Department of Mechanical and Aerospace Engineering

Assessing Design Options for a Self-Build Low Energy House with Building Simulation

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Signed: María del Carmen Bocanegra-Yáñez Date: 6th September 2014

“The cleanest energy is the one that is not consumed”

Abstract

Most self-build low energy houses are one-off, bespoke designs, which require a specific analysis to predict their future energy performance, highly dependent on their design and location. Building simulation can provide an indication of this performance and furthermore, it can be used to assess different design options. This project assesses design options for a self-build low energy house in Cornwall to improve its energy efficiency and cost effectiveness using ESP-r simulation tool.

A general methodology is developed to identify the tasks to carry out. The application of this methodology to the case study leads to the construction of a model introducing gathered data and assumptions to the ESP-r simulation tool. After model's verification, several design options regarding the thermal envelope, the heating/cooling system and the ventilation system of the house, are identified. Then, a comparison between the initial model of the house and the different design options is done based on energy efficiency (energy demand and efficiency of the energy system), environmental impact (CO_2 emissions) and costs (running cost, capital cost and payback period).

The general conclusion arising from the result analysis is that energy efficiency measures in buildings (additional insulation in constructions, better glazing, more efficient heating systems or the use of renewable energy sources) help to reduce the energy consumption, CO_2 emissions and running cots. However, they need of incentives in order to be cost effective. Finally, some recommendations for further work to improve the analysis of design options using building simulation are provided.

Keywords:

Low Energy Buildings, Integrated Building Performance Assessment, Energy Simulation tools.

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Nomenclature

A	Area (m^2)
ach	Air changes per hour
ASHP	Air Source Heat Pump
COP	Coefficient of Performance
C_p	Specific heat constant pressure (J/kgK)
IAQ	Indoor Air Quality
k	Thermal conductivity (W/mK)
$\dot{m}$	Mass flow rate (kg/s)
MVHR	Mechanical ventilation with heat recovery
Q	Heat transfer rate (W)
R	Thermal resistance (m^2K/W)
T	Temperature (K or °C)
U-value	Overall heat transfer coefficient or thermal transmittance (W/m^2K)
$\dot{V}$	Volume flow rate (m^3/s)
ρ	Density (kg/m^3)

Chapter 1. Introduction

Many new low-carbon buildings are examples of self-build, where the owner is closely involved in the building design. However, for such projects, basic thermal modelling using Standard Assessment Procedure (SAP) to demonstrate compliance with building regulations gives almost no indication of likely performance once built. Most self-build houses are one-off, bespoke designs and in any case the specific location and orientation will affect thermal performance. This means that the vast majority will need analysis specific to the design and location. Building simulation can provide an indication of actual performance and further, can be used to assess different design options. For this reason, this project will analyse different design options for a self-built low energy house using a building simulation tool.

Chapter 2 will set the aim of the project and the specific objectives defined to achieve this aim.

Chapter 3 includes a review of building energy consumption, main building legislation, regulations and standards, barriers to innovation in construction and state of the art of modelling and simulation tools in building design.

Chapter 4 will explain the methodology defined in this project and the tasks that have been identified.

Chapter 5 describes the main characteristics of the model built using ESP-r simulation tool determined by the property documentation (Ford, 2014) and assumptions, finishing with the verification of the model.

Chapter 6 describes the different design options that will be compared with the current model of the house in order to find an optimal solution.

In Chapter 7 a comparison between the initial model of the house and the different design options previously described will be carried out based on energy efficiency (energy demand and efficiency of the energy system), environmental impact (CO_2 emissions) and costs (running cost, capital cost and payback period).

Finally, Chapter 8 will highlight the conclusions that arise from the analysis of results previously developed for the different design options regarding the thermal envelope, the heating/cooling system and the ventilation system. A result summary with the best and worst option in every case according to the energy consumption, CO_2 emissions, capital cost and payback period is shown. Finally, some recommendations for further work to be done are provided.

Chapter 2. Aim and Objectives

2.1. Aim

The aim of this project is to assess design options for a self-build low energy house in Cornwall to improve its energy efficiency and cost effectiveness using ESP-r simulation tool.

2.2. Objectives

The project objectives are as follows:

- Define a general methodology to assess building design options using a simulation tool.
- Build the model for a self-build low energy house in Cornwall using ESP-r simulation tool.
- Identify design options to be considered in terms of:
    - Thermal envelope
    - Heating/cooling system
    - Ventilation system
- Obtain simulation results from the different options identified using the model previously built.
- Analyse the results to make final recommendations for the best options in terms of cost effectiveness, energy consumption and CO_2 emissions.
- Consider additional design options to solve a particular situation of the self-build low energy house analysed.

Chapter 3. Literature Review

This chapter includes a review of building energy consumption, main building regulations and standards, barriers to innovation in construction and state of the art of modelling and simulation tools in building design.

3.1. Energy Consumption in Buildings

According to the IEA (International Energy Agency, 2014), buildings represent 32% of total final energy consumption and an equally important source of carbon dioxide (CO_2) emissions. In terms of primary energy consumption, buildings represent around 40% in most IEA countries and thus, a more sustainable future begins with low energy buildings which must combine comfort and function using passive systems and new changing technologies.

The benefits of highly energy efficient houses include: fuel bill reduction, more comfortable inside environments, impact reduction of the built environment and better use of available energy sources (Zero Carbon Hub, 2014).

In the UK, domestic use was 29% of the final energy consumption in 2013, being the transport sector the only one that exceeded this percentage with 36% of the final energy consumption as shown in Figure 1 (Department of Energy & Climate Change, 2014).

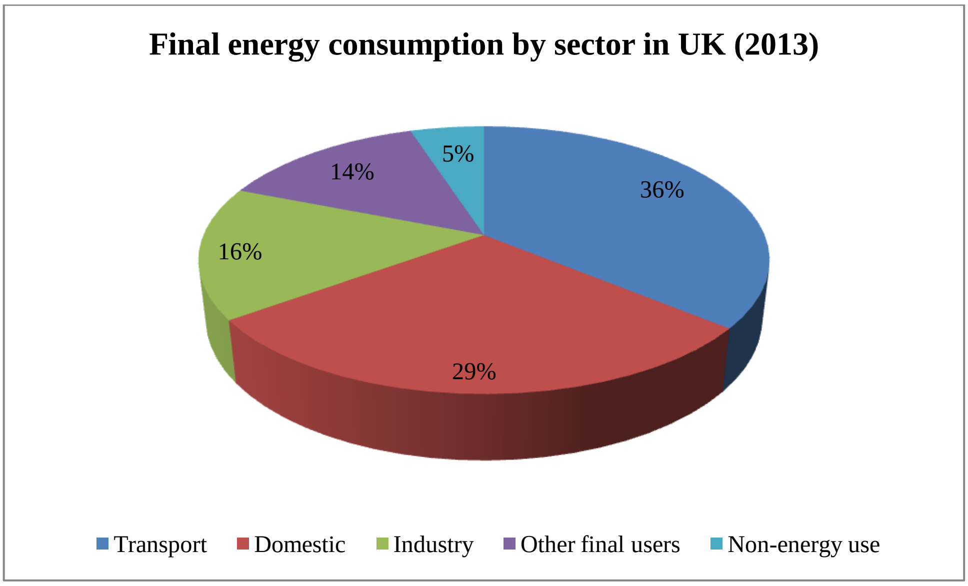

Figure 1. Final energy consumption by sector in UK 2013 (Department of Energy & Climate Change, 2014)

Most of the domestic energy consumption is used for space heating, being the 62% of the total energy consumption in 2011 (see Figure 2) according to the Housing Energy Fact File 2012: energy use in homes (Department of Energy & Climate Change, 2013).

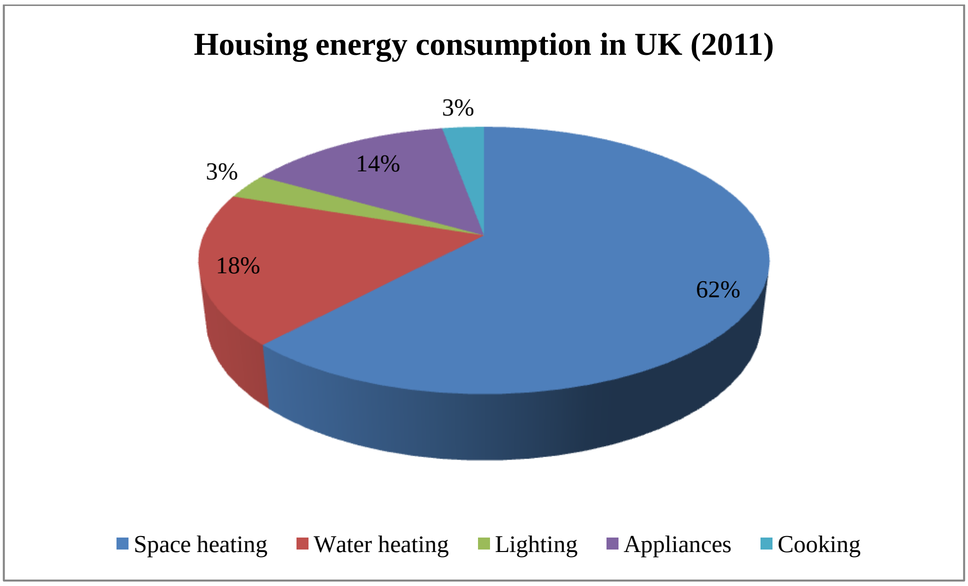

Figure 2. Housing energy consumption in UK 2011 (Department of Energy & Climate Change, 2013)

Thus, reduction of the heating demand when designing new buildings becomes crucial in order to improve the energy efficiency in future houses.

3.2. Legislation, Regulations and Standards

Policies to reduce building energy consumption and carbon emissions have been developed worldwide during the last decades. In this section a brief overview of the main legislation, regulations and standards regarding the use of energy in buildings is provided.

3.2.1. European Directive

The **European Directive 2002/91/EC** (The European Parliament and the Council of the European Union, 2003) is the policy that starts the path to energy efficiency in buildings. It is the first time that European Union members are required to establish a minimum level for energy efficiency in buildings and to define a methodology to measure the energy efficiency.

The objective of this directive is to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost effectiveness.

In particular for new buildings, the directive requires members to ensure that new buildings meet certain requirements, minimum energy performance standards. For existing buildings, the regulations require the assurance that, when performing major upgrades in buildings with a surface over 1000 m^2, buildings have to improve their energy efficiency to meet minimum requirements.

Another important change introduced by this directive is the Energy Certifications that a building owner has to make available to the possible buyer or tenant when buildings are built, sold or rented. The directive also establishes requirements for regular inspection of boilers and air conditioning systems in buildings with more than 15 years.

Directive 2010/31/EU (The European Parliament and the Council of the European Union, 2010) completes the previous directive establishing the European targets for reducing energy consumption by 20% by 2020 through improved energy efficiency and integration of renewable energy in buildings.

The directive establishes new requirements in relation to the methodology for calculating the energy performance of buildings and aims to increase the number of Nearly Zero-Energy Buildings (NZEB) to approach the level of passive houses by 2015.

Each Member State is responsible to apply its own measures to ensure that building requirements set by the European Directive are properly met. Country fact sheets regarding the status of implementation of the Energy Performance Building Directive (EPBD) can be found in the European portal for energy efficiency in buildings, “BUILD UP Web portal” - http://www.buildup.eu/.

Implementation of the Energy Performance Building Directive (EPBD) in the UK (Delorme, Bramhall, Samuel, McCrystal, & Hughes, 2013)

In the UK, the responsible administration is different depending on the jurisdiction (England, Wales, Scotland or Northern Ireland). These administrations are:

- **England and Wales:** Department for Communities and Local Government
- **Northern Ireland:** Department of Finance and Personnel
- **Scotland:** Scottish Building Standards Division

In all four jurisdictions, transposition of the EPBD is achieved by Building Regulations. Procedures for a National Calculation Methodology (NCM) have been defined depending on building nature. For non-residential buildings, the NCM is the Simplified Building Energy Model (SBEM), and for dwellings, the NCM is the Standard Assessment Procedure (SAP).

Energy Performance Certificates for dwellings

The use of SAP, through official software tools, leads to the Energy Performance Certificates (EPCs) for dwellings. These certificates vary from one jurisdiction to another but are very similar in essence. EPCs are used for buildings under construction, sale or rent, and they are valid for 10 years. They provide an *Energy Efficiency Rating*, which is a measure of the overall efficiency of a building. The higher the rating the more energy efficient the building is and the lower the fuel bills are likely to be.

In Scotland, EPCs are divided in two different ratings (see Figure 3), the *Energy Efficiency Rating* previously mentioned, and the *Environmental Impact (CO_2) Rating* that measures a building's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

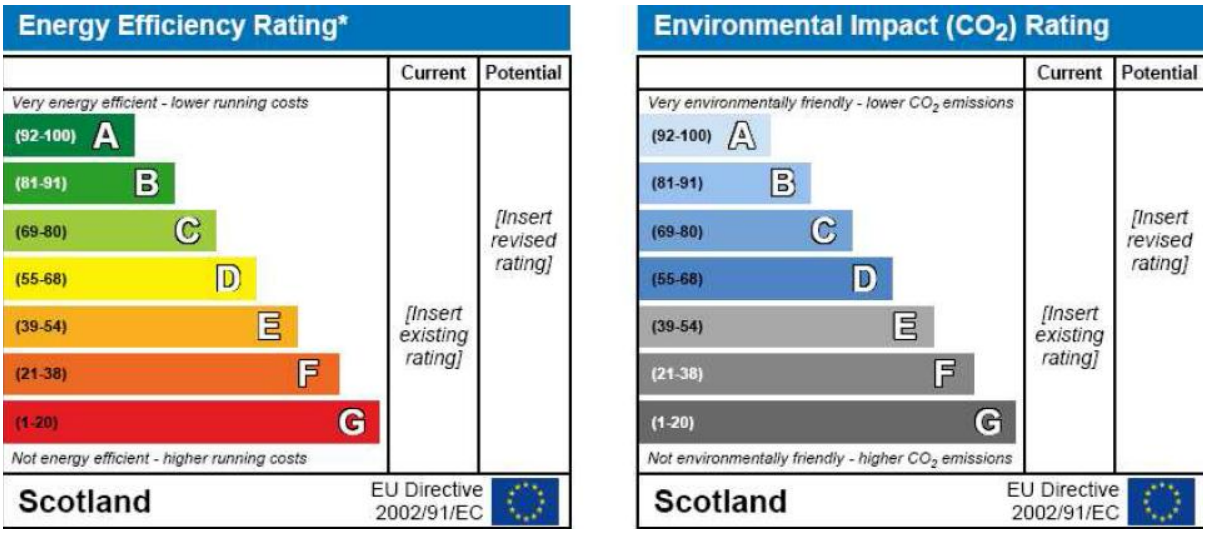

Figure 3. UK EPC ratings

3.2.2. Passive House Standard

Many energy performance standards have arise to promote energy consumption reduction in buildings through different measures. Passivhaus or Passive House Standard is probably the most worldwide known low energy building standard since its appearance in Germany in the early 1990s (Building Research Establishment, 2011). The main characteristics of the Passive House concept are listed in Table 1.

Table 1. Passive House Standard Characteristics (Building Research Establishment, 2011)

Main characteristics	
Insulation	U < 0.15 W/m^2K
Infiltration	Air Changes Per Hour ≤ 0.6 @ n50
Thermal bridges	Psi < 0.01 W/mK
Glazing	U < 0.8 W/m^2K and g > 0.5
High efficiency ventilation	• Heat recovery • Efficient fans • No noise
High efficient lighting system	
Renewable Energy	Thermal solar, PV, etc.
Solar control	Shading
Energy performance targets	
Specific Heating Demand	≤ 15 kWh/m^2. yr
Specific Cooling Demand	≤ 15 kWh/m^2. yr
Specific Heating Load	≤ 10 W/m^2
Specific Primary Energy Demand	≤ 120 kWh/m^2. yr

From the characteristics in Table 1, it can be seen that Passive House standard is based in reducing the energy demand needed for heating and cooling by the use of passive measures as very good insulation, air tightness and control of solar gains.

Apart from its obvious benefits reducing energy consumption and environment impact of buildings, the Passive House Standard can lead to health risks due to noise from installations, poor Indoor Air Quality (IAQ) or overheating according to (Hasselaar, 2008).

3.2.3. Zero Carbon Standard for Homes

A step forward from the PassivHaus Standard is the UK's proposed Zero Carbon Standard for Homes. The UK Government is committed to a challenging reduction of the CO_2 emissions target of 34% by 2020 and 80% by 2050 according to the national plan *"Increasing the number of Nearly Zero-Energy Buildings"*, under the Climate Change Act 2008. The target for residential buildings is that all new houses from 2016 need to meet the *Zero Carbon Standard* (Delorme, Bramhall, Samuel, McCrystal, & Hughes, 2013).

According to (Zero Carbon Hub, 2014), there are three main requirements that need to be met for a house to be zero carbon (see Figure 4):

- The fabric performance must meet the requirements of the *Fabric Energy Efficiency Standard (FEES).*
- Remaining CO_2 emissions after considering heating, cooling, lighting and ventilation, must be less than or equal to the *Carbon Compliance* limit established for Zero Carbon Homes.
- Remaining CO_2 emissions, from regulated energy sources (heating/cooling, lighting and hot water) must be zero.

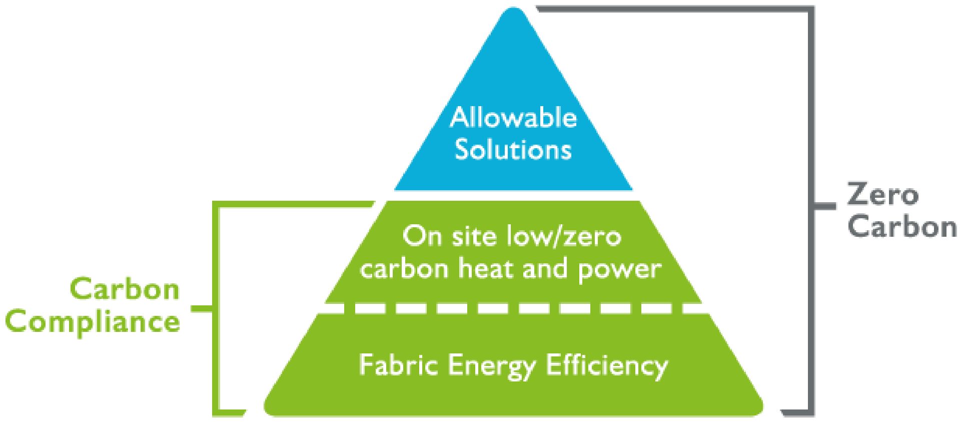

Figure 4. Proposed Zero Carbon home definition (Zero Carbon Hub, 2014)

3.3. Barriers for construction innovation

Despite the importance of the domestic energy consumption and the legislative efforts to reduce it, the way buildings are constructed evolves slowly compared to other sectors. Several studies have been carried out to find the main barriers to innovation in the construction sector.

One of the key barriers is that construction innovation diffusion is limited. According to (Mlecnik, 2013), knowledge is hardly spread outside specific research centres and demonstration projects. Other authors, as (K.J.Kulatunga, 2006), for example, consider "*diffusion of innovation, diffusion of knowledge regarding innovation, diffusion of innovation benefits within construction industry, organisational structures and cultures that promote innovation, management and coordination problems in innovation and measures to assess innovation*" as areas that need further research.

