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The Experimental Application of an Occupant Tracking Technology for Domestic Post-Occupancy Evaluation

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Thesis submitted to the University of Nottingham

for the degree of Doctor of Philosophy

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Abstract

From 1971 to 2004, the UK population increased by 6.5% to 59.8 million while the number of homes increased by 30% to 24.2 million. Despite this growth, the industry is still accused of delivering homes that are overly expensive, environmentally unsustainable and deficient in number. The wish of the Government is that by 2016 the number of annual new additions in England will have increased by a third to 200,000, though there is little planned to assess how they meet the changing lifestyle needs of consumers.

The Commission for Architecture and the Built Environment (CABE) has proposed that post-occupancy evaluation (POE) should be regarded as the preferred means of assessment; though a standard approach has yet to be developed for housing. Parallel to this, consumer surveys, including those carried out in this thesis, consistently report that 70% or more of buyers would pay more for an energy efficient home, which is generally regarded as one of the most important characteristics of a good home. However, the vast majority of existing homeowners are unable or unwilling to pay for the modifications that their homes require. In this thesis the connection is made that POE is also the most appropriate tool to investigate whether the supposed broader benefits of sustainability, such as improved comfort, lifestyle and energy security, can be evidenced in a quantifiable way so that they could be promoted to motivate homeowners to collectively improve the performance of the sector.

The efficiency of space use is emerging as an aspect of sustainability of special importance, and the density of new developments increased from 25 to 40 homes per hectare in the years 1997 to 2004. The culmination of this thesis is therefore a substantial experiment undertaken to inform interior layout designers, whereby the daily movements of a household of 4 were remotely tracked using a radio frequency identification (RFID) system. This application of RFID for space use POE was a novel one, and the data was collected in a more discreet and objective way than is possible using the preferred sociology techniques of interviews or ethnography. Although some technical concerns developed during the experiment, an estimated 94% of the desired data was accurately collected. The demonstrated conclusion was that recognisable patterns within the tracking data are insightful and can assist house designers to arrange spaces more effectively. Also that tracking systems could affect building energy efficiency directly if comfort heating, cooling and lighting are targeted to only those areas that are known to be occupied by a building management system. These conclusions were then expanded upon by a survey that demonstrated how a portfolio of household behaviours could be beneficial as a tool for designing efficient and sustainable interior spaces in the future.

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I am grateful for the financial support of the Engineering and Physical Sciences Research Council and the collaboration with David Wilson Homes Ltd., which made it possible to work on such a fascinating and involving project. In particular I mention DWH development director James Wilson and Dianne Page of McCann Erickson for the encouragement and positivity they both brought to the project team.

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Finally my thanks goes out to all of my friends and family, who were always patiently there to provide emotional support and inspiration during the many times when the going got tough. Special appreciation goes to my parents, George and Irene Holland, for undertaking the proof-reading duties, as well as to Niall Cremin in respect to our many conversations on the testing state of affairs that exist within UK housing.

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1 Introduction

The UK Government has announced that it expects the number of new homes constructed each year in England to increase by roughly a third by 2016. This is to meet the requirement in certain areas for affordable housing, since demand has pushed prices beyond what can be afforded by the key workers that the economy depends upon [1]. The Government has also pledged to reduce our society's annual carbon dioxide (CO_2) emissions by 15-25 million tonnes of carbon (MtC) by 2020. They recognise that the energy used in the construction, demolition and most significantly the operation of our homes is responsible for 30% of the UK's total energy demand and 40 MtC each year [2]. It is therefore proposed that a quarter of the pledged reduction will come through improvements in energy efficiency of the housing stock [3].

Many construction methods and technologies exist that can substantially reduce the energy demand of a building and improve its sustainability, though their uptake in the standard build has been too slow for many commentators. Two of the most significant barriers are the prevailing perception that the more-sustainable approach is as yet unproven and carries extra commercial risk, and secondly that homebuyers are not prepared to cover the premium that may at present be required to build to improved standards. The view expressed by James Wilson, Development Director of David Wilson Homes Ltd. is that,

"Currently market forces dictate that no one developer can go it alone and incorporate widespread sustainable solutions, as customers are not willing to pay the extra for them." (June 2002) [4]

More research has been called for into how homebuyers perceive the various aspects of sustainability, how following the sustainability agenda can improve the quality of homes delivered to the marketplace and how the increased build-cost can be absorbed within the industry [5]. The research described in this thesis investigates these points from a variety of approaches, though the overall objective is to present an argument for the uptake of post-occupancy evaluation (POE) in the housing industry. This emerging technique could be used to show how the need for new homes can be met in such a way that will encourage sustainability improvements across the whole stock, while also focussing the attention of designers on achieving occupant satisfaction, as new home designs are developed in response to the changing industry pressures.

Chapter 2 presents in some detail why housing is regarded as the source of a quarter of the UK's carbon savings proposed for 2020. The construction methods and technologies that have already been developed are reviewed, along with the steps being taken to promote the sustainability agenda of improving energy efficiency and social inclusion within the economic market.

Chapter 3 demonstrates the benefit of gathering opinions directly from the home buying public, and those already living in more-sustainable homes in particular. Although the survey reported on is small in scale, it indicates how this form of research can be conducted, as well as the limitations.

