Department of Mechanical and Aerospace Engineering

A Dynamic Modelling Approach to Assessing the Operational Performance of Net Zero Carbon Homes

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Signed: Jordan Grant Date: Friday 6th September 2013

Abstract

The 2008 Climate Change Act states that there should be a 34 % cut in 1990 greenhouse gas emissions by 2020 and at least an 80 % cut in emissions by 2050. With domestic buildings being responsible for over a quarter of the UK's greenhouse gas emissions, it would be impossible to meet these targets without tackling the emissions in the domestic building sector. In 2010, UK and Scottish governments made clear their intention to reduce carbon dioxide emissions from the domestic housing sector through their commitment to ensure that as of 2016, all new homes will be required to be zero carbon. For many years the governments focus has been on the supply side and renewable energy generation. However, more recently, the governments' policies have changed slightly in that now more than ever the focus is on the demand side and reducing energy demand. It is thought that from 2016, new homes will have to incorporate both the reduction of energy demand and the generation of renewable energy on-site to achieve the zero carbon status.

Although the concept of zero carbon housing has been around for a while, it has never been a requirement and so developers and house builders will need to learn how to properly design and build these homes relatively quickly. This project aims to aid developers and house builders by assessing the operational performance of an existing zero carbon house and focuses on how dynamic modelling, used at the design stage, can aid the development of these homes.

Results on the simulated operational performance of an existing zero carbon house are presented in terms of annual space heating demand and the carbon emissions associated with this. Modifications were then made to the simulation model and the impacts on operational performance were discussed. The modifications made in this project were enhancements to the airtightness of the model, enhancements to the external wall insulation and finally an upgrade from a basic control system to a sophisticated control system was implemented. It is thought that the results of these simulations, and dynamic modelling in general, can be an extremely useful design tool for optimising the operational performance of domestic buildings before construction has even begun.

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I would first like to thank everyone at the Energy Systems Research Unit who have enhanced my knowledge and have encouraged me throughout the Renewable Energy Systems and the Environment course. I would also like to give a special thanks to my academic supervisor Professor Joe Clarke. Throughout this individual project he has continued to support, encourage and guide me and for this I am truly grateful.

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1. Project Outline

1.1. Aims and Objectives

The aim of this project was to aid future design of net zero carbon homes by assessing the as built performance of an existing net zero carbon house in terms of its annual energy use on space heating and the carbon emissions associated with this as well as the environmental conditions within the house and to recommend modifications in order to reduce energy as far as possible whilst keeping the environmental conditions in the house at a comfortable level.

The aim of this project was achieved by setting out and completing the following objectives:

- Carry out a comprehensive and critical literature review into the following areas:
  - Energy use in the UK
    - Built Environment – Domestic Sector
  - Government Legislation (Code for Sustainable Homes, Government Incentives)
  - The Net Zero Carbon Housing Concept
  - Approaches, features and examples of Net Zero Carbon Homes
- Select a platform on which to model the existing net zero carbon house and learn how to build models from scratch using the package.
- Build a detailed simulation model of the existing net zero carbon home on the chosen platform.

- Simulate the house ‘as built’ and assess the operational performance in terms of annual space heating demand, carbon emissions and thermal comfort.
- Assess the operational performance of the house when modifications are made in the simulation environment such as enhancements in:
    - Air tightness
    - Insulation
    - Control Systems
- Make recommendations, based on the evaluation of my results, on how to optimise the energy performance of the house whilst keeping the thermal environment within the house pleasant.

1.2. Research Method: Dynamic Modelling

A dynamic modelling approach was taken for this project due to the immediate availability of an existing net zero carbon home which would allow a comprehensive simulation model of the house to be built. It was thought by simulating the house ‘as built’ that the operational performance of the house could be assessed to determine whether or not it was operating as it was expected to or how developers thought it should be. By making modifications to this model, building simulation can then be used as a design tool for developers who may wish to assess the impact certain modifications have on the operational performance of their development before the construction stage, saving both time and money. It is thought that by implementing dynamic modelling in the design stage, the operational performance of homes can be optimised.

In order to deliver one of the main objectives of the project, the analysis of the ‘as built’ performance of an existing net zero carbon house, the construction of a detailed simulation model of an existing net-zero carbon home was required and so a platform on which to achieve this had to be chosen.

ESP-r was selected as the platform on which to build the simulation model of the net-zero carbon home. ESP-r has been evolving constantly since Joe Clarke, of Strathclyde University, developed the initial prototype in 1974 and is now generally used as a building simulation suite, enabling users to explore the built environment through virtual representations and dynamic simulation to tell us much more about the built environment and, in some cases, aid the design process of future building projects.

ESP-r was chosen over other methods for a number of reasons. Firstly, it allows the user to determine exactly how detailed the model should be in terms of its geometry, constructions and materials, operational details and control systems. Another advantageous feature, for this project in particular, is that it allows the user to easily simulate the singular and cumulative effects of making various modifications to the model such as air change rates and the addition of advanced control systems for example. Finally, using ESP-r to model the house from scratch would be a challenge. Building models from scratch within the ESP-r platform is something the user had no experience of beforehand, and it was decided that this would add another, stimulating dimension to the project.

2. Literature Review

2.1. Domestic Energy Use and Carbon Dioxide Emissions in the UK

In 2012, domestic energy consumption accounted for 29 % of the total UK final consumption of energy products and its share of the final consumption is increasing year on year. (DECC, 2013) Since 1970, domestic energy usage has increased by as much as 32 % and over the last 20 years or so has increased by 6 %. This shows that domestic energy use is increasing year on year even although, at a household level, there has been a 12 % decrease in energy consumption. This can be explained by the increases in the number of homes and population over the last 20 years; although individual households are, in general, using less energy, this reduction is being cancelled out due to the 12 % increase in population and the 20 % increase in the number of homes over the past twenty years. So even although, at a household level, people are doing there bit to reduce energy consumption and carbon emissions, we are using more and more energy every year due to factors which are, in general, out of our control. This is why it is even more important that we continue to reduce our energy consumption and the associated carbon emissions as much as possible at a household level, through building fabric improvements and enhancements in low to zero carbon technology, to help to control this increase and possibly start to reduce the total domestic energy consumption year on year.

Of the total domestic energy use, by far the most prominent end use is space heating which represented 66 % of the total domestic energy use in 2012. Other end uses are: water heating, representing around 17 %; cooking, representing around 3 %; and lighting and appliances, representing around 15 % of the total domestic energy use. The percentage breakdown of domestic energy end use from 1970 to 2012 is shown in Fig 2.1, below. Space heating, of course, is mainly dependent on the external temperatures and so it may be expected to remain roughly constant. However, increases in occupant’s expectation levels of internal temperatures, sustained growth in central heating and overall increases in number of households have seen the percentage share of domestic energy use for space heating increase year on year since

1970. This increase has continued even though there have been major developments in insulation and other building fabric enhancements.

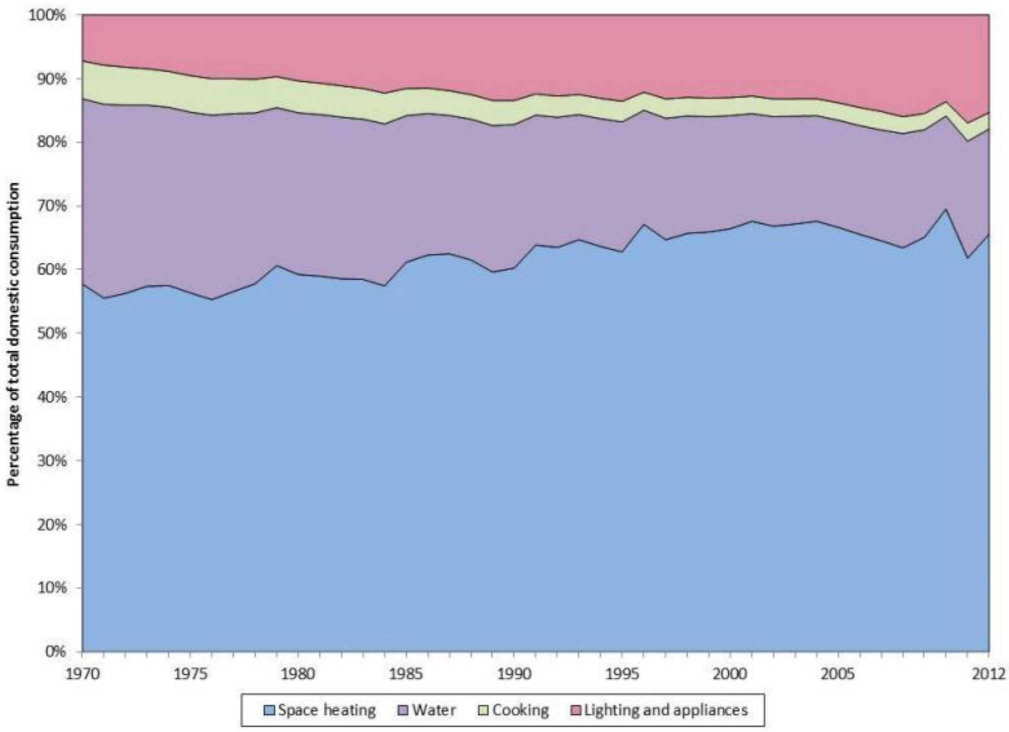


Fig 2.1: Domestic energy consumption in the UK by end use (1970 – 2012)

Carbon dioxide emissions and energy use are obviously interlinked; almost all energy use results in the emission of CO_2 to the atmosphere. However, the trend in carbon emissions is slightly different to that of domestic energy use, mainly due to there being different carbon emissions associated with different types of fuel. Carbon dioxide emissions from domestic use have seen a decrease from 1970 to 1995 and have since remained broadly constant regardless of the increases in the number of homes and population. Although increases in the number of homes, population and use of appliances have slowed down the reduction of carbon emissions, changes such as enhancements in appliance efficiencies, insulation and other building fabric enhancements have fought against these factors to ensure carbon emissions are reduced. The reduction, however, has not been as significant as many hoped for with ambitious carbon reduction targets set out in the 2008 Climate Change Act to be met and so it is vital that more enhancements are made in order to reduce carbon emissions in the domestic sector. Fig 2.2, below, shows the trend in CO_2 emissions from domestic energy use from 1970 to 2009.

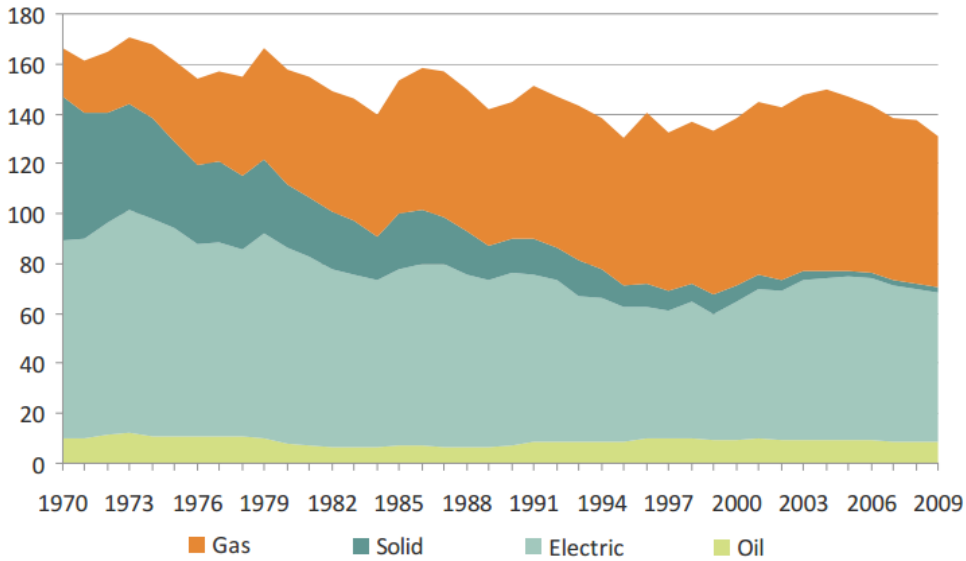


Fig 2.2: CO_2 emissions from housing energy (million tonnes) (DECC, 2011)

As can be seen from the figure above, the use of gas has increased significantly since 1970 while the use of solid fuel has fallen dramatically to an almost negligible percentage. Oil has remained generally constant, with only a very small decrease in its use and while electricity use has fallen by around a quarter since 1970, its share of the overall carbon emissions remains the same.

2.2. Government Legislation on Domestic Energy Use

2.2.1. Code for Sustainable Homes

The Code for Sustainable Homes was first introduced to UK, excluding Scotland, in 2007 and is the national standard for the sustainable design and construction of new homes. It is an assessment method which not aims not only to reduce carbon emissions, but also to promote standards of sustainable design above the current minimum standards set out by the building regulations.

The code provides nine measures of sustainable design: energy/CO_2 emissions, water, materials, surface water run-off, waste, pollution, health and wellbeing, management and ecology. (UK Government, 2011) Six of the nine areas have a mandatory performance requirement that must be met before a project can be assessed and the performance in the other three areas is flexible. The six areas that have mandatory performance requirements associated with them are: energy and CO_2 emissions, water, materials, surface water run-off, waste and health and wellbeing. (BREEAM, 2013) The code gives dwellings a level rating of between zero and six depending on its performance on the mandatory standards and the proportion of flexible standards achieved, where level zero is an extremely poor performance and level six is an extremely good performance. The percentage weightings of each of the nine categories is shown below in Table 2.1. (Al-Hassan, 2009)

Category of Environmental Impact	Weight Factor (% of points contribution)
Energy and CO_2 Emissions	36.4 %
Water	9 %
Materials	7.2%
Surface Water Run-off	2.2 %
Waste	6.4 %
Pollution	2.8 %
Health and Wellbeing	14 %
Management	10 %
Ecology	12 %

Table 2.1: Percentage weight of each of the assessed categories in the Code for Sustainable Homes

The assessment is carried out in two stages, the first of which is an initial assessment carried out at the design stage and the final assessment and certification is carried out at the post-construction stage. The initial assessment focuses on the detailed design and documentation of the project including architectural drawings, contractor instructions and any commitments made during the design stage. Once the initial assessment is complete, the project is granted an interim certificate of compliance. The final assessment then takes place post construction, which involves confirmation of compliance, based on the design stage review, through scrutinising site records and carrying out visual inspections. This final assessment results in a final certificate of compliance which will give the home a rating between level zero and level six.

Although complying with the Code for Sustainable Homes is not compulsory, except for new homes funded by the Homes and Communities Agency (HCA) who are required to me CSH level 3, all new homes promoted or supported in any way by the Welsh Assemble Government or their sponsored bodies who are required to meet the CSH level 3 and any new self-contained social housing in Northern Ireland who are also required to meet CSH level 3, it is thought that 2016 building regulations may be very close to CSH level 6 due to the government's 2016 zero carbon new homes target. There are several criteria that must be met for a home to achieve CSH level 6. Fabric specification that must be met in order for a home to achieve CSH level 6 is outlined in Table 2.2, below.

CSH Level 6 Requirement	
Floor U-Value	0.1 W/m^2K
Roof U-Value	0.1 W/m^2K
Wall U-Value	0.12 W/m^2K
Window U-Value	0.8 W/m^2K (and triple glazed)
Skylight U-Value	1.1 W/m^2K (and triple glazed)
Door U-Value	0.88 W/m^2K
Air Permeability at 50 Pa	$\leq 2\ m^3/hr/m^2$
Thermal Bridge Y-Value	0.04
MVHR Efficiency	92 %
Heat Loss Parameter	$0.6 \leq HLP \leq 0.8$

Table 2.2: Fabric specification requirements for code for sustainable homes level 6 certificate

The requirements in the table above are not the only requirements that must be met to achieve CSH level 6 status however. There are many more requirements such as: the home must have net zero emissions of carbon dioxide from all energy use in the home, achievable through fabric improvements and low/zero carbon technologies; the home must be designed to use no more than 80 litres of water person per day, achievable through scaling down time spent in showers, capacities of dishwashers and washing machines etc.; the home must have energy efficient appliances; it must supply accessible water butts; it must reduce surface water run-off as much as possible; it must use highly environmentally friendly materials; it must aim to minimise construction waste; it must have maximum, accessible provisions for recycling; it must aim to improve day lighting, sound insulation and security; it must adhere to the Building to the Lifetime Homes Standard and it must aim to minimise the ecological impact of the construction of the home. Only once all of the requirements listed above and the required fabric specifications are met can a home be classified as CSH level 6.

Although the code for sustainable homes level 6 certificate is a good outline of what to expect when the 2016 building regulations are introduced, it is thought by some that further research and new government policies are needed if sustainable energy is to be delivered for this sector and to ensure the delivery of new housing is not hampered whilst failing to meet energy goals. (McManus, 2010

2.2.2. Government Incentives

In an attempt to meet the ambitious targets outlined in the previous section, the UK government have introduced a number of incentives that aim to reduce energy use and carbon emissions, promote energy efficiency in terms of building fabric and tackle environmental issues associated with domestic energy use. The three main incentives offered by the UK government are the Renewable Energy Feed-In Tariff (REFIT), the Green Deal and the Renewable Heat Incentive.

2.2.2.1. The Renewable Energy Feed In Tariff (REFIT)

Feed-in tariffs are the most popular policy used around the world for accelerating the investment in renewable energy systems. (Couture et al, 2010) The Renewable Energy Feed-In Tariff (REFIT) was introduced in the UK 2010. It is designed to encourage and accelerate investment in domestic scale renewable electricity generating systems. It does this by paying homeowners who generate electricity from renewable resources at their home a tariff that is dependent not only on the amount of electricity they generate but also on the technology used to generate it and homeowners will be paid the tariff regardless of whether or not the electricity is used by them or exported to the grid. Not only will the homeowner receive payment for the electricity they generate, but they will also save money on their electricity bill as they will be using their own electricity and less from the grid.

Most domestic-scale renewable energy systems are included in the scheme including solar PV panels, wind turbines, hydroelectricity, anaerobic digesters and micro combined heat and power (CHP). Although it is a government policy, it is the energy supplier to the homeowner who will pay the feed in tariff (FIT) to the homeowner and most are required by law to do so. In the UK, almost all of the REFIT payments are made to homeowners who generate electricity from solar panels. Table 2.3, below, details the feed-in tariff homeowners would receive for different capacity solar PV installations. (Energy Savings Trust, 2013) It can also be seen below that the tariffs are decreasing with time as solar PV panels are becoming more popular and so perhaps in the near future they may cease to exist at all.

Total Installed Capacity (kW)	Tariff with eligibility date 1st Aug – 31 Oct 2012	Tariff with eligibility date 1st Nov – 30 Jun 2013	Lower tariff (if EPC requirement not met) with eligibility date 1st Aug – 30 Jun 2012
< 4 kW (new build & retrofit)	16.0 p/kWh	15.44 p/kWh	7.1 p/kWh
4 - 10 kW	14.5 p/kWh	13.99 p/kWh	7.1 p/kWh
10 – 50 kW	13.5 p/kWh	13.03 p/kWh	7.1 p/kWh
Stand-Alone	7.1 p/kWh	7.1 p/kWh	7.1 p/kWh

Table 2.3: Renewable energy feed-in tariff for solar PV installations

Table 2.4, below, shows some figures for the feed in tariff for other renewable electricity generating systems.

Technology	Tariff Band (Kw Capacity)	Tariffs from 1st Dec 2012 – 31 Mar 2014
Hydro	< 15	21.65 p/kWh
	15 – 100	20.21 p/kWh
Wind	< 1.5	21.65 p/kWh
	1.5 – 15	21.65 p/kWh
	15 – 100	21.65 p/kWh
Micro-CHP	< 2	12.89 p/kWh

Table 2.4: Renewable energy feed-in tariffs for hydro, wind and micro-CHP systems

There are obvious advantages of this incentive for homeowners in that they can make money as well as save money on electricity bills. However, there is one real weakness of the REFIT which makes the scheme rather controversial; the tariff is paid to the homeowner by their electricity suppliers who, in general, are constantly increasing their prices. It is thought by many that part of the reason behind the increase in prices is to cover the money paid through the REFIT and so homeowners, who are not generating electricity, perhaps because they cannot afford to, have the right to feel as if they are subsidising more well-off households' renewable energy projects. (Klien, 2012)

2.2.2.2. The Green Deal

The Green Deal is another government incentive which aims to promote energy efficiency in homes by encouraging homes and businesses to carry out energy refurbishments such as insulation enhancements, boiler and glazing replacements and advanced control system installations which will be funded by a loan of up to £10,000. Before any loan is granted, qualified Green Deal Assessors will come to the home and assess the feasibility of enhancements. The assessor will then produce a Green Deal Report prior to the appointment of a Green Deal Provider who will source quotes, oversee installation and provide the loan. The loan is then repaid through the energy bills over a maximum of 25 years with the interest rates expected to be far outweighed by the financial savings from the energy efficiency enhancements. It is important to note also that the loan is lodged against the property and not against the owner or occupier and the loan is passed on to the new owner if the property is sold.

2.2.2.3. The Renewable Heat Incentive

The Renewable Heat Incentive (RHI), introduced in the UK in 2011, is applicable to households, landlords, businesses, farmers, schools, hospitals, care homes, communities etc. Similarly to the REFIT, it is based on fixed payments for energy generation. However, the RHI pays a fixed amount for heat generated for local use through heat pumps, biomass boilers and solar thermal panels. In contrast to the REFIT, the fixed payment is covered by the treasury and not by energy users and so it is less controversial. It is a rather simplistic concept which involves three steps: the installation of renewable heat systems in the property; the heat production measured; a fixed payment made to the homeowner based on the kWh generated, the technology type and the system size.

2.3. Net Zero Carbon Housing

2.3.1. Net Zero Carbon Housing Concept and Criteria

In 2010, the government made it clear that by 2016 all new homes built in the UK should be zero carbon, i.e. the net CO_2 emissions from the home should be zero. This commitment is based upon a three step hierarchical approach illustrated in Fig 2.3, below.

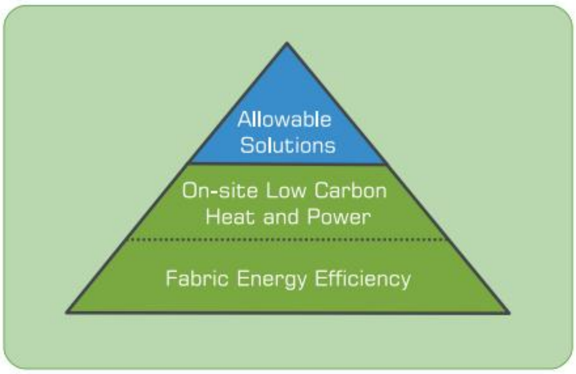


Fig 2.3: Hierarchical approach to achieving zero carbon homes by 2016

For a domestic building to be classified as 'net zero carbon' there are three strict requirements that must all be met. The three requirements are:

- **Fabric Energy Efficiency:** The fabric performance in a net zero carbon house must meet the Fabric Energy Efficiency Standard (FEES). (Zero Carbon Hub, 2013)

- **On-site Low Carbon Technology:** Any remaining carbon emissions after heating, cooling, lighting and ventilation must be reduced to less than or equal to the Carbon Compliance limit for zero carbon homes through low-to-zero carbon technologies, (DECC, 2011) and

- **Allowable Solutions:** Any remaining carbon emissions after the previous two conditions have been met must be reduced to zero through the use of allowable solutions which will be explained in more detail later.