Regarding this lack of diffusion in the UK, the Association for Environment Conscious Building (AECB) has developed a *Low Energy Building Database* as an education and dissemination tool to help inform the planning and development of low energy new build and refurbishment (The Association for Environment Conscious Building, 2011). This database can be accessed through:
http://www.lowenergybuildings.org.uk/

Another barrier to construction innovation is fragmentation, as projects are usually developed by a group of independent companies, each one working in a different part of the project (Mlecnik, 2013) and (J., 1998) in (Benmansour & Hogg, 2002). To solve this, flow of technical information should be improved by the use of intermediary agents between different parts of the construction chain.

3.4. Modelling and Simulation Tools in Building Design

As reduction of building energy consumption gets more importance, new ways to construct buildings appear, but since innovation in construction is not widely spread, many new low energy buildings are examples of self-build, where the owner is closely involved in the building design and most of these designs are one-off, bespoke designs. This means that the vast majority will need analysis specific to the design and location in order to predict the building performance. Buildings are very complex with a huge number of characteristics that affect its final performance once built. In this context, building simulation can provide an indication of actual performance and further, can be used to assess different design options before the building is constructed.

According to (Brahme, O'Neill, Sisson, & Otto, 2009) and (Pollock, Roderick, McEwan, & Wheatley, 2006), simulation tools are usually used at a detailed design stage when most of the decision regarding the building envelope and systems are already taken. To get the most from building simulation, it needs to be carried out at an early stage of the project, during the concept stage, so significant changes to the initial design can be implemented at a low cost. This is similar to what happens with product design (see Figure 5), where changes in late stages of the product design lead to huge additional costs and delays, and therefore, they need to be avoided.

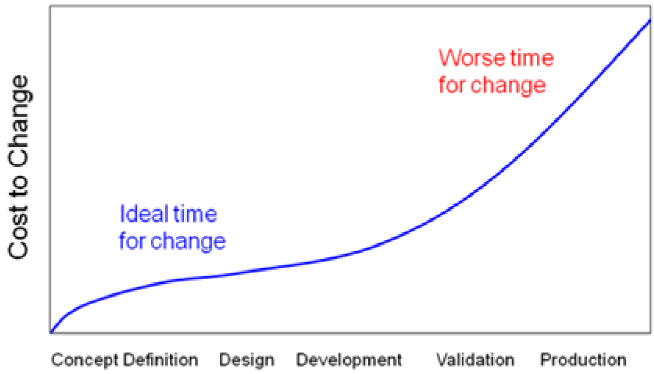

Figure 5. Cost to change a product design (Hartley) in (The MITRE Corporation, 2014)

There are many simulation tools that can be used to predict energy performance in buildings. They differ in complexity, accuracy, technical options that can be modelled, etc. Therefore, selection of the simulation tool will depend upon the specific objectives to be met. The U.S. Department of Energy has sponsored a directory with information on 417 building software tools for evaluating energy efficiency, renewable energy, and sustainability in buildings (U.S. Department of Energy, 2011). This directory can be accessed through the Energy Efficiency & Renewable Energy (EERE) web site:
http://apps1.eere.energy.gov/buildings/tools_directory/

The simulation tool used in this thesis is ESP-r, an integrated energy modelling tool developed by the University of Strathclyde in the 1970s (Energy Systems Research Unit).

Energy modelling and simulation tools are in constant evolution to meet the needs of practitioners, engineers and architects. Some of the current challenges of building simulation software can be found in the latest newsletter of the IBPSA (International Building Performance Simulation Assotiation, 2014) and are as follows:

- Definition and Simulation of Occupant Behavior in Buildings
- Couple different simulation programs for co-simulation
- Bridging the Energy Performance Gap

These and more challenges need to be met for simulation software to be robust and improve the accuracy and credibility of the predicted energy performance of buildings at early stages, avoiding general public scepticism.

Chapter 4. Methodology

A well-defined methodology is essential to meet the objectives of the project in an efficient way. Therefore, the work needs to be divided into small tasks forming a project plan. This chapter explains the methodology defined in this project (shown in Figure 6) and the tasks identified.

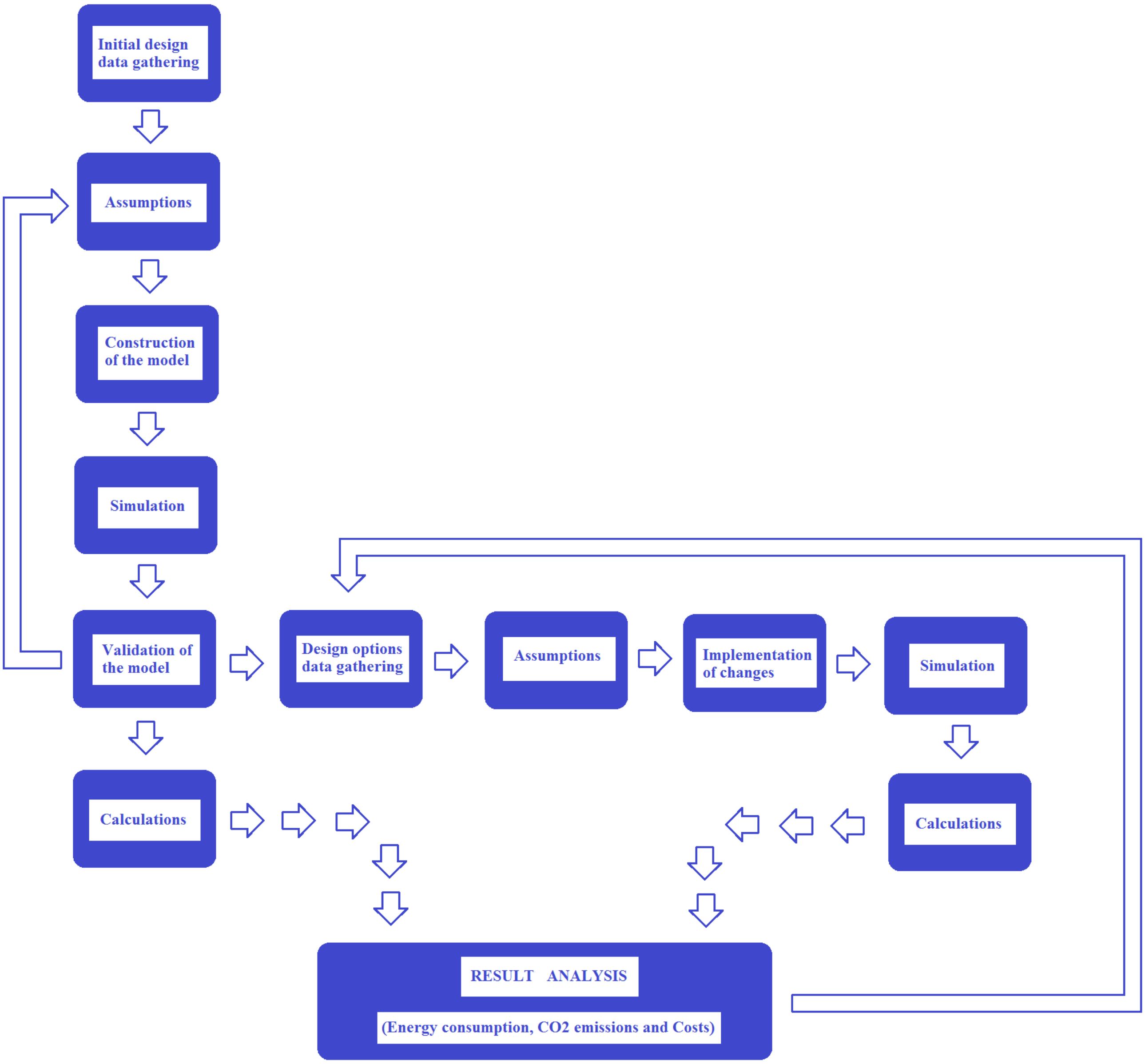

Figure 6. Methodology

4.1. Initial design data gathering

First, the information required to implement the model using ESP-r needs to be clear. Depending on the objectives to be achieved and the software to be used, different kind of information may be gathered and a different degree of detail will be required. For the purpose of this project, the model should be simple since a rough calculation of the energy demand will be enough to compare the initial design of the house with other design options.

The data required of the initial design of the house has been classified according to the following categories:

- **Location and climate:**

  The location of the house will influence greatly its energy demand. Cold climates will increase the heating demand, being the cooling demand negligible. On the other hand, in warm climates overheating will be the main problem to avoid.

- **Geometry:**

  Plans of the house are needed in order to build the model in ESP-r. It is important to pay attention not only at the dimensions of the different rooms but also at their use within the house, as the zones of the model may unify several rooms for simplicity. For example, two bedrooms will have the same use in the house and therefore, they can be modelled by one unique zone without introducing a significant error.

  It is also important to know the dimensions and location of the windows in the building, since they will determine the solar gains which will vary the final heating and cooling demand of the house.

- **Materials and constructions:**

  Details of materials and constructions are crucial. It is necessary to gathered construction data of the walls, floors and roofs as they will determine the heat transfer between the inside and outside of the building. Also, characteristics of the glazing are important to determine the heat transfer and the solar gains through the windows.

- **Internal gains:**
  Internal gains include the occupancy, lighting and equipment of the house. These heat gains will reduce the heating demand and increase the cooling demand so it is important to have the most accurate data as possible to include in the model.

- **Infiltration and ventilation:**
  Ventilation is the change of air in buildings by introducing fresh air. Adequate ventilation is essential to reach comfort inside buildings since excessive moisture and other contaminants, usually CO_2, may be removed. However, an increase in ventilation rates is not always beneficial since it may lead to significant heat losses. Therefore, information about the ventilation system and its control becomes very important to determine the energy demand of the building.

  This air flow can also occur through gaps and cracks in the fabric of the building by unintentional infiltration. In this case, the air tightness or air permeability of the building will determine the infiltration rate and the associated heat losses.

- **Heating/cooling system:**
  Information of the heating and cooling system to be installed in the house will determine the energy consumption, running costs and CO_2 emissions once the energy demand is obtained from the model simulation.

4.2. Initial design assumptions

After all the possible data from Section 4.1 has been gathered, assumptions for gaps or missing data are required. All assumptions need to be based in common practices or guides.

4.3. Construction of the model

Next, all the information gathered and assumed needs to be implemented in ESP-r simulation tool in order to build the model of the house. To help in the model construction, guide can be found in *The ESP-r Cookbook* (Hand, 2011).

4.4. Simulation of the model

Once the model is complete, simulations need to be run in ESP-r. These simulations will depend on the results needed. In this case, calculation of the energy demand is needed to compare different design options so a whole-year simulation will be run.

4.5. Verification of the model

At this point, it is crucial to investigate the results obtained from the simulations to verify the model and make sure it is reasonable. This can be done comparing the energy demand obtained with that required by low energy building standards, for example. Also, specific results regarding certain parts of the model where assumptions were made should be carefully checked.

If the results found are suspected to be inaccurate, some assumptions previously made need to be changed. These changes will be implemented in the model and simulations will be run until the results obtained are considered reasonable.

4.6. Initial design calculations

Results from the simulation of the ESP-r model will provide the energy demand that corresponds to the initial design of the house. Then calculations will be made to obtain:

- Energy consumption of the heating/cooling system initially planned using the energy demand and the system's efficiency.
- CO_2 emissions related to the energy consumed depending on the type of fuel used.
- Running costs of the system according to the actual price of the fuel used.

4.7. Design options data gathering

This is a key task within the project as it will influence the further results and conclusions of the analysis. First, design option to be considered need to be identified. In this case, the following categories are considered:

- **The thermal envelope of the house:**
  Since space heating counts for 62% of the total domestic energy consumption (see Section 3.1) special effort will be made to reduce the heating and cooling demand of the house. As explained in Section 4.1, materials and constructions of walls, floors, roofs and windows are crucial in the thermal behaviour of the building. The insulation and glazing will determine the heat transfer between the inside and outside of the building and the solar gains through the windows. Thus, when designing a new house, analysis of changes in the insulation layer thickness of each type of construction and changes in the type of glazing, is essential.

- **The heating/cooling system:**
  Analysis of different options for the heating and cooling system to be installed in the house is important since it will determine the final energy consumption, running costs and CO_2 emissions. In instance, a very well isolated house with a poor heating system will lead to high energy consumption, running costs and probably CO_2 emissions (depending on the type of fuel), so the heating/cooling system is as important as the thermal envelope of the house.

- **The type of ventilation:**
  As already mentioned in Section 4.1, the ventilation type and control is very important to determine the energy demand of the building since the air flow will lead to heat losses. Thus, it is interesting to consider different ventilation systems to analyse its effect in the energy demand of the house and the comfort conditions inside the building.

Once the design options to be considered are identified, specific data of each option needs to be gathered as it was done for the initial design of the house.

4.8. Design options assumptions

When all the data needed for the different design options in Section 4.7 cannot be gathered, assumptions may be considered. It is important that all the assumptions are based in common practices or guides.

4.9. Implementation of changes

Next, all the information gathered and assumed needs to be implemented in ESP-r simulation tool in order to change the initial model already built.

4.10. Simulation of model changes

For every change made to the model, simulations in ESP-r will be run for a whole year in order to obtain the energy demand.

4.11. Design options calculations

Results from the ESP-r simulations will provide the energy demand that corresponds to the different design options. Then, as it was done in Section 4.6, calculations will be made to obtain:

- Energy consumption of the heating/cooling system using the energy demand and the system's efficiency.
- CO_2 emissions related to the energy consumed depending on the type of fuel used.
- Running costs of the system according to the actual price of the fuel used.

4.12. Result analysis

Finally, the results obtained from simulations and calculations are analysed to compare the different design options considered. This analysis will be based on the energy consumption of the heating/cooling system, CO_2 emissions related to the energy consumed and the costs (both capital and running costs).

It is possible that after this analysis, additional design options appear to be interesting to solve a particular situation. In that case, steps from design options data gathering onwards may be repeated.

Chapter 5. Model description

This chapter describes the main characteristics of the model built using ESP-r simulation tool. These characteristics have been determined by the property documentation (Ford, 2014) and assumptions. They will determine the thermal behaviour of the building and are divided according to the following categories:

- Location and climate
- Geometry
- Materials and constructions
- Internal gains
- Infiltration and ventilation
- Heating/cooling system

Once the model is built, it is crucial to investigate the results obtained to verify the model and make sure it is reasonable. If the results found are suspected to be inaccurate, some assumptions previously made need to be changed.

5.1. Location and climate

The house is situated in Downderry, Cornwall, in the South-West of England (Figure 7), where the climate is mild. In this type of climate, especial attention needs to be paid to the cooling demand and how likely the house is to overheat. Figure 8 shows the historic average high and low temperature for each month of the year and the maximum and minimum recorded temperatures.

Figure 7. Location of the house (google maps)

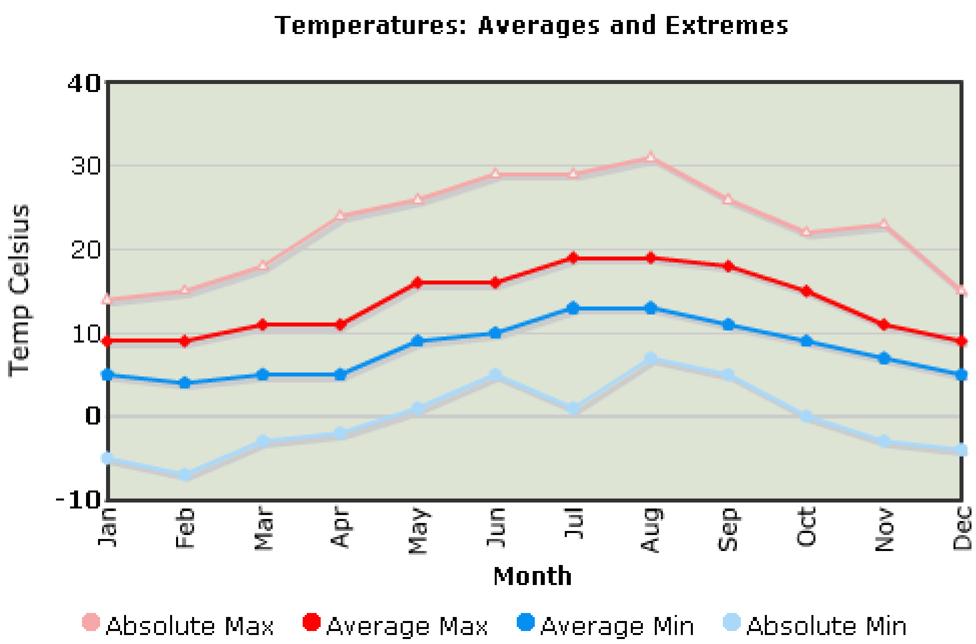

Figure 8. Average and extremes temperatures of Downderry, Cornwall (Climate Profile: Downderry)

ESP-r does not include a climate file for Cornwall so a climate data set was downloaded from the United States Department of Energy (DoE) Energy Efficiency and Renewable Energy (EERE) web site. The climate file downloaded corresponds to Jersey - Channel Islands, since the climate in this area is similar to the one in Cornwall. This file was in EPW format and it was needed to convert it to IWC format in order to import it to ESP-r. The ambient temperature and solar radiation throughout a year for Channel Island are shown in Figure 9 and Figure 10 respectively.

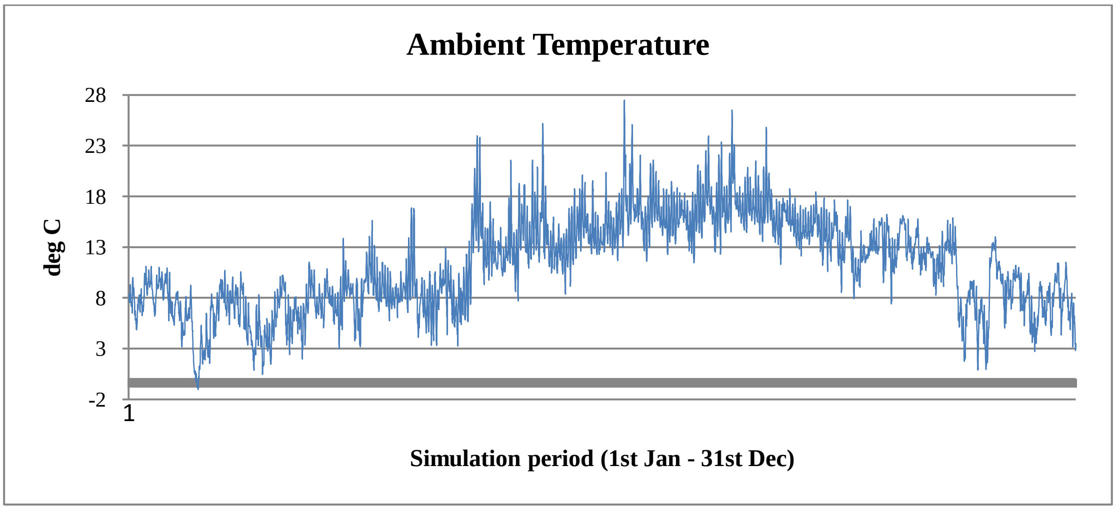

Figure 9. Channel Islands – Ambient temperature (U.S. Department of Energy, 2012)

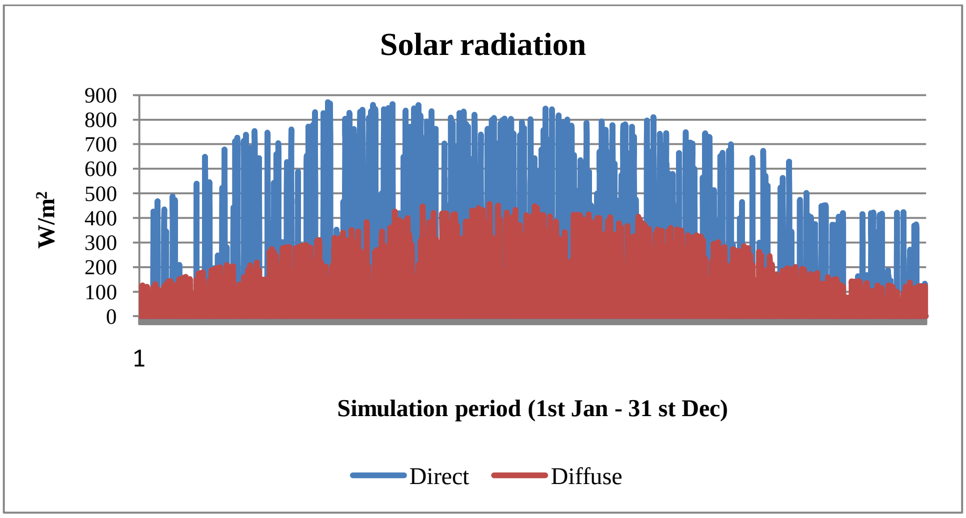

Figure 10. Channel Island – Solar radiation (U.S. Department of Energy, 2012)

5.2. Geometry

The building consists of four floors. The different uses and surface areas of each floor are detailed in Table 2.

