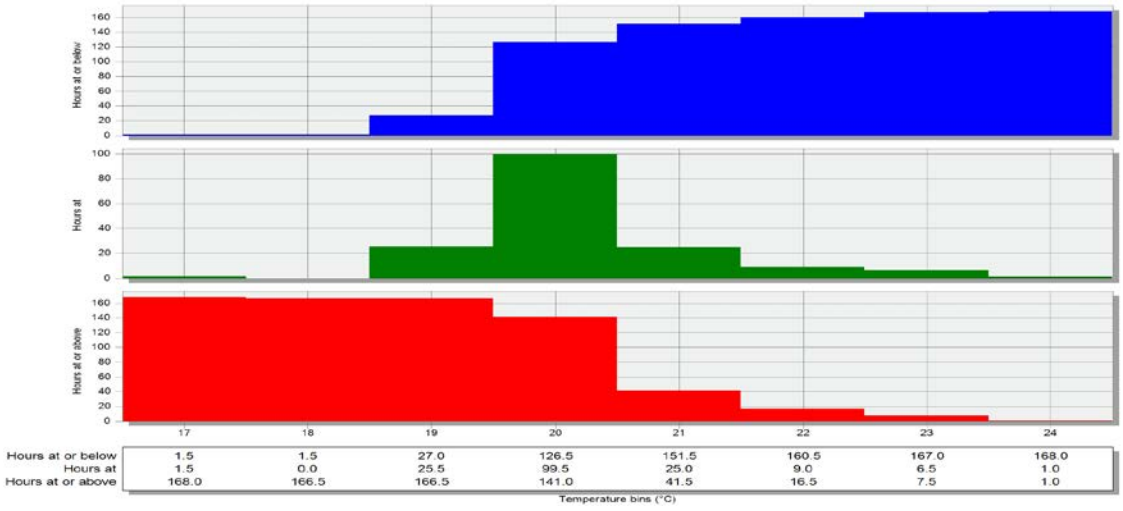
Typical winter week – ground floor living room simulation

As mentioned earlier, the flexible PH housing design does not use any heating system but a system that contains mechanical circulation with heat recovery. From the internal comfort and temperature distribution results, it is possible to verify how the average temperature profile stays constantly around 20°C due to heat recovery, insulation and solar gain (see Figures 12 & 13).



Air Temperature (°C)	21.55	20.68	20.49	21.97	20.81	21.03	19.80	21.01	18.74	20.50
Radiant Temperature (°C)	20.59	20.14	19.80	23.79	20.50	21.91	20.48	20.56	20.31	20.08
Operative Temperature (°C)	21.07	20.41	20.14	22.88	20.65	21.47	20.14	20.78	19.53	20.29
Outside Dry-Bulb Temperature (°C)	2.40	-1.10	1.30	3.40	-2.40	2.20	0.30	3.60	7.30	2.70

Figure 12: Typical winter week – temperature and discomfort hours (all clothing)



Hours at or below	1.5	1.5	27.0	126.5	151.5	160.5	167.0	168.0
Hours at	1.5	0.0	25.5	99.5	25.0	9.0	6.5	1.0
Hours at or above	168.0	166.5	166.5	141.0	41.5	16.5	7.5	1.0

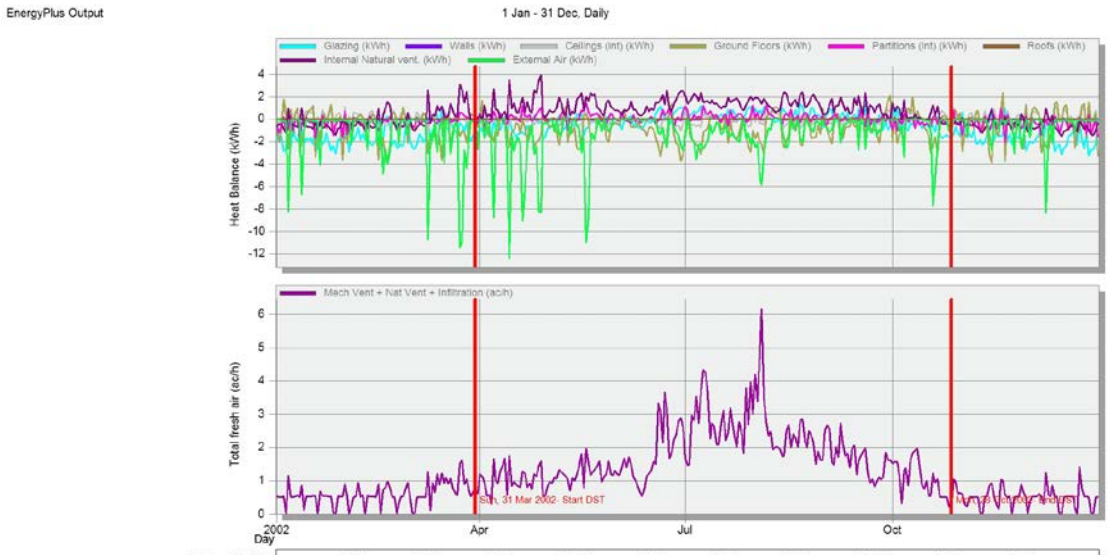
Figure 13: Typical winter week – temperature distribution