2.3.1.1. Fabric Energy Efficiency Standard (FEES)

In recent years it has become the realisation that focussing on energy demand and carbon reduction without recognising the need for improvements in building fabric efficiency is neither practical nor cost effective. For example, almost any house, regardless of the state of the building fabric, could in theory become 'zero carbon' simply by installing renewable energy systems to offset their carbon emissions. However, this approach would almost certainly involve large capital, running and maintenance costs.

It is because of this realisation that a 'fabric first' approach is now being adopted and minimum standards of fabric heat loss have been set out. (McAlister, 2013) The Fabric Energy Efficiency Standard (FEES) was established in response to developing a strategy for the 2016 zero carbon homes requirement by a Task Group led by the Zero Carbon Hub. (Zero Carbon Hub, 2013) The standard sets minimum performance levels in terms of the building fabric to reduce the space heating and cooling demand within houses and to reach the zero carbon standard. The standard also sets a Target Fabric Energy Efficiency (TFEE) for different standard of dwelling. The TFEE is measured as the annual space heating and cooling demand of the dwelling, in $kWh/m^2/year$, and can be affected by: fabric U-values, thermal bridging, air tightness, thermal mass and other features such as passive solar design. There are two levels of

FEES that can be achieved: Interim FEE and Full FEES. From 2013 the interim FEE is required, where the TFEE would be 43 kWh/m^2/year for apartment blocks and mid-terrace houses and 52 kWh/m^2/year for end-terrace, semi-detached and detached houses. However Full FEES is recognised as the standard to meet by 2016 and is the minimum requirement for zero carbon homes. To achieve full FEES, the TFEE would be set at 39 kWh/m^2/year for apartment blocks and mid-terraced houses and at 46 kWh/m^2/year for end-terrace, semi-detached and detached houses. (Zero Carbon Hub, 2013)

Good fabric energy efficiency can be achieved through certain measures such as ensuring that the building has as low an air infiltration rate as possible, using high grade insulation in exterior walls and using low U-value materials. The (Zero Carbon Hub, 2009) suggest the following example of fabric specifications, shown in Table 2.5, below, should be enough to meet the Target Fabric Energy Efficient Standard

	4-Storey Apartment Block	Mid Terrace House	End Terrace/Semi-Detached House	Detached House
Target Energy Efficiency Standard	39 kWh/m^2/year	39 kWh/m^2/year	46 kWh/m^2/year	46 kWh/m^2/year
Wall U-Value	0.18 W/m^{2}K	0.18 W/m^{2}K	0.18 W/m^{2}K	0.18 W/m^{2}K
Floor U-Value	0.18 W/m^{2}K	0.18 W/m^{2}K	0.18 W/m^{2}K	0.14 W/m^{2}K
Roof U-Value	0.13 W/m^{2}K	0.13 W/m^{2}K	0.13 W/m^{2}K	0.11 W/m^{2}K
Window U-Value	1.4 W/m^{2}K	1.4 W/m^{2}K	1.4 W/m^{2}K	1.3 W/m^{2}K
Air Permeability at 50 Pa	3 m^3/m^2/hr	3 m^3/m^2/hr	3 m^3/m^2/hr	3 m^3/m^2/hr
Thermal Bridge y-value	0.05 W/m^{2}K	0.05 W/m^{2}K	0.05 W/m^{2}K	0.04 W/m^{2}K

Table 2.5: Example of fabric specification that will meet the Fabric Energy Efficiency Standard (FEES)

2.3.1.2. Carbon Compliance

As previously mentioned, zero carbon homes can only be achieved by meeting the three criterion outlined above in section 2.2.1. The first requirement: that an energy efficient approach in terms of the building fabric must be taken to building design, together with the second requirement: that remaining CO2 emissions must be reduced through on-site low and zero carbon technologies, are referred to as Carbon Compliance. This is illustrated in Fig 2.4, below, where the hierarchical approach to achieving zero carbon homes as well as where Carbon Compliance fits in with this is shown.

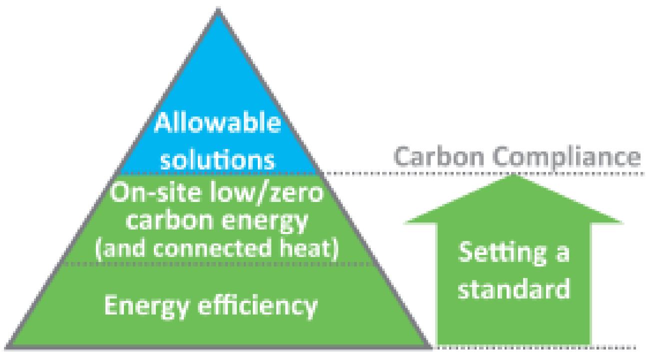


Fig 2.4: Carbon Compliance limit

Carbon Compliance is basically a target emissions level that applies to the built performance of homes. It is recommended that from 2016, Carbon Compliance limits for the built performance of homes should be 10 kg CO_2/m^2/year for detached houses, 11 kg CO_2/m^2/year for attached houses such as semi-detached houses, end-tenements and mid-tenements and 14 kg CO_2/m^2/year for low rise flats, (Zero Carbon Hub. 2013) which is a realistic target that will help reach the zero carbon objective.

The Carbon Compliance limit, 10 kg CO_2/m^2/year for a detached house for example must be met by first improving the fabric energy efficiency of the home to the TFEE, as described previously, and then through low-to-zero carbon heat and power technologies such as high efficiency boilers, biomass boilers, photovoltaic panels, solar hot water, air source heat pumps etc.

2.3.1.3. Allowable Solutions

Once a home has reduced its CO_2 emissions to the Target Fabric Energy Efficiency through energy efficient building fabric and then further to the Carbon Compliance limit through the integration of low carbon heat and power technologies, there may still be some remaining CO_2 emissions. However, for a home to qualify as a zero carbon home, the net CO_2 emissions must be zero and so any remaining carbon emissions after the FEES and Carbon Compliance requirements have been met must be reduced to zero through Allowable Solutions. Allowable solutions currently under government consideration include paying into a carbon fund and investing in carbon reduction programs.

If, for example, a detached house met the FEES and the Carbon Compliance requirements but could not reduce its carbon emissions any further, the remaining carbon emissions are 10 kg CO_2/m^2/year. If a developer chose to use a carbon fund in order to achieve zero carbon status, the whole 10 kg CO_2/m^2/year would have to be paid for. Assuming that the amount of remaining carbon that must be addressed using allowable solutions is defined as the amount of carbon emitted over 30 years, as per the government definition, then for a 150 m^2 detached home, 45,000 kg of CO_2 will need to be paid for through a carbon fund. Assuming a figure of £46 per tonne of CO_2, (Zero Carbon Hub, 2013) the one-off payment for the detached house would be £2070. The amount paid to the carbon fund would then go towards carbon reduction projects.

The second example of an allowable solution is the investment in a carbon reduction project associated with the development. This could mean that a developer may opt to invest in a district heating extension at the development, for example, to negate the reaming carbon emissions associated with the development as opposed to paying into a carbon fund, where there is no guarantee that your development will benefit from the money you put in. However, this may not suit everyone due to circumstantial limitations of different housing and it is thought that paying into a carbon fund will be more popular.

It is thought that through the use of building simulation, the three requirements outlined above could be achieved much more easily. If building simulation is used at the design stage of a development it can be used to assess the benefits of particular methods of construction for example. It is thought that by implementing building simulation, developers could ensure their development would meet the criteria above well in advance of the construction stage, by simulating using different construction materials etc. and assessing which ones meet their requirements best, optimising the operational performance of the development. This project aims to show these benefits through the dynamic modelling and simulation of an existing zero carbon house and carrying out modifications to assess their impacts. The following section outlines three common approaches adopted by developers when designing and constructing zero carbon homes, all of which could be significantly improved had building simulation been implemented at the design stage.

2.3.2. Approaches to Achieving Zero Carbon Housing

There are three main approaches that are often adopted by developers to achieve net zero carbon status for their development: A balanced approach, an extreme fabric approach and an extreme low or zero carbon technology approach.

2.3.2.1. The Balanced Approach

A balanced approach to achieving net zero carbon status for homes would typically involve a fabric performance of roughly the level of the Fabric Energy Efficiency Standard (FEES). Generally, a balanced approach would mean that the Carbon Compliance limit would just be met by integrating a reasonable amount of low or zero carbon technologies without overdoing it. A balanced approach would typically mean that there will be remaining emissions, around 11 kg CO_2/m^2/year for a semi-detached home, and so the development would only become zero carbon once these had been eradicated through allowable solutions. Although this approach means that developers will definitely have to pay to eliminate their remaining carbon emissions, it is thought that this will be the easiest approach to implement in the future as it is closest to what has been done before.

2.3.2.2. The Extreme Fabric Approach

Typically, developers who adopt the extreme fabric approach will achieve a fabric performance that will easily surpass the Fabric Energy Efficiency Standard and perhaps even come close to achieving the Carbon Compliance Limit. This means that to reach the Carbon Compliance limit, very few low/zero carbon technologies are required. This means however, that there will still be remaining carbon emissions that will have to be eliminated through allowable solutions. Although, as with the balanced approach, remaining carbon emissions will still need to be paid for most likely through a carbon fund, this approach is a reliable method of reducing carbon emissions as well as a proven method of reducing primary energy consumption within the home.

2.3.2.3. The Extreme Low/Zero Carbon Technologies Approach

This approach, in contrast to the balanced and extreme fabric approaches, aims to achieve zero carbon status without the need for allowable solutions. It does this by using only fabric and on-site low/zero carbon technology. Typically, this approach would require a fabric performance which surpasses the FEES and an abundance of low/zero carbon technologies such as solar PV panels, biomass boilers, air source heat pumps etc. Should this approach be carried out effectively, with all carbon emissions been reduced to zero through only fabric energy efficiency measures and low/zero carbon technology then there will be no need for a developer to pay for emissions through allowable solutions. If, however, it is not carried out effectively and there is still some remaining carbon emissions then the developer must pay for these through allowable solutions. Although it is thought, in general, that this approach is very ambitious, it is likely to be much more expensive to implement than the previous two approaches. One advantage of this approach is that once the low/zero carbon technologies are in place it is easy to scale up the capacity of the technology to meet the required standard.

2.3.3. Examples

2.3.3.1. Abbey Walk, Storrington – A Balanced Approach

The zero carbon development at Abbey Walk, Storrington is comprised of 12 two, three and four bedroom, terraced and semi-detached detached family homes, with floor areas ranging from 80 m^2 to 105 m^2. The main aim of the developers was to reduce carbon emissions and promote energy efficiency through affordable means and straightforward measures that could easily be replicated.

Although it was never the developers' initial ambition for the scheme to be zero carbon, zero carbon status by adopting a balanced approach; fabric energy efficiency measures, on-site low/zero carbon technology and allowable solutions were all used in roughly the same measures. Through fabric efficiency measures such as airtight timber-frame constructions with high grade insulation in the floor, roof and walls and triple-glazed timber-framed windows, the development specification, shown below in Table 2.6, resulted in a slightly better performance than required by the Fabric Energy Efficiency Standard (FEES). (Zero Carbon Hub, 2013)

External walls U-Value	0.15 W/m^2K
Roof and Floor U-Value	0.10 W/m^2K
Thermal bridge Y-Value	0.06 $W/m^2/K$
Air Permeability rate at 50 Pa	3 $m^3/h/m^2$

Table 2.6: Specification of Abbey Walk zero carbon development

Once the full FEES had been reached through the fabric energy efficiency measures mentioned above, low and zero carbon technologies were integrated into the development to lower the carbon emissions further towards, and possibly surpassing, the Carbon Compliance Limit. At Abbey Walks, high-efficiency condensing gas boilers were installed, they utilised solar hot water with thermal stores, installed mechanical ventilation with heat recovery (MVHR) and used 100 % low-energy lights. These low and zero carbon technologies reduced the developments carbon emissions to 10.9 kg CO_2/m^2/year, slightly under the Carbon Compliance Limit for developments of this type which is 11 kg CO_2/m^2/year. To become a zero carbon development, the remaining carbon emissions were then eliminated by paying into a carbon fund, which cost the developers between £1,300 and £1,700 per dwelling depending on the size.

2.3.3.2. Standings Court, Horsham – An Extreme Fabric Approach

Standings Court in Horsham comprises of 12 homes built to Passivhaus standard, five houses and 21 flats built to the governments Code Level 5. The developers adopted an extreme fabric approach to achieve zero carbon status meaning the fabric energy efficiency measures taken alone meant that the development surpassed the FEES and came close to achieving the Carbon Compliance Limit just by enhancing the building fabric. The developers chose to adopt this approach as they felt that the homes should be as energy efficient as possible as well as being comfortable for occupants all year round without the need for complicated heating and cooling systems. The development achieved performance levels well in advanced of the FEES through features such as a structurally insulated panel (SIP) system, resulting in a well-insulated, airtight structure and the early inclusion of a special tape to increase airtightness throughout the development. (Zero Carbon Hub, 2013) Table 2.7, below, shows the overall fabric specification of the homes built to passivhaus standard, which is well in advance of the full FEES shown previously.

External walls U-Value	0.08 to 0.11 W/m^2K
Roof and Floor U-Value	0.8 W/m^2K
Thermal bridge Y-Value	0.02 W/m^2K
Air Permeability rate at 50 Pa	$\leq 0.6\ m^3/h/m^2$

Table 2.7: Overall fabric specification of homes built to Passivhaus standard at Standings Court, Horsham

Low to zero carbon technologies such as high-efficiency condensing gas boilers and 100 % low energy lights were integrated into the development to further reduce the carbon emissions to the Carbon Compliance Limit. Once the low to zero carbon technology had been installed, the remaining carbon emissions associated with the development was 9.9 to 10.7 kg CO_2/m^2/year. The remaining carbon emissions were then eliminated through paying into a carbon fund, costing the developer between £1,600 and £1,800 for each home depending on the size. It was only after the remaining carbon emissions had been paid for could the development be classed as zero carbon.

2.3.3.3. Lovejoy Lane, Windsor – An Extreme Low/Zero Carbon Technologies Approach

Lovejoy Lane in Windsor is an example of a development which has achieved zero carbon status by adopting an extreme low to zero carbon technologies approach. Unlike the previous two examples, developers of Lovejoy Lane always intended for it to be zero carbon and aimed to achieve this without the need for allowable solutions such as paying into a carbon fund.

As with the previous two examples, the Fabric Energy Efficiency Standard (FEES) must be met through fabric efficiency measures alone and so the developers here met this requirement through using structurally insulated panels (SIPs) similar to the Standings Court example in Horsham. Table 2.8, below, illustrates the overall fabric specification for the homes in Lovejoy Lane.

External walls U-Value	0.18 W/m^2K
Roof U-Value	0.1 W/m^2K
Floor U-Value	0.15 W/m^2K
Windows U-Value	0.8 W/m^2K
Thermal bridge Y-Value	0.02 W/m^2K
Air Permeability rate at 50 Pa	5 $m^3/h/m^2$

Table 2.8: Overall fabric specification for zero carbon homes at Lovejoy Lane, Windsor

As can be seen from Table 2.8, above, the developments fabric performance is not as advanced as the previous example at Standings Court, Horsham. However, it still meets the full FEES requirement. Through the integration of low and zero carbon technologies, the development not only surpasses the Carbon Compliance Limit but it achieves zero carbon status without the need for any allowable solutions. The low to zero carbon technologies used in this particular development were: large areas (23 to 27 m^2) of solar PV panels on roof-tops with a generating capacity of between 3.2 and 3.8 kWh per home; high-efficiency condensing gas boilers, and in one home an air-to-water heat pump is used, five homes have solar hot water systems integrated; all homes have a sophisticated mechanical ventilation with heat recovery (MVHR) system and 100 % low energy lighting; and all homes exploit maximum passive solar gains from southern orientations. Although, technically speaking, there are no remaining carbon emissions to be eliminated, there is still a value that can be calculated which will be a negative value. For this development, the remaining carbon emissions value is between -0.2 and -1.7 kg CO_2/m^2/year.

3. The Resource Efficient House, Ravenscraig

As mentioned in the project aims and objects section, an assessment of the operational performance of an existing net zero carbon house was to be carried out. The reasons behind the decision to model and simulate a real, existing net zero carbon house were that it would indicate whether or not the developers have indeed achieved their goal of net zero carbon status for the house as built. Modifications can then be made to the model in order to optimise the building and successful modifications would, in practice, be fed back to the design team who could then use these modifications in future developments saving both time and money. The dynamic modelling of such a house was made possible due to having an existing net zero carbon house available to visit, take measurements and obtain data on the design and construction. The Building Research Establishment (BRE) made this possible by allowing access to one of their plots, the Resource Efficient House, at their Innovation Park at Ravenscraig, Scotland. The Innovation park was opened in 2012 with the ambition to showcase future potential in domestic housing in a demonstration environment. The innovation park has eleven development plots, eight of which have been purchased by developers and construction is underway on these plots. The Resource Efficient House is one development which is complete and built to the Scottish building standards expected to be rolled out in 2016. A brief description of the Resource Efficient House follows.

3.1. Brief Description of the Resource Efficient House, Ravenscraig

In working with house-builders, developers and housing industry specialists to build the Resource Efficient House, developers attempted to showcase the future of housing in Scotland. The main themes behind the development were the reduction of construction waste, not only at the build stage but throughout the full life cycle of the building, to promote resource efficiency, waste prevention and sustainable material procurement and to lower carbon emissions. On top of this, the two-storey, three-bedroom family home is situated within the BRE Innovation Park at Ravenscraig, Scotland, and is designed to achieve 2016 level energy compliance and Gold Standard in Building Regulations Section 7: Sustainability in keeping with requirements set out by BRE. .

In terms of the surrounding area, the land is very flat and there are very few buildings within a mile radius. The effects of these conditions can be felt immediately when visiting the house; the site is evidently windier than urban environments and the house itself is never in the shade of any other buildings.

In collaboration with house builders, the developers decided that a modular construction using structurally insulated panels (SIPS) was the best solution for what they were trying to achieve. The house is made up of four modular 'pods' which were constructed off-site in a factory so as to reduce construction waste. Fig 3.1, below, shows the house from the South West and immediately a number of design features are noticeable.

Fig 3.1: Resource Efficient House from South West

3.2. Design Features & Technologies

3.2.1. Glazing and Orientation

Glazing and building orientation are two features that a significant amount of thought went into during the design phase. As can be seen from Fig 3.1, above, there are four very large windows in the living area, situated at the south west corner of the building. This is a deliberate design feature which utilises passive solar gains, allowing more solar radiation to enter the building during the hours when this area of the building is most likely to be occupied and need heating. Similarly, there are large areas of glazing at the east of the building in the kitchen and dining area. Again this is was a conscious decision at the design stage to maximise solar gains in the morning, when these areas are most likely to be occupied.

3.2.2. Building Fabric

To meet zero carbon requirements, the building fabric is an area that has been thought of by developers at every stage of the construction of the house and full details of the constructions used in the house will be detailed later. However the main decisions taken by the developers in terms of the building fabric were to use extremely low U-value structurally insulated panels (SIPs) which were constructed off-site, use argon filled triple glazing with low U-values and use doors with low U-values.

3.2.3. Renewable Energy Technology

In keeping with net zero carbon requirements, there have been several renewable energy technologies installed within the building. On the roof of the building, there are nine solar PV panels installed as well as an area of solar glass which together can produce a maximum of 2.1 kW of electricity. There is also a 2.3 kW biomass stove in the living area which has been sized so that all of the space heating demand in the house can be covered by the stove alone. In situations where the space heating demand is greater than the supply available, there are electric heaters in all rooms of the house which can be run off the PV electricity supply or from grid electricity. Finally, an air source heat pump is used as the energy source for providing the domestic hot water supply to the house.

3.2.4. Other Resource Efficient Features

Other features of the house that are in line with the resource efficiency theme include the use of recycled materials. The stairs were constructed from 100 % reclaimed oak and steel, the worktops and cupboards in the kitchen area were made from 100 % recycled plastic coffee cups and 70 % recycled plastic respectively, reclaimed carpet tiles were used were possible and the bath is made from 55 % recycled material. On top of this bin storage areas in the kitchen area and outside the house meet the 2016 gold building regulations.

4. Modelling of Net Zero Carbon House, Ravenscraig

One of the main objectives of this project, as outlined in section 1, was to assess the operational performance of an existing net zero carbon house and research ways to achieve net zero energy performance in practice through dynamic modelling. To achieve this, a detailed simulation model of an existing net zero carbon house was built. As there is currently no net zero carbon house models, or anything similar, within the ESP-r platform, it is thought that by building a detailed model from scratch including the material and construction databases as well as the form and composition of the house, that this could be used in the future by researchers and could perhaps be developed further. It is important to note that in this section only the modelling of the existing house is described and, at this point, there are no modifications, although several modifications will be made, and described, later. It is believed that these modifications are difficult to implement in practice in that they cost significant amounts of time, effort and money, which backs up further the choice to carry out the modifications to the building within a simulation environment beforehand and to assess the impacts of any modifications in this environment before implemented them in the existing building.

4.1. Initial Planning

Before any modelling work in ESP-r commenced, several decisions had to be made. For example, the level of detail in which to go in to in terms of the geometry of the house, the materials and constructions used, how the building should be used and any control systems in place.

Initially it was decided that taking advantage of being able to visit the house regularly was the best option and so, with help from a fellow student, the geometry of the house, including the positions of all windows and doors was measured one day using a tape measure and initial plans were drawn up which consisted of over 30 hand-drawn plans and elevations of the house including the detail of all windows and doors. It was decided that this method would allow the construction of a detailed wireframe model within ESP-r, at least in terms of its geometry. Fig 4.1, below, shows the level of detail in the initial plans.

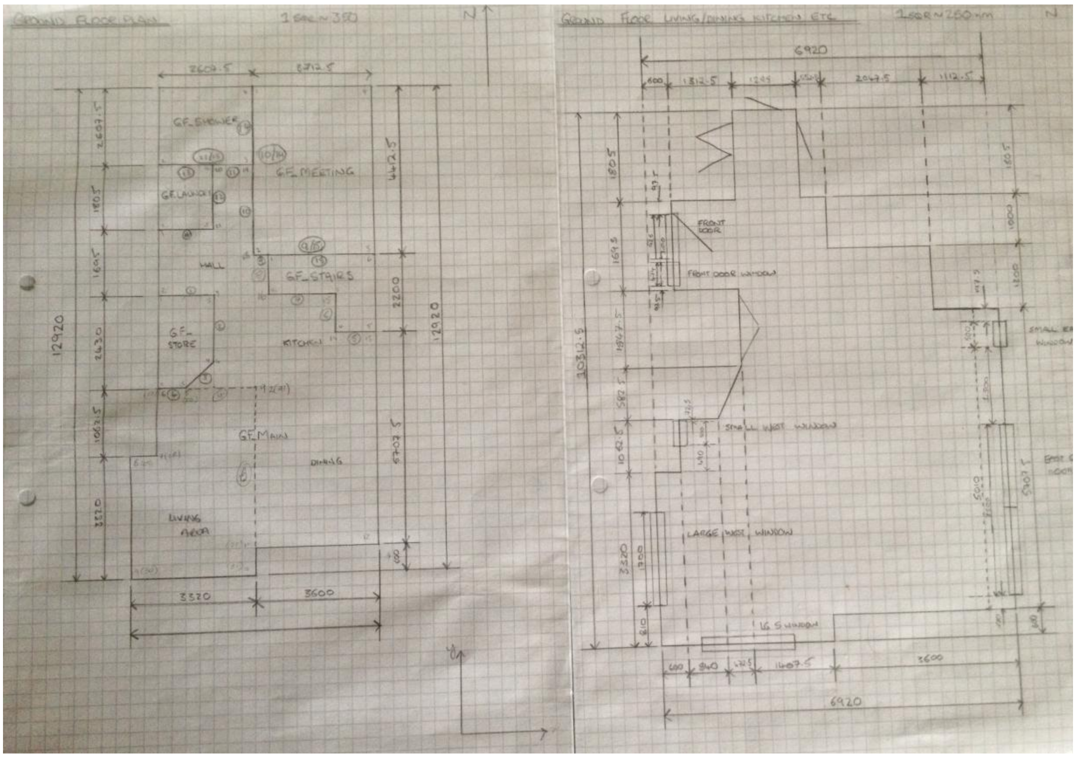


Fig 4.1: Initial Plans: Plan of ground floor and plan of ground floor living/hall area

As can be seen from the initial plans, shown above, there is a great level of detail. This approach was taken as the author wanted the geometry of the model to be as accurate as possible, particularly the location of windows and areas of glazing, as it was thought that this could significantly improve the validity of any results and conclusions to come out of the project. Shortly after beginning the modelling, an architect's drawing file of the house became available which was used to cross check the initial plans from measuring. Some slight changes were made to the initial plans although, in general, they were a very accurate representation of the geometry of the house. The architect's drawings came in extremely useful when building the materials and construction databases. Screenshots of the architects drawing file can be found in Appendix A: Drawing File for Resource Efficient House.