Table 2. Area and uses of the house

Floor	Area (m^2)	Use
Basement	44.8	Lobby, wet room, staircase and garage
Ground floor	44.8	Three single bedrooms, family bathroom and staircase
First floor	31.4	Kitchen, living room and staircase
Second floor	16.7	Double bedroom, shower room and staircase

Each floor was modelled as an independent zone to keep the model relatively simple. Once all the external geometry was defined, internal walls were added to the model (see Figure 11). The internal mass will change the thermal behavior of the building because it absorbs and releases heat to the surrounding areas.

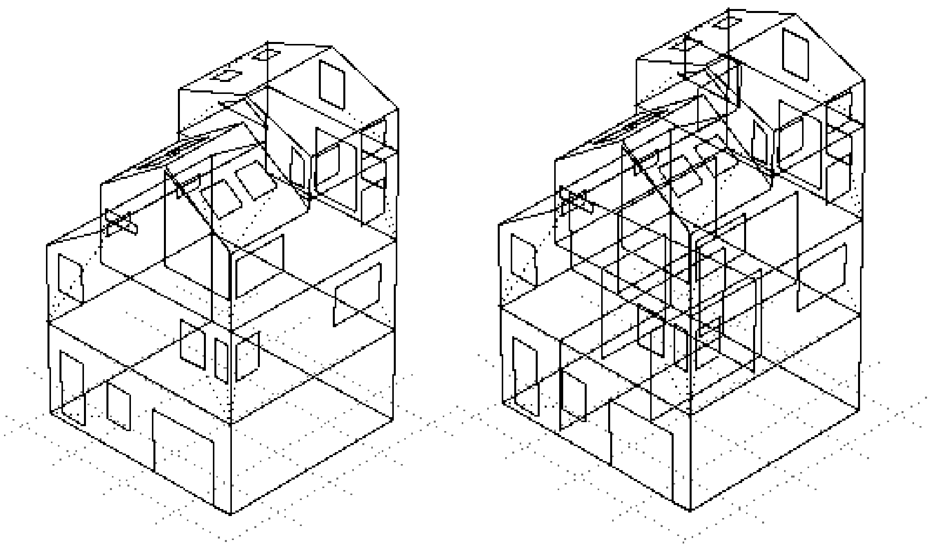

Figure 11. Base model without internal walls (left) and with them (right)

Finally, since the house is surrounded by a valley and other houses, shadings needed to be added to the model so the solar gains calculated by the software were accurate enough (see Figure 12).

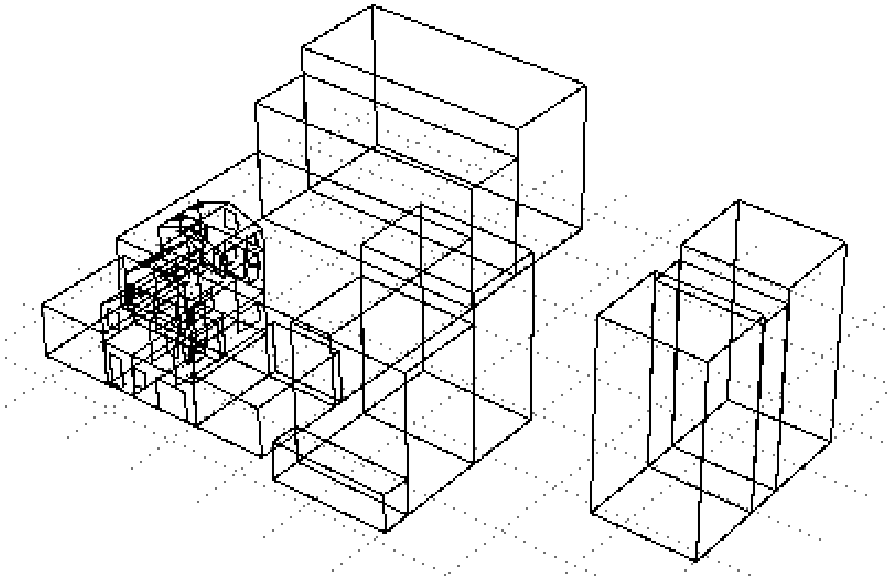

Figure 12. Model of the house including the shading from other houses and the valley

5.3. Materials and constructions

This section describes the characteristics of the different constructions used in the model from the property documentation (Ford, 2014) and assumptions made.

Table 3. Main construction characteristics

Construction		U-value (W/m^2K)	Insulation		
			Thickness (mm)	Thermal Conductivity (W/mK)	Type
External wall	Generic	0.15	300	0.038	Mineral wool
	Basement	0.11	300	0.035	Rigid foam
Internal wall	Generic	1.50	-	-	-
	Basement	0.11	300	0.035	Rigid foam
Floor	Generic	0.31	100	0.038	Mineral wool
	Basement	0.25	90	0.035	Rigid foam
	Suspended	0.20	150	0.035	Rigid foam
Roof		0.12	300	0.038	Mineral wool
Glazing		1.97	-		
Door		2.06	-		

The calculation of the U-values of the different constructions has been calculated as explained in *CIBSE Guide A, Section 3.3.10. Thermal transmittance for elements composed of plane homogenous layers* (The Chartered Institution of Engineers London, 2006). The thermal resistance is obtained by adding the thermal resistances of its component parts and the adjacent air layers. Finally, the thermal transmittance is calculated as the inverse of the total thermal resistance, thus:

$$U = 1 / (R_{si}+R_1+R_2 + \ldots + R_a + R_{se}) \quad (5.1)$$

where U is the thermal transmittance (Wm^2/K), R_{si} is the internal surface resistance (m^2K/W), R_1 and R_2 are the thermal resistances of components 1 and 2 (m^2K/W), R_a is the thermal resistance of the air spaces (m^2K/W) and R_{se} is the external surface resistance (m^2K/W).

The values for the internal and external surface resistance may be obtained for different directions of the heat flow according to Table 3.8 and Table 3.9 of CIBSE Guide A (The Chartered Institution of Engineers London, 2006).

5.3.1. External wall

Generic

This is the construction used for all the external walls of the building except for the basement. It is a softwood timber frame made up of studs 145 mm and 45 mm deep tied by a 300 mm OSB cross piece. Therefore the depth of insulation is 300 mm except between the studs where it must be 110 mm. The insulation material used is mineral wool.

Figure 13. Timber wall construction (Ford, 2014)

Thermal transmittance for elements composed of bridged layers can be calculated by the *Combined Method* from CIBSE Guide A. (The Chartered Institution of Engineers London, 2006). This method calculates the thermal resistance of the bridged element as the average of the upper and lower limiting values. Therefore, the thermal resistance is given by the equation 5.2:

$$R_b = {}^{1}\!/_{2}\,(R_L + R_U) \tag{5.2}$$

where R_b is the thermal resistance of the bridge structure, R_L is the lower limit of thermal resistance and R_U is the upper limit of thermal resistance, all of them in m^2K/W.

The lower limit of thermal resistance is calculated as:

$$R_L = R_{se} + R_1 + \frac{1}{\left(\frac{P_m}{R_{m2}}\right) + \left(\frac{P_n}{R_{n2}}\right) + (P_p/R_{p2})} + R_3 + \cdots + R_z + R_{si} \tag{5.3}$$

where P_m, P_n and P_p are the proportions of the total surface area occupied by elements composed of materials m, n and p.

The upper limit of thermal resistance is calculated as:

$$R_U = \left(\frac{P_m}{R_{se} + R_{m2} + (R_1 \ldots + R_Z) + R_{si}} + \frac{P_n}{R_{se} + R_{n2} + (R_1 \ldots + R_Z) + R_{si}} + \frac{P_p}{R_{se} + R_{p2} + (R_1 \ldots + R_Z) + R_{si}}\right)^{-1} \tag{5.4}$$

where P_m, P_n and P_p are the proportions of the total surface area occupied by elements composed of materials m, n and p.

Using equations 5.2, 5.3 and 5.4, the thermal resistance of the timber frame wall may be calculated.

Timber frame part

Table 4. U-value calculation for the timber frame part of the generic external wall

Material	Thickness (m)	Proportion of surface area	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface				0.04
Timber cladding	0.0300		0.140	0.21
Battens	0.0200		0.130	0.15
OSB	0.0090		0.130	0.07
Timber frame	0.1450		0.140	1.04
Mineral wool	0.1100	0.85	0.038	2.89
OSB	0.1100	0.15	0.130	0.85
Timber frame	0.0450		0.140	0.32
OSB	0.0090		0.130	0.07
Plasterboard	0.0125		0.160	0.08
Inner surface				0.13

R_L	4.24
R_U	0.22

U-value	0.45

Insulation part

Table 5. U-value calculation for the insulation part of the generic external wall

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Timber cladding	0.0300	0.140	0.21
Battens	0.0200	0.130	0.15
OSB	0.0090	0.130	0.07
Mineral wool	0.3000	0.038	7.89
OSB	0.0090	0.130	0.07
Plasterboard	0.0125	0.160	0.08
Inner surface			0.13

R	8.65
U-value	0.12

U-value external wall	**0.15**

Basement external wall

This is a concrete wall with rigid foam insulation as it is under ground.

Table 6. U-value calculation for the basement external wall

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Concrete	0.1500	0.770	0.19
Foam	0.3000	0.035	8.57
Plasterboard	0.0125	0.160	0.08
Inner surface			0.13

R	9.01
U-value	**0.11**

5.3.2. Internal wall

Generic

This construction has been defined using the default internal wall in ESP-r. It does not have any insulation layer since it separates internal zones that are heated or cooled to the same level. This wall is used, therefore, in all the internal walls of the house except the basement, where the lobby and the wet room need to be separate from the garage.

Table 7. U-value calculation for the generic internal wall

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Plasterboard	0.0125	0.16	0.08
Breeze block	0.1500	0.44	0.34
Plasterboard	0.0125	0.16	0.08
Inner surface			0.13

R	0.67
U-value	**1.50**

Basement

This construction has been defined using the default internal wall in ESP-r adding 300 mm of insulation since this wall separates the garage from the lobby, wet room and staircase.

Table 8. U-value calculation for the basement internal wall

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Plasterboard	0.0125	0.160	0.08
Breeze block	0.1500	0.440	0.34
Foam	0.3000	0.035	8.57
Plasterboard	0.0125	0.160	0.08
Inner surface			0.13

R	9.24
U-value	**0.11**

5.3.3. Floors

Generic

This construction has been defined as the inverse construction of the default ceiling construction in ESP-r and it separates the first and second floor.

Table 9. U-value calculation for the generic floor

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Ceiling mineral	0.01	0.030	0.33
Mineral wool	0.10	0.038	2.63
Inner surface			0.17

R	3.17
U-value	**0.31**

Basement

This construction has been defined using the ground floor that is already defined in ESP-r but adding an insulation layer to meet the minimum U-value required by the regulations (0.25 W/m^2K).

Table 10. U-value calculation for the basement floor

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Earth std	0.600	1.280	0.47
Gravel base	0.150	0.360	0.42
Heavy mix concrete	0.150	1.400	0.11
Gap	0.050	-	0.17
Foam (phenol - rigid)	0.090	0.035	2.57
Chipboard	0.019	0.150	0.13
Inner surface			0.17

R	4.07
U-value	**0.25**

Suspended floor

This is a suspended timber floor defined using the suspended floor that is already defined in ESP-r but adding a 300 mm-insulation layer. This type of construction separates the basement and the ground floor.

Table 11. U-value calculation for the suspended floor

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Steel	0.040	50.000	0.00
Heavy mix concrete	0.140	1.400	0.10
Foam	0.150	0.035	4.29
Gap	0.050	-	0.17
Chipboard	0.019	0.150	0.13
Wilton	0.006	0.060	0.10
Inner surface			0.17

R	4.99
U-value	**0.20**

5.3.4. Roof

This construction has been defined using the default roof construction in ESP-r adding 300 mm of insulation.

Table 12. U-value calculation for the roof

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Aluminum	0.003	210.000	0.00
Gap	0.025	-	0.17
Mineral wool	0.300	0.038	7.89
Aluminum	0.003	210.000	0.00
Inner surface			0.10

R	8.20
U-value	**0.12**

5.3.5. Glazing

This is uPVC double glazed (air filled) with low-e coating.

Table 13. U-value calculation for the glazing

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Low-e glass	0.012	1.05	0.01
Air gap	0.012		0.32
Low-e glass	0.006	1.05	0.01
Inner surface			0.13

R	0.51
U-value	**1.97**

5.3.6. Door

Doors are assumed to be made of oak wood.

Table 14. U-value calculation for the doors

Material	Thickness (m)	Thermal Conductivity (W/mK)	Resistance (m^2K/W)
Outer surface			0.04
Oak	0.06	0.19	0.32
Inner surface			0.13

R	0.49
U-value	**2.06**

5.4. Internal gains

The internal gains of a building account for the heat generated by the occupants, the lighting and the appliances within each zone. The calculation of this heat generation is explained next.

5.4.1. Occupancy

To calculate the heat generated by the occupants, an occupancy profile needs to be defined. This has been done assuming a typical five member-family behaviour differentiating between weekdays and weekends/holidays using common sense.

Weekdays

The number of occupants (N) assumed in each zone during weekdays is shown in Table 15.

Table 15. Number of occupants assumed during weekdays

N	Zone			
Schedule	**Garage**	**Ground floor**	**First floor**	**Second floor**
0-7	0	3	0	2
7-8	1	2	1	1
8-18	0	0	1	0
18-23	0	0	5	0
23-0	0	3	0	2

Once the occupancy profile is defined, the total heat generation by occupants can be calculated using the Table 1.4 of CIBSE Guide A, *Typical metabolic rate and heat generation per unit area of body surface for various activities* (The Chartered Institution of Engineers London, 2006). The heat generated by the occupants during weekdays is shown in Table 16 and Figure 14.

Table 16.Total heat generation by occupants during weekdays

Total Heat Generation (W)	Zone			
Schedule	**Garage**	**Ground floor**	**First floor**	**Second floor**
0-7	0.0	221.4	0.0	147.6
7-8	126.0	252.0	126.0	126.0
8-18	0.0	0.0	270.0	0.0
18-23	0.0	0.0	585.0	0.0
23-0	0.0	221.4	0.0	147.6

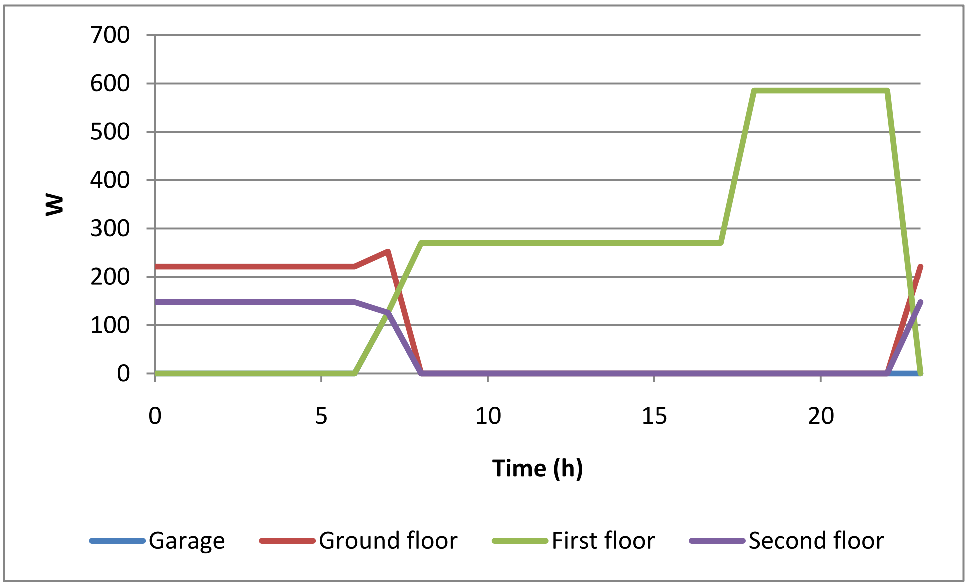

Figure 14. Occupancy heat gain profile for weekdays

To include the occupancy gains in ESP-r it is necessary to specify the sensible and latent parts of this heat generation. These have been calculated using the proportion of sensible and latent gains from Table 6.1 of CIBSE Guide A, *Benchmark values for internal heat gains for offices (at 24 °C, 50% RH)* (The Chartered Institution of Engineers London, 2006). The sensible heat gain of an office with an occupancy density of 4 people/m^2 is 20 W/m^2 while the latent heat gain is 15 W/m^2. Therefore, the proportion of sensible heat gain is 57% and 43% for latent heat gain.

Saturdays, Sundays and holidays

The heat generated by the occupants during weekends and holidays is calculated in the same way as for weekdays, assuming an occupancy profile for a typical five member-family using common sense. Table 17 shows the number of occupants (N) in each zone.

Table 17. Number of occupants assumed during weekends and holidays

N	Zone			
Schedule	**Garage**	**Ground floor**	**First floor**	**Second floor**
0-10	0	3	0	2
10-11	1	2	1	1
11-17	0	0	2	0
17-0	0	0	4	0

The heat generated by the occupants during weekdays is shown in Table 17 and Figure 15.

Table 18. Total heat generation by occupants during weekends and holidays

Total Heat Generation (W)	Zone			
Schedule	**Garage**	**Ground floor**	**First floor**	**Second floor**
0-10	0	221.4	0	147.6
10-11	126	252.0	126	126.0
11-17	0	0.0	540	0.0
17-0	0	0.0	468	0.0

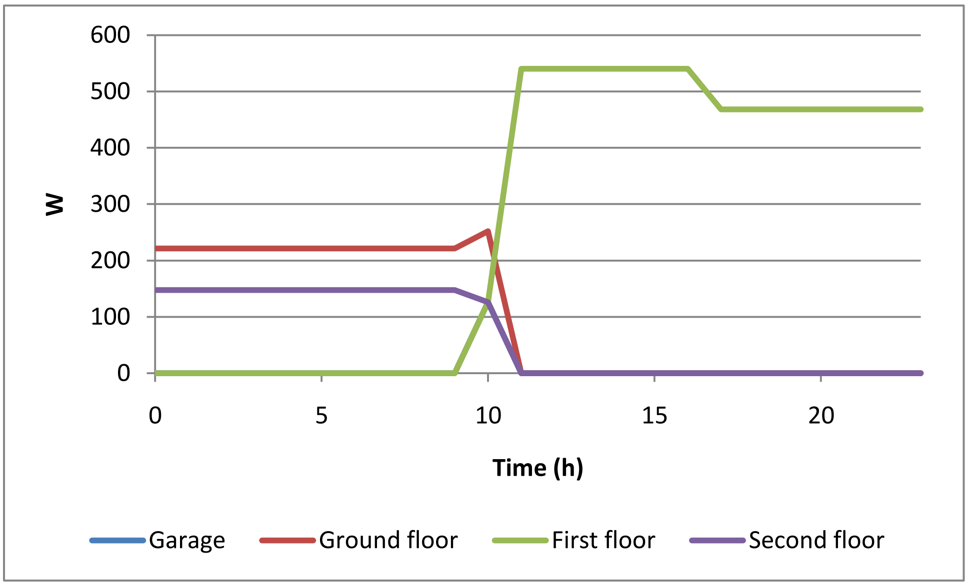

Figure 15. Occupancy heat gain profile for weekends and holidays

5.4.2. Lighting

To calculate the heat generated by the lighting, the illuminance (lux) required for each type of room needs to be determined. This can be found in Table 1.5 of CIBSE Guide A (The Chartered Institution of Engineers London, 2006). The illuminance of each zone in the model may then be calculated multiplying the proportion of area of each type of room by the maintained illuminance. The results are shown in Table 19 where the illuminance is set to zero when no one is in that zone according to the occupancy profile defined previously.