4 Discussion

The aim of this study was not only to manage the internal gains from sun, people and appliances, but also to maintain comfort conditions with support from the combination of mechanical and natural ventilation. Accordingly with the findings, it is evident how ventilation plays an important role to maintain the indoor comfort. During the summer period, the air change rate per hour touches peak of 6 with an average value of 3. In the winter time, the ventilation rate appears constant and on average value of 0.4, value that is set to be the minimum as a requirement inside a home for performance of healthy conditions.

Building simulation calculated the natural ventilation rates referring to schedules in which parameters like timing, opening, occupancy, and so on are set. In real life situations, the occupant/user should pay attention to the ventilation aspect in order to have a good behaviour to save energy. For this reason, all results have to be related to the people variable, their behaviour and then attention for environment and energy.

In Figure 14, heat balance and total fresh air for the entire year are shown.



Glazing (kWh)	-2.91	-2.05	-0.38	-0.38	-0.04	0.38	0.82	-0.47	-1.52	-1.73
Walls (kWh)	-0.03	-0.02	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	-0.02
Ceilings (int) (kWh)	0.30	0.56	-0.13	-0.32	-0.31	-0.34	-0.25	-0.37	0.50	0.39
Ground Floors (kWh)	-0.52	0.59	-1.47	-1.28	-1.48	-1.02	-1.04	-0.71	0.28	-0.35
Partitions (int) (kWh)	-0.52	-0.09	-0.22	-0.11	-0.07	-0.26	0.09	-0.58	-0.26	-0.29
Roofs (kWh)	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
Internal Natural vent. (kWh)	-1.03	-0.58	0.84	0.74	1.13	0.95	1.70	1.30	-0.41	-0.54
External Air (kWh)	-0.12	-0.07	-0.08	-0.20	-0.02	-1.32	-0.67	-1.14	-0.03	-0.03
Mech Vent + Nat Vent + Infiltration (ac/h)	0.01	0.52	0.92	1.10	1.15	2.73	2.29	0.92	0.51	0.52

Figure 14: Heat balance and total fresh air (ac/h)

5 Conclusions

This paper attempts to describe an approach taken for different design phases to propose a new sustainable building, from the early stages of design to the building simulation component for performance evaluation. Collaboration between architecture and engineering (i.e. building science) helped to find comfort solutions combining both structural and architectural features with energy systems where building simulation played an important role.

PHPP has been very useful to find specific energy and heat demand, and to verify whether the building achieves the Passivhaus standard. On the other hand, DB can simulate indoor comfort conditions in detail which makes it easier for the designer to understand the PH planning stages and how to manage the results obtained by changing parameters and finding new solutions to fulfil all the requirements set to meet such a standard. Despite the two software packages were used for various analyses in the study, PHPP and DB have many features and provided similar results when compared with each other however, no one alone could provide a complete analysis of the building.

Moreover, a flexible house design needs to be tested in different configuration to understand the response of a passive house in different kind of scenario. DB allowed for defining every space for a specific use and with activity schedules by simulating a real tenant's behaviour. Although PHPP is a useful tool to have for good analyses on a building design, including a lot of energy and comfort calculations and outputs, it is still lacking more free thinking and testing of the living conditions home environments. As mentioned above, only studying an average comfort can be tested but without any understanding the conduct of spaces. Nevertheless, PHPP can provide a quick response to understand whether the building can reach the goal of passive house design. Furthermore, only with continued comparison of the two software packages' results during each design step it was possible to have an adequate awareness of the building.

6 Acknowledgements

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