It was also decided, at this stage, that the model should be an as accurate representation of the existing house as possible, not only in terms of the geometry but in terms of the climate, how the building is used and control systems. Again, it was thought that by providing an accurate representation of the real house within the simulation environment would improve validity of any results and conclusions to come out of the project.

4.2. Material/Construction Databases

As previously mentioned, an as accurate as possible representation of the materials and constructions used in the real house were sought after for use in the simulation model.

4.2.1. Materials Database

One major advantage of using ESP-r as the platform on which to model the house is that it allows the user to build up their own materials database. ESP-r has an existing materials database, which has stored the thermo-physical properties of a plethora of materials such as brick, concrete, woods, metals and gases.

To model the existing house at Ravenscraig, some existing materials in ESP-r could be used. However, some others such as Scottish larch, used for external cladding on an area of the building, was not available in ESP-r and had to be input manually. When inputting a new material manually there are a number of things the user must know about the material. For any material, the following must be input: the name of the material, a brief description of the material and perhaps details of the source of data, the conductivity of the material (W/m-K), its density (kg/m^3), its specific heat (J/kg-K), its emissivity and absorptivity, its typical thickness (mm) and finally the user must indicate whether the material is opaque, transparent or a gas. For Scottish Larch, a density of 556 kg/m^3 and a moisture content of 18 % were taken from (Russwood, 2013) These values were then used in the equation $k = G(B + CM) + A$, (Woodweb, 2009) where A, B, and C are constants for T ~ 24 °C, moisture content, M < 25 % and specific gravity, G > 0.3, to calculate a conductivity of 0.138 W/m-K. A specific heat of 1800 J/kg-K was calculated for the material using a similar equation from the same source. The emissivity and absorptivity were 0.9 and 0.65, respectively. The typical thickness was 20 mm and it was an opaque construction.

Similar research and calculations were undertaken in order to build up a database of all of the materials that would be required to build up the constructions within the model. Table 4.1, below, lists each of the materials used in the model and their properties.

Name	**k (W/m-K)**	**ρ (kg/m^3)**	**C (J/kg-K)**	**Ɛ**	**a**
Scotlarch	0.138	556	1800	0.9	0.65
OSB 3	0.13	620	1700	0.9	0.7
ZWS Oak	0.19	700	2390	0.9	0.65
Air Layer 25	0.14	0	0	0.99	0.99
Air Layer 50	0.14	0	0	0.99	0.99
Service Void	0	0	0	0.99	0.99
Air Gap	0	0	0	0.99	0.99
Polyurethane	0.03	30	837	0.9	0.5
Mineral Wool	0.04	25	1000	0.9	0.7
Plasterboard	0.21	900	1000	0.91	0.26
Plywood	0.15	700	1420	0.9	0.65
External Render	0.57	1300	1000	0.91	0.7
Particle Board	0.11	640	1210	0.9	0.9
Slate	2	2700	753	0.9	0.6
Lime Cement	0.8	1800	1120	0.9	0.6

Table 4.1: Thermo-physical properties of materials used to build a model of the Resource Efficient House

4.2.2. Constructions Database

Once all materials had been input into the materials database including their thermo-physical properties, bespoke constructions can then be built up using layers of these materials to represent constructions in the existing house. As with materials, there are several existing constructions within the ESP-r constructions database already. However, for this project, it was decided that bespoke project-specific constructions should be built in order to best represent the existing house.

As with any new materials, ESP-r requires several attributes to be associated with constructions when creating them such as: a unique name, an optical property if the construction is not opaque, the number of layers of material present in the construction and an indication of whether or not the construction is symmetrical. Once these attributes have been input, each layer must have the following attributes: the name of the material, in this case chosen from the materials database outlined in section 4.2.1., the thickness of the layer and for air gaps, such as wall cavities and service voids, the resistance to heat flow for horizontal, vertical and sloped positions.

When building up the constructions database, the architect's drawing file was extremely useful as it allowed the accurate sizing and positioning of each layer. Fig 4.2, below, shows the make-up of the external wall towards the north of the building.

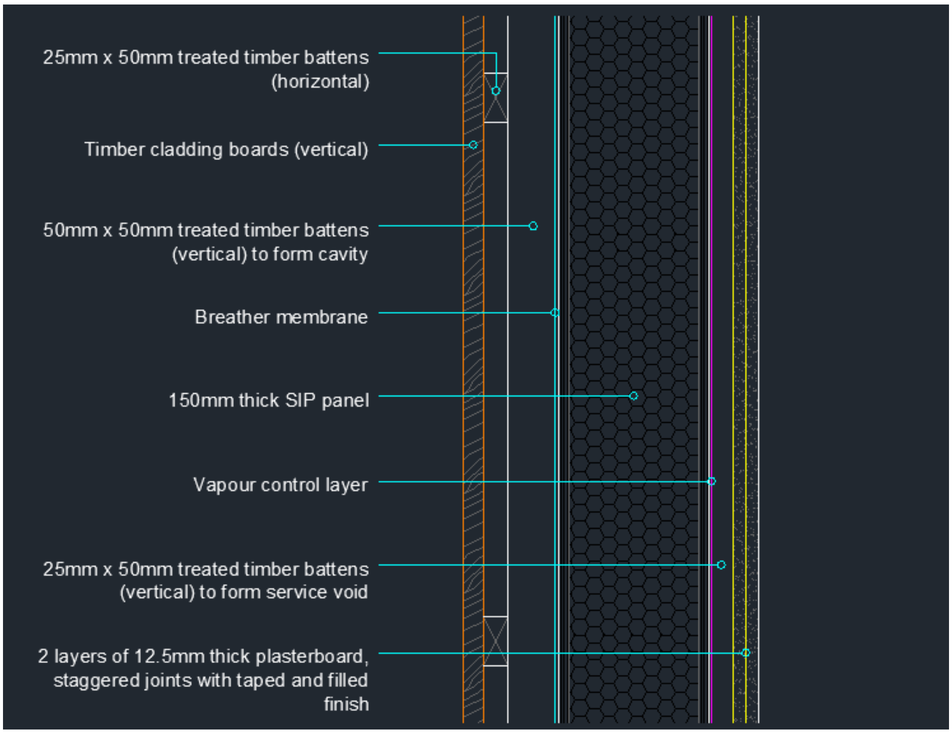


Fig 4.2.: Construction details for external wall (larch cladded)

Details from the figure above allowed an accurate representation of the external wall construction to be built within the simulation environment. It can be seen that the construction has a layer of larch timber on the external surface, followed by an air gap created by timber battens. It then has a cavity followed by a structurally insulated panel and then another air gap to create a service void and finally a double layer of plasterboard at the internal surface. For this particular construction, the previously mentioned attributes required were input; the unique name given to the construction was ext_larch, it was opaque, there were nine layers of material present in the construction and it was not a symmetrical construction. The names, thicknesses and thermo-physical properties of each material, as well as their position in the construction can be seen in Fig 4.3, below.

```
 Details of opaque construction: ext_larch and overall thickness  0.320

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext    20.0     0.138   556.  1800. 0.90 0.65    12.  0.14 Scotlarch : russwood.co.uk/cladd
    2   25.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    3   50.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    4   11.0     0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    5  128.0     0.030    30.   837. 0.90 0.50    90.  4.27 Polyurethane foam bd : Polyureth
    6   11.0     0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    7   25.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    8   25.0     0.210   900.  1000. 0.91 0.26    11.  0.12 Plasterboard (wallboard) : Inter
 Int    25.0     0.210   900.  1000. 0.91 0.26    11.  0.12 Plasterboard (wallboard) : Inter
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.182  0.183  0.181 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.18
 External surface admittance Y=  2.86  w=  3.15 decrement factor f=  0.81  phi=  1.21 surfac
 Partition admittance Y=  2.96  w=  3.22 surface factor f=  0.81  phi=  1.27
```

Fig 4.3: External larch construction specification

As can be seen from fig 4.3, above, the ESP-r simulation platform can calculate the U-values associated with the construction based on the thermo-physical data associated with the materials present in the construction. The U-value calculated for the north external wall is 0.18 W/m^2, which is acceptable under the regulations for the fabric specification of zero carbon homes outlined earlier.

In total, 12 constructions were built up in this way, each accurately representing a different construction used within the house. Full details, similar to those given for the north external wall, are available in Appendix B: Construction Specification.

4.3. Building the Model

4.3.1. Climate Patterns, Location and Orientation

Before the form and composition of any ESP-r model can be defined, a representative climate file must be selected and typical weeks must be found. As previously mentioned, the existing house is situated in Ravenscraig, Scotland. It is roughly 18 miles from Glasgow City Centre and so this close proximity suggests that a Glasgow climate file may be the best option. However, as there was no Glasgow climate file available in ESP-r, a Dundee climate file was chosen as this was the closest geographically to the existing house and it was thought that this would be accurate enough for the level of investigation going to be undertaken.

Once the climate file was selected, typical weeks for simulation were investigated and chosen. Table 4.2, below, highlights the maximum, minimum and mean temperatures for each of the five typical weeks selected as well as the dates that they cover.

Typical Week	Period Start Date	Period End Date	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)
Winter (Early Year)	05/02	11/02	13	-3.3	4.3
Spring	08/04	14/04	15.2	-0.1	7.2
Summer	08/08	14/08	22.5	8.8	15.6
Autumn	30/09	06/10	16.5	4.1	10.8
Winter (Late Year)	23/12	29/12	11.3	0.4	5.38

Table 4.2: Summary of typical weeks for Dundee climate

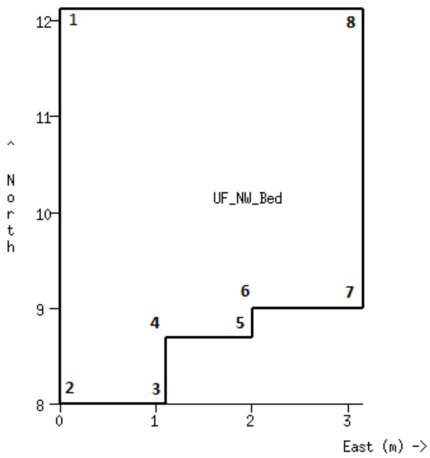
In selecting Dundee as the climate file, the site location was changed automatically to give a site latitude and longitudinal difference of 56.6 and -3, respectively. A simple trigonometric calculation using dimensions from the architect's drawing file yielded a building orientation of 32° from North.

4.3.1. Geometry and Attribution

Once the initial planning and drawings had been done, an appropriate climate file had been selected and materials and constructions databases were built from scratch, the geometrical form and composition of the house could then be built.

There are several different ways of building up wire-frame models in ESP-r however, for this project, it was decided that the best strategy for this would be to build up zones starting with a polygon plan which requires the user to input how many walls each zone has, the height of the zone base, the height of the zone ceiling and the x and y co-ordinates of each vertex in the zone.

In Fig 4.4, below, the plan view and associated vertex co-ordinates for the upstairs North West bedroom is illustrated.



	Index	X-coord	Y-coord	Z-coord
a	1	7.355	10.639	2.400
b	2	5.176	7.151	2.400
c	3	6.120	6.562	2.400
d	4	6.490	7.155	2.400
e	5	7.249	6.681	2.400
f	6	7.411	6.940	2.400
g	7	8.389	6.329	2.400
h	8	10.035	8.964	2.400
i	9	7.355	10.639	4.800
j	10	5.176	7.151	4.800
k	11	6.120	6.562	4.800
l	12	6.490	7.155	4.800
m	13	7.249	6.681	4.800
n	14	7.411	6.940	4.800
o	15	8.389	6.329	4.800
p	16	10.035	8.964	4.800

Fig 4.4: Plan (left) and vertex co-ordinates (right) of the upper-floor North West bedroom

As can be seen from the figure, the room has eight walls and so the eight base vertex co-ordinates were input and ESP-r generated the eight ceiling co-ordinates. ESP-r then uses these vertex co-ordinates to build the wireframe of the zone. Fig 4.5, below, shows the resultant perspective view of the upper-floor North West bedroom with vertex numbers included.

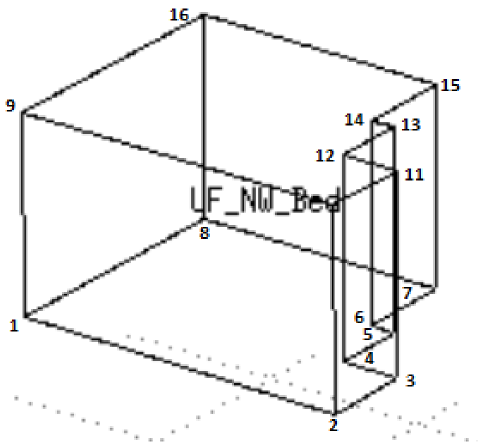


Fig 4.5: Perspective view of the upper-floor North West bedroom

Once the wire-frame zone has been built, the user must then define the composition and a boundary condition for each surface within the zone. Using the previous example of the upper-floor North West bedroom, shown in Fig 4.5, above, there are 13 surfaces in the zone including the floor and the ceiling. Each of these surfaces were assigned a unique name, a construction chosen from the previously built constructions database and a facing or boundary condition which lets ESP-r know the condition at the outside of the surface. There are many different boundary conditions available to choose from and the most common, for this project, were: exterior, similar to current, surface in other zone and ground (monthly profile). For example, the surface enclosed by vertices 1, 2, 10 and 9 was given the unique name ‘UF_BED_WEXT’, the construction chosen was the external larch that was built from scratch and the boundary condition was set to ‘exterior’.

The same method of building up zones from inputting base vertex co-ordinates and assigning a zone height was used to construct the 15 zones in the house. The ground floor and upper floor plans are shown in Fig 4.6, below.

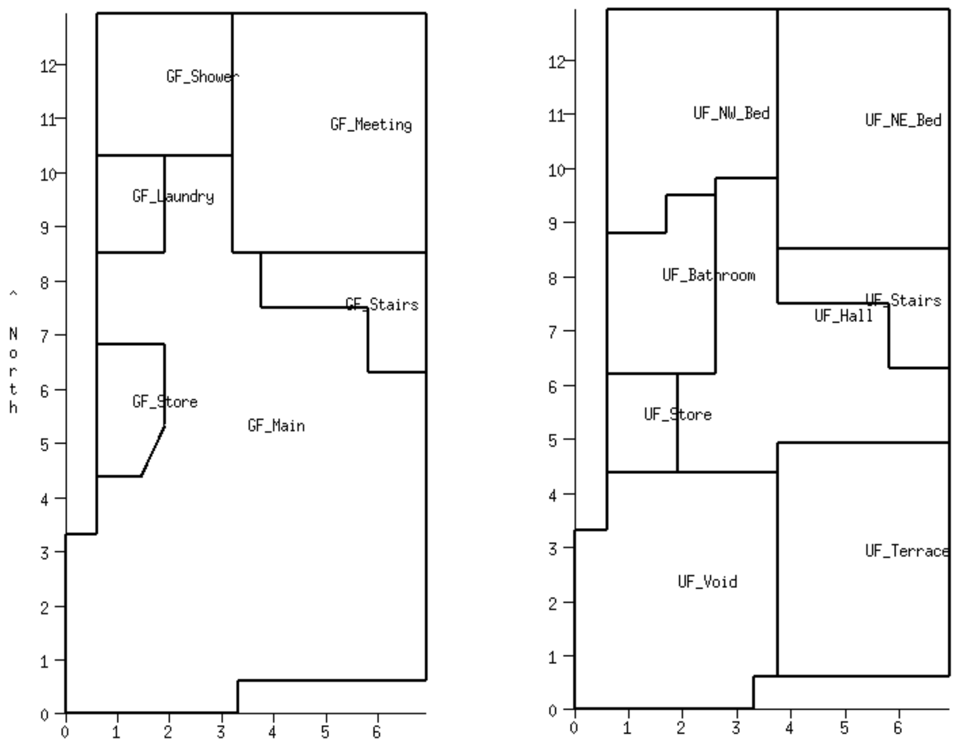


Fig 4.6: Ground floor plan (left) and upper floor plan (right) of wire-frame model of the Resource Efficient House at Ravenscraig

When building multiple zones in a house for example, it is vitally important that you get the co-ordinates in the initial drawings correct as this should ensure that all the zones fit together perfectly, like in Fig 4.6 above, with no overlapping edges. To ensure a perfect fit first time when modelling the resource efficient house, a significant amount of time was spent on the initial plans and vertex co-ordinates were then written out on paper and checked, and cross checked, before inputting anything into ESP-r. Again, ESP-r then used the base vertex co-ordinates and the height input to build up the wire-frame model zone-by-zone. Fig 4.7, below, shows the perspective view of the wire-frame model of the whole house from the south west.

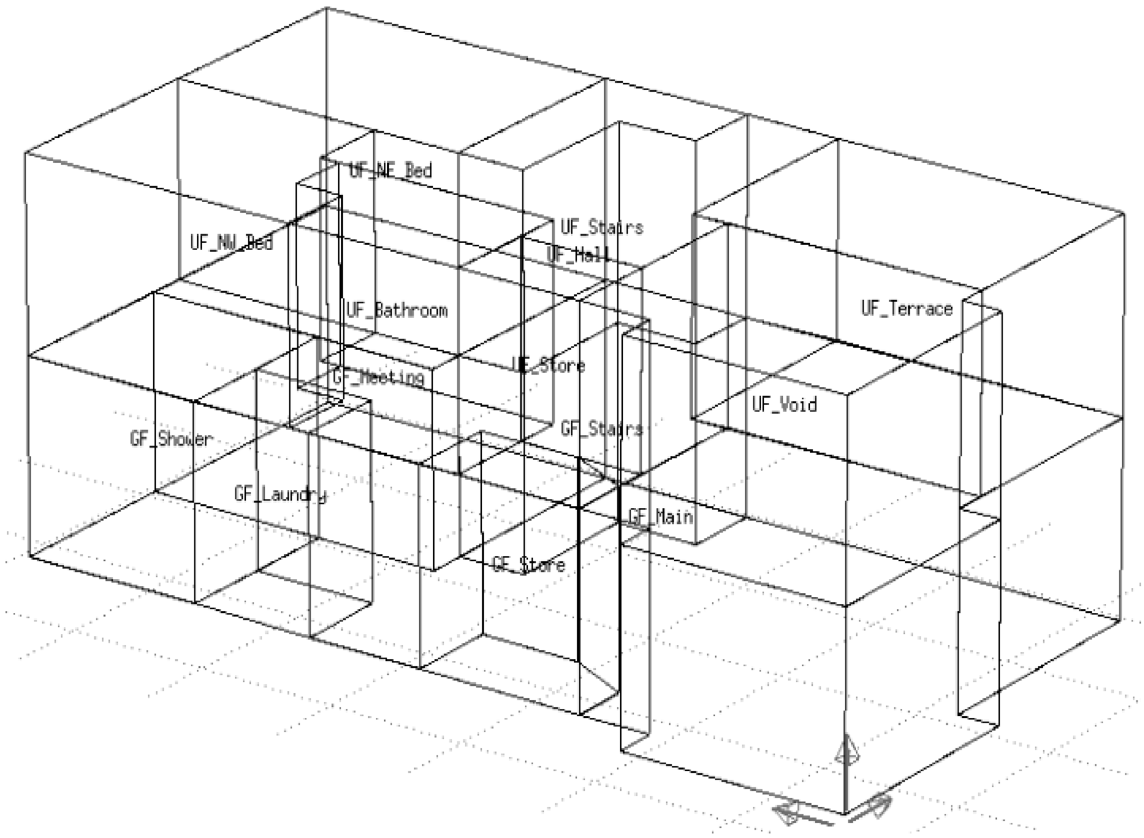


Fig 4.7: Perspective view of the wire-frame model of the Resource Efficient House from the south west

As mentioned previously, each surface in a zone must be given a unique name, a composition and a boundary condition and so these attributes were defined for all 15 zones individually as they were built.

4.3.2. Windows and Doors

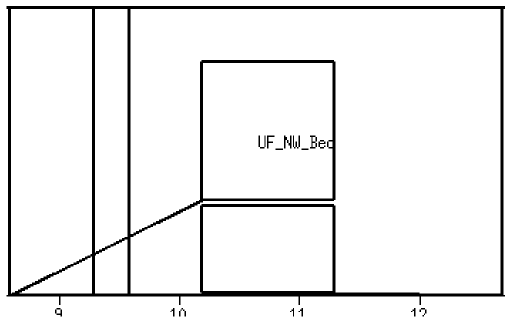
Once all of the zones were built geometrically and had been attributed a name, composition and boundary condition, the next step was to add in windows and doors to each of the zones. It was felt that not only would these features make it easier for others to understand the model but that they are thermally important in that the size and position in a dwelling like this, which has been designed to optimise solar gain, can have a significant effect on the thermal performance of the building. It is because of this that exact sizes and positions of windows and doors were measured accurately and cross checked using architect's plans, which became available later in the project, before being input into the simulation model.

Continuing with the upper-floor North West bedroom as an example, windows and doors were inserted into two different surfaces within zone. The initial drawings and the architect's plans show that the zone had two windows on the west wall, one above the other, and door to the hall on one of the south walls.

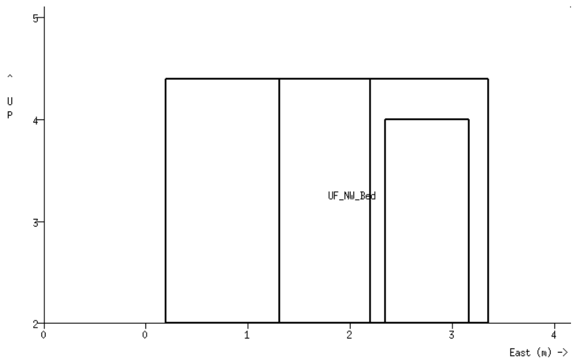
Inserting a door into a surface is fairly simple to do: the user must define a surface in which to insert the door, the x-offset and the height of the door, all of which were available from the initial plans that were drawn at the planning stage. Once the position of the new surface is confirmed, surface usage attributes must be chosen. For this particular surface, the usage attributes chosen were that it was a normal door and it was undercut. It was thought that this would best represent the door in the existing house as there was a gap at the bottom of the door in the existing house.

A similar method was used to insert the windows into the west surface of the zone although, to insert windows, an x-offset, a z-offset, a width and a height needed to be input. Again, all of this information was taken straight from the initial plans drawn at the planning stage of the project. Similarly to when inserting a door, once the positioning is correct, surface usage attributes must be assigned to the new surface. For the windows in this particular zone, a closed window (façade code compliant) was chosen to best represent the existing windows.