Table 19. Maintained illuminance during weekdays

Illuminance (lux)	Zone			
Schedule	**Garage**	**Ground floor**	**First floor**	**Second floor**
0-7	0.00	0.00	0.00	0.00
7-8	89.68	105.02	175.48	108.98
8-18	0.00	0.00	175.48	0.00
18-23	0.00	0.00	175.48	0.00
23-0	0.00	0.00	0.00	0.00

Once the illuminance required is calculated, the power installed can be obtained taking into account the type of lamp to be used. According to (McMullan, 2012), the type of lamp that is usually used in domestic buildings is compact fluorescent. For this type of lamp an average installed density of 8 W/m^2 is needed to get 300 lux according to CIBSE Guide A, Table 6.4 *Lighting energy targets* (The Chartered Institution of Engineers London, 2006). Therefore, 8 W/m^2 is the installed power density of all the zones in the model when they are occupied otherwise the power is set to zero. The heat generated by the lamp will be released to the zone through convection and radiation in a proportion of 70% and 30% respectively according to CIBSE Guide A, Table 6.6 *Energy dissipation in lamps*. Figure 16 and Figure 17 show the lighting gain profile for weekdays and weekends/holidays respectively.

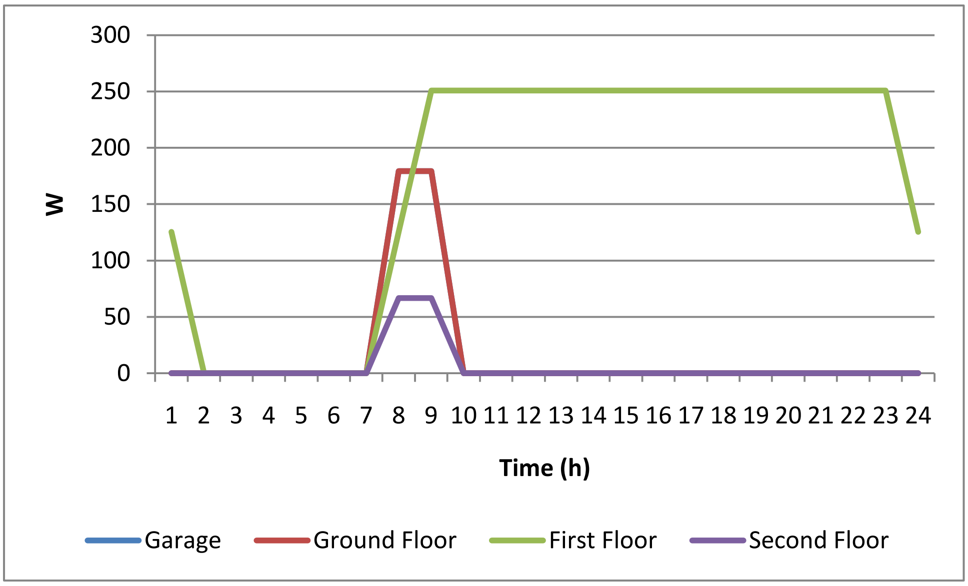

Figure 16. Lighting heat gain profile for weekdays

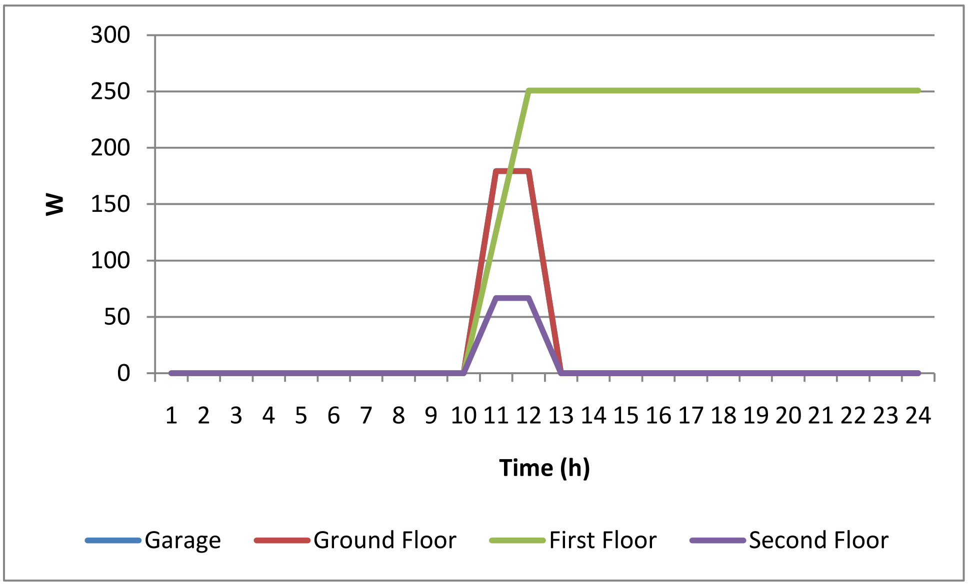

Figure 17. Lighting heat gain profile for weekends and holidays

5.4.3. Equipment

The heat generated by typical home equipment is shown in Table 20 below.

Table 20. Heat generated by typical home equipment (McMullan, 2012)

Equipment	Heat generation (W)
Desktop computer	150
Hair dryer	800
Gas cooker	3500
Fridge-freezer	150
TV	100

Using the values in Table 20, the equipment profile has been made up assuming typical uses of the rooms within the house using common sense. For example, the fridge-freezer will be always ON while the TV and the desktop computer are assumed to be used only during the evening.

Weekdays

Table 21 shows the appliance use for the different zones for weekdays.

Table 21. Equipment profile during weekdays

<table>
<tr><th>Equipment used</th><th colspan="4">Zone</th></tr>
<tr><th>Schedule</th><th>Garage</th><th>Ground floor</th><th>First floor</th><th>Second floor</th></tr>
<tr><td>0-7</td><td rowspan="5">No equipment</td><td>No equipment</td><td>Fridge-freezer</td><td>No equipment</td></tr>
<tr><td>7-8</td><td>Hair dryer</td><td>Fridge-freezer + Cooker for half an hour</td><td>Hair dryer</td></tr>
<tr><td>8-18</td><td rowspan="3">No equipment</td><td>Fridge-freezer + Cooker for an hour</td><td rowspan="3">No equipment</td></tr>
<tr><td>18-23</td><td>Fridge-freezer + TV+2 computers</td></tr>
<tr><td>23-0</td><td>Fridge-freezer</td></tr>
</table>

Once the equipment or appliance profile is defined, the heat gains can be calculated taking into account the heat generated by each device using the values in Table 20, giving the profile shown in Table 22 and Figure 18. To understand this profile, a clarification needs to be made. To calculate the heat gain due to the cooker when it is ON for an hour during the period from 8 to 18 hours, it is assumed that this is ON intermittently during the period so the heat gain has been divided between the number of hours in order to calculate the heat gain during the period.

Table 22. Equipment heat generation during weekdays

W	Zone			
Schedule	**Garage**	**Ground floor**	**First floor**	**Second floor**
0-7	0	0	150	0
7-8	0	800	1900	800
8-18	0	0	500	0
18-23	0	0	550	0
23-0	0	0	150	0

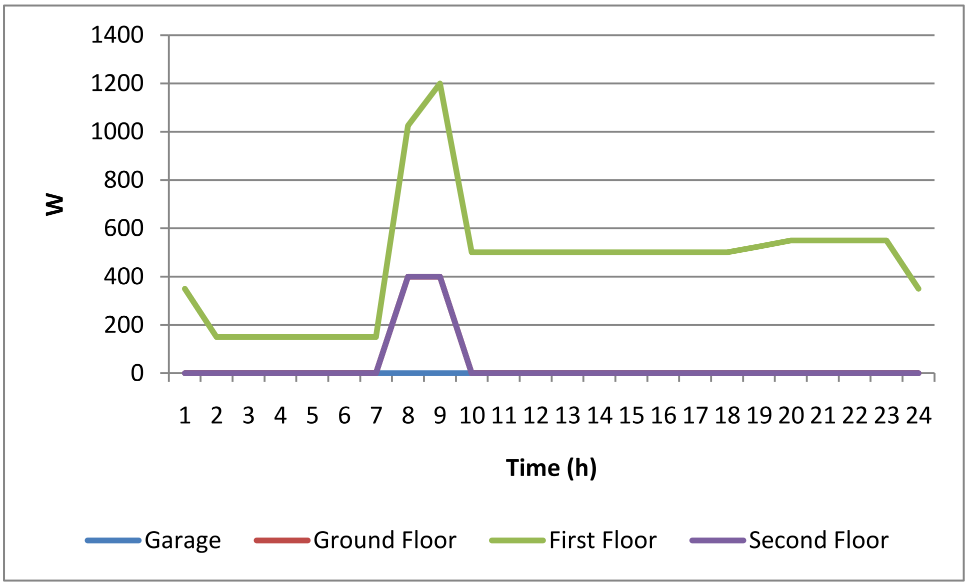

Figure 18. Equipment heat gain profile for weekdays

Saturdays, Sundays and holidays

The heat generated by the appliances during weekends and holidays is calculated in the same way as for weekdays. Table 23 and Figure 19 show the equipment heat gain profile for weekends and holidays.

Table 23. Equipment heat generation during weekends and holidays

W	Zone			
Schedule	**Garage**	**Ground floor**	**First floor**	**Second floor**
0-10	0	0	150	0
10-11	0	800	1900	800
11-17	0	0	833	0
17-0	0	0	550	0

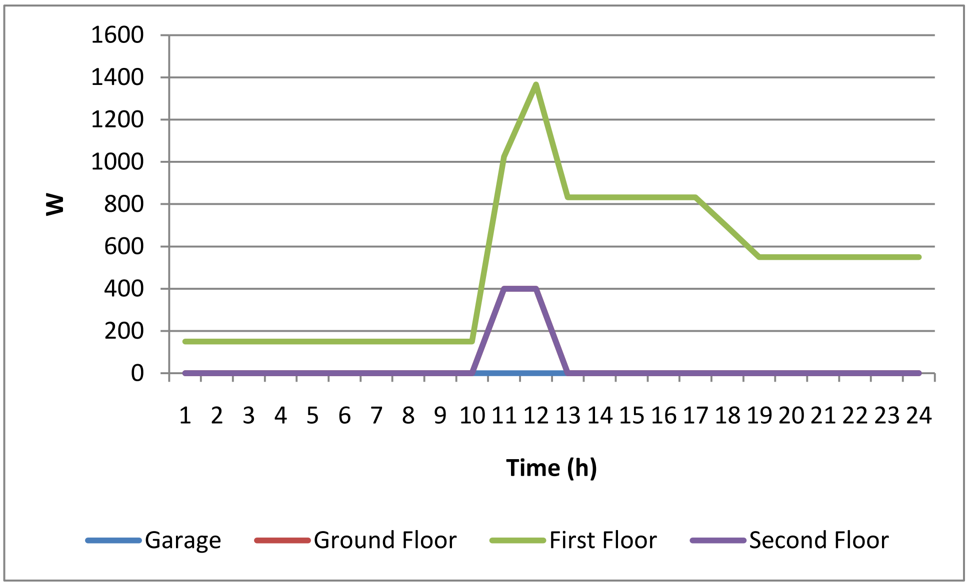

Figure 19. Equipment heat gain profile for weekends and holidays

5.5. Infiltration and Ventilation

To take into account the heat losses due to the air flow that enters a zone from the outside (infiltration) and from other zones (ventilation), an air flow network has been defined in ESP-r. This network is formed by nodes, components and connections as shown in Figure 20.

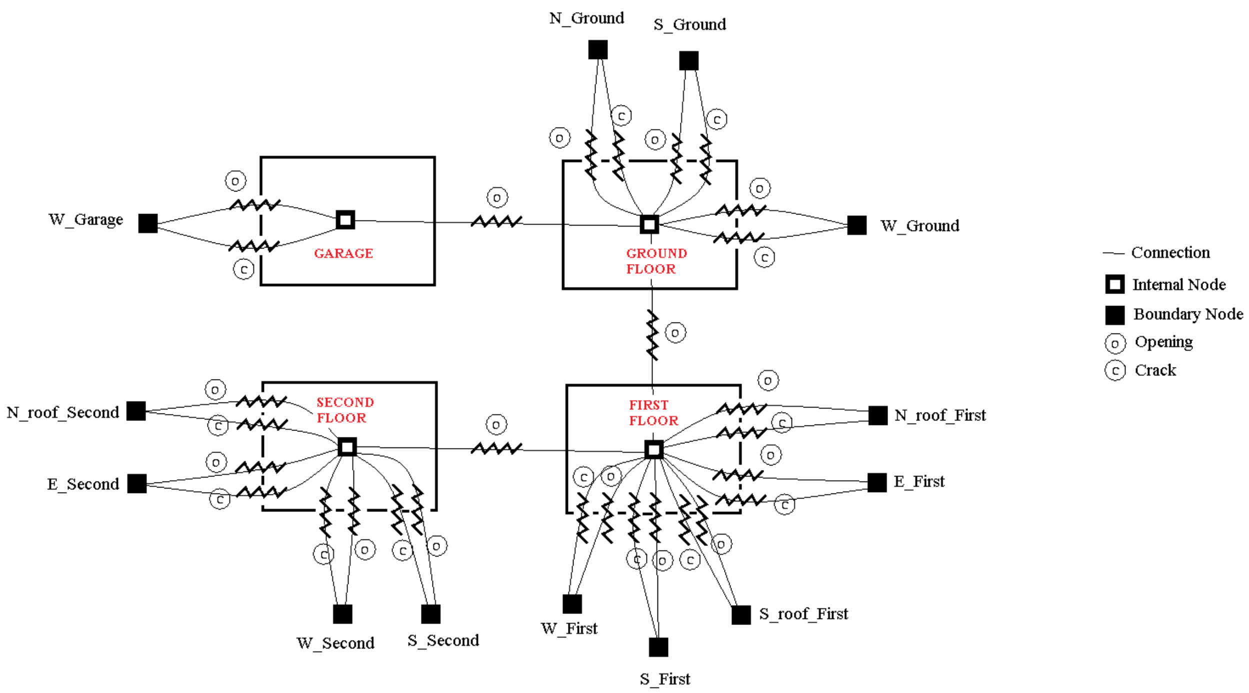

Figure 20. Air flow network for the low energy house in Cornwall

The nodes can be internal, to represent the air in each zone, or boundary nodes, to represent the air located outside the building. Two different types of components have been defined: opening and crack. The opening is used to define windows and staircases. There are no fans in this case as the ventilation is natural. For each external opening there is a crack to take into account undesirable infiltration into the building due to little cracks in the façade. These cracks are assumed to be 5 mm wide and of the same length as the window they relate to. Table 24 summarises the characteristics of all the components in the network.

Table 24. Characteristics of the air flow network components

Component	Area (m^2)	Width (m)	Length (m)
W_Wind_Gar	1.080	-	-
W_crack_Gar	-	0.005	4.10
Stairs_Gar_Gr	1.650	-	-
W_Wind_Ground	2.700	-	-
N_Wind_Ground	0.720	-	-
S_Wind_Ground	3.240	-	-
W_crack_Ground	-	0.005	1.40
N_crack_Ground	-	0.005	1.80
S_crack_Ground	-	0.005	2.70
Stairs_Gr_F	1.650	-	-
W_Wind_First	5.880	-	-
N_roof_Wind_First	1.620	-	-
E_Wind_First	3.960	-	-
S_Wind_First	3.150	-	-
S_roof_Wind_First	1.620	-	-
W_crack_First	-	0.005	3.90
N_roof_crack_First	-	0.005	1.20
E_crack_First	-	0.005	2.40
S_crack_First	-	0.005	2.70
S_roof_crack_First	-	0.005	1.20
Stairs_F_S	1.650	-	-
W_Wind_Second	0.975	-	-
N_roof_Wind_Second	0.720	-	-
E_Wind_Second	1.080	-	-
S_Wind_Second	1.620	-	-
W_crack_Second	-	0.005	2.40
N_roof_crack_Second	-	0.005	1.64
E_crack_Second	-	0.005	0.90
S_crack_Second	-	0.005	2.20

Once the air flow network has been defined, it can be controlled depending on the inside air temperature of the zones and the occupancy profile to simulate people opening the windows if the inside temperature rises over the comfort temperature. Table 25 shows the comfort temperatures for winter and summer for each room type that can be found in CIBSE Guide A Table 1.5 (The Chartered Institution of Engineers London, 2006).

Table 25. Winter and summer comfort temperatures

Room type	Winter comfort temperature (°C)	Summer comfort temperature (°C)
Bathrooms	20 – 22	23 – 25
Bedrooms	17 – 19	23 – 25
Hall/stairs/landings	19 – 24	21 – 25
Kitchen	17 – 19	21 – 23
Living rooms	22 – 23	23 – 25
Garages	-	-

From the reference values in Table 25, common heating, window opening, and cooling set points are assumed for the ground, first and second floor.

- Heating set point → 19 °C
- Window opening set point → 22 °C
- Cooling set point → 25 °C

These set points have been defined as follows:

- **Heating set point:**

  The ground floor is formed by three bedrooms, one family bathroom and the staircase. In this case, bedrooms have most of the floor area and therefore, the heating set point should be between 17 and 19 °C. Since the bathroom requires a higher comfort temperature (between 20 and 22 °C), the higher set point for bedrooms (19 °C) is taken as the set point for the zone in the model. The same reasoning can be applied to the second floor as it is formed by one double bedroom and a bathroom.

  The first floor is formed by the kitchen, the living room and the staircase. In this case, the kitchen and the living room have the same floor area so the heating set point has been calculated as an average between the minimum temperature for the kitchen and the maximum temperature for the living room. This calculation gives 20 °C as a result, a very similar value to the set point of the ground and second floor (19 °C) thus, for simplicity it is assumed the same heating set point for the whole building.

- **Cooling set point:**

  The summer comfort temperatures for bedrooms, bathrooms and living rooms are the same (23 to 25 °C). The higher temperature (25 °C) is chosen as the cooling set point for the ground and second floors so there can be space for setting the window opening set point.

  For kitchens, summer comfort temperatures are slightly lower (21 to 23 °C) but as in the case of the heating set point, for simplicity, the same cooling set point is chosen for the whole building.

- **Window opening set point:**

  To simulate occupants opening windows when inside temperature rises over certain limit, a window opening set point has been defined. This set point temperature is set at 22 °C. This temperature is slightly below the maximum summer comfort temperature range (23 to 25 °C) for most areas in the house (bedrooms, bathrooms and living room) and therefore the cooling effect of natural ventilation can be analysed. If this natural ventilation is not enough to keep the inside temperature within the comfort range, then the cooling system will turn ON.

There is not temperature control for the basement since it is formed by the garage, lobby, wet room and staircase so it is assumed to be unoccupied most of the time (see Section 5.4.1).

The control selected is ON/OFF, therefore windows are assumed to be either closed or fully opened. A more precise control may be set up if CO_2 concentrations are also included to simulate people opening the windows either when the inside temperature is too high or when the CO_2 concentration is over 1000 ppm, since higher concentrations have been shown to affect the body physically and psychologically (Indoor Air Quality UK). Typical CO_2 concentrations in the environment are around 400 parts per million (ppm) volume based concentration.

At this point it is important to be careful with the way the airflow network has been defined because if the names of the nodes are too long, ESP-r will shut down when trying to define the CO_2 control, and will not clarify where the error is. This is easily fixable shorting the name of the nodes in the following files:

- Airflow network file (.afn)
- Contaminant file (.ctm)
- Configuration file (.cfg)

5.6. Heating/Cooling System

The default heating system that is planned to be installed in the house is an Air Source Heat Pump (ASHP) air to water with underfloor heating or radiators. However, the system that has been defined in the ESP-r model is an ideal heating/cooling system with the maximum capacity allowed (999 kW). This system will help to find the heating/cooling demand of the building.

Once the heating and cooling loads are calculated, a specific ASHP may be chosen and information about the performance of the actual system to be installed may be gathered, but before this a verification of the model is needed.

5.7. Verification of the model

Once all the characteristics of the model have been defined in ESP-r, verification of the model is needed to check if the results make sense. First, check of the air flow network control system was carried out to make sure windows were opened appropriately according to the zone temperatures and the occupancy schedule. To do this in an easy way, simulations were run for a winter day (when temperatures are low and windows should remain closed most of the time) and a summer day (when temperatures are high and windows will likely iterate between opened and closed state during the occupancy hours). Figure 21 and Figure 22 show the results obtained for zone temperatures and infiltrations through the windows (excluding uncontrolled airflows through the cracks) for a winter and a summer day respectively.

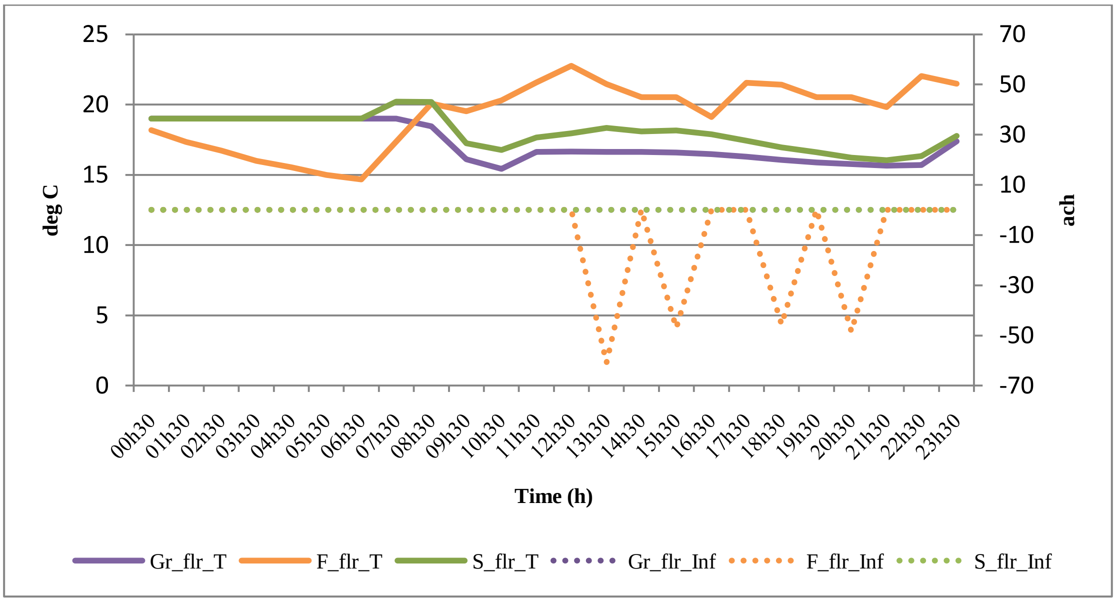

Figure 21. Temperature and infiltrations for a winter day

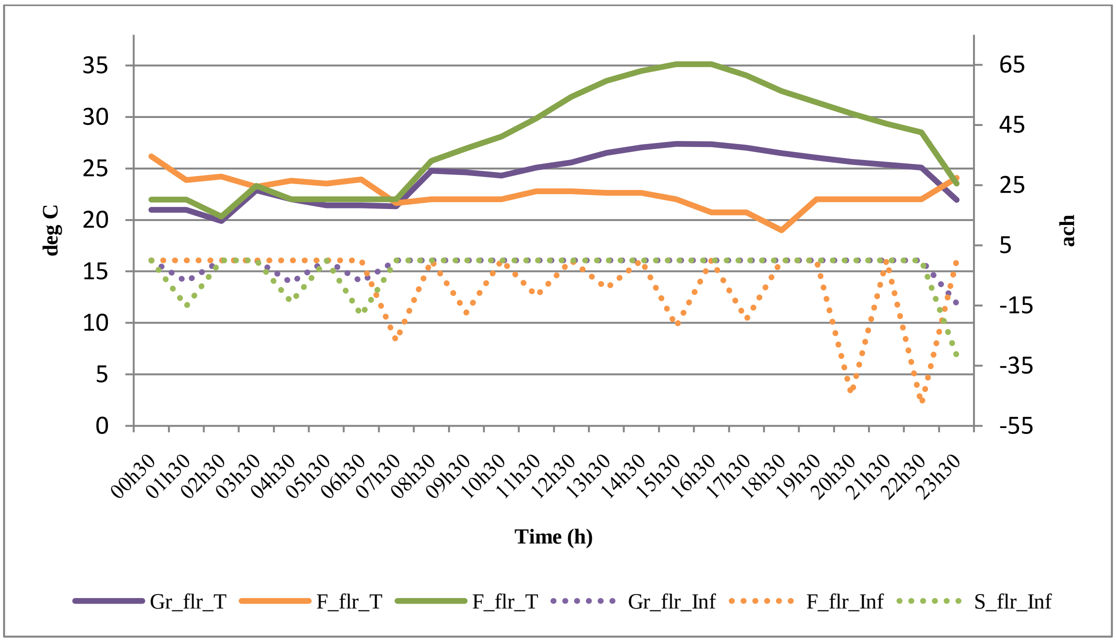

Figure 22. Temperature and infiltrations for a summer day

Results shown in the graphs above confirm that the control of the air flow network has been set properly since windows in the ground and second floor remain closed during the winter day, as temperatures inside these zones never exceed 22 °C. In contrast, during the summer day simulated, windows are opened intermittently through the occupied periods.

Next, the magnitude of the air flows was checked and it was found that the air changes per hour (ach) were too high (reaching a maximum of 2,094.4 ach in the first floor as shown in Figure 23). This value is not reasonable as people will not usually open the entire area of all the windows in a room at the same time. In order to get more reasonable values for the infiltrations, several window opening areas were simulate, getting the results in Table 26.

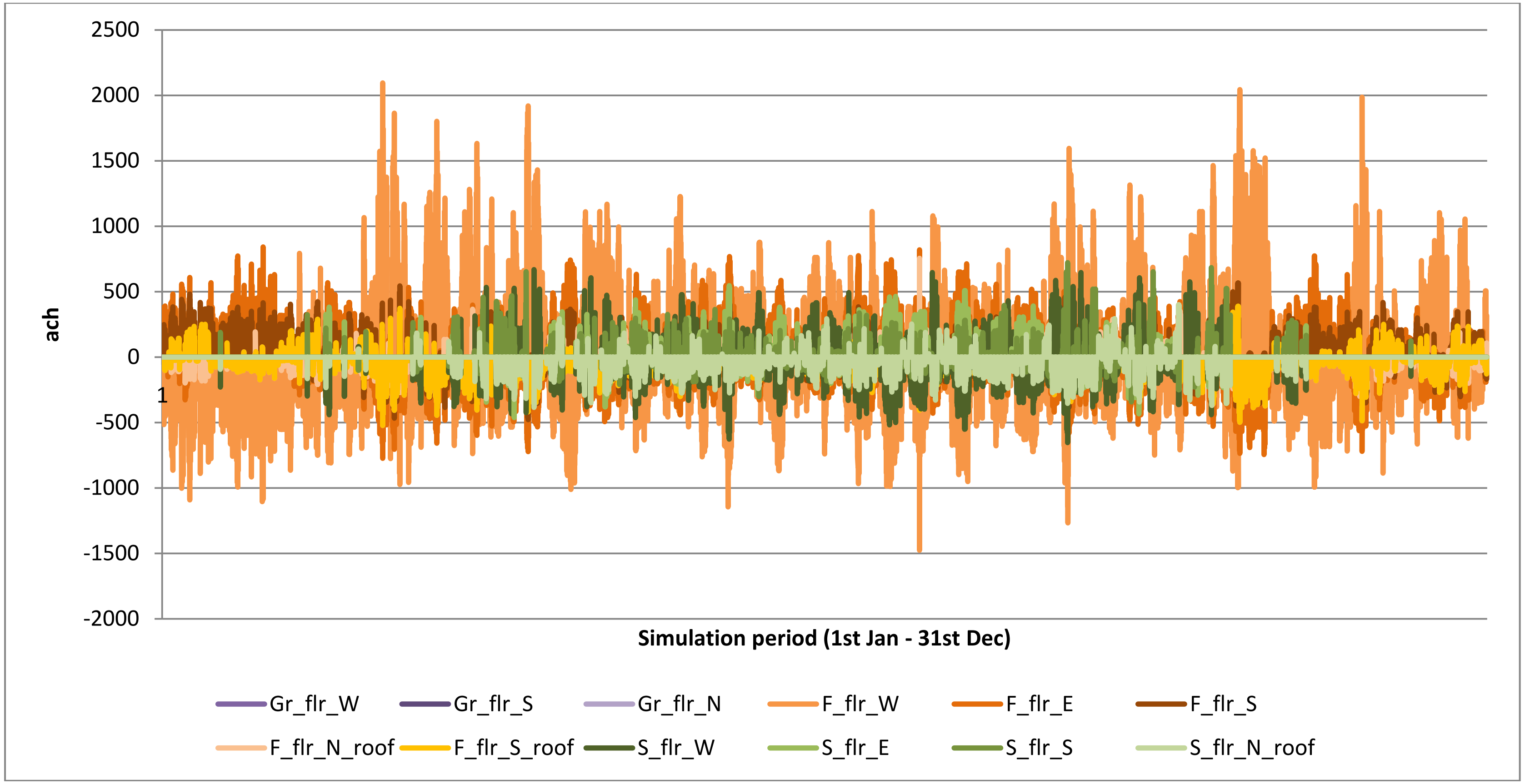

Figure 23. Infiltrations through windows

Table 26. Results for different window opening area

% Area of window opened	Max infiltration through the windows (ach)	Energy demand (kWh)		Max inside temperature (°C)
		Heating	Cooling	
0	0.00	259.40	9,690.60	40.98
0.4	9.05	431.40	6,057.70	41.20
1	21.81	1,208.60	3,740.10	41.18
4	83.42	9,088.60	1,676.70	40.63
10	209.10	29,458.50	1,236.10	39.88
100	2,094.40	361,854.60	1,057.30	39.82

From the results above, it can be seen that the window opening area has a great influence on the heating demand and the infiltrations through the windows, ranging from zero ach and 259.4 kWh when windows are fully closed to 2,094.4 ach and 361,854.6 kWh when windows are fully opened. In opposition, the cooling demand and the maximum temperature inside the zones change slightly as the window opening area changes, ranging from 9,690.6 kWh and 40.98 °C when windows are fully closed, to 1,057.3 kWh and 39.82 °C.

Finally, after looking at the infiltration results in Table 26, it is assumed that windows are going to open 1% of the total area giving a maximum infiltration rate of 21.81 ach. In this case, the heating demand is 1,208.60 kWh/year and the cooling demand is 3,740.10 kWh/year.

The energy required per year and floor area can be obtained dividing the heating and cooling demand by 92.9 m^2 (floor area excluding the basement which is not conditioned). This way, the energy required per year and floor area obtained by the model can be compared with the passive house standard to see if the results are reasonable for a low energy house (see Table 27).

Table 27. Specific Energy Demand Comparison

Specific Energy Demand ($kWh/m^2 \cdot year$)	Model	Passive House Standard
Heating	13.01	15.00
Cooling	40.26	15.00

Results in Table 27 show that the specific heating demand of de model meets the passive house standard target. However, the specific cooling demand of the model is approximately 2.5 times the passive house standard target so design options to reduce this demand will be considered.

Chapter 6. Design options considered

This chapter describes the different design options that will be compared with the actual model of the house in order to find an optimal solution. The options considered are divided in the following categories:

- Thermal envelope
- Heating/cooling system
- Ventilation system

6.1. Thermal envelope

Design options considered regarding the thermal envelope include changes in the insulation thickness of the different constructions and changes in the type of glazing of the windows. Typical U-values for upgrading the fabric and glazing of detached houses can be found in *Changes to Part L of the Building Regulations 2013 - Impact Assessment* (Department for Communities and Local Government, 2013). Table 28 shows the U-values and the insulation thicknesses that lead to those U-values. Since the external wall is composed of bridged layers, an equivalent insulation thickness for ESP-r has also been calculated. Values in orange correspond to the initial design of the house. Table 29 shows the different types of glazing considered and their U-values.

Table 28. Insulation thickness changes

Type of Construction	U-value (W/m²K)	Insulation layer thickness (m)	
		Real	ESP-r equivalent
Generic external wall	0.28	0.115	0.105
	0.22	0.170	0.145
	0.20	0.190	0.160
	0.18	0.220	0.180
	0.15	0.300	0.220
	0.10	0.550	0.340
Roof	0.16	0.220	
	0.15	0.240	
	0.13	0.270	
	0.12	0.300	
	0.11	0.320	
	0.10	0.360	
Suspended floor	0.20	0.150	
	0.18	0.170	
	0.17	0.180	
	0.15	0.210	
	0.13	0.240	
	0.11	0.300	

Table 29. Glazing changes

Type of glazing	U-value (W/m²K)
Double glazing	1.97
Triple glazing	1.60
Triple glazing with argon	1.40

6.2. Heating/cooling system

Alternative design options considered for the heating/cooling system include: ASHP air to water, ASHP air to air, electric boiler and biomass boiler. Data has been gathered to find specific systems that can provide the maximum heating load (4.19 kW) obtained from the simulation in ESP-r.

- **ASHP air to water:**

  The default heating system that is planned to be installed in the house is an Air Source Heat Pump (ASHP) air to water with underfloor heating or radiators. Even though in recent years, this type of systems has been used to provide heating and cooling, the cooling efficiency is limited (ATECYR, 2010), so a complementary system needs to be used. Therefore, in this case, it is assumed that the ASHP air to water will provide only heating. To find the characteristics of the system, the maximum heating load needs to be obtained from the model so a heat pump that has sufficient capacity can be selected. In this case the maximum load is 4.19 kW. The ASHP chose is the STÜHMR DOMESTIC RANGE Air to Water Heat Pumps Model AXHW-05 with a nominal capacity of 5.1 kW (slightly greater than the maximum heating load obtained from the simulation in ESP-r), and a nominal Coefficient of Performance (COP) of 4.1.

- **ASHP air to air:**
  This system can provide heating and cooling. The ASHP chose is the Greensource air to air heat pump with a heating capacity of 6 kW (slightly greater than the maximum heating load obtained from the simulation in ESP-r) and a nominal COP of 4.6. The cooling capacity is 4 kW and the nominal EER is 5.1.

- **Electric boiler with underfloor or radiators:**
  This system will provide only heating as the ASHP air to water initially planned. The electric boiler chose is the Amptec electric flow boiler with a heating capacity of 4 kW, which is slightly smaller than the maximum heating load obtained from the simulation in ESP-r but very similar, so it is considered adequate to meet the heating requirements of the house. The efficiency is 99.8%.

- **Biomass boiler with underfloor heating or radiators:**
  Again, this system will only be able to provide heating. The boiler chose is the wood pellet boiler Windhager UK VarioWIN1 with a heating capacity of 12 kW. This capacity is much greater than the maximum heating load obtained from the simulation in ESP-r (4.19 kW) since smaller biomass boilers are not common. The efficiency is 92.6%.

6.3. Ventilation system

Design options regarding the ventilation system are natural ventilation, mechanical ventilation and mechanical ventilation with heat recovery (MVHR).

Natural ventilation

The initial design of the house assumes natural ventilation through the windows as explained in Section 5.5.

Mechanical Ventilation

The ventilation rate required for each zone in the model, shown in Table 31, have been calculated using the suggested air supply rates for each type of room in a dwelling, that can be found in Table 1.5 of CIBSE Guide A (The Chartered Institution of Engineers London, 2006) (see Table 30).

Table 30. Suggested air supply rates for dwellings (The Chartered Institution of Engineers London, 2006)

Use	Air supply
Bathroom	15 L/s
Bedroom	1ach
Hall/Stairs	-
Kitchen	60 L/s
Living room	1 ach
Garage	6 ach

Table 31. Ventilation rates for the model zones

Zone	Air supply (L/s)	Air supply (m^3/h)
Basement	147.50	531.00
Ground floor	36.67	132.00
First floor	76.41	275.08
Second floor	21.39	77.00

For uncontrolled ventilation, it is assumed that the air flow is 0.4 ach (air changes per hour), since the house is assumed to have a good air tightness.

When defining the mechanical ventilation control system in ESP-r, the fans are set to provide the minimum ventilation required continuously.

Mechanical Ventilation with Heat Recovery (MVHR)

Once the minimum ventilation rate required is calculated, a specific MVHR system may be found. In this case, the minimum ventilation rate required is 1,015.08 m^3/h and the system chose is Model PAUL maxi 1201 DC with a rate capacity of 1,200 m^3/h (slightly greater than the minimum ventilation rate required). The heat recovery ratio[1] is 90.7% and the electricity consumption 585 W (Paul Wärmerückgewinnung, 2010).

One way of setting up an MVHR in an air flow network in ESP-r is to make a mixing box zone and supply all fresh air from that. Then, using the MVHR efficiency (90.7% in this case) set up the room to extract 90.7% to the mixing box. This ensures 90.7% of heat is extracted and supplied to the inlet.

6.4. Trade-off

To complete the analysis of design options, a combination of different options have been considered. Assuming there is a fixed budget for the construction of the building, the ASHP air to water initially planned may be substituted by an electric boiler, spending the difference cost on additional insulation and upgrading of the glazing.

6.5. Solution to avoid overheating

Finally, since the ASHP air to water initially planned to be installed is assumed to provide only heating to the house, a design option to avoid overheating of the house during the summer period has been analysed. This option considers the installation of blinds in the windows of the ground, first and second floor. For the simulation in ESP-r, it is considered that occupants will change the blinds from its open position to a middle point of the window when the inside temperature exceeds 22 ºC.

[1] Value for supply and extract air volume flow at t_{Au} = -10 °C, φ_{Au} = 90 % r.F. and t_{Ab} = 22 °C, φ_{Ab} = 50 % r.F.

Chapter 7. Analysis of results

In this chapter a comparison between the initial model of the house and the different design options previously described will be carried out based on the final energy consumption, CO_2 emissions and costs (both capital and running costs).

7.1. Energy consumption

The energy consumed by the heating/cooling system of the house can be calculated using the energy demand obtained by the model and the efficiency of the system.

$$Energy\ consumption = \frac{Energy\ demand}{Efficiency} \tag{7.1}$$

Equation 7.1 will be applied to the different design options simulated in order to calculate the energy consumed in every case.