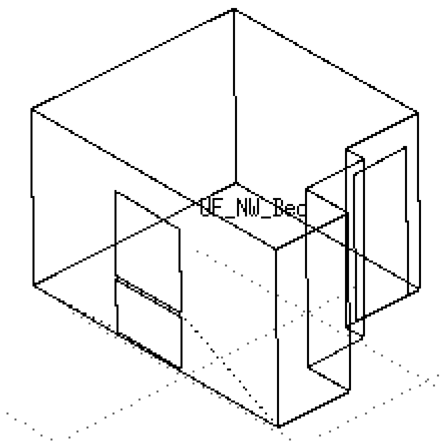
Fig 4.8 a-c, below, shows the west elevation, south elevations and perspective view of the upper-floor north west bedroom complete with windows and the door.



(a)



(b)



(c)

Fig 4.8: Upper-floor North West bedroom with windows and doors. (a) West elevation, (b) South elevation and (c) Perspective

The same method was used repeatedly to insert windows and doors to all 15 zones. As previously mentioned, surface usage attributes were given to each of the new surfaces and it is important to note that not all surfaces were assigned the same usage attribute. For example, the front door is used very differently from a door between two internal zones and so the front door was chosen to be a ‘door entrance’ which meant that it was used a lot and that it was airtight because, unlike the door in the upper-floor North West bedroom, there were no gaps around the door. As with all other surfaces, windows and doors must have a composition and a boundary condition and so these were attributed to each window and door as they were built.

Fig 4.9, below, shows the model once all windows and doors have been inserted into their respective zones. Note here that only the exterior surfaces are shown due to the large number of internal surfaces making the wireframe model difficult to interpret.

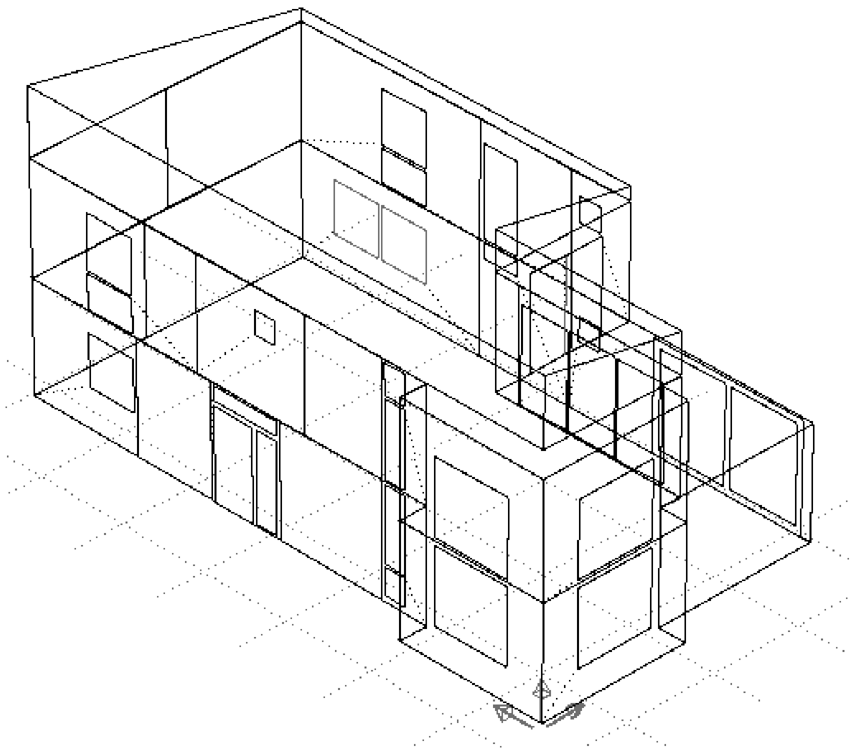


Fig 4.9: Perspective view of the exterior surfaces of all zones after all windows and doors had been inserted

4.3.3. Roof and Other Shading

The next step in building the model was to build the over-hanging roof and the pillars in the roof terrace. Both these features can be seen in Fig 3.1. Since the only real effect on the thermal performance of the building that these features will have comes as a result of the shading they give to zones, it was decided to build both the roof and the pillars on the roof terrace as solar obstructions and calculate shading for the affected zones.

Building solar obstructions is relatively straightforward in ESP-r as all that is required is the co-ordinates of each vertex of the obstruction. The architect's plans came in very useful here as neither the roof or the pillars had been measured during the initial planning stage.

Fig 4.10, below, shows the whole house complete with roof and pillars on the roof terrace. Unfortunately ESP-r does not allow the user to view only the exterior surfaces of the zones and solar obstructions at the same time and so all surfaces are shown.

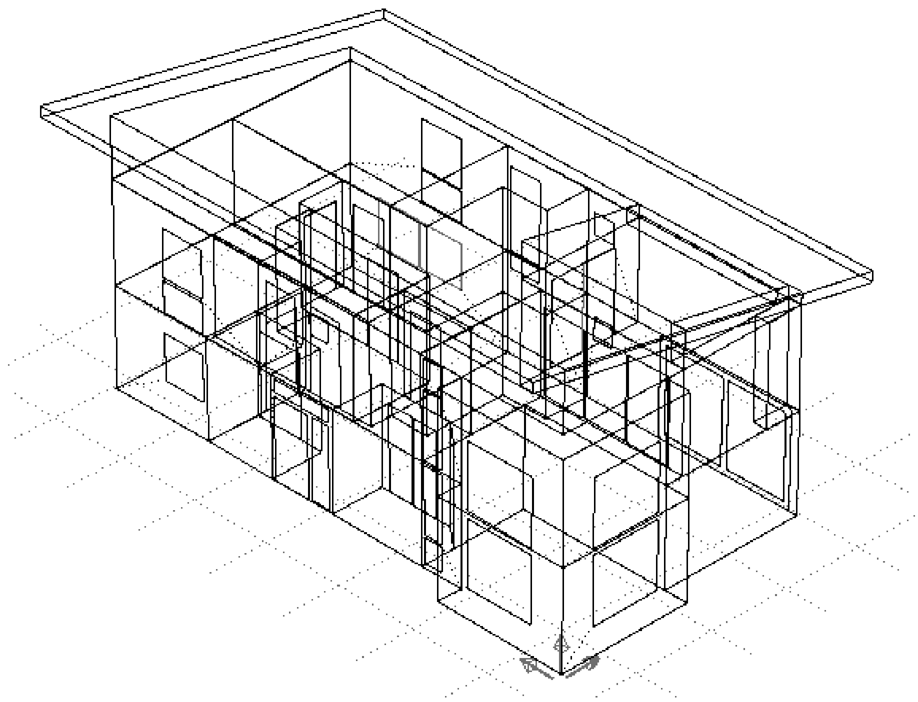


Fig 4.10: Perspective of the wire-frame model of the Resource Efficient House complete with windows, doors and solar obstructions in the form of an over-hanging roof and pillars

4.3.4. Operational Schedules

4.3.4.1. Air Infiltration

For this particular project, the air infiltration rate was set according to real data obtained in another project on-going at the existing house. Kevin Connolly, of Strathclyde University, carried out three blower door tests on the existing house and shared the results of these. The first blower door test measured an air infiltration rate of 4.8 ac/h. Enhancements were then made to the building façade such as sealing cracks and gaps between walls and floors and a second blower door test was carried out. The second test measured an infiltration rate of 2.57 ac/h. Further enhancements were then made to the existing house such as improving the seal around doors and windows and plumbing in the kitchen and a third and final blower door test was carried out. This final test measured an air infiltration rate of 1.4 ac/h.

As a starting point for this project, the air infiltration rate was set to 4.8 ac/h, the first result. The reason behind this is that it was thought that starting with a worst case scenario and then showing the effects and benefits of making the enhancements would be of more value to the project.

4.3.4.2. Casual Gains

Once the form and composition of the model were complete and an air infiltration value had been set, the next stage was to think about how the building is used in terms of occupancy, lighting and small power and hence define patterns within the simulation environment that explain the sensible and latent heat gains from each of these factors. Casual gains are an extremely important factor in terms of the buildings thermal performance and so an accurate representation of how the existing building is designed to operate was sought after. The Resource Efficient House is designed to operate as a family home and so this is kept in mind when defining operational schedules.

Operational schedules are split up into three types: occupancy, lighting and small power. They are input into ESP-r on a four day type basis: one pattern for weekdays, one for Saturdays, one for Sundays and one for holidays. The platform requires the user to define how many periods of occupancy, for example, there are in a particular zone in the house, the sensible and latent heat gain associated with that gain type and the convective and radiant percentages. For example, a zone may only be occupied by one person from 12midnight until 8am, such as a bedroom, and so the number of occupancy periods would be two, one person from 12midnight until 8am and then no occupants from 8am until 12midnight, and the sensible and latent heat gain would be 72 W and 31 W, respectively. (Thomas, 2002) As the house is designed to operate as a typical family home, the occupancy schedules were based on four occupants: two adults working weekdays from 9am to 5pm and two children attending school, college or university during weekdays.

Occupancy

On weekdays, between the hours of 11pm and 7am, the ground-floor bedroom is occupied by two adults and both upper-floor bedrooms are occupied by one person each. From 7am to 8am the kitchen is occupied by three people and the shower occupied by one. The house is then empty until 4pm when it is assumed the children will return from school or college and from 4pm until 6pm the living area is then occupied by two people. The living area is then empty for one hour from 6pm when it is likely that all occupants will be in the kitchen/dining area for dinner. From 7pm until 11pm the living area is occupied by two people. During the evening the kitchen/dining area is occupied by one person between 5pm and 6pm, representing one person cooking a meal. It is then occupied by four people between 6pm and 7pm, representing the family eating a meal, and it is then occupied by one person between 8pm and 9pm, representing one person washing up after dinner. The kitchen/dining area is then empty for the rest of the night. The office space on the upper floor is occupied by one person from 8pm until 11pm every weeknight, representing either an adult working at home or one of the children playing on the computer, and the bathroom is used for one hour at 7pm every weeknight.

On Saturdays the occupancy pattern is significantly different to the weekday patterns. The ground floor bedroom is occupied by two people from 12midnight until 10am and the upper-floor bedrooms are occupied by one person each between 1am and 11am. Between 10am and 11am the kitchen/dining area and the shower room are occupied by one person each to represent one adult making breakfast and one showering, respectively. Between 11am and 12noon, the shower room is occupied by one person and the kitchen dining area is occupied by three to represent the family getting showered and having their breakfast in the morning. The living area has varying occupancy all day to represent people coming and going, to go shopping or on a trip for example. The kitchen is occupied by one person from 5pm to 6pm, again to represent someone cooking a meal. It is then occupied by all four occupants for an hour and then occupied by one person for an hour after then.

The occupancy pattern on Sundays and Holidays are very similar to the pattern for the Saturday although the bedrooms are occupied an hour earlier to represent the occupants going to bed earlier.

The sensible and latent heat gain from occupants varied depending on how active they were, i.e. were they sleeping, standing, sitting etc.? All sensible and latent heat gains were sourced from (Thomas, 2002).

Lighting and Small Power

Similarly for lighting, information regarding sensible and latent heat gains are input for each of the four day types. Creating the operational patterns for lighting was far simpler than for the occupancy. It is assumed that, for all zones, lights are only on after 8pm and when the zone is occupied. The Resource Efficient House had differing numbers of lights within each zone although they were all 14 W energy efficient LED bulbs.

Small power operational schedules are defined in the same way. The main areas affected by small power heat gain were: the living area, which had a large LED television powered on when the living area was occupied; the kitchen/dining area, which had a fridge, freezer, oven, toaster and a small television; the bedrooms, all of which had a television; and the upper floor hall, which had a computer. All of the associated sensible and latent heat gains for small power were also taken from (Thomas, 2002) Fig 4.11, below, shows the casual gains pattern for the living area.

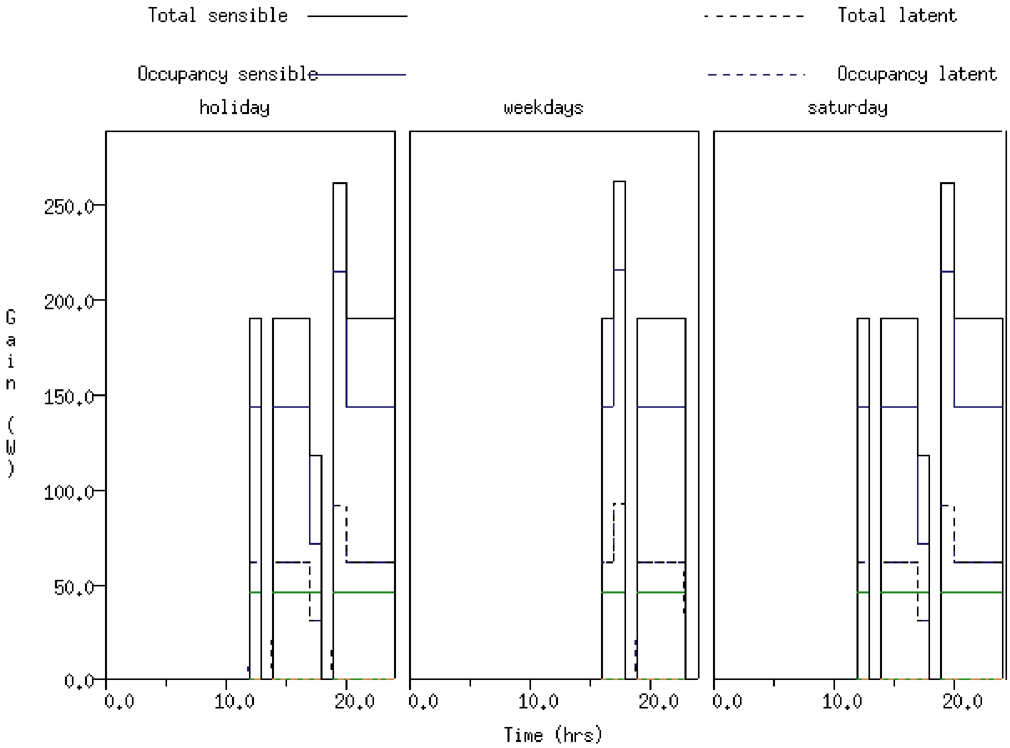


Fig 4.11: Casual gains for living area

Similar patterns for occupancy, lighting and small power were defined for all 15 zones in the model.

4.3.5. Control System

Before heating demand profiles can be generated for any building simulation in ESP-r, an appropriate control system must be defined. To define a control loop in ESP-r, the user must first define what is sensed, temperature for example, where the sensor is, a rule related to the sensed variable and how and where the interaction happens.

The control system in the initial model was very basic, representing that in the existing house. Before defining the control logic, it was necessary to input that the existing house had 2300 kW heating capacity and no cooling capacity. The basic control system was then designed to keep zone temperatures above 18 °C during the night and above 19 °C during the day when the house is occupied. When the house is not occupied, the temperature is allowed to free float. Modifications will be made toward a more sophisticated control system later.

5. Simulation and Results Analysis

5.1. ‘As built’ Energy Consumption & Carbon Emissions Analysis

In this section, the ‘as built’ performance of the Resource Efficient House at Ravenscraig will be investigated in terms of the energy consumption on space heating and the carbon dioxide emissions associated with this in order to gauge how close it is to achieving the zero carbon standard. As the existing house is relatively new, it was only constructed and installed in 2012, it is expected that the initial simulations will show that it is not yet up to the zero carbon standard. In the following sections, enhancements will be made to the model in an attempt to further reduce the energy used for space heating and CO_2 emissions from the house and move the house closer towards achieving net zero carbon status.

For the initial simulations it is important to note that the model represents the house as built, which has a leaky façade in terms of air infiltration, which is initially set at 4.82 ac/h, it does not use blinds or shutters on any of the windows to prevent heat loss and there is only a very basic control loop active which keeps habitable zone temperatures above 19 °C when occupied during the day and above 18 °C when occupied during the night. Outwith times where the building is occupied, the zone temperatures are allowed to free-float.

5.1.1. Space Heating Demand

Initial simulations within the ESP-r platform allowed the generation of an annual space heating demand profile. Fig 5.1, below, shows this demand profile for the whole year.

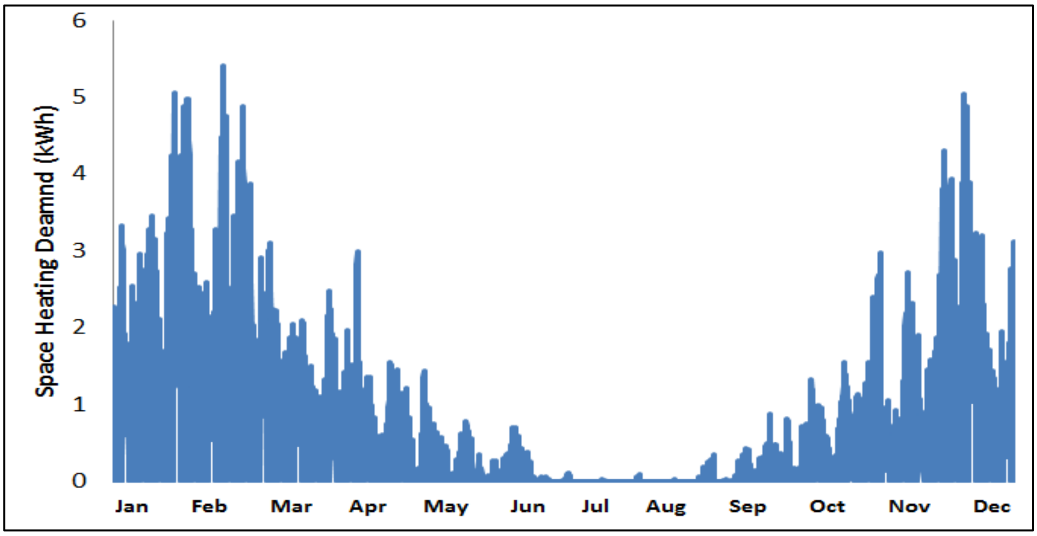


Fig 5.1: Annual heating demand for base case.

As expected, the space heating demand at the start of the year, during winter, is high, particularly in the larger areas such as the kitchen/dining/hall area where the peak heating demand is almost 2.5 kW in some weeks, almost half of the total peak heating demand at that particular time.

ESP-r also allows the user to view the space heating demand for the whole house in terms of the amount of energy delivered to each zone and the number of hours in which heating was required. This is shown in Fig 5.2, below.

Zone total sensible and latent plant used (kWhrs)

id	Zone name	Sensible heating Energy (kWhrs)	Sensible heating No. of Hr rqd	Sensible cooling Energy (kWhrs)	Sensible cooling No. of Hr rqd	Humidification Energy (kWhrs)	Humidification No. of Hr rqd	Dehumidification Energy (kWhrs)	Dehumidification No. of Hr rqd
1	GF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
2	GF_Laundry	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
3	GF_Shower	2378.22	7069.0	0.00	0.0	0.00	0.0	0.00	0.0
4	GF_Meeting	5223.33	7085.0	0.00	0.0	0.00	0.0	0.00	0.0
5	GF_Stairs	1461.63	6800.0	0.00	0.0	0.00	0.0	0.00	0.0
6	UF_NW_Bed	3387.11	6942.0	0.00	0.0	0.00	0.0	0.00	0.0
7	UF_Bathroom	1839.83	7075.0	0.00	0.0	0.00	0.0	0.00	0.0
8	UF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
9	UF_Void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
10	UF_NE_Bed	4166.16	7033.0	0.00	0.0	0.00	0.0	0.00	0.0
11	UF_Stairs	1391.65	6871.0	0.00	0.0	0.00	0.0	0.00	0.0
12	UF_Hall	4395.40	6991.0	0.00	0.0	0.00	0.0	0.00	0.0
13	gf_hall	7930.94	6346.0	0.00	0.0	0.00	0.0	0.00	0.0
14	GF_Living	4044.82	6591.0	0.00	0.0	0.00	0.0	0.00	0.0
15	Roof_void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	All	36219.1	68803.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig 5.2: Total space heating demand for the base case

As can be seen, the annual space heating demand for the whole house was 36,219.1 kWh. Having calculated a floor area of 150 m^2 for the whole house, this space heating demand is equivalent to 241 kWh/m^2, an extremely high value and one far greater than would be expected in an average existing home today. Immediately, this gives rise to concerns that the building is perhaps not operating as it should be and that modifications are going to have to be made in order to reduce the space heating demand for the house. By introducing building simulation at the earliest possible stage in the design phase of a development, this space heating demand could be reduced by testing new ideas and making improvements to the building fabric so that developers will know, should they construct the house properly, what they can expect in terms of space heating demands. It will be shown in the following section how modifications, easy to make within the simulation environment, can significantly affect the space heating demand in a dwelling and so simulation should be considered at the design stage, not post-construction unless the modification is simple to implement in practice.

5.1.2. Carbon Dioxide Emissions

The existing house is designed so that all of the space heating demand is covered by a 2.3 kW biomass boiler. As can be seen from Fig 5.1, the space heating demand exceeds 2.3 kW occasionally and so for all of the space heating demand to be covered by the biomass boiler, enhancements will have to be made or the capacity of the biomass boiler will have to be increased. Of course, zone temperatures can be difficult to control using a biomass system due to the start-up and shut-down times associated with them. Assuming that the biomass boiler can match the space heating demand and that the carbon emissions associated with burning the wood pellets is 0.016 kg CO_2/kWh, based on 130 kWh/tonne manufactured (15 kg CO_2/MWh) and 1 kg CO_2/MWh for transport (Biomass Energy Centre, 2013), this means that the amount of CO_2 emitted annually as a result of space heating was 580 kg CO_2, equivalent to 3.9 kg CO_2/m^2/year. This value surpasses the Carbon Compliance limit of 10 kg CO_2/m^2/year for a house of this type.

5.2. Energy Consumption & Carbon Emissions Analysis: Building with Modifications

In this section, modifications will be made to the building fabric and control systems within the simulation environment and the effects of these modifications will be analysed in terms of the annual space heating demand and the associated carbon dioxide emissions. The modifications that will be looked at in this section are: air tightness, insulation improvements, control system improvements and the use of shutters over windows at night. As previously mentioned, it is believed that the results of this section could be useful in future building design. Some building enhancements require significant time, effort and money to implement in practice, but very little to implement in the simulation environment. For example, improvements in the external wall insulation of a building is an enhancement which would take significant effort in the real world and would almost certainly be a costly procedure; in the Resource Efficient House at Ravenscraig, the procedure is made even more difficult due to the structurally insulated panel (SIP) construction, meaning that the external wall insulation is in the form of a polyurethane foam board enclosed by two sheets of plywood and so any changes to the insulation are extremely difficult to carry out in practice at the post-construction stage. This is one case where building simulation can be used to quickly show the effects that different scenarios in terms of the external wall insulation may have had; different types of insulation foam could be tested and different thicknesses could also be tested. Of course, if used at the design stage, building simulation could help developers optimise their buildings operational performance before construction has begun.

5.2.1. Air Tightness

If the government's ambitious targets on energy consumption and CO_2 emissions reduction are to be met, one area that must be looked at is the air tightness of buildings. Air infiltration can be described as the flow of air through unintentional cracks or gaps in a building's exterior surfaces. High air infiltration rates can lead to significant heat loss and draughts in domestic buildings, affecting energy bills and occupant comfort, respectively. By enhancing the air tightness of the buildings, heat loss and the associated CO_2 emissions can be reduced and bring benefits such as the potential for smaller heating systems being enough to cover the demand leading to lower energy bills as well as ensuring the comfort of occupants.

For the investigation into the effect of the air tightness of buildings, in terms of space heating and CO_2 emissions, an initial air changes per hour (ac/h) value must be input into the ESP-r platform. Fortunately, for this part of the investigation, I got the chance to assist a fellow student in carrying out the initial blower door test on the existing house as well observe two other tests once upgrades to the air tightness of the house had been made. The blower door test is simply a method of testing the air tightness of domestic sized buildings and in some cases the air flow between particular zones in buildings. There are three main pieces of equipment that are used to carry out a blower door test: an adjustable fan mount which is fitted to an external door, a variable speed fan used to pressurise/depressurise the building and a manometer to measure the pressure differential across the fan and building envelop. Once the equipment was in place and the building was prepared according to (ATTIMA, 2010), the first blower door test was carried out in order to measure the air changes per hour at 50 Pa.

A value of 4.82 ac/h at 50 Pa was calculated after the first blower door test for the existing house (Connolly, 2013) This value was much higher than what would be expected for a zero carbon house and it was found that the main reasons behind the high value was poor sealing around the seating area in the living area and the patio doors, drainage pipes in the kitchen and air leakage through sockets. Although the value was much higher than expected, it was used as the value at which to run the initial simulation as it would give a worst case scenario and a baseline for which to compare the effect of air tightness enhancements made in the existing building. As previously mentioned, it is expected that these initial simulations of the house, as built, may suggest that the house is not operating as it should and so the effects of enhancing the air tightness of the building will also be investigated. Fortunately, due to the project work carried out by (Connolly, 2013), a further two values were calculated: a value of 2.57 ac/h was recorded after some enhancements were made to the sealing around the seating area in the living room and a value of 1.4 ac/h was recorder after enhancements were made to the plumbing and the patio doors.

Fig 5.2, highlighted earlier, shows the results of the initial simulation in terms of the annual space heating demand in kWh and the number of hours required for each zone as well as the totals for the whole house, as built. As previously mentioned, the total space heating demand was 36,219.1 kWh, equivalent to 241 kWh/m^2 which is actually much higher than the average energy consumption in an average existing house. The total number of hours that space heating was required, for all zones, was 68803 hours, almost 80 % of the total hours in the year.

This, of course, is an extremely poor result for the developers as the target set for the house was a value of 1 ac/h and so some enhancements were made to the air tightness in the existing house, including sealing the draughty areas around the living area seating, and then a second blower door test was carried out. A resultant value of 2.57 ac/h at 50 Pa was measured and then used within the simulation environment to investigate the effects of enhancing the air tightness of the building. Fig 5.3, below, shows the results of this second simulation in terms of the annual space heating demand and number of heating hours required in the house.

Zone total sensible and latent plant used (kWhrs)

id	Zone name	Sensible heating Energy (kWhrs)	Sensible heating No. of Hr rqd	Sensible cooling Energy (kWhrs)	Sensible cooling No. of Hr rqd	Humidification Energy (kWhrs)	Humidification No. of Hr rqd	Dehumidification Energy (kWhrs)	Dehumidification No. of Hr rqd
1	GF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
2	GF_Laundry	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
3	GF_Shower	1428.74	6969.0	0.00	0.0	0.00	0.0	0.00	0.0
4	GF_Meeting	2971.60	6986.0	0.00	0.0	0.00	0.0	0.00	0.0
5	GF_Stairs	807.23	6106.0	0.00	0.0	0.00	0.0	0.00	0.0
6	UF_NW_Bed	1835.61	6560.0	0.00	0.0	0.00	0.0	0.00	0.0
7	UF_Bathroom	1015.23	6987.0	0.00	0.0	0.00	0.0	0.00	0.0
8	UF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
9	UF_Void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
10	UF_NE_Bed	2222.00	6843.0	0.00	0.0	0.00	0.0	0.00	0.0
11	UF_Stairs	759.49	6498.0	0.00	0.0	0.00	0.0	0.00	0.0
12	UF_Hall	2367.17	6725.0	0.00	0.0	0.00	0.0	0.00	0.0
13	gf_hall	3403.51	5210.0	0.00	0.0	0.00	0.0	0.00	0.0
14	GF_Living	2208.04	5985.0	0.00	0.0	0.00	0.0	0.00	0.0
15	Roof_void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	All	19018.6	64869.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig 5.3: Annual space heating demand at 2.57 ac/h

As can be seen, both the number of heating hours required and the amount of heating required reduced significantly when improvements were made to the building. The total space heating demand is now 19,018.6 kWh, which is equivalent to 127 kWh/m^2 for the house at Ravenscraig. Although this result is much better, representing a 47 % reduction in the space heating requirement, it suggests that the house, even after the first set of air tightness enhancements, still performs similar to a typical dwelling, perhaps somewhere between a new build and an average existing house, and not like a net zero carbon house. (Byrne, 2013)

A second set of air tightness enhancements were then made to the existing building, including sealing improvements to the plumbing in the kitchen and wet rooms and also to the patio doors. These enhancements were made in an attempt to further reduce the air infiltration and, again, a blower door test was carried out. The third blower door test returned a value of 1.4 ac/h at 50 Pa, much closer to the target set by developers which was 1 ac/h at 50 Pa. The developers thought that this value was close enough to their target and that they had done everything they feasibly could in order to improve the air tightness of the building and so this was the final value for the existing house.

The air infiltration rate was then changed to 1.4 ac/h in the model to represent the existing house in its current state and a third simulation was run. Fig 5.4, below, shows the results of this simulation in terms of the annual space heating demand and the required heating hours for the year.

Zone total sensible and latent plant used (kWhrs)

id	Zone name	Sensible heating Energy (kWhrs)	Sensible heating No. of Hr rqd	Sensible cooling Energy (kWhrs)	Sensible cooling No. of Hr rqd	Humidification Energy (kWhrs)	Humidification No. of Hr rqd	Dehumidification Energy (kWhrs)	Dehumidification No. of Hr rqd
1	GF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
2	GF_Laundry	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
3	GF_Shower	916.21	6636.0	0.00	0.0	0.00	0.0	0.00	0.0
4	GF_Meeting	1769.55	6676.0	0.00	0.0	0.00	0.0	0.00	0.0
5	GF_Stairs	451.64	4905.0	0.00	0.0	0.00	0.0	0.00	0.0
6	UF_NW_Bed	1030.79	5776.0	0.00	0.0	0.00	0.0	0.00	0.0
7	UF_Bathroom	570.82	6595.0	0.00	0.0	0.00	0.0	0.00	0.0
8	UF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
9	UF_Void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
10	UF_NE_Bed	1192.00	6190.0	0.00	0.0	0.00	0.0	0.00	0.0
11	UF_Stairs	426.12	5706.0	0.00	0.0	0.00	0.0	0.00	0.0
12	UF_Hall	1283.69	6045.0	0.00	0.0	0.00	0.0	0.00	0.0
13	gf_hall	1324.41	3752.0	0.00	0.0	0.00	0.0	0.00	0.0
14	GF_Living	1200.02	4780.0	0.00	0.0	0.00	0.0	0.00	0.0
15	Roof_void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	All	10165.3	57061.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig 5.4: Annual space heating demand at 1.4 ac/h

Again it can be seen that the air tightness enhancements have had a significant effect on the space heating demand. The annual space heating demand for the house was reduced further to 10,165.3 kWh, which is equivalent to 68 kWh/m^2. This represents a 47 % reduction since the second simulation and a 72 % reduction overall; it means that the house is now operating at a good level in terms of its energy use, albeit not yet what may be expected from a zero carbon building.

If the air infiltration was further reduced to 0.6 ac/h at 50 Pa, the requirement for Passive House standard, and it is expected that this would further reduce the annual space heating requirement to the level that the developers sought. Through virtual simulation, the effects of such enhancements can be analysed. The air infiltration rate in the house was set to 0.6 ac/h at 50 Pa within the simulation environment and a fourth simulation was run. The results of the simulation are illustrated in Fig 5.5, below.

Zone total sensible and latent plant used (kWhrs)

id	Zone name	Sensible heating Energy (kWhrs)	Sensible heating No. of Hr rqd	Sensible cooling Energy (kWhrs)	Sensible cooling No. of Hr rqd	Humidification Energy (kWhrs)	Humidification No. of Hr rqd	Dehumidification Energy (kWhrs)	Dehumidification No. of Hr rqd
1	GF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
2	GF_Laundry	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
3	GF_Shower	502.39	5570.0	0.00	0.0	0.00	0.0	0.00	0.0
4	GF_Meeting	835.96	5408.0	0.00	0.0	0.00	0.0	0.00	0.0
5	GF_Stairs	177.14	3264.0	0.00	0.0	0.00	0.0	0.00	0.0
6	UF_NW_Bed	451.87	4268.0	0.00	0.0	0.00	0.0	0.00	0.0
7	UF_Bathroom	224.70	4838.0	0.00	0.0	0.00	0.0	0.00	0.0
8	UF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
9	UF_Void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
10	UF_NE_Bed	429.87	4361.0	0.00	0.0	0.00	0.0	0.00	0.0
11	UF_Stairs	178.46	4049.0	0.00	0.0	0.00	0.0	0.00	0.0
12	UF_Hall	473.93	4094.0	0.00	0.0	0.00	0.0	0.00	0.0
13	gf_hall	181.98	1493.0	0.00	0.0	0.00	0.0	0.00	0.0
14	GF_Living	481.27	3182.0	0.00	0.0	0.00	0.0	0.00	0.0
15	Roof_void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	All	3937.6	40527.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig 5.5: Annual space heating demand at 0.6 ac/h

As can be seen from the figure above, the final push from an air infiltration of 1.4 ac/h to 0.6 ac/h has a significant on the annual space heating demand. If the house were to have an actual air infiltration of 0.6 ac/h at 50 Pa, simulation methods show that the annual space heating requirement would be 3937.6 kWh, equivalent to 26 kWh/m^2, which almost meets the passive house standard of 15 kWh/m^2. As well as this, the number of heating hours required is reduced to 40527, equivalent to around 46 % of the total hours in a year.

Fig 5.6, below, shows the reduction in the annual space heating demand at each stage of the air tightness enhancements.

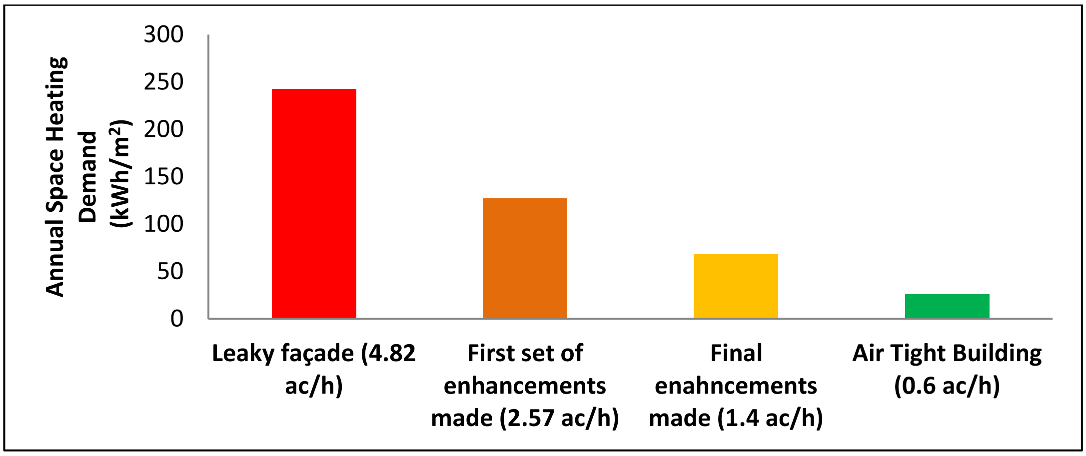


Fig 5.6: Annual space heating demand reduction step-by-step

From Fig 5.6, above, it can be seen that significant reductions in space heating demand can be achieved just by making enhancements to the building in order to reduce air infiltration. It shows that just by properly sealing air gaps around walls, floors and doors as well as sealing any air leakages in pipework in the kitchen can reduce the space heating demand by 72 %.

The information in the figure above can be translated into a similar graph for the carbon emissions associated with the annual space heating of the house if it is covered entirely by the biomass stove. Fig 5.7, below, shows the annual carbon emissions for the initial model and then for each stage of the modifications.

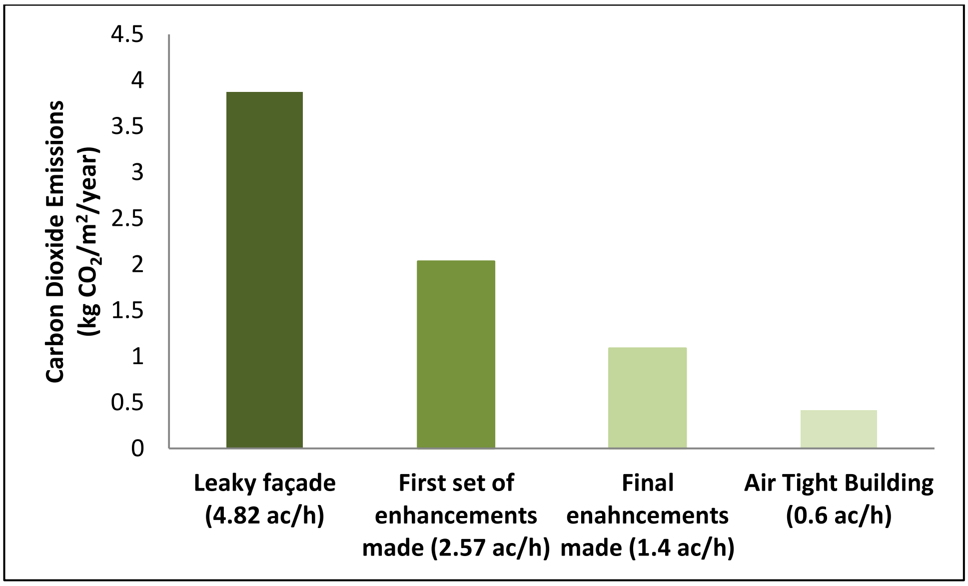


Fig 5.7: Annual CO_2 reduction at each stage of enhancements

As can be seen from Fig 5.7 above, although the carbon emissions per m^2 of floor are already low due to the type of technology used to supply the energy, significant percentage reductions can be made by enhancing the airtightness of the dwelling.

The results found in this section do not come as a surprise; it is expected that as the airtightness of the building is increased, the annual energy demand of the building and the corresponding carbon emissions will decrease. This is expected because as cracks and gaps around walls and doors are sealed, the airtightness is increased meaning that there is much less internal heat lost to the outside of the building and less cool air can penetrate through the sealed cracks from outside to inside the building. This, of course, means that internal temperatures are more likely to be higher as a result and so less heating will be needed. These results also build a case for the implementation of building simulation in the design stage. If used here, developers would've know what to expect in terms of their heating demand and carbon emissions should they achieve certain levels of air tightness and they would've known at the design stage what level of airtightness would optimise the operational performance of the house which would've saved the time and effort making step-by-step enhancements post-construction and carrying out monitoring.

5.2.2. Insulation

As outlined in previous sections, insulation improvements can have a significant impact on a buildings energy consumption and subsequent carbon emissions. In this section, the thickness of the external wall insulation will be increased incrementally within the simulation environment and the effects on both the space heating demand and the carbon emissions associated with it will be investigated. The type of insulation used in the model is polyurethane foam and this is kept constant throughout the initial simulations; only the thickness of the insulation used is changed initially. The specification of the insulation will then be upgraded in a further investigation. Table 5.1, below, outlines the thermo-physical specification of the insulation material.

Conductivity	0.03 W/mK
Density	30 kg/m^3
Specific Heat	837 J/kgK
Emissivity	0.9
Absorptivity	0.5
Vapour Res	90 MNs/gm

Table 5.1: Thermo-physical specification of polyurethane foam insulation

The initial thickness of the external wall insulation in the model was 128 mm, representing the exact thickness of the polyurethane insulation in the existing house at Ravenscraig. Results of the initial 'as built' simulation, i.e. with an air infiltration rate of 4.82 ac/h, are detailed in section 5.1.1, above. The main points of interest is that the annual space heating demand was 36,219.1 kWh, equivalent to 241 kWh/m^2 and the associated carbon emissions were 580 kg CO_2 for the year, equivalent to 3.9 kg CO_2/m^2/year.

The thickness of the polyurethane insulation was then changed to 138 mm and an annual simulation was run to assess how significant an effect, if any, this had on the space heating demand and the carbon emissions associated with this. Fig 5.8, below, shows the results of the simulation in terms of the annual space heating demand for each zone and the total for the full year.

Zone total sensible and latent plant used (kWhrs)

Zone		Sensible heating		Sensible cooling		Humidification		Dehumidification	
id	name	Energy (kWhrs)	No. of Hr rqd	Energy (kWhrs)	No. of Hr rqd	Energy (kWhrs)	No. of Hr rqd	Energy (kWhrs)	No. of Hr rqd
1	GF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
2	GF_Laundry	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
3	GF_Shower	2372.72	7070.0	0.00	0.0	0.00	0.0	0.00	0.0
4	GF_Meeting	5215.31	7085.0	0.00	0.0	0.00	0.0	0.00	0.0
5	GF_Stairs	1459.43	6801.0	0.00	0.0	0.00	0.0	0.00	0.0
6	UF_NW_Bed	3378.47	6942.0	0.00	0.0	0.00	0.0	0.00	0.0
7	UF_Bathroom	1836.32	7075.0	0.00	0.0	0.00	0.0	0.00	0.0
8	UF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
9	UF_Void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
10	UF_NE_Bed	4156.56	7033.0	0.00	0.0	0.00	0.0	0.00	0.0
11	UF_Stairs	1389.36	6873.0	0.00	0.0	0.00	0.0	0.00	0.0
12	UF_Hall	4390.09	6989.0	0.00	0.0	0.00	0.0	0.00	0.0
13	gf_hall	7924.94	6346.0	0.00	0.0	0.00	0.0	0.00	0.0
14	GF_Living	4064.06	6596.0	0.00	0.0	0.00	0.0	0.00	0.0
15	Roof_void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	All	36187.3	68810.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig 5.8: Annual space heating demand for Resource Efficient House with 138mm external wall insulation

As can be seen from Fig 5.8, above, by increasing the thickness of the polyurethane insulation in the external wall by 10 mm, the total annual space heating demand is reduced from 36,219.1 kWh to 36,187.3 kWh, which is equivalent to 241 kWh/m^2. Although a slight reduction is evident, the reduction is less than 0. 1 % of the original space heating demand. This initial simulation suggests that increasing the thickness of the external wall insulation may not be a worthwhile enhancement to make to the building because the external wall insulation thickness is limited by the thickness of the wall; for this particular building, the insulation in the external wall could only realistically be 20 to 40 mm thicker than what the current size and so there may not be enough room to increase the thickness of insulation to a level where the additional thickness is making a significant difference to the space heating demand.

Further investigations were made into the effects of increasing the thickness of the external wall insulation by carrying out simulations with insulation thicknesses of 148 mm and 158 mm. Figures 5.9 and 5.10, below, show the space heating demand for these enhancements respectively.

Zone total sensible and latent plant used (kWhrs)

id	Zone name	Sensible heating Energy (kWhrs)	Sensible heating No. of Hr rqd	Sensible cooling Energy (kWhrs)	Sensible cooling No. of Hr rqd	Humidification Energy (kWhrs)	Humidification No. of Hr rqd	Dehumidification Energy (kWhrs)	Dehumidification No. of Hr rqd
1	GF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
2	GF_Laundry	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
3	GF_Shower	2367.76	7070.0	0.00	0.0	0.00	0.0	0.00	0.0
4	GF_Meeting	5208.09	7085.0	0.00	0.0	0.00	0.0	0.00	0.0
5	GF_Stairs	1457.49	6801.0	0.00	0.0	0.00	0.0	0.00	0.0
6	UF_NW_Bed	3370.75	6942.0	0.00	0.0	0.00	0.0	0.00	0.0
7	UF_Bathroom	1833.19	7076.0	0.00	0.0	0.00	0.0	0.00	0.0
8	UF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
9	UF_Void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
10	UF_NE_Bed	4147.96	7033.0	0.00	0.0	0.00	0.0	0.00	0.0
11	UF_Stairs	1388.08	6873.0	0.00	0.0	0.00	0.0	0.00	0.0
12	UF_Hall	4384.62	6990.0	0.00	0.0	0.00	0.0	0.00	0.0
13	gf_hall	7917.24	6345.0	0.00	0.0	0.00	0.0	0.00	0.0
14	GF_Living	4059.22	6599.0	0.00	0.0	0.00	0.0	0.00	0.0
15	Roof_void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	All	36134.4	68814.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig 5.9: Annual space heating demand for Resource Efficient House with 148mm external wall insulation

Zone total sensible and latent plant used (kWhrs)

Zone		Sensible heating		Sensible cooling		Humidification		Dehumidification	
id	name	Energy (kWhrs)	No. of Hr rqd	Energy (kWhrs)	No. of Hr rqd	Energy (kWhrs)	No. of Hr rqd	Energy (kWhrs)	No. of Hr rqd
1	GF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
2	GF_Laundry	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
3	GF_Shower	2363.33	7070.0	0.00	0.0	0.00	0.0	0.00	0.0
4	GF_Meeting	5201.65	7085.0	0.00	0.0	0.00	0.0	0.00	0.0
5	GF_Stairs	1456.07	6803.0	0.00	0.0	0.00	0.0	0.00	0.0
6	UF_NW_Bed	3363.84	6942.0	0.00	0.0	0.00	0.0	0.00	0.0
7	UF_Bathroom	1830.41	7076.0	0.00	0.0	0.00	0.0	0.00	0.0
8	UF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
9	UF_Void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
10	UF_NE_Bed	4140.20	7032.0	0.00	0.0	0.00	0.0	0.00	0.0
11	UF_Stairs	1386.40	6872.0	0.00	0.0	0.00	0.0	0.00	0.0
12	UF_Hall	4380.22	6990.0	0.00	0.0	0.00	0.0	0.00	0.0
13	gf_hall	7911.56	6346.0	0.00	0.0	0.00	0.0	0.00	0.0
14	GF_Living	4044.87	6601.0	0.00	0.0	0.00	0.0	0.00	0.0
15	Roof_void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	All	36078.6	68817.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig 5.10: Annual space heating demand for Resource Efficient House with 158mm external wall insulation

It can be seen from the two figures above that increasing the thickness of the external wall insulation to 148 mm and 158 mm reduced the total space heating demand in the house to 36,134.4 kWh and 36,078.6 kWh, respectively. These two values are equivalent to 240.8 kWh/m^2 and 240.5 kWh/m^2, respectively. Again, it can be seen that although there are reductions in the space heating demand as a result of increasing the external wall insulation, these reductions are very slight; increasing the thickness of the external wall insulation by 30 mm only reduces the total space heating demand by 0.4 %.

Due to the structurally insulated panel (SIP) construction of the house, any changes that are made to the insulation would have to be thought of at the design stage before the house was constructed and so, although the reductions in energy demand are very slight here, it would be beneficial if the optimum thickness of external wall insulation was used to reduce the space heating demand as much as possible at the design stage.

Another enhancement to the external wall insulation that could be made is a an upgrade of the insulation material itself. Again, due to the SIP construction with polyurethane foam insulation, there are limits to the changes that can be made.

However, research by (Jarfelt & Ramnas, 2006) suggests that thermal conductivities of as low as 0.022 W/mK are achievable using polyurethane foam board.