7.1.1. Initial design

The electrical power consumption of the heat pump compressor ($\dot{Q}_e$) is a function of the rate of heat delivery to the load ($\dot{Q}_o$) and the performance characteristics of the heat pump (COP).

$$\dot{Q}_e = \frac{\dot{Q}_o}{COP} \tag{7.2}$$

Both, the COP and heat output rate of a heat pump vary depending upon the condenser and evaporator temperatures (temperature to which the heat is being delivered and temperature from which it is being taken).

$$COP = f_1(T_e, T_c) \tag{7.3}$$

$$\dot{Q}_o = f_2(T_e, T_c) \tag{7.4}$$

where T_e is the evaporator temperature and T_c the condenser temperature.

Assuming that the heat pump works properly, it can be assumed that during its operation, the temperature at which heat is delivered is relatively constant.

$$COP \cong f_1(T_e) \tag{7.5}$$

$$\dot{Q}_o \cong f_2(T_e) \tag{7.6}$$

Figure 24 shows the COP curve for the selected ASHP. Using this curve and the ambient temperature from ESP-r, the COP for each time step of the simulation period can be calculated. Then, according to Equation 7.2, energy consumption for each time step may be calculated dividing the heat load given by ESP-r by the COP calculated giving a final value of 333.3 kWh/year.

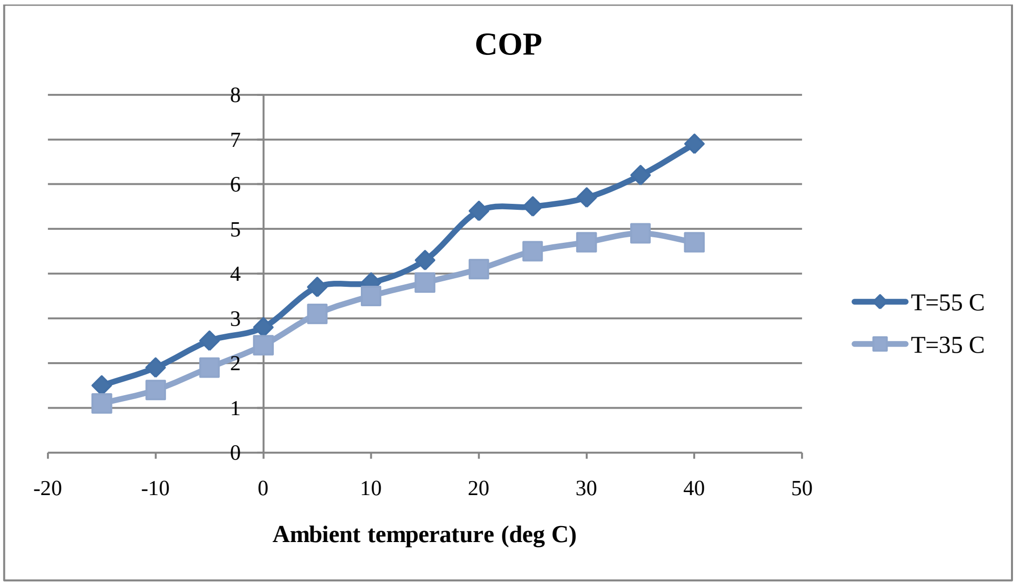

Figure 24. COP Curve for the ASHP STÜHMR AXHW-05

7.1.2. Alternative design options

Once energy demand for the different design options has been obtained from ESP-r simulations, energy consumption can be calculated using Equation 7.1 as already explained.

Thermal envelope

Design options considered regarding the thermal envelope include changes in the insulation thickness of the different constructions and changes in the type of glazing of the windows. These changes will vary the final energy demand of the building and therefore the energy consumption. Table 32 and Table 33 show the energy demand obtained from the simulations and the energy consumption calculated assuming the heating system is the ASHP air to water initially planned.

Table 32. Energy consumption for the insulation thickness changes

Type of Construction	U-value (W/m^2K)	Energy demand (kWh)		Energy consumption (kWh)	
		Heating	Cooling	Heating	Cooling
Generic external wall	0.28	1490.2	3446.0	410.37	-
	0.22	1336.5	3579.8	367.99	-
	0.20	1304.1	3621.3	359.22	-
	0.18	1264.8	3669.0	348.52	-
	0.15	1208.6	3740.1	333.30	-
	0.10	1096.8	3859.6	303.03	-
Roof	0.16	1248.4	3649.2	344.02	-
	0.15	1236.0	3684.3	340.81	-
	0.13	1230.1	3695.6	339.16	-
	0.12	1208.6	3740.1	333.30	-
	0.11	1224.2	3697.4	337.56	-
	0.10	1206.5	3731.1	332.64	-
Suspended floor	0.20	1253.3	3697.1	345.59	-
	0.18	1243.6	3708.2	342.99	-
	0.17	1240.4	3703.9	342.14	-
	0.15	1229.9	3718.5	339.17	-
	0.13	1223.7	3727.9	337.44	-
	0.11	1208.6	3740.1	333.30	-

Table 33. Energy consumption for the glazing changes

Type of glazing	U-value (W/m^2K)	Energy demand (kWh)		Energy consumption (kWh)	
		Heating	Cooling	Heating	Cooling
Double glazing	1.97	1208.60	3740.10	333.30	-
Triple glazing	1.60	1184.00	3071.00	327.27	-
Triple glazing with argon	1.40	1163.80	3569.60	322.81	-

Looking at the results in Table 32, it can be seen that the heating demand decreases when the U-value of the constructions decreases, since the building is better isolated and therefore heat losses to the outside are reduced. Upgrading the external walls from a U-value of 0.28 to 0.10 will lead to savings around 26% of the heating energy consumption. Upgrading the roof and suspended floor has less influence on the energy consumption, leading to savings around 3.5%.

In opposition, the cooling demand increases when the U-value of the constructions decreases as the insulation will keep the internal heat gains of the building inside the zones, leading to a reduction of the heat released to the ambient.

The heating system assumed is an ASHP air to water which will only provide heating to the house. Thus, the best option taking into account the energy consumption, will always be the one with the smallest U-value, even though the house will have a greater cooling demand and therefore inside temperature will be higher. Simulations were run to check maximum temperatures in the house when changing the U-value of the external walls and results show that maximum temperatures remain quite constant, with a temperature difference of 1.3 degrees between the smallest and the highest U-value.

Results in Table 33 show a different situation. In this case, both, heating and cooling demand decrease when reducing the U-value of the glazing since a better glazing improves the insulation of the building but will not keep the internal gains as much as the constructions since windows will be opened when the inside temperature goes over 22 degrees as already explained in Section 5.5.

Heating/cooling system

Alternative design options considered for the heating/cooling system include: ASHP air to water, ASHP air to air, electric boiler and biomass boiler. These changes will vary only the energy consumption maintaining the energy demand of the building invariable. Table 34 shows the energy consumption calculated using Equation 7.1.

Table 34. Energy consumption for the heating/cooling system changes

Heating/Cooling system	Efficiency/COP/EER	Energy consumption (kWh)	
		Heating	Cooling
ASHP Air to water	4.1	333.30	-
ASHP Air to air	4.6/5.1	262.74	733.35
Electric boiler	0.998	1,211.03	-
Biomass boiler	0.926	1,305.19	-

Results in Table 34 show that the best option, regarding the heating energy consumption, is the ASHP air to air, as this system has the highest efficiency (COP of 4.6). However, this system provides also cooling to the building, and thus, total energy consumption (996.09 kWh) is greater comparing to the ASHP air to water, which supplies only heating. An additional benefit of the ASHP air to air would be a greater comfort as the maximum inside temperature drops 10 degrees compared with the systems that provide only heating.

Ventilation system

Design options regarding the ventilation system are natural ventilation, mechanical ventilation and mechanical ventilation with heat recovery (MVHR). These changes will vary the final energy demand of the building and therefore the energy consumption.

Energy demand for the natural and mechanical ventilation options have been obtained from simulations run in ESP-r. In the case of the MVHR, the heat demand has been calculated subtracting the energy recovered to the loads calculated by ESP-r for every time step. Therefore,

$$Q_{demand} = \sum_{t} (Q_{load} - Q_{recovered})_t \tag{7.7}$$

where Q_{demand} is the heat demand, Q_{load} is the heat load from ESP-r and $Q_{recovered}$ is the heat recovered calculated.

The heat recovered is calculated as a percentage of the ventilation load. It is assumed that the MVHR system chose works at the heat recovery ratio specified in its technical data (90.7%) at all times, even though this ratio will change throughout the year depending on the air conditions inside and outside the building.

The ventilation load at every time step is calculated using the heat transfer equation for dry air:

$$\dot{Q}_{vent} = \dot{m}_{vent} C_p \Delta T = \rho_{air} \dot{V}_{vent} C_p (T_{zone} - T_{amb}) \qquad (7.8)$$

where $\dot{m}_{vent}$ is the ventilation mass flow, C_p is the specific heat of the air and ΔT is the temperature difference between the outside (T_{amb}) and the inside (T_{zone}) of the building.

As illustrated in Equation 7.8, the ventilation mass flow can be expressed as the ventilation volume flow rate ($\dot{V}_{vent}$) multiply by the air density (ρ_{air}). At sea level and under standard conditions (temperature of 25 ºC and pressure of 1 atmosphere), the density of the air is 1.225 kg per m^3 and the specific heat of the air is 1.006 kJ/kgK. Since the location of the house is close to the sea level and it is in a region with moderate climate, the error introduced by using these values will be negligible.

Table 35 shows the results obtained for the energy demand and the energy consumption calculated assuming that the heating system is the ASHP air to water initially planned. The energy consumption calculated does not include the electricity consumed by the fans of the mechanical ventilation systems.

Table 35. Energy consumption for ventilation system change

Ventilation type	Energy demand (kWh)		Energy consumption (kWh)	
	Heating	Cooling	Heating	Cooling
Natural	1,208.61	3,740.10	333.30	-
Mechanical	6,744.36	1,049.99	1,856.17	-
MVHR	2,683.73	1,049.99	744.10	-

Results in Table 35 show that continued mechanical ventilation leads to a heat demand approximately 5.6 times higher compared to natural ventilation, and a cooling demand 3.6 times smaller. Therefore, in terms of energy consumption of the heating system, natural ventilation is better than installing a mechanical ventilation system.

When using MVHR, the heat demand decreases by 60% compared to that obtained with the mechanical ventilation system without heat recovery. Still, the heat demand when using a MVHR system doubles the heat demand when using natural ventilation. This result was not expected as the heating demand when using MVHR should be less than the heating demand when using natural ventilation due to the heat recovered from the ventilation air flow.

This result is due to different air flow rates for the two ventilation options compared. The MVHR supplies the minimum ventilation required continuously while for natural ventilation, people are responsible for supplying fresh air to the house. In this case, the assumption of people opening the windows when inside temperature rises over 22 ºC will probably lead to an insufficient ventilation rate. Therefore, in this case, natural ventilation is the best option in terms of energy consumption of the heating system.

Despite this result, other aspects, like indoor air quality (IAQ), could be taking into account when considering mechanical ventilation. Natural ventilation control has been defined as occupants opening the windows when inside temperature exceeds 22 ºC but to check if the resulting ventilation rate is enough for a good air quality, results of CO_2 concentration inside the zones have been gathered from ESP-r (see Figure 25 and Figure 26).

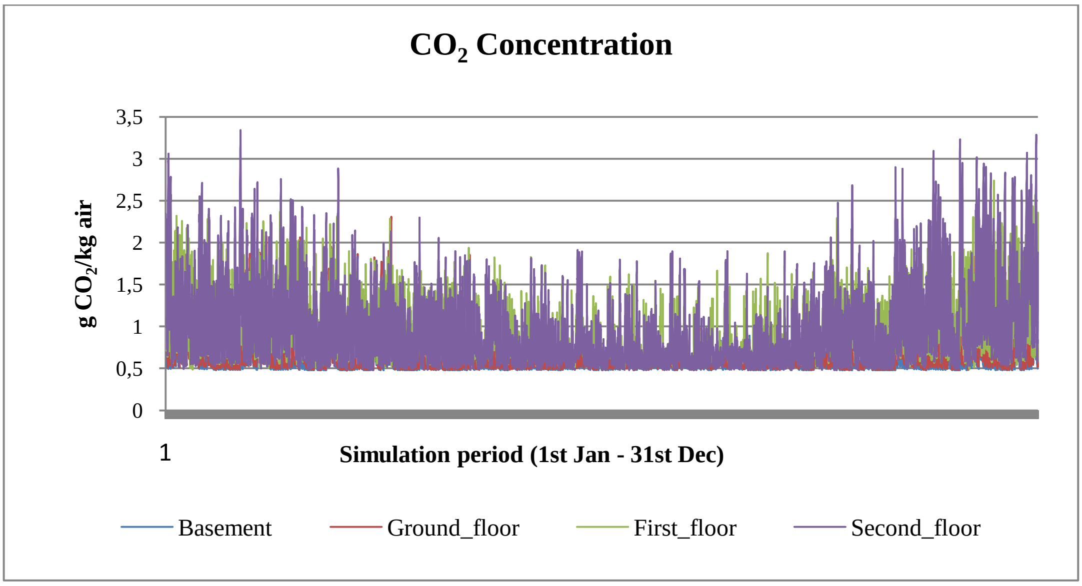

Figure 25. CO_2 concentration inside zones for Natural Ventilation

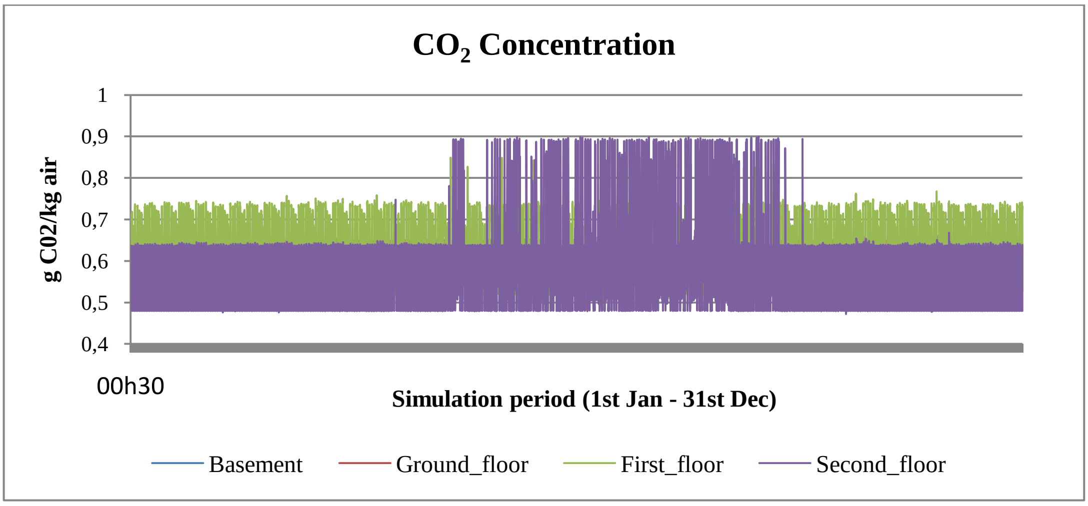

Figure 26. CO_2 concentration inside zones for Mechanical Ventilation

Initial CO_2 concentration is 0.48 g CO_2/kg air (480 ppm mass based concentration or 309 ppm volume based concentration)[2], which corresponds to the ambient CO_2 concentration. The only source for CO_2 is the occupancy previously described in Section 5.4.1.

Analysing natural ventilation results (Figure 25), it can be seen that control based on occupants opening the windows was not enough to meet the CO_2 concentration

[2] Volume based concentration calculated for a pressure of 1 bar and a temperature of 15 °C, where density of CO_2 is 1.87 kg/m^3 and 1.202 kg/m^3 for the air.

required in the house, which should be less than 1,000 ppm (volume based concentration) which is 1.56 g CO2/kg air. The mechanical ventilation system would provide a good solution for the IAQ as CO_2 concentrations remain very low with a maximum value of 0.9 g CO_2/kg air (see Figure 26).

7.2. CO_2 emissions

In this section, CO_2 emissions from the energy consumed by the heating/cooling system are calculated. This calculation will be carried out taking into account the different energy sources (electricity and biomass) according to the UK Government conversion factors for greenhouse gas reporting (Department of Environment, Food & Rural Affairs, 2014) shown in Table 36.

Table 36. DEFRA Carbon Factors 2014

Energy source	CO_2 emissions (kg CO_2/kWh)
Electricity	0.490230
Biomass (wood chips or pellets)	0.011838

Thermal envelope

Table 37 and Table 38 show the CO_2 emissions calculated from the energy consumption shown in Table 32 and Table 33.

Table 37. CO_2 emissions for the insulation thickness changes

Type of Construction	U-value (W/m^{2}K)	CO_2 emissions (kg CO_2)
Generic external wall	0.28	201.17
	0.22	180.40
	0.20	176.10
	0.18	170.85
	0.15	163.39
	0.10	148.55
Roof	0.16	168.65
	0.15	167.08
	0.13	166.27
	0.12	163.39
	0.11	165.48
	0.10	163.07
Suspended floor	0.20	169.42
	0.18	168.14
	0.17	167.73
	0.15	166.27
	0.13	165.42
	0.11	163.39

Table 38. CO_2 emissions for the glazing changes

Type of glazing	U-value (W/m^2K)	CO_2 emissions (kg CO_2)
Double glazing	1.97	163.39
Triple glazing	1.60	160.44
Triple glazing with argon	1.40	158.25

Since the heating system is the ASHP air to water initially planned, the energy source is electricity for all the options considered. Therefore, results in Table 37 and Table 38 show, as expected, that the best option taking into account the CO_2 emissions, will always be the one with the smallest U-value, even though the house will have a greater cooling demand when decreasing the U-value of external wall, roof and suspended floor.

Heating/cooling system

Table 39 shows the CO_2 emissions calculated from the energy consumption shown in Table 34. In this case, energy sources are electricity and biomass, depending on the heating system considered.

Table 39. CO_2 emissions for the heating/cooling system changes

Heating/Cooling system	Efficiency/COP/EER	CO_2 emissions (kg CO_2)	
		Heating	Cooling
ASHP Air to water	4.1	163.39	-
ASHP Air to air	4.6/5.1	128.80	359.51
Electric boiler	0.998	593.68	-
Biomass boiler	0.926	15.45	-

Results in Table 39 show that the best option, regarding the CO_2 emissions, is the biomass boiler, being the worst one the electric boiler. Upgrade of the ASHP air to water initially planned to a biomass boiler will lead to a saving of the CO_2 emissions of more than 90%.

These results were expected as the carbon factor for the biomass is very low (0.011838 kg CO_2/kWh), as shown in Table 36, since it takes into account that trees absorb CO_2 from the atmosphere when they grow up. On the other hand, the carbon factor for electricity in the UK is quite high (0.490230 kg CO_2/kWh) since electricity generation in UK power stations is carbon-intensive, although some electricity is exported to Ireland and imported from France (much less carbon-intensive than UK electricity). More information on how these factors are calculated can be found in the *Methodology Paper for Emission Factors* (Department of Energy and Climate Change, 2014).

Ventilation system

Table 40 shows the CO_2 emissions calculated from the energy consumption shown in Table 35.

Table 40. CO_2 emissions for the ventilation system changes

Ventilation type	CO_2 emissions (kg CO_2)
Natural	163,39
Mechanical	909,95
MVHR	364,78

Since the heating system is the ASHP air to water initially planned, the energy source is electricity for all the options. Therefore, results in Table 40 show, as expected, that the best option, regarding the CO_2 emissions, is the natural ventilation system. However, other parameters, as IAQ, could be taking into account when considering installing a mechanical ventilation system as already analysed in Section 7.1.2.

7.3. Costs

Financial aspects are crucial when considering different design options as they will determine whether a more energy efficient or environment friendly system is cost-effective.