The thermal conductivity of the polyurethane foam board was then reduced to 0.022 W/mK within the materials database and an annual simulation was run while the insulation thickness was kept at 158 mm. It was found that by reducing the thermal conductivity of the polyurethane foam from 0.03 W/mK to 0.022 W/mK, the annual space heating demand was reduced to 35817.5 kWh. This represents around a 2 % reduction from the base case. In terms of the carbon emissions, by upgrading the polyurethane foam to a conductivity of 0.022 W/mK and increasing the thickness of the insulation, annual carbon emissions were reduced from 580 to 573 kg CO_2.

Although the reductions in space heating demand are only very slight at each stage of the enhancements to the insulation, it is believed that the overall 2 % reduction by increasing the thickness of insulation and upgrading the conductivity of the insulation could be achieved without much extra work at the design stage and along with other measures, such as air infiltration enhancements, could improve energy consumption and reduce the space heating demand.

If this insulation upgrade was made to the airtight (0.6 ac/h) model described in the previous section, the space heating demand would be reduced from 3937.6 kWh to 3500 kWh, which represents a reduction of around 11 %, over five times the size of reduction evident when improving insulation on the leaky, base case building. This shows that improving the buildings insulation has more of an effect when the air infiltration in the building is at a minimum. Fig 5.11, below, shows the effects of upgrading the insulation in the base case model as well as the effect of the same upgrade to an airtight building.

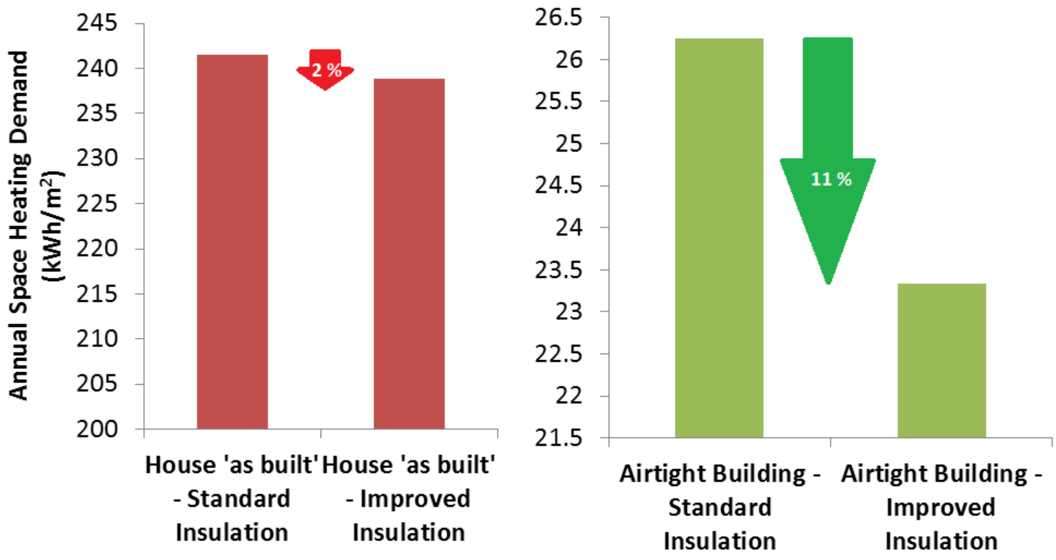


Fig 5.11: The effect of Insulation Improvements for the base case model (left) and for an airtight building (right). Here the base case model is as described in section 5.1, i.e. the air infiltration rate is 4.82 ac/h and it has basic control. The airtight building is the base case model with an upgrade in air infiltration to 0.6 ach/h. The insulation improvement is as described in this section, i.e. an increase of 30 mm to 158 mm insulation and a reduction in the thermal conductivity of the insulation to 0.022 W/mK.

It can be seen from fig 5.11, above, that increasing the thickness of the external wall insulation and decreasing its conductivity as well as making enhancements to the airtightness of the building can achieve significant reductions in the space heating demand. This is also true for the carbon emissions; annual carbon emissions have been reduced from 580 kg $CO_{2,}$ or 3.9 kg CO_2/m_2/year, for the base case model which had a leaky façade and no insulation improvements, to 56 kg CO_2, or 0.4 kg CO_2/m^2/year, once the air infiltration of the building had been reduced to 0.6 ac/h and the insulation had been improved.

It has been shown in this section that although slight in comparison to enhancements in airtightness, improving the external wall insulation can reduce energy demand and the carbon emissions associated with this. Again, it is believed that only by using building simulation at the design stage to analyse different insulation types, thicknesses, specification can the optimum be chosen and so it should be used as a design tool at the earliest possible stage.

5.2.3. Control

As previously mentioned, the initial control system in the model was very basic, representing the control system in the existing house. Initially, the control system in the model was designed to keep zone temperatures above 18 °C during the night and above 19 °C during the day when the house was occupied. When the house was not occupied, the temperature was allowed to free float. All previous simulations have been run with this basic control loop active and so the next stage of the project was to upgrade the control system to a more sophisticated one and analyse the effects this had on the space heating demand and the carbon emissions associated with this.

Five control loops were designed in order to build up the new sophisticated control system. The first control loop was designed to keep the air temperatures in the upper-floor bedrooms above 18 °C when the rooms are occupied, above 15 °C when the house was occupied but the rooms were not, and when the house was not occupied the temperatures in the rooms were allowed to free-float. The second control loop applied exactly the same control logic to the ground-floor bedroom, the only difference was that the ground-floor bedroom was occupied at slightly different times. The third control loop was designed to keep the air temperatures in the living and kitchen/dining areas above 19 °C when the house was occupied, excluding sleeping hours. When the house was not occupied and during sleeping hours, i.e. during the night, the temperatures were allowed to free-float. The fourth control loop was designed to keep the air temperature in the upper-floor office space above 19 °C when the zone was occupied, above 15 °C when the house was occupied, excluding sleeping hours. Again, when the house was not occupied or during sleeping hours, the temperatures in this zone were allowed to free-float. Finally, the fifth control loop was designed to keep the air temperatures in zones with unpredictable usage, such as bathrooms and shower rooms, above 15 °C when the house was occupied and, as with previous control loops, the zone temperature was allowed to free-float when the house was not occupied and during sleeping hours.

An annual simulation was then run with the new sophisticated control system active and the annual space heating demand was generated. Fig 5.12, below, shows the annual space heating demand for each zone in the house as well as the total annual space heating demand measured once the control system has been upgraded.

Zone total sensible and latent plant used (kWhrs)

Zone id	Zone name	Sensible heating Energy (kWhrs)	Sensible heating No. of Hr rqd	Sensible cooling Energy (kWhrs)	Sensible cooling No. of Hr rqd	Humidification Energy (kWhrs)	Humidification No. of Hr rqd	Dehumidification Energy (kWhrs)	Dehumidification No. of Hr rqd
1	GF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
2	GF_Laundry	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
3	GF_Shower	800.18	2817.0	0.00	0.0	0.00	0.0	0.00	0.0
4	GF_Meeting	3984.18	5897.0	0.00	0.0	0.00	0.0	0.00	0.0
5	GF_Stairs	406.01	2279.0	0.00	0.0	0.00	0.0	0.00	0.0
6	UF_NW_Bed	2679.83	5626.0	0.00	0.0	0.00	0.0	0.00	0.0
7	UF_Bathroom	662.46	2899.0	0.00	0.0	0.00	0.0	0.00	0.0
8	UF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
9	UF_Void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
10	UF_NE_Bed	3268.24	5761.0	0.00	0.0	0.00	0.0	0.00	0.0
11	UF_Stairs	432.09	2554.0	0.00	0.0	0.00	0.0	0.00	0.0
12	UF_Hall	2171.61	3879.0	0.00	0.0	0.00	0.0	0.00	0.0
13	gf_hall	2985.89	2907.0	0.00	0.0	0.00	0.0	0.00	0.0
14	GF_Living	1822.77	2995.0	0.00	0.0	0.00	0.0	0.00	0.0
15	Roof_void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	All	19213.3	37614.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig 5.12: Annual space heating demand for the base case model with sophisticated control system installed

As can be seen from the figure above, the new control system has significantly reduced the annual space heating demand for the house. Before the running simulations with the sophisticated control system active, the space heating demand for the house was 36,219.1 kWh, or 241.5 kWh/m^2. The space heating demand after running a simulation with the sophisticated control system was 19,213.3 kWh, equivalent to 128 kWh/m^2. This represents a 47 % reduction in the annual space heating demand just by installing a sophisticated control system. It should be noted, however, that in terms of the energy consumption per square metre of habitable floor area, the house was still not operating at a level that would be expected of a zero carbon house and it was performing rather more like somewhere between an existing home and a typical newly built home. In terms of carbon emissions, the amount of CO_2 emitted annually before and after the update was 580 kg and 307 kg, respectively. The latter figure is equivalent to 2 kg CO_2/m^2/year which is well beyond the Carbon Compliance Limit and will most likely be cancelled out by the low to zero carbon technologies integrated into the building.

It was expected that, as a more sophisticated control system was installed, the annual space heating demand of the house, and the carbon dioxide emissions associated, would be reduced. This was expected because the sophisticated control system meant that particular zones needed much less heating over the year because the control logic stated that they only required to be at certain temperatures at times when the zone was occupied and at much lower temperatures otherwise. In contrast, the basic control system meant that much more energy was being used on space heating because even zones which were not occupied were being kept at higher temperatures.

A further simulation was then run to investigate whether or not the installation of the control system had as significant an effect on the airtight building with insulation improvements installed, as described previously. It is thought that even although the space heating demand for this example is already low, the installation of the control system described would have a positive effect on the annual space heating demand and carbon emissions. Fig 5.13, below, shows the annual space heating demand for the airtight building with insulation improvements and the control system upgrade.

Zone total sensible and latent plant used (kWhrs)

Zone		Sensible heating		Sensible cooling		Humidification		Dehumidification	
id	name	Energy (kWhrs)	No. of Hr rqd	Energy (kWhrs)	No. of Hr rqd	Energy (kWhrs)	No. of Hr rqd	Energy (kWhrs)	No. of Hr rqd
1	GF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
2	GF_Laundry	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
3	GF_Shower	139.82	1871.0	0.00	0.0	0.00	0.0	0.00	0.0
4	GF_Meeting	534.12	3872.0	0.00	0.0	0.00	0.0	0.00	0.0
5	GF_Stairs	3.44	230.0	0.00	0.0	0.00	0.0	0.00	0.0
6	UF_NW_Bed	342.18	3165.0	0.00	0.0	0.00	0.0	0.00	0.0
7	UF_Bathroom	66.78	1800.0	0.00	0.0	0.00	0.0	0.00	0.0
8	UF_Store	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
9	UF_Void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
10	UF_NE_Bed	318.72	2852.0	0.00	0.0	0.00	0.0	0.00	0.0
11	UF_Stairs	39.89	1227.0	0.00	0.0	0.00	0.0	0.00	0.0
12	UF_Hall	198.06	1937.0	0.00	0.0	0.00	0.0	0.00	0.0
13	gf_hall	200.05	944.0	0.00	0.0	0.00	0.0	0.00	0.0
14	GF_Living	201.39	1332.0	0.00	0.0	0.00	0.0	0.00	0.0
15	Roof_void	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	All	2044.4	19230.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig 5.13: Annual space heating demand for airtight building with insulation improvements and a sophisticated control system

It can be seen from the figure above that the annual space heating demand has been reduced from 3,500 kWh, for the airtight building with only basic control, to

2,044.4 kWh. The new annual space heating demand is equivalent to 13 kWh/m^2, representing a 41.5 % reduction and meaning the house would be operating to Passivhaus Standard (<15 kWh/m^2). Fig 5.14, below, shows graphically the space heating demand reductions seen for both the base case model and for the airtight model with insulation improvements.

Fig 5.14: Annual space heating demand reductions evident when installing advanced control systems to the base case model (left) and the airtight model with insulation improvements described previously (right), respectively.

As can be seen from the figure above, large reductions in the annual space heating demand is evident from installing a sophisticated control systems in both models, although for the airtight building the control system upgrade is around 6 % less effective. It is thought that this may be the case because the annual space heating demand is already very low for the airtight building and it becomes more and more difficult to reduce the demand further as the building begins to perform better in terms of its heating demand. In this case, a lot of the energy savings that were made by the control system alone in the initial simulation on the base case model are already made by other measures, such as the air tightness enhancements, in the airtight building simulation before the control system becomes active and so although a significant reduction is evident in both cases, it was expected that the reduction would be less significant for the airtight building as a lot of the energy use that would be reduced by the control system has already been eliminated. This, like the previous two simulations, builds a case for implementing simulation at the design stage. Had developers used simulation to show the effects of different control systems, it is likely that they would have installed the more sophisticated one, reducing their energy demand and carbon emissions. In reality, a basic control system has been installed and should it not perform well it will need to be replaced and so this effort spent replacing the system could be avoided by using simulation at the design stage.

5.3. Environmental Conditions Analysis

It has been shown that through enhancements to the airtightness, insulation and control systems in homes, significant reductions towards zero carbon status in terms of the annual space heating demand and the associated carbon emissions can be made. This section of the report will focus on the impact that these changes have to the environmental conditions in the house in terms of the zone temperatures and thermal comfort levels. The 'as built' performance of the house will be assessed first before a second simulation is run with the enhancements made and the impact of these modifications will be discussed. For the following investigations, only six zones of interest will be looked at as these zones are occupied most often are of more thermal importance; the zones are the living area, kitchen/dining area, office area, ground-floor bedroom and the two upper-floor bedrooms.

5.3.1. House as Built

As previously mentioned, the initial model of the Resource Efficient House did not operate to the standard that would be expected of zero carbon house; the building had a very leaky façade, leading to significant heat loss through gaps in the walls and around doors which increased the annual space heating demand and there was only a very basic control system installed which meant that unnecessary heat was being supplied to zones which were not occupied which again increased the space heating demand.

5.3.1.1. Zone Temperature

Firstly, the dry bulb temperature of the zones of interest were looked at along with the ambient temperatures to confirm concerns resulting from previous investigations that the house, in its initial state, would very rarely be operating at a level where heating was not needed and that only in the very height of summer temperatures would naturally be above the minimum zone set point temperature. Fig 5.15, below, shows the annual zone temperatures of the base case model alongside the ambient temperature.

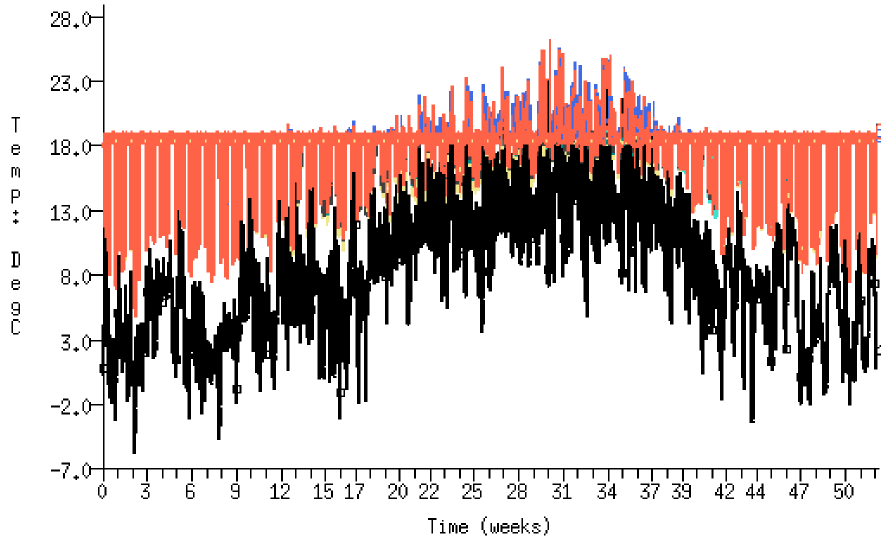


Fig 5.15: Annual zone temperatures (colour) and the annual ambient temperatures (black) for the Resource Efficient House.

As can be seen from the figure above, zones in the initial model very rarely met the minimum temperature set point, as expected. The result confirms that only in the middle of summer, when the ambient temperatures are at a maximum, zones in the initial model did not require space heating. This can be seen more clearly in Fig 5.16, below, by looking at the zone temperatures and ambient temperatures in typical winter and summer weeks.

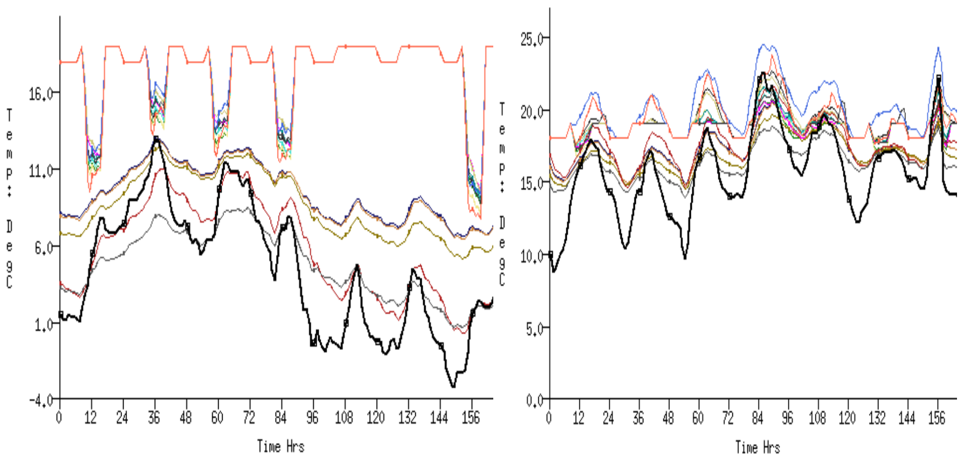


Fig 5.16: Zone and ambient temperatures in the base case model during a typical winter week (left) and a typical summer week (right)

It can be seen clearly from the figure above that temperatures in all zones of interest, on average, are below the minimum set point temperature of 19 °C. The same pattern was observed for the transition day simulation and so this means that for the vast majority of the year, zone temperatures were significantly lower than the minimum set point temperature and the basic control system ensured that heat was supplied to these zones almost all year round, resulting in a very high annual heating demand, as discussed earlier.

On taking a closer look at the summer week in Fig 5.16, above, it can also be seen that only in the living area (GF_Living), the kitchen/dining area (gf_hall) and one of the upstairs bedrooms (UF_NW_Bed) does the maximum temperature in the zone exceed 24 °C, a figure often used as the temperature limit at which the zone becomes uncomfortable and needs cooling. (Parry and Irvine, 1980) Fig 5.17, below, shows the number of hours each zone is above and below 24 °C.

Zone db temperature (degC)
Reporting number of hours above 24.00

Description	Maximum value	Maximum occurrence	Minimum value	Minimum occurrence	Mean value	No of hours above	No of hours below	% above
GF_Meeting	22.37	04-Aug@16h30	5.30	16-Jan@15h30	17.66	0.00	8760.00	0.0
UF_NW_Bed	24.21	27-Jul@20h30	6.23	16-Jan@15h30	17.78	1.00	8759.00	0.0
UF_NE_Bed	22.38	04-Aug@16h30	6.08	16-Jan@15h30	17.80	0.00	8760.00	0.0
UF_Hall	22.19	11-Aug@21h30	5.98	16-Jan@15h30	17.77	0.00	8760.00	0.0
gf_hall	25.58	30-Jul@18h30	6.24	16-Jan@15h30	18.19	56.00	8704.00	0.6
GF_Living	26.19	30-Jul@17h30	4.71	16-Jan@15h30	17.84	27.00	8733.00	0.3

Total number of hours greater than query point: 84.00 (0.2%)
Total number of hours less than or equal to query point: 52476.00 (99.8%)

Fig 5.17: Hours that zone temperatures were above/below 24 °C.

As can be seen from the figure above, on further inspection, the zone temperatures in the three zones mentioned earlier very rarely exceed 24 °C and the number of hours they exceed 24 °C combined is only 84 hours out of the whole year, representing 0.2 %. As temperatures rarely exceed 24 °C and the basic control system is designed to keep the zone temperatures above certain set points when the house is occupied, it is believed that the house will perform well in terms of thermal comfort, even if the annual heating demand is extremely high. This will be discussed in the next section.

Later in this report, zone dry bulb temperature will be investigated again with modifications made to the model such as the airtightness, insulation and control systems enhancements outlined in section 5.2. Table 5.2, below, shows the average dry bulb temperatures for the zones of interest for typical winter, transition and summer weeks respectively.

Zone/Ambient	Winter Week Average Temp (°C)	Transition Week Average Temp (°C)	Summer Week Average Temp (°C)
Ambient	4.32	7.22	15.6
Living Area	17.16	17.79	19.29
Kitchen/Dining Area	17.49	18.08	20.07
Ground-floor Bedroom	17.22	17.67	18.72
Upper-floor NE Bedroom	17.41	17.82	18.83
Upper-floor NW Bedroom	17.32	17.74	18.75
Upper-floor Office Space	17.39	17.73	18.84

Table 5.2: Average zone dry bulb and ambient temperatures for the base case model over typical winter, transition and summer weeks, respectively.

The information in the table above will be the point of reference for assessing the impact on zone temperatures after modifications have been made.

5.3.1.2. Thermal Comfort

Thermal comfort can be described as the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. (ANSI/ASHRAE, 2010) The ESP-r platform predicts the thermal comfort of occupants based on the work of (Fanger, 1970) Before assessments of thermal comfort can be carried out, there are several factors that must be input in ESP-r which are important for the thermal comfort assessment. The three main inputs are the activity level, clothing level and the air speed. For the following simulations, the activity level was set at 90, the air speed was set to the default speed of 0.1 and the clothing level was calculated to be 0.9 for winter week simulations, 0.75 for transition week simulations and 0.6 for summer week simulations. The clothing level was derived using a calculation outlined in ESP-r. The calculation is based on each piece of clothing being assigned a value which are added together to give a total which is then multiplied by 0.82 to give the clothing value to be used for the thermal comfort assessment. For the following summer week simulations, for example, it was decided that the occupants would be wearing a light short sleeve shirt (0.14), a light sweater (0.2), underwear (0.05), light trousers (0.26), light socks (0.03) and shoes (0.04). Adding the unit values, in brackets, together and multiplying by 0.82 gives a clothing value of 0.6 for the summer week simulations. The exact same calculation was used, albeit with different levels of clothing, to derive clothing values representative of typical clothing levels of transition and winter weeks. As will be seen in the following figures, there are a number of variables associated with the thermal comfort assessment: zone air temperature, mean radiant temperature (MRT), relative humidity, the standard effective temperature (SET), the predicted mean vote based on Fanger's work (PMV*), predicted mean voted based on ET rather than TO (PMV) and the predicted percentage dissatisfied. ESP-r assesses the thermal comfort based on the PMV values in line with the ASHRAE thermal sensation scale.

A simple comfort assessment was then carried out on the living area of the base case model for the first day of the typical winter week, the 5th February. As ESP-r assesses the hourly thermal comfort for a whole day, it is impractical to show thermal comfort assessments for all zones of interest. It was felt that the living area would be the most likely to display signs of thermal discomfort because clothing levels would be at a minimum compared to those in the rest of the house; in bedrooms it was thought that the clothing level would be far greater as they are only occupied at night where a duvet would almost certainly be used, meaning that there would be less chance of thermal discomfort. Fig 5.18, below, shows the results of the thermal comfort assessment.

Activity level 89.98, Clothing level 0.90, Air speed 0.10
Default mean radiant temperature

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	18.0	15.9	24.	21.4	-0.58	-0.49	10.	comfortable, pleasant
1.5	18.0	15.7	23.	21.3	-0.60	-0.50	10.	slightly cool, acceptable
2.5	18.0	15.7	24.	21.3	-0.60	-0.51	10.	slightly cool, acceptable
3.5	18.0	15.6	24.	21.3	-0.60	-0.51	10.	slightly cool, acceptable
4.5	18.0	15.6	24.	21.2	-0.60	-0.51	11.	slightly cool, acceptable
5.5	18.0	15.5	26.	21.2	-0.60	-0.51	10.	slightly cool, acceptable
6.5	18.0	15.5	28.	21.3	-0.59	-0.50	10.	slightly cool, acceptable
7.5	18.5	15.6	28.	21.5	-0.54	-0.45	9.	comfortable, pleasant
8.5	19.0	15.8	28.	21.8	-0.47	-0.39	8.	comfortable, pleasant
9.5	16.1	15.2	34.	20.3	-0.77	-0.69	15.	slightly cool, acceptable
10.5	10.4	13.8	50.	16.9	-1.37	-1.35	43.	cool, unpleasant
11.5	9.5	12.7	55.	16.1	-1.51	-1.51	52.	cool, unpleasant
12.5	10.6	12.9	54.	16.7	-1.39	-1.38	44.	cool, unpleasant
13.5	10.6	13.0	58.	16.8	-1.37	-1.36	44.	cool, unpleasant
14.5	11.0	13.0	60.	17.0	-1.33	-1.31	41.	cool, unpleasant
15.5	11.1	13.1	62.	17.1	-1.30	-1.29	40.	cool, unpleasant
16.5	15.4	14.0	49.	19.5	-0.86	-0.80	19.	cool, unpleasant
17.5	19.0	15.7	41.	22.0	-0.40	-0.34	7.	comfortable, pleasant
18.5	19.0	16.1	40.	22.1	-0.38	-0.32	7.	comfortable, pleasant
19.5	19.0	16.2	39.	22.1	-0.38	-0.32	7.	comfortable, pleasant
20.5	19.0	16.4	41.	22.2	-0.36	-0.30	7.	comfortable, pleasant
21.5	19.0	16.5	42.	22.3	-0.34	-0.28	7.	comfortable, pleasant
22.5	19.0	16.6	42.	22.3	-0.34	-0.27	7.	comfortable, pleasant
23.5	18.5	16.4	43.	22.0	-0.40	-0.33	7.	comfortable, pleasant

Fig 5.18: Thermal comfort assessment for the living area in the base case model during a typical winter day

As can be seen from the figure above, during the night the living area is slightly cool. This is not a concern as the living area is not occupied during the night. The living area is slightly cool until around 7am when the zone becomes comfortable and pleasant due to the basic control system initiating the heating of the zone. Throughout the day, the comfort varies between slightly cool and acceptable to cool and unpleasant, which again is not a concern as the house is not occupied. At around 5pm, the heating comes on again while the house is occupied and the environment is described as comfortable and pleasant for the rest of the evening. These results of the initial thermal comfort assessment suggest that the expectation that the initial model of the house would be thermally comfortable during occupied hours may be correct. However, transition and summer week thermal comfort assessments were run in order to check whether or not they would yield the same results.

Figures 5.19 and 5.20, below, show the thermal comfort assessment results for the transitional week and the summer week respectively. Here, the transitional day used was the first day of the typical spring week, the 14th April, and the summer day used was the first day of the typical summer week, the 8th August. Again, the thermal comfort assessments shown below relate to the living area only.

Activity level 89.98, Clothing level 0.75, Air speed 0.10
Default mean radiant temperature

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	18.5	20.2	35.	21.9	-0.48	-0.30	7.	comfortable, pleasant
1.5	18.0	19.5	34.	21.4	-0.59	-0.42	9.	comfortable, pleasant
2.5	18.0	18.9	33.	21.2	-0.63	-0.47	10.	comfortable, pleasant
3.5	18.0	18.6	33.	21.0	-0.66	-0.50	10.	comfortable, pleasant
4.5	18.0	18.2	33.	20.9	-0.68	-0.52	11.	slightly cool, acceptable
5.5	18.0	17.9	33.	20.8	-0.71	-0.55	11.	slightly cool, acceptable
6.5	18.0	17.8	34.	20.7	-0.71	-0.56	11.	slightly cool, acceptable
7.5	18.5	17.8	34.	21.0	-0.65	-0.49	10.	comfortable, pleasant
8.5	19.0	17.9	35.	21.3	-0.59	-0.43	9.	comfortable, pleasant
9.5	16.9	17.5	41.	20.1	-0.82	-0.68	15.	slightly cool, acceptable
10.5	13.4	16.8	50.	18.0	-1.21	-1.12	31.	cool, unpleasant
11.5	13.4	16.5	49.	17.9	-1.23	-1.15	33.	cool, unpleasant
12.5	14.1	17.1	48.	18.5	-1.12	-1.02	27.	cool, unpleasant
13.5	14.2	17.6	49.	18.8	-1.06	-0.96	24.	cool, unpleasant
14.5	14.8	18.1	47.	19.3	-0.97	-0.86	20.	cool, unpleasant
15.5	15.1	18.5	47.	19.6	-0.92	-0.79	18.	slightly cool, acceptable
16.5	17.2	19.1	44.	21.0	-0.65	-0.50	10.	slightly cool, acceptable
17.5	19.0	20.4	42.	22.3	-0.36	-0.20	6.	comfortable, pleasant
18.5	19.0	20.7	41.	22.4	-0.34	-0.17	6.	comfortable, pleasant
19.5	19.0	20.6	40.	22.4	-0.35	-0.19	6.	comfortable, pleasant
20.5	19.0	20.4	42.	22.3	-0.36	-0.20	6.	comfortable, pleasant
21.5	19.0	20.2	42.	22.2	-0.37	-0.21	6.	comfortable, pleasant
22.5	19.0	20.0	41.	22.1	-0.39	-0.23	6.	comfortable, pleasant
23.5	18.5	19.4	41.	21.7	-0.50	-0.34	7.	comfortable, pleasant

Fig 5.19: Thermal comfort assessment for living area in base case model during typical transition day

Activity level 89.98, Clothing level 0.60, Air speed 0.10
Default mean radiant temperature

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	20.0	21.4	75.	22.3	-0.22	-0.10	5.	comfortable, pleasant
1.5	19.4	20.9	75.	21.7	-0.37	-0.23	6.	comfortable, pleasant
2.5	19.0	20.5	76.	21.3	-0.46	-0.32	7.	comfortable, pleasant
3.5	18.8	20.2	76.	21.1	-0.52	-0.37	8.	comfortable, pleasant
4.5	18.5	20.0	76.	20.8	-0.59	-0.43	9.	comfortable, pleasant
5.5	18.3	19.7	76.	20.5	-0.66	-0.50	10.	comfortable, pleasant
6.5	18.3	19.5	77.	20.5	-0.66	-0.50	10.	comfortable, pleasant
7.5	18.7	19.5	77.	20.7	-0.60	-0.44	9.	comfortable, pleasant
8.5	19.1	19.7	76.	21.0	-0.53	-0.38	8.	comfortable, pleasant
9.5	19.4	19.7	75.	21.2	-0.49	-0.35	8.	comfortable, pleasant
10.5	19.5	19.8	76.	21.3	-0.46	-0.32	7.	comfortable, pleasant
11.5	19.4	19.8	79.	21.3	-0.45	-0.32	7.	comfortable, pleasant
12.5	19.6	19.9	78.	21.5	-0.41	-0.28	7.	comfortable, pleasant
13.5	20.0	20.0	79.	21.8	-0.33	-0.22	6.	comfortable, pleasant
14.5	20.2	20.2	76.	21.9	-0.30	-0.18	6.	comfortable, pleasant
15.5	20.2	20.3	72.	21.9	-0.33	-0.20	6.	comfortable, pleasant
16.5	20.4	20.6	71.	22.1	-0.28	-0.15	5.	comfortable, pleasant
17.5	21.2	21.2	66.	22.7	-0.14	-0.01	5.	comfortable, pleasant
18.5	20.9	21.4	58.	22.5	-0.24	-0.07	5.	comfortable, pleasant
19.5	20.1	21.1	53.	21.9	-0.41	-0.21	6.	comfortable, pleasant
20.5	20.2	21.0	55.	21.9	-0.39	-0.20	6.	comfortable, pleasant
21.5	20.0	21.0	62.	21.9	-0.37	-0.20	6.	comfortable, pleasant
22.5	19.5	20.8	66.	21.6	-0.43	-0.27	6.	comfortable, pleasant
23.5	18.6	20.2	71.	20.9	-0.59	-0.42	9.	comfortable, pleasant

Fig 5.20: Thermal comfort assessment for living area in base case model during typical summer day

A very similar pattern can be seen in Fig 5.19, above, for the transition day comfort assessment to the winter day comfort assessment in that during the occupied hours, the environment is comfortable and pleasant. Out with the occupied hours, the environmental conditions for the transition day are slightly better in that they vary from cool and unpleasant to slightly cool and acceptable. However, this is just a result of the increase in ambient temperatures from winter to spring and there is no real benefit in terms of the occupants' thermal comfort as the zones are not occupied at these times. Out with the occupied hours, however, the zone still requires space heating in order to achieve the comfortable and pleasant environmental condition and so this backs up the previous concerns that the house almost certainly is not operating as it should initially, before any modifications were made.

Fig 5.20, above, shows the thermal comfort assessment for the summer day and it can be seen that the environmental conditions throughout the 24 hour assessment period were comfortable and pleasant. In fact, it was found after investigating the energy delivered on that day that no heating was needed in the living area whatsoever; the house was kept at a comfortable and pleasant level throughout the 24 hours by the ambient conditions alone. However, it was believed that this would be the case for many existing houses and that this particular model is performing no better than an existing house. In a zero carbon house, it is a reasonable to expect that even during transition months, space heating should not always be needed in order to make the occupied zones thermally comfortable. Therefore, in the following section the zone temperatures and thermal comfort of the Resource Efficient house will be assessed with different levels of enhancements made and it is expected that comfortable environments are achievable without heating during transition months. It is also though, however, that this may lead to the house over heating in summer.

Although it has been found that environmental conditions, in terms of thermal comfort can be kept relatively good through a basic control system to manage the space heating in the building, it is suggested by (Chana et al, 2005) that, because of the high air infiltration rate in the initial model, the environmental conditions in terms of health risks is not as good as people are vulnerable to harmful pollutants entering the building from outside.

5.3.2. House with Modifications

In this section, the dry bulb temperatures and thermal comfort of zones of interest will be investigated after enhancements have been made to the model. The enhancements that were carried out are the same as those outlined in section 5.2: enhancements to airtightness, insulation and the control system.

An initial simulation with all of the enhancements, described previously, in effect. This was done as it was thought that the model with all modifications resulted in the best possible performance in terms of reducing the annual space heating demand and the carbon emissions associated with it. The aim of this investigation is to assess whether or not these enhancements, although beneficial in reducing energy demand, are beneficial in terms of zone temperatures and thermal comfort.

5.3.2.1. Zone Temperature

An annual simulation was then run with all modifications and the dry bulb temperatures in zones of interest was investigated. Fig 5.21, below, shows the annual zone temperatures for the house with modifications alongside the annual ambient temperature.

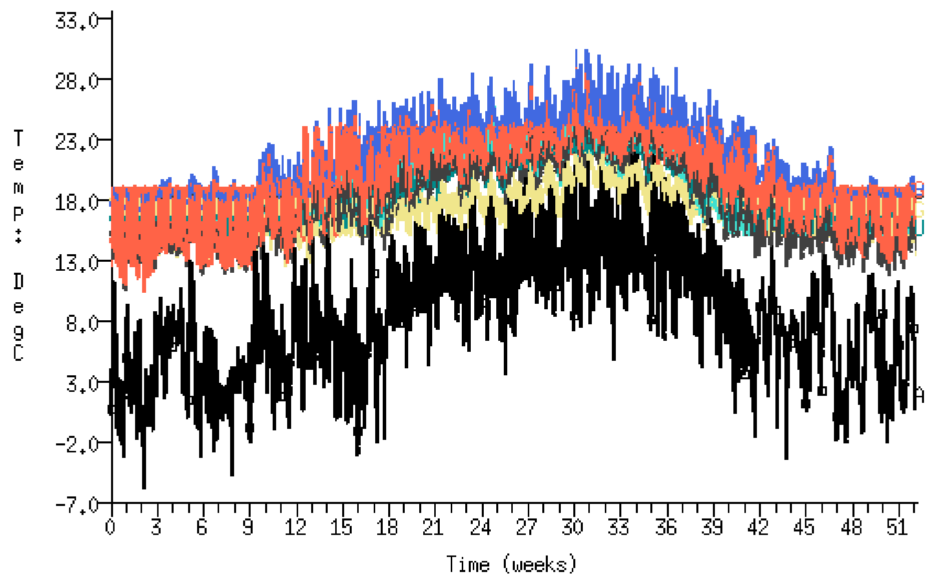


Fig 5.21: Annual zone temperature (colour) and ambient temperature (black) of the model with modifications made

As can be seen from the figure above, the annual zone temperatures observed here are quite different to those observed for the base case model. The zone temperatures here exceed the minimum set point temperatures for during the night and day, 18 and 19 °C respectively, regularly from around the middle of March to the end of October, whereas before, these temperatures rarely exceeded the minimum set point temperatures at all and only just exceeded them at the very height of summer. It can also be seen that when heating is needed, the zone starting temperatures are higher here than for the base case model and so this is further confirmation of why less heating is needed in the model with modifications. Results such as this, of course, are to be expected for the model after the modification were made because the air tightness enhancements and improvements in insulation ensured that much less heat was being lost to the outside environment and the house was able to keep in the heat that it had gained from the large areas of glazing in the house.

On taking a closer look at Fig 5.21, it can be seen however that zone temperatures, particularly in the living and kitchen/dining areas, shown in red and blue respectively, often exceed 24 °C and reach maximum temperatures of close to 30 °C. Fig 5.22, below, shows the number of hours that zone temperatures in the house with modifications are above and below 24 °C during a typical summer week.

Zone db temperature (degC)
Reporting number of hours above 24.00

Description	Maximum value	Maximum occurrence	Minimum value	Minimum occurrence	Mean value	No of hours above	No of hours below	% above
GF_Meeting	23.06	10-Aug@14h30	18.17	13-Aug@22h30	20.41	0.00	168.00	0.0
UF_NW_Bed	24.25	09-Aug@21h30	20.63	13-Aug@22h30	22.04	2.00	166.00	1.2
UF_NE_Bed	24.05	10-Aug@21h30	21.14	13-Aug@22h30	22.33	2.00	166.00	1.2
UF_Hall	24.00	08-Aug@21h30	20.87	10-Aug@06h30	22.22	0.00	168.00	0.0
gf_hall	30.01	10-Aug@11h30	23.85	10-Aug@23h30	25.32	117.00	51.00	69.6
GF_Living	26.26	11-Aug@15h30	21.41	14-Aug@06h30	23.50	22.00	146.00	13.1

Total number of hours greater than query point: 143.00 (14.2%)
Total number of hours less than or equal to query point: 865.00 (85.8%)

Fig 5.22: Number of hours that zones within model with modifications are above/below 24 °C

As can be seen from the figure above, temperatures in the kitchen/dining area (gf_hall) exceed 24 °C for 117 hours of the week, representing over two thirds of the time. It can also be seen that the maximum temperature in this zone reaches 30 °C at one point. Results such as this lead to the suggestion that, because of the high temperatures during summer weeks, and perhaps even in transition weeks, the thermal comfort in these two zones in particular will not be as good as the initial model, even if the space heating demand is much greater. This will be discussed further in the following section.

5.3.2.2. Thermal Comfort

As with the investigation into zone temperatures, initial simulations were run with all of the modifications, described previously, active. Here, the thermal comfort for zones of interes in typical winter, transition and summer days will be looked at and the effect of the modifications on this will be analysed.

Fig 5.23, below, shows the results of the thermal comfort assessment carried out on the living area in the house with modifications during a typical winter day, 5th February here.

Activity level 90.00, Clothing level 0.90, Air speed 0.10
Default mean radiant temperature

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	15.0	15.7	54.	20.1	-0.77	-0.70	15.	slightly cool, acceptable
1.5	13.9	15.0	47.	19.1	-0.95	-0.90	22.	cool, unpleasant
2.5	14.1	14.8	40.	19.1	-0.97	-0.91	23.	cool, unpleasant
3.5	13.7	14.5	37.	18.8	-1.03	-0.97	25.	cool, unpleasant
4.5	13.6	14.3	35.	18.6	-1.06	-1.01	26.	cool, unpleasant
5.5	13.3	14.1	35.	18.4	-1.10	-1.05	28.	cool, unpleasant
6.5	13.2	13.9	36.	18.3	-1.13	-1.08	30.	cool, unpleasant
7.5	12.9	13.7	38.	18.1	-1.16	-1.11	31.	cool, unpleasant
8.5	12.9	13.5	39.	18.0	-1.17	-1.13	32.	cool, unpleasant
9.5	12.9	13.5	40.	18.0	-1.17	-1.12	32.	cool, unpleasant
10.5	13.0	13.7	41.	18.1	-1.14	-1.10	30.	cool, unpleasant
11.5	13.4	14.0	41.	18.4	-1.09	-1.04	28.	cool, unpleasant
12.5	13.8	14.3	41.	18.8	-1.03	-0.97	25.	cool, unpleasant
13.5	14.1	14.6	42.	19.1	-0.97	-0.91	23.	cool, unpleasant
14.5	14.4	14.8	44.	19.3	-0.93	-0.86	21.	cool, unpleasant
15.5	14.6	15.0	45.	19.5	-0.88	-0.82	19.	cool, unpleasant
16.5	16.9	15.7	45.	20.9	-0.62	-0.54	11.	slightly cool, acceptable
17.5	19.0	16.5	50.	22.4	-0.30	-0.25	6.	comfortable, pleasant
18.5	19.0	16.7	58.	22.6	-0.23	-0.21	6.	comfortable, pleasant
19.5	19.0	16.7	58.	22.6	-0.23	-0.21	6.	comfortable, pleasant
20.5	19.0	16.8	59.	22.7	-0.21	-0.19	6.	comfortable, pleasant
21.5	19.0	16.9	64.	22.8	-0.17	-0.16	6.	comfortable, pleasant
22.5	19.0	16.9	67.	22.9	-0.15	-0.15	5.	comfortable, pleasant
23.5	18.1	16.6	69.	22.3	-0.28	-0.26	6.	comfortable, pleasant

Fig 5.23: Thermal comfort assessment of living area in the model with modifications during a typical winter day

As can be seen, the pattern observed here is similar to that observed in fig 5.18 for the base case model. Here, the zone is still cool and unpleasant out with times where the zone is occupied and heating is required to make the zone feel comfortable and pleasant during occupied hours. The only difference here is that the temperatures are allowed to free-float from throughout the night and during the day until it is occupied at 5pm and so the time where heating is required is significantly reduced. This result was expected because, although enhancements have been made, the ambient temepratures were still very low in the winter and so heating will still be required, albeit less heating.

It has been shown that the modifiations made to the model have little effect on the thermal comfort of occupants during typical winter days as, although the house is, on average, warmer it still needs heating, albeit less, to get the house to a comfortable and pleasant level. However, it is expected that during typical transition and summer days, periods of over heating and poor thermal comfort during occupied hours may be evident. Fig 5.24, below, shows the results of the thermal comfort assessment carried out on the living area in the house with modifications on a typical transition day, the 8th April.

Activity level 90.00, Clothing level 0.75, Air speed 0.10
Default mean radiant temperature

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	16.8	17.4	60.	20.2	-0.75	-0.63	13.	slightly cool, acceptable
1.5	16.2	16.9	52.	19.6	-0.88	-0.77	17.	slightly cool, acceptable
2.5	16.0	16.6	47.	19.3	-0.95	-0.83	20.	cool, unpleasant
3.5	15.8	16.4	44.	19.1	-1.00	-0.89	22.	cool, unpleasant
4.5	15.6	16.2	43.	18.9	-1.04	-0.93	23.	cool, unpleasant
5.5	15.4	15.9	42.	18.7	-1.08	-0.97	25.	cool, unpleasant
6.5	15.2	15.8	42.	18.5	-1.11	-1.00	26.	cool, unpleasant
7.5	15.2	15.6	43.	18.5	-1.12	-1.02	27.	cool, unpleasant
8.5	15.2	15.6	45.	18.5	-1.11	-1.01	27.	cool, unpleasant
9.5	15.4	15.7	46.	18.6	-1.08	-0.98	25.	cool, unpleasant
10.5	15.6	15.9	47.	18.9	-1.03	-0.93	23.	cool, unpleasant
11.5	16.1	16.4	47.	19.3	-0.96	-0.84	20.	cool, unpleasant
12.5	16.8	17.1	45.	19.9	-0.84	-0.71	16.	slightly cool, acceptable
13.5	17.4	17.6	43.	20.5	-0.74	-0.60	13.	slightly cool, acceptable
14.5	17.8	18.0	43.	20.8	-0.68	-0.53	11.	slightly cool, acceptable
15.5	18.3	18.6	41.	21.3	-0.58	-0.43	9.	comfortable, pleasant
16.5	19.6	19.5	42.	22.2	-0.36	-0.21	6.	comfortable, pleasant
17.5	21.2	20.4	46.	23.5	-0.07	0.05	5.	comfortable, pleasant
18.5	21.2	20.4	52.	23.6	-0.01	0.08	5.	comfortable, pleasant
19.5	20.4	20.1	54.	23.1	-0.12	-0.02	5.	comfortable, pleasant
20.5	20.8	20.1	54.	23.3	-0.08	0.02	5.	comfortable, pleasant
21.5	20.9	20.1	57.	23.5	-0.03	0.05	5.	comfortable, pleasant
22.5	20.6	19.9	60.	23.3	-0.06	0.01	5.	comfortable, pleasant
23.5	19.7	19.5	61.	22.6	-0.21	-0.11	5.	comfortable, pleasant

Fig 5.24: Thermal comfort assessment for living area in model with modifications during a typical transition day

As can be seen from the figure above, a similar pattern is evident; the thermal comfort in the zone ranges from slightly cool and acceptable to cool and unpleasant during the night. Zone temperatures start to increase from around 11am and from around 3pm the environental conditions in the zone are described as comfortable and pleasant and remain like this until midnight. So again, the over all thermal comfort, in the living area at least, has not been affected that much during the hours when the zone is occupied; the only difference is that during the typical transition day, no space heating whatsoever was needed in order to achieve a comfortable and pleasant environment.

Fig 5.25, below, shows the results of the thermal comfort assessment on the living area in the house with modifications during a typical summer day.