In this analysis, both, capital and running costs are considered since capital costs will determine whether an option may be purchased or not, and running costs will determine if the option considered is really worth it in the medium to long term.

7.3.1. Capital costs

Thermal envelope

Incremental costs for upgrading the fabric and glazing of detached houses can be found in the *Changes to Part L of the Building Regulations 2013 - Impact Assessment* (Department for Communities and Local Government, 2013). This data has been approximate to regression curves in order to calculate the incremental costs for the U-values simulated in ESP-r.

External wall

Table 41 and Figure 27 show the incremental costs of upgrading the external walls. These incremental costs are based on the minimum U-value required by the building regulations (0.28 W/m^{2}K). Since the initial design of the house has a very low U-value (0.15 W/m^{2}K), most of the options would lead to cost savings (negative incremental capital cost) of choosing higher U-values that the one initially planned.

Table 41. Incremental costs for upgrading the external wall

U-value (W/m^{2}K)	0.28	0.22	0.2	0.18	0.15	0.1
Cost/Area (£/m^2)	0.00	5.05	7.58	10.10	16.57	34.56
Incremental Capital Cost (£)	0.00	699.43	1,049.84	1,398.86	2,294.96	4,786.69

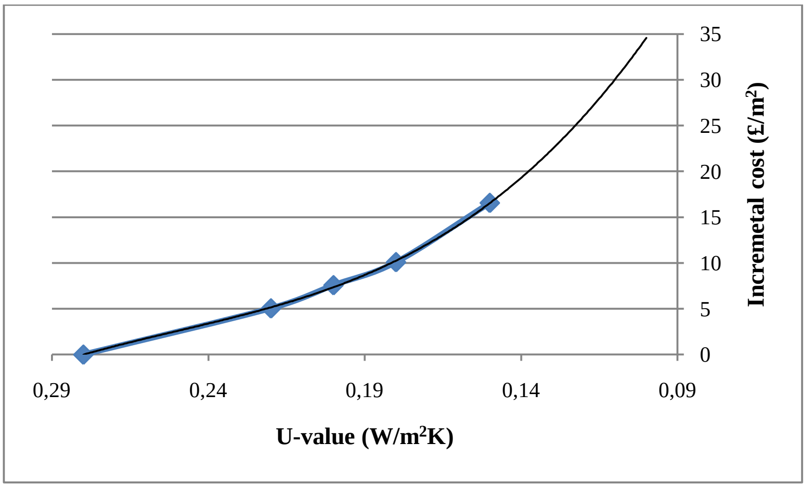

Figure 27. Incremental costs for upgrading the external wall

Suspended floor

Table 42 and Figure 28 show the incremental costs of upgrading the suspended floor above the basement. These incremental costs are based on the minimum U-value required by the building regulations (0.2 W/m^{2}K). Again, since the initial design of the house has a very low U-value (0.11 W/m^{2}K), all the options considered would lead to cost savings (negative incremental capital cost) of choosing higher U-values that the one initially planned.

Table 42. Incremental costs for upgrading the suspended floor

U-value (W/m^{2}K)	0.2	0.18	0.17	0.15	0.13	0.11
Cost/Area (£/m^2)	0.00	0.65	1.16	2.62	4.66	7.24
Incremental Capital Cost (£)	0.00	29.12	51.97	117.38	208.77	324.27

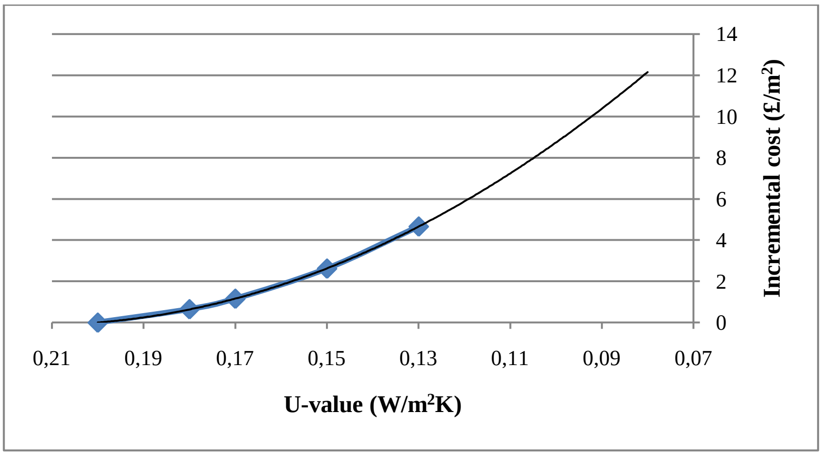

Figure 28. Incremental costs for upgrading the suspended floor

Roof

Table 43 and Figure 29 show the incremental costs of upgrading the roof. These incremental costs are based on the minimum U-value required by the building regulations (0.16 W/m^{2}K). Again, since the initial design of the house has a very low U-value (0.12 W/m^{2}K), most of the options considered would lead to cost savings (negative incremental capital cost) of choosing higher U-values that the one initially planned.

Table 43. Incremental costs for upgrading the roof

U-value (W/m^{2}K)	0.16	0.15	0.13	0.12	0.11	0.1
Cost/Area (£/m^2)	0.00	0.30	1.07	2.04	3.73	6.40
Incremental Capital Cost (£)	0.00	14.35	51.18	97.80	178.42	305.99

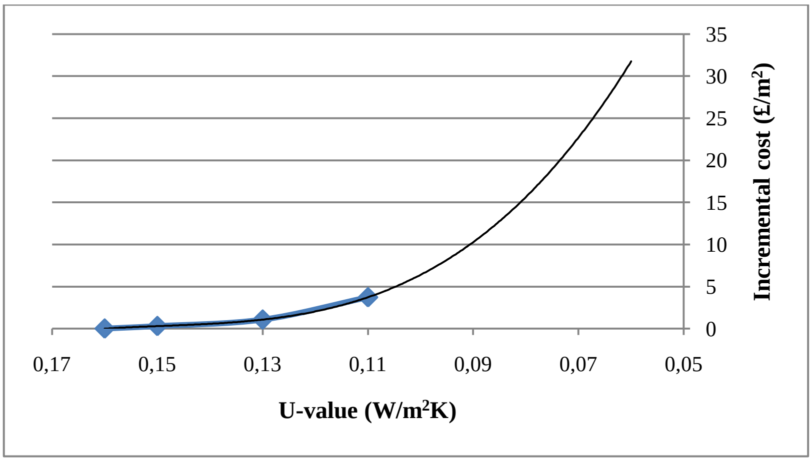

Figure 29. Incremental costs for upgrading the roof

Glazing

Table 44 and Figure 30 show the incremental costs of upgrading the glazing of a detached house. These incremental costs are based on a U-value of 1.8 W/m^{2}K, which is slightly smaller than the minimum required by the building regulations (2 W/m^{2}K). In this case, in opposition to the fabric upgrades analysis, the initial design of the house has a high U-value (1.97 W/m^{2}K), so all the options considered would lead to incremental cost of choosing smaller U-values that the one initially planned.

Table 44. Incremental costs for upgrading the glazing

U-value (W/m^{2}K)	1.8	1.6	1.5	1.4	1.2	0.8
Cost/Area (£/m^2)	0.00	25.00	30.00	32.50	62.50	117.25
Incremental Capital Cost (£)	0.00	709.13	850.95	921.86	1772.81	3,325.80

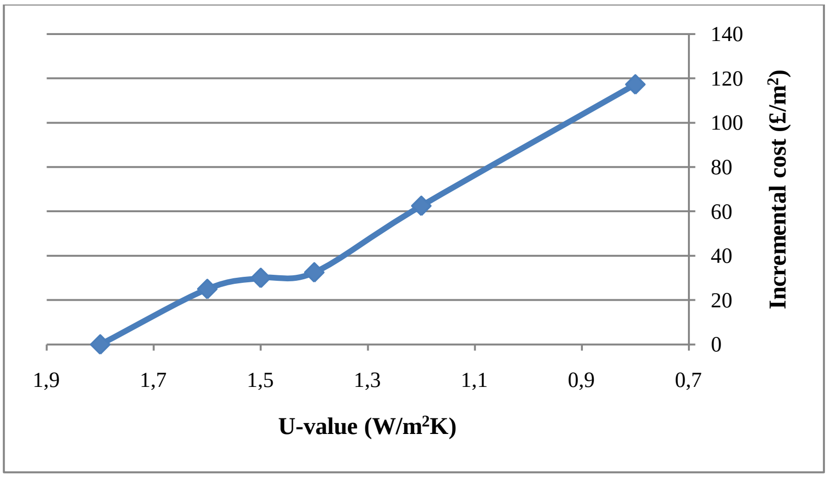

Figure 30. Incremental costs for upgrading the glazing

Heating/cooling system

Capital cost data regarding the different heating/cooling systems considered has been gathered from several sources as follows:

ASHP air to water

According to (Energy Saving Trust, 2014), installing a typical ASHP system costs around £7,000 to £14,000.

Electric boiler

According to the *Boiler Installation Cost and Prices Guide* (ServiceMagic Ltd, 2014), an electric boiler costs between £500 and £1,300 plus around £600 for installation.

Biomass boiler

An automatically fed pellet boiler for an average home costs between £14,000 and £19,000 including installation, flue, fuel store and VAT at 5% according to (Energy Saving Trust, 2014).

ASHP air –air

According to (Energy Saving Trust, 2014), installing a typical ASHP system costs around £7,000 to £14,000.

Ventilation system

MVHR systems can cost in the region of £1,500 to £3,000 according to (Centre for Sustainable Energy, 2013).

7.3.2. Running costs

The running costs or operational costs will be the costs associated to the energy consumed by the heating/cooling system of the building. In order to calculate these costs, energy price data has been gathered and it is shown in Table 45.

Table 45. Energy prices July 2014 (Nottingham Energy Partnership, 2014)

Energy source	Cost (p/kWh)
Electricity (standard rate)	16.02
Biomass (wood chips or pellets)	6.11

Running costs for the different options considered are shown in the next section, together with the simple payback period, in order to find which option is the most cost-effective.

7.3.3. Simple Payback Period

Once the capital and running costs for each option are calculated, a cost analysis may be carried out using the simple payback period method. The simple payback period is the time in which the initial cash outflow of an investment (capital cost of each option considered) is expected to be recovered from the cash inflows (running cost savings) generated by the investment. The equation to calculate the simple payback period for even cash flow per period is:

$$Payback\ period = \frac{Initial\ Investment}{Periodic\ Cash\ Flow} \tag{7.9}$$

When analysing different options using the simple payback method, the option with the shortest payback will be the best one.

This method has the advantage of its simplicity but it does not take into account the time value of money. A possible solution would be the use of the discounted payback period method, which takes into account that cash inflow in the future will worth less due to the devaluation of money with time. This method is more accurate but adds complexity to the analysis, so in this case, simple payback period method has been chosen.

Thermal envelope

Table 46 and Table 47 show the costs analysis for the different options considered regarding the thermal envelope of the building. Running costs have been calculated from the energy consumption shown in Table 32 and Table 33. The simple payback period has been calculated using Equation 7.9, where the initial investment is the incremental capital cost of each option and the periodic cash flow is the saving (running cost difference) compared to the case with the minimum U-value required by the regulations.

Table 46. Costs for the insulation thickness changes

Type of Construction	U-value (W/m^2K)	Costs		Simple Payback (yr)	Incentive needed (£)
		Incremental Capital (£)	Running (£/yr)		
Generic external wall	0.28	0.00	65.74	0.00	0.00
	0.22	699.43	58.95	103.03	631.55
	0.20	1,049.84	57.55	128.14	967.91
	0.18	1,398.86	55.83	141.19	1,299.78
	0.15	2,294.96	53.39	185.88	2,171.49
	0.10	4,786.69	48.54	278.37	4,614.73
Roof	0.16	0.00	55.11	0.00	0.00
	0.15	14.35	54.60	27.90	9.21
	0.13	51.18	54.33	65.76	43.40
	0.12	97.80	53.39	56.92	80.62
	0.11	178.42	54.08	172.25	168.06
	0.10	305.99	53.29	167.81	287.76
Suspended floor	0.20	0.00	55.36	0.00	0.00
	0.18	29.12	54.95	69.86	24.95
	0.17	51.97	54.81	94.09	46.45
	0.15	117.37	54.34	114.20	107.09
	0.13	208.77	54.06	159.82	195.71
	0.11	324.27	53.39	164.65	304.57

Table 47. Costs for the glazing changes

Type of glazing	U-value (W/m^2K)	Costs		Simple Payback (yr)	Incentive needed (£)
		Incremental Capital (£)	Running (£/yr)		
Double glazing	1.97	0.00	53.39	0.00	0.00
Triple glazing	1.60	709.13	52.43	735.13	707.58
Triple glazing with argon	1.40	921.86	51.71	548.76	919.17

Results in Table 46 and Table 47 show that reducing the U-value of the different constructions and the glazing from those required by the regulations, is never worth it according to the simple payback period, which has a minimum value of 27.90 years when upgrading the U-value of the roof from 0.16 to 0.15 W/m^2K.

Therefore, energy efficiency measures in buildings need of incentives to become cost-effective. Thus, incentive needed for a 10 year-simple payback period has been calculated for each design option considered, since these measures are assumed to last around 20 years at least. The maximum incentive needed is £ 4,614.73, which corresponds to the case of upgrading the external walls from 0.28 to 0.10 W/m^2K.

Heating/cooling system

Table 48 shows the costs analysis for the different options considered regarding the heating/cooling system of the building. Running costs have been calculated from the energy consumption shown in Table 34, and the simple payback period has been calculated using Equation 7.9. The initial investment is the capital cost difference between each option and the electric boiler since its option has the minimum capital cost. The periodic cash flow is the saving (running cost difference) between each option and the electric boiler.

Table 48. Costs for the heating/cooling system changes

Heating/Cooling system	Costs		Simple Payback (yr)	Incentive needed (£)
	Incremental Capital (£)	Running (£/yr)		
ASHP Air to water	7,000 - 14,000	53.39	36.27 - 91.74	3,693.87 - 11,493.87
ASHP Air to air	7,000 - 14,000	159.57	148.11 - 374.64	4,755.67 - 12,555.67
Electric boiler	1,100 - 1,900	194.01	0.00	0.00
Biomass boiler	14,000 - 19,000	79.75	105.90 - 156.66	10,957.40 - 16,757.40

The results in Table 48 show that selecting a system other than an electric boiler is never worth it according to the simple payback period, which has a minimum value of 36.27 years when installing a £ 7,000 - ASHP air to water.

Again, these energy efficiency measures need of incentives to become cost-effective. The incentives needed for a 10 year-simple payback period range from £ 3,693.87 for an ASHP air to water, to £ 16,757.40 for a biomass boiler.

It is important to notice that the results in Table 48 show quite extent ranges for the simple payback period and incentive needed for a 10 year-simple payback because there are very sensitive to the capital costs, which are not fixed values.

Ventilation system

Table 49 shows the costs analysis for the different options considered regarding the ventilation system of the building. Running costs have been calculated from the energy consumption shown in Table 35, and the simple payback period has not been calculated in this case since the initial investment of a mechanical ventilation system will never be recovered. As explained in Section 7.1.2, other parameters, as IAQ, could be taking into account when considering installing a mechanical ventilation system.

Table 49. Costs for ventilation system change

Ventilation type	Costs	
	Incremental Capital (£)	Running (£/yr)
Natural	0	53.39
Mechanical	1,500 – 3,000	297.36
MVHR	1,500 – 3,000	119.20

7.4. Trade-off

To complete the analysis of design options, a combination of different options have been considered. Assuming there is a fixed budget for the construction of the building, the ASHP air to water initially planned may be substituted by an electric boiler, spending the difference cost on additional insulation and upgrading of the glazing.

Table 50 shows the comparison between the initial design of the house and this trade-off between the heating/cooling system and the thermal envelope.

Table 50. Results for Trade-off comparison

	Energy demand (kWh)		Energy consumption (kWh)	Running cost (£/yr)	CO_2 emissions (kg CO_2)
	Heating	Cooling			
Initial design	1,208.60	3,740.10	333,30	53.39	163,39
Trade-off	1,163.75	3,569.50	1,166.08	186.81	571,65

The results in Table 50 show that the trade-off option has a lower heating and cooling demand since the thermal envelope of the house is improved. However, the energy consumed by the heating system is greater and so are the running costs and the CO_2 emissions, because the efficiency of the ASHP air to water is more than 3 times greater than the efficiency of the electric boiler, while the difference in the energy demand is negligible. Therefore, the trade-off is not worth it in terms of energy consumption, costs or CO_2 emissions.

7.5. Solution to avoid overheating

Finally, since the ASHP air to water initially planned to be installed is assumed to provide only heating to the house, a design option to avoid overheating of the house during the summer period has been analysed. This option considers the installation of blinds in the windows of the ground, first and second floor. For the simulation in ESP-r, it is considered that occupants will change the blinds from its open position to a middle point of the window when the inside temperature exceeds 22 ºC.

The results in Table 51 show that installing blinds may reduce the cooling demand by 66.5% while the heating demand increases slightly (less than 10%).

Table 51. Results for blinds comparison

	Energy demand (kWh)	
	Heating	**Cooling**
Initial design	1,208.60	3,740.10
Blinds	1,326.50	1,251.40

Chapter 8. Conclusions and recommendations

This chapter highlights the conclusions that arise from the analysis of results previously developed for the different design options regarding the thermal envelope, the heating/cooling system and the ventilation system. A result summary with the best and worst option in every case according to the energy consumption, CO_2 emissions, capital cost and payback period is shown in Table 52. Finally, some recommendations for further work to be done are provided.

8.1. Thermal envelope

Since the heating system planned in first place is an ASHP air to water, which is assumed to provide only heating to the house, the best option in terms of energy consumption will always be the one with the smallest U-value (smallest heating demand), even though the cooling demand will be greater as already discussed in Section 7.1.2. For the same reason, the best option, according to the CO_2 emissions, will also be the one with the smallest U-value. Additional insulation in external walls will reduce the heating demand by 26%, having a greater effect than additional insulation in roofs and floors, or upgrading of the glazing.

On the other hand, the cost analysis (Table 46 and Table 47) shows that reducing the U-value of the different constructions and the glazing, from the minimum required by the regulations, is never worth it unless an incentive is provided. Therefore, research on grants and incentives that promote energy efficiency measures in buildings should be carried out to find the most cost-effective option.

8.2. Heating/cooling system

Results from the heating/cooling systems analysed, show that the systems that consume less energy correspond to the ASHPs, both air to air and air to water, since heat pumps have very high efficiencies (COP around 4). The selection between an ASHP air to air or an ASHP air to water will depend upon the level of comfort desired since the ASHP air to air will usually provide heating and cooling to the house, decreasing therefore, the maximum inside temperature during the summer period.

In terms of CO_2 emissions, the best option is, obviously, the biomass boiler as the energy source is renewable, and the worst option is the electric boiler. However, according to the cost analysis, selecting a system other than an electric boiler is never worth it unless incentives are available due to its low capital cost. Again, research should be carried out to find grants or incentives that promote low carbon systems, compensating the difference in capital cost between an electric boiler and a more environment friendly system.

8.3. Ventilation system

Results showed that natural ventilation is better than installing a mechanical ventilation system in terms of energy consumption, CO_2 emissions and costs. However, the use of continuous mechanical ventilation provides further benefits as already discussed:

- Cooling demand will decrease
- Good solution for IAQ as minimum required ventilation is always provided

An important result obtained shows that it is essential to include heat recovery (MVHR) when using mechanical ventilation since heating demand decreases by 60% compared to that obtained with the mechanical ventilation without heat recovery.