Activity level 90.00, Clothing level 0.65, Air speed 0.10
Default mean radiant temperature

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	28.6	28.8	43.	29.4	1.34	1.51	51.	warm, unpleasant
1.5	27.7	28.1	39.	28.5	1.09	1.31	41.	warm, unpleasant
2.5	27.2	27.6	37.	27.9	0.94	1.19	35.	warm, unpleasant
3.5	26.7	27.1	35.	27.4	0.83	1.08	30.	warm, unpleasant
4.5	26.3	26.7	35.	27.1	0.75	1.00	26.	warm, unpleasant
5.5	25.9	26.3	36.	26.8	0.68	0.92	23.	warm, unpleasant
6.5	25.6	26.0	37.	26.6	0.63	0.86	21.	warm, unpleasant
7.5	25.4	25.7	39.	26.4	0.61	0.82	19.	warm, unpleasant
8.5	25.4	25.6	40.	26.4	0.61	0.81	19.	warm, unpleasant
9.5	25.4	25.6	41.	26.5	0.64	0.83	19.	warm, unpleasant
10.5	25.5	25.6	42.	26.6	0.67	0.85	20.	warm, unpleasant
11.5	25.6	25.7	43.	26.7	0.70	0.87	21.	warm, unpleasant
12.5	25.8	25.9	43.	26.9	0.74	0.92	23.	warm, unpleasant
13.5	26.2	26.4	41.	27.2	0.80	0.99	26.	warm, unpleasant
14.5	26.9	27.2	38.	27.7	0.91	1.13	32.	warm, unpleasant
15.5	27.5	27.6	36.	28.0	0.98	1.22	36.	warm, unpleasant
16.5	28.1	27.7	37.	28.4	1.08	1.31	41.	warm, unpleasant
17.5	29.4	28.0	41.	29.4	1.34	1.50	51.	warm, unpleasant
18.5	29.2	27.9	46.	29.6	1.42	1.51	51.	warm, unpleasant
19.5	28.3	27.6	49.	29.2	1.33	1.40	46.	warm, unpleasant
20.5	28.7	27.6	49.	29.5	1.40	1.45	48.	warm, unpleasant
21.5	28.7	27.6	52.	29.7	1.48	1.47	49.	warm, unpleasant
22.5	28.4	27.4	55.	29.7	1.48	1.44	48.	warm, unpleasant
23.5	27.6	27.0	57.	29.1	1.35	1.31	41.	warm, unpleasant

Fig 5.25: Thermal comfort assessment of the living room in the model with modifcations during a typical summer day

The figure above shows a very different pattern to that observed for the winter and transition days; here the environmental conditions in the house are described as warm and unpleasant throughout the 24 hour assessment period. This is due to the significantly higher ambient temperatures observed during the summer day as well as the increased solar radiation entering the building in combination with the enhancements made to the fabric of the building. Fig 5.26, below, shows the zone tempreature in the zones of interest, the ambient temperature and the solar radiation entering the building during a typical summer week.

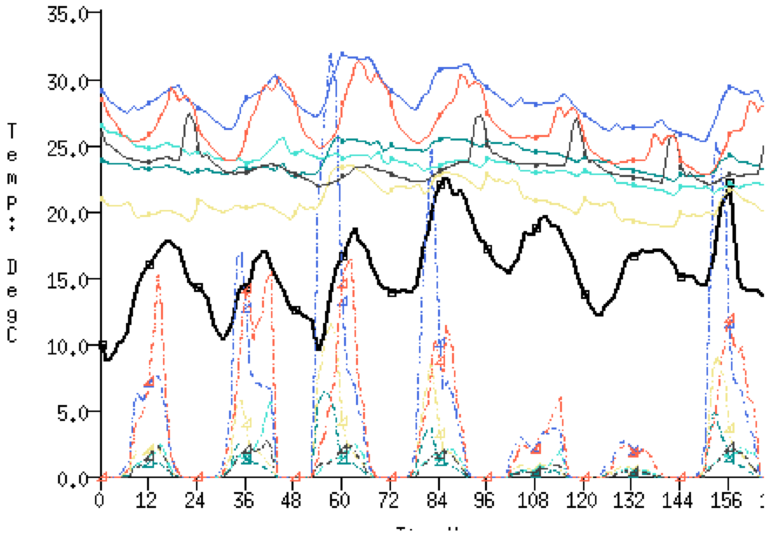


Fig 5.26: Zone temperature (solid colour), ambient temperature (black) and solar radiation entering zones (dotted colour)

As can be seen from the figure above, only the the living area and the kithen/dining area, shown in red and blue respectively, regularly exceed 24 °C. This is due not only to to the increased ambient temperatures during the summer but the high amount of solar radiation entering these zones during a typical summer week. It can be seen that the maximum zone temperatures of the living and kitchen/dining areas coincide with the times where there is most solar radiation entering the zones. This result was expected because of the large areas of glazing and the southern orientation of these zones meaning that there was more heat gain in these zones than in others leading them to overheat.

It can also be seen from the figure above that other than the living and kitchen/dining areas, zone temperatures tend not to exceed 24 °C regularly and when investigating the thermal comfort in other zones, the bedrooms and the upper-floor office space for example, it was found that during occupied hours the environmental condtions were, in general, pleasant and comfortable. This suggests that only in the two zones of the building which are overheating, the living and kitchen/dining area, should action be taken to reduce the temperature and improve the environmental condition.

Due to the short period of time that the kitchen/dining area is occupied and the buildings location, it is thought that an air flow could be created simply by opening a window and this would significantly improve the thermal comfort in the zone. The same idea could be used in the living area which is only occupied during the evenings on weekdays and occupancy varies at weekends. Again, by creating and airflow, temperatures in the two zones of interest would decrease and improve the indoor thermal comort. However, this may only be an option in this particular climate; Scotland is a particularly cool and windy country compared to other European countries and even compared to some cities in the South of the UK; although the zone temperatures are actually not that high to begin with and can be significantly reduced simply by opening a window here, simulation in a hotter climate will almost certainly yeild higher zone temperatures and a poorer thermal comfort. This is an area which could be assessed in future work and it would be expected that results of this would show a need for mechanical cooling/ventilation in zero carbon homes in hotter climates during summer weeks, adding to the overall energy use and so this becomes another barrier to overcome.

5.4. Recommendations

It has been shown in sections 5.1. to 5.3. that enhancements to the airtightness, external wall insulation and control systems can all reduce the annual space heating demand in domestic buildings based on the 'as built' performance of a zero carbon home and so some key recommendations follow from this. If the ambitious targets set out in the 2008 Climate Change Act are to be met, there will need to be serious reductions in the amount of energy used in the domestic sector which accounts for over a quarter of all energy use in the UK. Of this, 66 % is used for space heating and so this must be reduced. The previous sections show that by enhancing the building fabric and control systems, not only could a significantly reduced annual heating demand be achievable but it is achievable while keeping the environmental conditions at a good level. Although for this particular building it was shown that two zones in particular were vulnerable to overheating during the height of summer it is believed that this problem could be alleviated simply by opening windows to create an air flow at times where the thermal comfort in the building is poor. However, this may only be applicable in this particular climate, where temperatures are not as high as other European countries and wind speeds are great. A possible future area of study could be to assess how replicable homes like this are in warmer climates.

Another recommendation which I think is obvious from the previous sections is that building simulation should be used as a design tool at the earliest possible stage of a development. I firmly believe that building simulation can aid the design team in that they can test particular constructions, orientations, design features in the simulation environment well in advance of the construction stage. If it is found out post-construction, as was the case here, that the building was not operating as it should it becomes much more difficult to improve the buildings performance. For example, if a development has realised that the type of insulation or glazing they have used is unsuitable for their needs, then it is much more difficult to change this post-construction; it will take significant amounts of time, effort and most likely money. In a simulation environment this is very simple; it takes up very little time, effort and it does not cost anything. By adopting this approach the developers could have tested a number of different scenarios for their building before finalising the design and beginning the constructions stage.

6. Conclusions and Future Work

To conclude, the aim of aiding future low-to-zero carbon domestic building design has been completed through the completion of the objectives listed in section 1 of this report. A comprehensive literature review was carried out which looked at: current energy use in the UK with a focus on the built environment and in particular the domestic sector and what legislation is in place to help reduce energy demand and carbon emissions, the concept of net zero carbon housing including approaches, features and examples and how the implementation of building simulation could improve these approaches.

A comprehensive simulation model of the Resource Efficient House was then built within the ESP-r building simulation platform and an ‘as built’ operational performance assessment was carried out. It was found that the house, in its initial state, did not did not perform as well as expected or hoped for by developers in terms of the space heating demand and carbon emissions associated. This was mainly due to the high air infiltration in the building to begin with which mean that unwanted cool air was entering the building from outside through cracks and gaps around windows, doors and where the walls meet the floors.

Enhancements were then made to the model and simulations were run. It was found, as expected, that by making enhancements to the building fabric such as making the building more airtight and increasing the thickness and decreasing the conductivity of the external wall insulation as well as upgrading the control system in the house, significant reductions could be made to the annual space heating demand and the carbon emissions associated with this. It was also found that as more enhancements were made, the temperatures in the zones within the building increased to a point where during the summer two zones in particular, the south facing living and kitchen/dining areas were overheating and were uncomfortable thermally. It was decided that for this particular building, because of its location, the overheating and poor thermal comfort could be alleviated simply by creating an air flow in the zones affected by opening windows/doors to reduce the internal temperatures. However, it may not always be as simple as this in warmer climates and so any area of future research may be to simulate in a warmer environment, perhaps in Southern Europe, to determine whether or not mechanical cooling/ventilation would be needed in zero carbon homes in warmer climates which would of course add to the cost of the building and to the energy demand if cooling was required.

The main conclusion from this piece of work, however, is that building simulation can save vast amounts of time, effort and money if used as a design tool for the domestic sector. Simulation can effortlessly output the effects of the enhancements covered in this thesis and others such as the building orientation, different types of constructions and materials and many more. If used at the design stage of a development, developers could assess the impact of any number of design features they may want for their development well in advance of the construction stage thus saving time, effort and money that would be wasted should modifications need done to the building post-construction.

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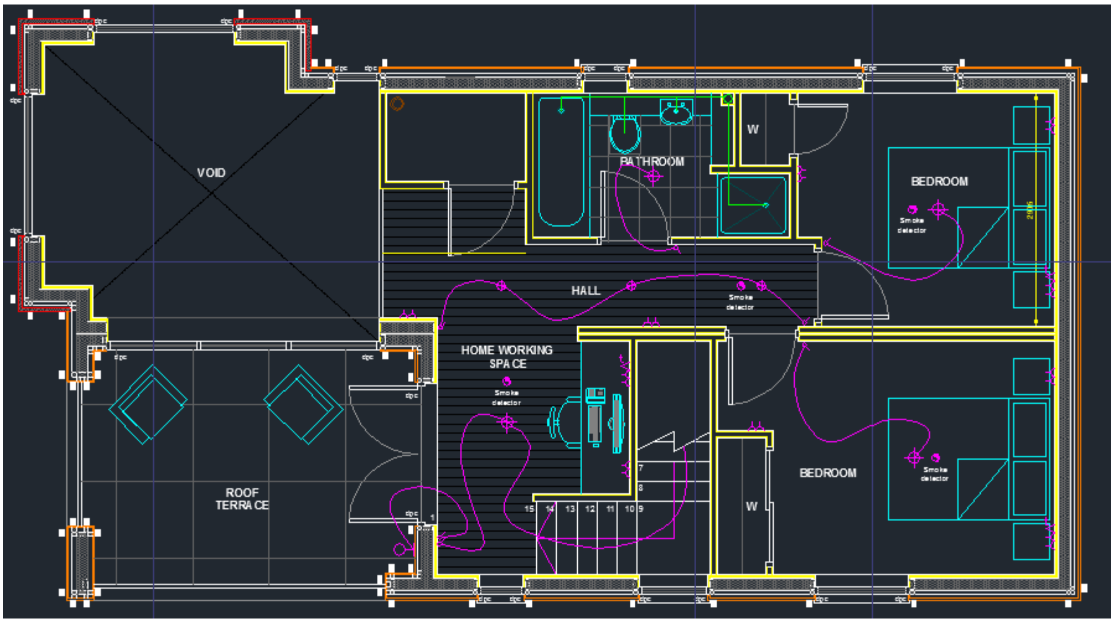
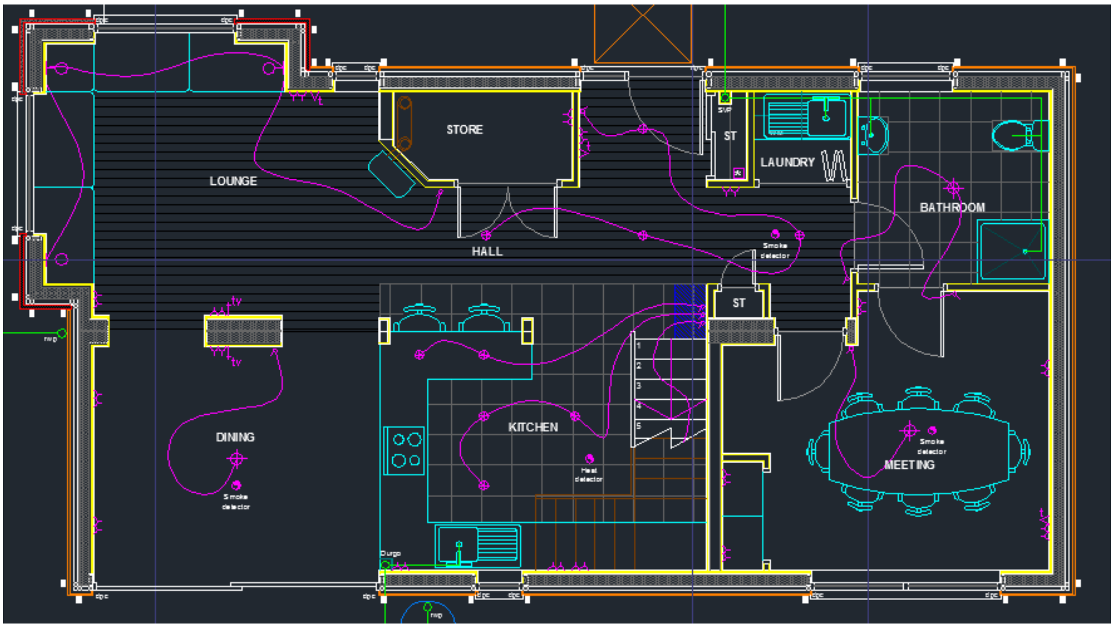
Appendix A: Drawing File for Resource Efficient House



Upper-floor Plan of the Resource Efficient House



Ground-floor Plan of the Resource Efficient House

Appendix B: Construction Specification

```
 Layer|Thick |Conduc-|Density|Specif|IR   |Solar|Difful R     |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext    15.0     0.570  1300.  1000. 0.91 0.70    19.  0.03 Render External 20 mm : Render E
    2   20.0     0.110   640.  1210. 0.90 0.90    10.  0.18 particle board underlay : Partic
    3   25.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    4   20.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    5   11.0     0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    6  158.0     0.020    30.   837. 0.90 0.50    90.  7.90 Polyurethane foam bd : Polyureth
    7   11.0     0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    8   25.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    9   25.0     0.210   900.  1000. 0.91 0.26    11.  0.12 Plasterboard (wallboard) : Inter
 Int    25.0     0.210   900.  1000. 0.91 0.26    11.  0.12 Plasterboard (wallboard) : Inter
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.109  0.109  0.108 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.11
 External surface admittance Y=  2.89  w=  3.16 decrement factor f=  0.81  phi=  1.23 surfac
 Partition admittance Y=  2.95  w=  3.17 surface factor f=  0.80  phi=  1.26
```

External Wall – White Render

```
 Layer|Thick |Conduc-|Density|Specif|IR   |Solar|Difful R     |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext    35.0     2.000  2700.   753. 0.90 0.60    48.  0.02 slate : Slate
    2   10.0     0.800  1800.  1120. 0.90 0.60    75.  0.01 lime cement mortar : lime cement
    3   19.0     0.150   700.  1420. 0.90 0.65   576.  0.13 plywood 700d : Plywood (700 dens
    4   11.0     0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    5  158.0     0.020    30.   837. 0.90 0.50    90.  7.90 Polyurethane foam bd : Polyureth
    6   11.0     0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    7   20.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    8   25.0     0.210   900.  1000. 0.91 0.26    11.  0.12 Plasterboard (wallboard) : Inter
 Int    25.0     0.210   900.  1000. 0.91 0.26    11.  0.12 Plasterboard (wallboard) : Inter
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.114  0.114  0.113 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.11
 External surface admittance Y=  2.89  w=  3.16 decrement factor f=  0.81  phi=  1.23 surfac
 Partition admittance Y=  2.95  w=  3.17 surface factor f=  0.80  phi=  1.26
```

External Wall – Stone Cladded

```
 Layer|Thick |Conduc-|Density|Specif|IR   |Solar|Difful R     |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext    20.0     0.138   556.  1800. 0.90 0.65    12.  0.14 Scotlarch : russwood.co.uk/cladd
    2   25.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    3   20.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    4   11.0     0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    5  158.0     0.020    30.   837. 0.90 0.50    90.  7.90 Polyurethane foam bd : Polyureth
    6   11.0     0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    7   25.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    8   25.0     0.210   900.  1000. 0.91 0.26    11.  0.12 Plasterboard (wallboard) : Inter
 Int    25.0     0.210   900.  1000. 0.91 0.26    11.  0.12 Plasterboard (wallboard) : Inter
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.110  0.110  0.109 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.11
 External surface admittance Y=  2.89  w=  3.16 decrement factor f=  0.81  phi=  1.23 surfac
 Partition admittance Y=  2.95  w=  3.18 surface factor f=  0.81  phi=  1.27
```

External Wall – Larch Cladded

```
 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Difful R    |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
    1   40.0     0.190   700.  2390. 0.90 0.65    12.  0.21 ZWS Oak : Copy of oak. Default t
 ISO 6946 U values (horizontal/upward/downward heat flow)=  2.628  2.853  2.378 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  2.56
 External surface admittance Y=  2.96  w=  1.20 decrement factor f=  0.67  phi=  0.63 surfac
 Partition admittance Y=  1.97  w=  4.88 surface factor f=  0.96  phi=  0.91
```

Front Door

```
Tripple glazing Pilk Kglass argon: with id of: tr_Kgl_arg
with 5 layers [including air gaps] and visible trn: 0.61
Direct transmission @ 0, 40, 55, 70, 80 deg
  0.382 0.361 0.313 0.193 0.077
Layer| absorption @ 0, 40, 55, 70, 80 deg
   1  0.260 0.264 0.264 0.255 0.195
   2  0.001 0.001 0.001 0.001 0.001
   3  0.103 0.111 0.115 0.107 0.083
   4  0.001 0.001 0.001 0.001 0.001
   5  0.098 0.095 0.086 0.061 0.028
```

Triple Glazed Windows

```
 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Difful R    |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext    22.0     0.150   800.  2093. 0.91 0.65    96.  0.15 chipboard : Chipboard
    2   95.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    3  100.0     0.040    25.  1000. 0.90 0.70    30.  2.50 Mineral wool batt 100mm : Insula
    4    9.0     0.130   620.  1700. 0.90 0.70  1200.  0.07 OSB3 : OSB wood based on the SBE
    5    9.0     0.130   620.  1700. 0.90 0.70  1200.  0.07 OSB3 : OSB wood based on the SBE
    6   50.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    7  100.0     0.040    25.  1000. 0.90 0.70    30.  2.50 Mineral wool batt 100mm : Insula
    8   13.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    9   12.5     0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
 Int    12.5     0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.164  0.165  0.163 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.16
 External surface admittance Y=  1.62  w=  4.30 decrement factor f=  0.93  phi=  0.72 surfac
 Partition admittance Y=  1.68  w=  4.30 surface factor f=  0.93  phi=  0.75
```

Floor

```
 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Difful R    |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext    12.5     0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
    2   12.5     0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
    3   13.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    4  100.0     0.040    25.  1000. 0.90 0.70    30.  2.50 Mineral wool batt 100mm : Insula
    5   50.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    6    9.0     0.130   620.  1700. 0.90 0.70  1200.  0.07 OSB3 : OSB wood based on the SBE
    7    9.0     0.130   620.  1700. 0.90 0.70  1200.  0.07 OSB3 : OSB wood based on the SBE
    8  100.0     0.040    25.  1000. 0.90 0.70    30.  2.50 Mineral wool batt 100mm : Insula
    9   95.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
 Int    22.0     0.150   800.  2093. 0.91 0.65    96.  0.15 chipboard : Chipboard
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.164  0.165  0.163 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.16
 External surface admittance Y=  2.40  w=  3.94 decrement factor f=  0.89  phi=  1.08 surfac
 Partition admittance Y=  2.46  w=  3.95 surface factor f=  0.89  phi=  1.11
```

Inverse of Floor

```
 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Difful R    |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext   300.0    0.050    12.  1000. 0.90 0.70    30.  6.00 Min wool quilt 250 mm tb : Quilt
    2  150.0    0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    3    9.0    0.030   290.  2000. 0.90 0.60     8.  0.30 ceil_cass : ZWS CEiling Cassette
    4   11.0    0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    5  128.0    0.020    30.   837. 0.90 0.50    90.  6.40 Polyurethane foam bd : Polyureth
    6   11.0    0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
 Int    12.5    0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.075  0.076  0.075 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.08
 External surface admittance Y=  1.64  w=  4.60 decrement factor f=  0.95  phi=  0.74 surfac
 Partition admittance Y=  1.65  w=  4.59 surface factor f=  0.95  phi=  0.75
```

Ceiling

```
 Details of opaque construction: ZWS_ceil_inv linked to ZWS_ceil & with overall thickness  0

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Difful R    |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext    12.5    0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
    2   11.0    0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    3  128.0    0.020    30.   837. 0.90 0.50    90.  6.40 Polyurethane foam bd : Polyureth
    4   11.0    0.130   620.  1700. 0.90 0.70  1200.  0.08 OSB3 : OSB wood based on the SBE
    5    9.0    0.030   290.  2000. 0.90 0.60     8.  0.30 ceil_cass : ZWS CEiling Cassette
    6  150.0    0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
 Int   300.0    0.050    12.  1000. 0.90 0.70    30.  6.00 Min wool quilt 250 mm tb : Quilt
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.075  0.076  0.075 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.08
 External surface admittance Y=  0.20  w=  2.07 decrement factor f=  0.98  phi=  0.05 surfac
 Partition admittance Y=  0.21  w=  2.19 surface factor f=  0.98  phi=  0.05
```

Inverse of Ceiling

```
 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Difful R    |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext    12.5    0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
    2   25.0    0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    3   25.0    0.040    12.  1000. 0.90 0.70    30.  0.63 Mineral wool 25 : Insulation (Mi
    4   25.0    0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
 Int    12.5    0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.797  0.817  0.773 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.79
 External surface admittance Y=  1.07  w=  2.45 decrement factor f=  0.90  phi=  0.33 surfac
 Partition admittance Y=  0.79  w=  5.59 surface factor f=  0.99  phi=  0.36
```

Single Partition Wall

```
 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Difful R    |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
 Ext    12.5    0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
    2   25.0    0.040    12.  1000. 0.90 0.70    30.  0.63 Mineral wool 25 : Insulation (Mi
    3   50.0    0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
    4   25.0    0.040    12.  1000. 0.90 0.70    30.  0.63 Mineral wool 25 : Insulation (Mi
 Int    12.5    0.210   900.  1000. 0.91 0.26    11.  0.06 Plasterboard (wallboard) : Inter
 ISO 6946 U values (horizontal/upward/downward heat flow)=  0.585  0.596  0.572 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  0.58
 External surface admittance Y=  0.95  w=  3.10 decrement factor f=  0.93  phi=  0.34 surfac
 Partition admittance Y=  0.81  w=  5.58 surface factor f=  0.99  phi=  0.37
```

Double Partition Wall

```
 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R     |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W
    1   40.0     0.190   700.  2390. 0.90 0.65    12.  0.21 ZWS Oak : Copy of oak. Default t
 ISO 6946 U values (horizontal/upward/downward heat flow)=  2.628  2.853  2.378 (partition)

Admittance calculations using Rsi   0.12 Rso   0.06 & Uvalue=  2.56
 External surface admittance Y=  2.96  w=  1.20 decrement factor f=  0.67  phi=  0.63 surfac
 Partition admittance Y=  1.97  w=  4.88 surface factor f=  0.96  phi=  0.91
```

Internal Door