8.4. Trade-off

Trade-off between the heating/cooling system and the thermal envelope was also analysed. The ASHP initially planned was substituted by an electric boiler, spending the difference cost on additional insulation and upgrading the glazing. Results showed that the trade-off option decreases the heating and cooling demand but the energy consumed by the heating system is greater and so are the running costs and the CO_2 emissions, so this option is not worth it.

8.5. Solution to avoid overheating

Simulation results showed that the installation of blinds is a good solution to avoid overheating during the summer period as it may reduce the cooling demand by 66.5% while the heating demand increases slightly (less than 10%).

8.6. Result summary

A result summary with the best and worst option in every case according to the energy consumption, CO_2 emissions, capital cost and payback period is shown in Table 52. The general conclusion that arises from these results is that energy efficiency measures in buildings (additional insulation in constructions, better glazing, more efficient heating systems or the use of renewable energy sources) help to reduce the energy consumption, CO_2 emissions and running cots but they need of incentives in order to be cost effective.

From an environmental point of view, when considering additional insulation in constructions, the best option is to increase the insulation of external walls. Regarding the heating/cooling systems, the options considered should be either a heat pump to reduce the energy consumption, or a renewable energy source to reduce the CO_2 emissions. Finally, the ventilation should be natural or MVHR to decrease the heating demand while guarantying the minimum ventilation rate is provided to the house.

Table 52. Results summary

Design Option	Energy Consumption	CO_2 Emissions	Costs	
			Incremental Capital Cost	Simple Payback Period
Generic external wall				
U = 0.28 W/m^{2}K	✗	✗	✓	✓
U = 0.22 W/m^{2}K				
U = 0.20 W/m^{2}K				
U = 0.18 W/m^{2}K				
U = 0.15 W/m^{2}K				
U = 0.10 W/m^{2}K	✓	✓	✗	✗
Roof				
U = 0.16 W/m^{2}K	✗	✗	✓	✓
U = 0.15 W/m^{2}K				
U = 0.13 W/m^{2}K				
U = 0.12 W/m^{2}K				
U = 0.11 W/m^{2}K				✗
U = 0.10 W/m^{2}K	✓	✓	✗	
Suspended floor				
U = 0.20 W/m^{2}K	✗	✗	✓	✓
U = 0.18 W/m^{2}K				
U = 0.17 W/m^{2}K				
U = 0.15 W/m^{2}K				
U = 0.13 W/m^{2}K				
U = 0.11 W/m^{2}K	✓	✓	✗	✗
Glazing				
Double glazing	✗	✗	✓	✓
Triple glazing				✗
Triple glazing with argon	✓	✓	✗	
Heating/cooling System				
ASHP Air to water	✓			
ASHP Air to air	✓			✗
Electric boiler		✗	✓	✓
Biomass boiler	✗	✓	✗	✗
Ventilation System				
Natural	✓	✓	✓	✓
Mechanical	✗	✗	✗	✗
MVHR			✗	✗

8.7. Further work

Finally, recommendations for further work to improve the analysis of design options carried out are provided.

8.7.1. Construction of the model

The model built using ESP-r simulation tool is a simplified model for a high level analysis. This model can be improved in order to be more accurate. Some options that can be implemented are:

- Definition of more zones to differentiate, for example, between the lobby, wet room and garage, or between different bedrooms.
- Inclusion of CO_2 control to the air flow network so occupants can open the windows either when temperature is too high or CO_2 concentration is too high.
- Definition of the ASHP so the simulation tool can provide its energy consumption.
- Definition of an MVHR making a mixing box zone to supply all fresh air from that and use the MVHR efficiency so that percentage of heat is extracted and supplied to the inlet.

8.7.2. Verification of the model

When possible, comparison between the energy consumption of the model with energy consumption measured from similar houses in the area should be done. This is not an easy thing to do since energy consumption data is not usually available.

8.7.3. Design options considered

Beside the design options considered in this project, more options can be analysed, for example:

- **Passive solar design**: change in dimensions and number of windows could be done, as well as inclusion of windows reveals for shading.
- **Renewable energy sources**: inclusion of thermal solar, PV or a domestic wind turbine could be also analysed.

8.7.4. Cost analysis

The cost analysis carried out could be improved using the discounted payback period method, which takes into account that cash inflow in the future will worth less due to the devaluation of money with time. Also, possible grants and incentives from the government and other organizations could be added to the analysis.

8.7.5. Sensitivity analysis

Several assumptions have been made throughout the project, for example, occupant's behaviour (occupancy schedule, control of windows by the occupants, etc), which can alter the predicted energy performance significantly (Clarke, 2006). Therefore, a sensitivity analysis could be carried out to check the effect of the assumptions made to see how they influence the results.

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Appendix I. Geometry Details

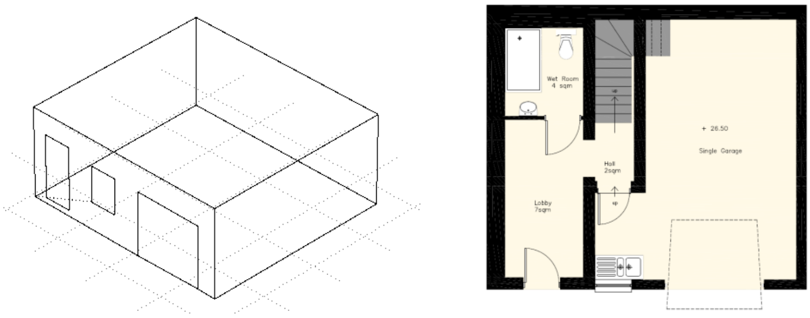

Figure 31. Basement model (left) and plan (right) (Ford, 2014)

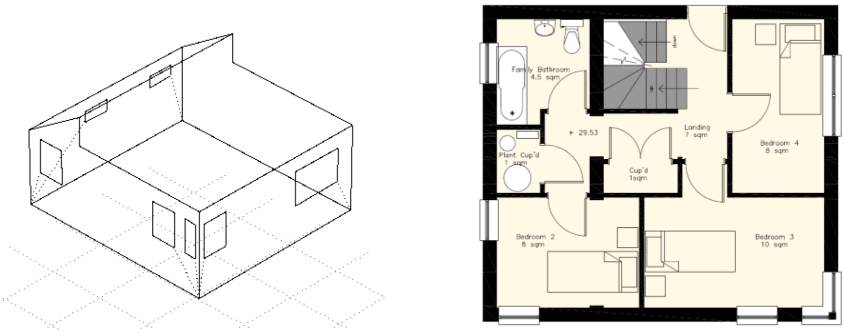

Figure 32. Ground floor model (left) and plan (right) (Ford, 2014)

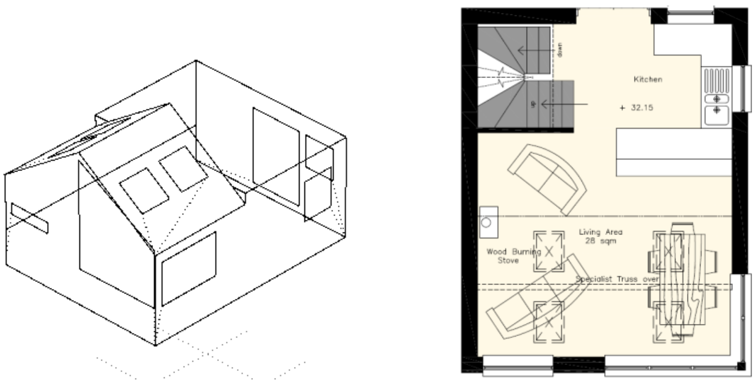

Figure 33. First floor model (left) and plan (right) (Ford, 2014)

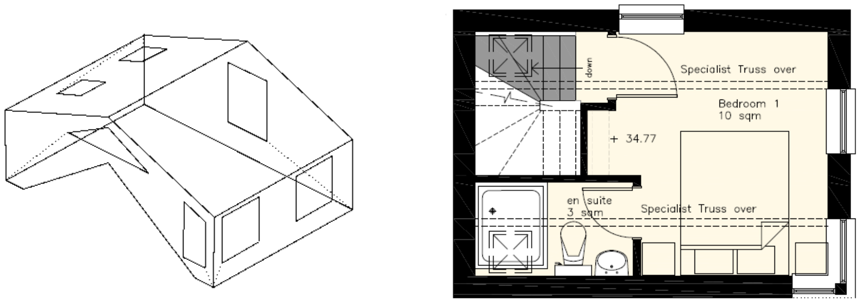

Figure 34. Second floor model (left) and plan (right) (Ford, 2014)

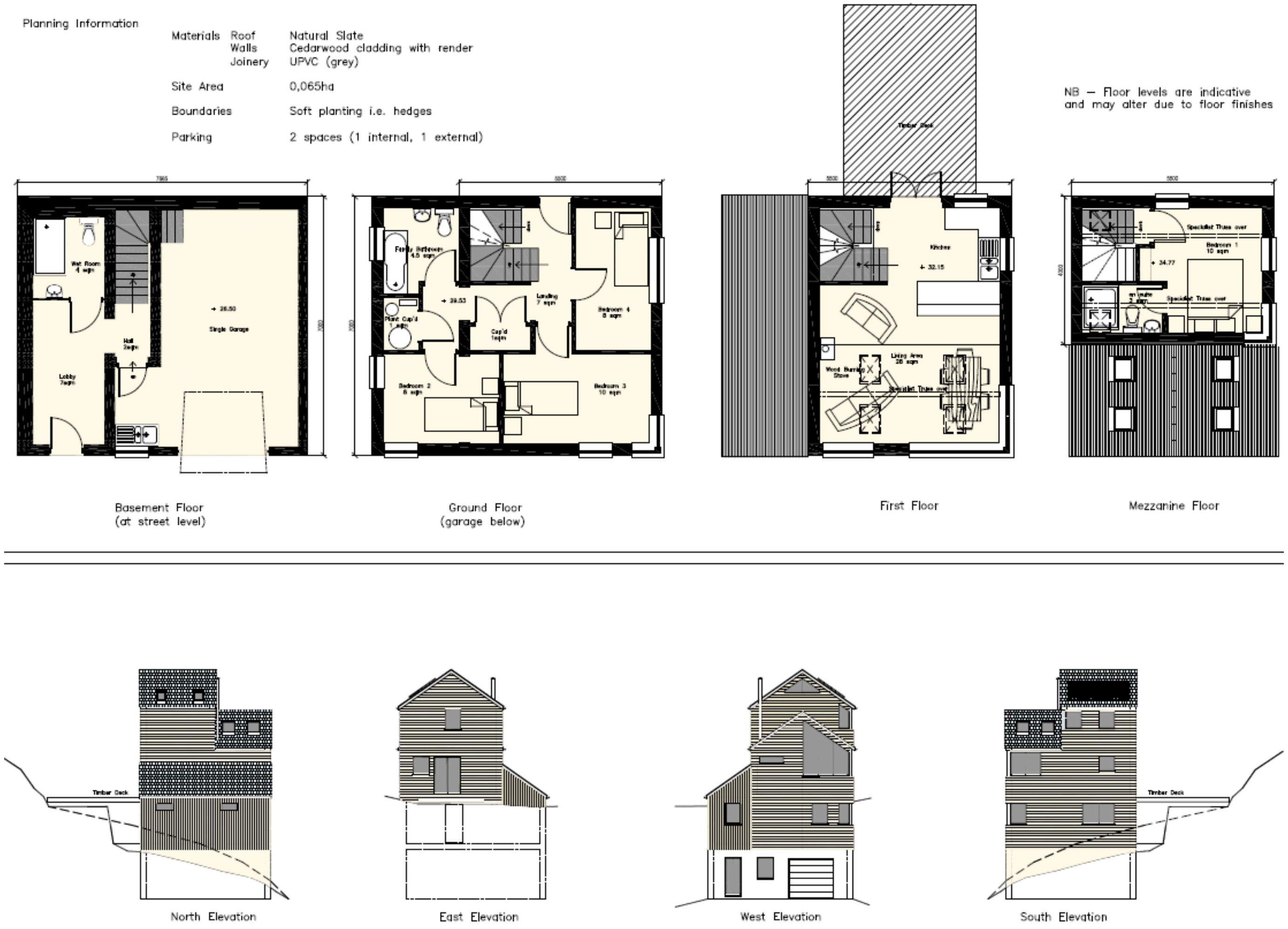

Figure 35. Floor plans and elevations (Ford, 2014)

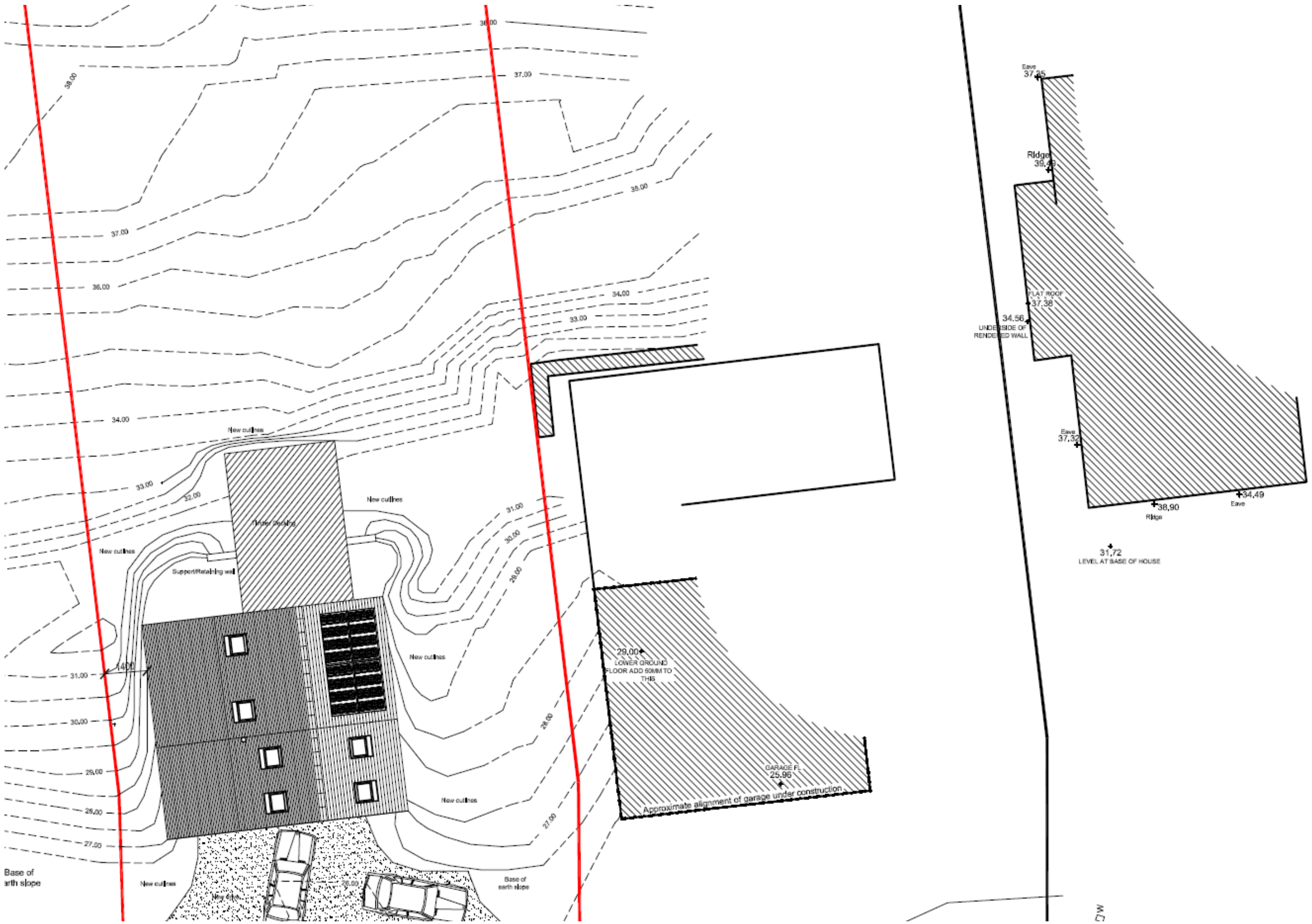

Figure 36. Site plan (Ford, 2014)

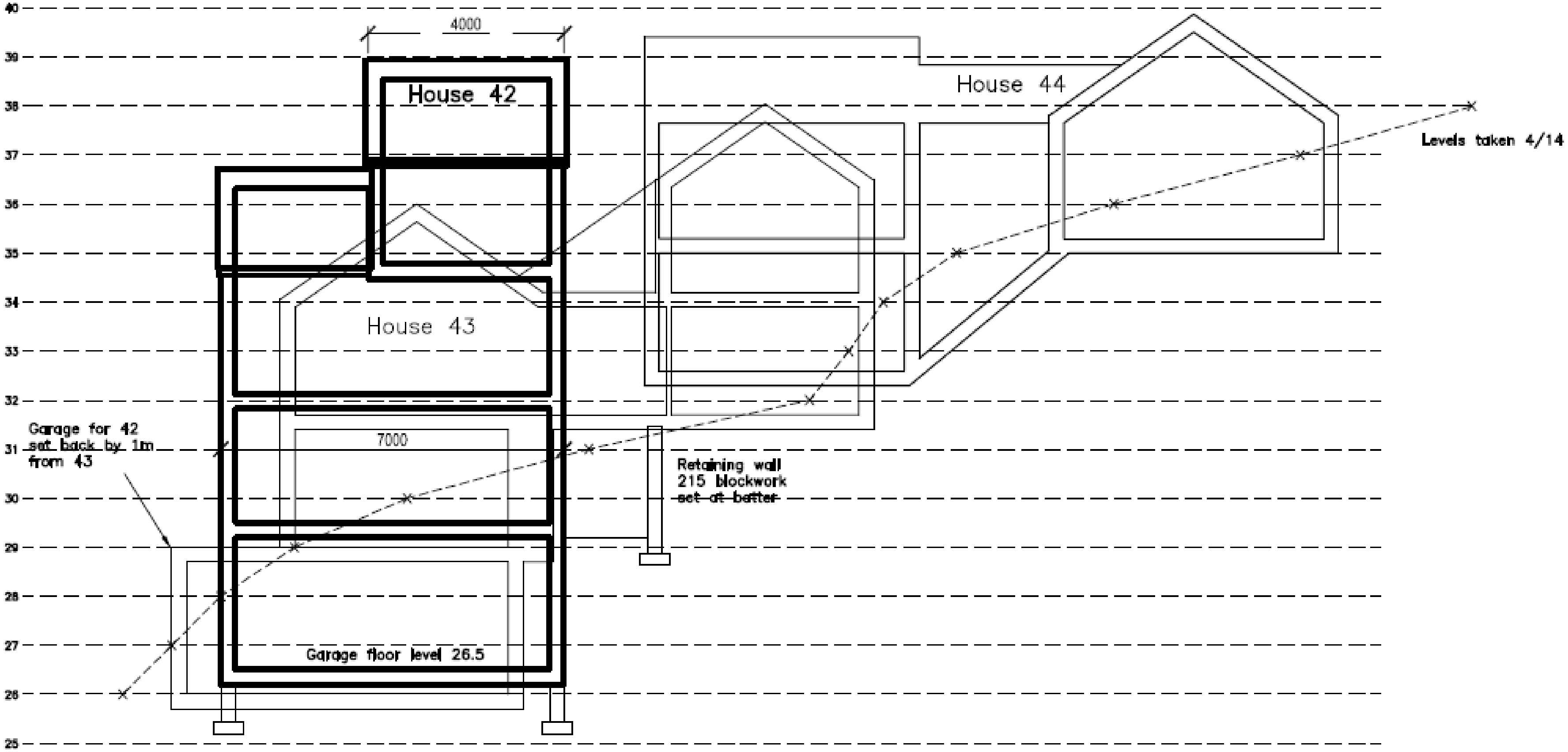

Figure 37. Diagrammatic Sections (Ford, 2014)