This review of surveys leads onto a discussion on the potential benefits of using the practice of post-occupancy evaluation (POE) within the housing sector. POE has already been used within the commercial sector to show that buildings that are energy efficient and easy to manage are also very often the most comfortable and satisfactory to work in [6] and it is argued in Chapter 4 that a similar parallel is likely between sustainability and occupant satisfaction in housing. POE could be used to address the fact that not enough is known of how constructed homes perform compared to their designers' intentions, whether they meet their buyers' subjective expectations, and how their achievements are affected by improvements in sustainability.

One particular aspect of POE is investigated in more detail in Chapter 5, since space use is becoming of ever greater concern to builders as they are under pressure to develop sites to increasing densities. The historical legacy of the domestic form is reviewed, along with the approaches developed by social science to study how space is made use of.

This review culminates in Chapter 6 by presenting the work of the computer sciences on researching building space use, and in particular the tracking technologies developed for the purpose of context-aware computing. The connection is made between the abilities of these technologies and the requirements of the POE approach to collect reliable and quantifiable data.

The literature review ends and Chapter 7 introduces the experimental study that was undertaken to investigate how a 'home of the future' built by one of the UK's largest builders performed on several aspects of sustainability.

Chapter 8 discusses the study results that relate to the energy use of the home; in particular the thermal heating demand, risk of summertime overheating due to solar gains, and the electrical energy demand of the kitchen and utility room appliances. Although the limited time and resources prevented the application of a complete POE method, this was an ideal opportunity to assess several prediction tools that may in future become a part of a standard approach.

Chapter 9 then reviews the detailed study of how the space within a dwelling was used by its occupants, to evaluate the efficiency of the floor layout and space allocation. This was an innovative application of a tracking technology that was stretched to its capability limits by the context in which it was being used for the first time. Its effectiveness was nevertheless proven as a means of gathering the information required to enhance the more traditional methods of space use research and enable comparable POE findings to be generated.

This is advanced in Chapter 10 by a demonstration of how a post-occupancy study on a small set of subjects can be fed into a means of understanding the behaviours of the mainstream house buying public. A survey is developed using the findings of the POE, to improve on its relevance and ability to provide more generalised theories on how households live within their homes.

This thesis not only argues for the uptake of POE within the domestic sector, but also demonstrates how certain aspects may be aided using computational modelling packages and occupant tracking technologies. The connection is repeatedly made between the requirement to use space within new homes more effectively to improve their sustainability. In addition, the potential of comparing the findings of POE is stressed, as this would enable more-sustainable homes to be marketed using the improvements in occupant satisfaction that they may also bring.

2 Sustainability of the Built Environment

In 2004, the UK's Sustainable Buildings Task Group (SBTG) stated that,

"*The way we use natural resources for buildings and the levels of pollutants emitted in the process of buildings, and in the use of buildings once occupied, are unsustainable. The construction industry must embrace more sustainable forms of building.*" [7]

In defining sustainability, the 1987 Brundtland Commission said,

"*Sustainability is a development that satisfies the needs of the present without jeopardizing the ability of future generations to satisfy their own needs.*" [8]

In practice, sustainable development demands a compromise to ensure that the resource intensive economic activities that provide us with today's food, shelter, manufactured goods and services can be continued indefinitely into the future, providing the 'triple bottom line' of worldwide economic growth, environmental protection and social well being.

In the sector of the built environment, the objective of sustainable development is to inspire construction companies to develop techniques that allow the trend for rising living standards to become compatible with the necessity to reduce our greenhouse gas (GHG) emissions to limit the impact of climate change on the planet's ecosystems. Climate change has become a significant issue for our society. The scientific consensus is that considerable changes are at present occurring in the composition of our planet's atmosphere more rapidly than in our history. Temperatures, sea levels and the prevalence of extreme climatic phenomenon are all rising. While in some countries the political leaders remain divided on the extent to which manmade pollution of the latter half of the 20th century has influenced the observed climate change, here in the UK the Government has little doubt. Prime Minister Tony Blair has warned that within a decade extreme climatic events would be the cause of $150 billion of destruction each year [9]. The Government sees the reduction of the GHG emissions by all nations as a matter of urgency if we are to stabilize climatic change and the devastation it could bring.

Of the most common anthropologic GHG, carbon dioxide (CO_2) does not have the worst climate change potential. Methane has 27 times the relative heat trapping effect of CO_2, nitrous oxide (N_2O) has 200 times, and CFC-12 has 10,000 times. When the actual concentrations we release are taken into consideration however, it is estimated that energy related CO_2 contributes up to 78% of our impact [10], so must be the focus of our attention. Additionally, actions that reduce CO_2 emissions will usually bring reductions in other GHG.

The UK's Royal Commission on Environmental Pollution (RCEP) estimated that a 60% reduction in worldwide CO_2 emissions is required by 2050 to prevent catastrophic climate change [11], which was accepted as a target in the Government's 2003 Energy White Paper [3]. An intermediate reduction target was set of 15-25 million tonnes of carbon (MtC) by 2020.

The RCEP had also stated that there had essentially been no improvement in the energy efficiency of the UK's building stock in the previous decade. In 2000, the energy used to heat, light and service our homes was responsible for almost 30% of the UK's energy use and 40 MtC [12], approximately double the 2020 reduction target set by the RCEP and Government. The significance of the building designer's role in our efforts to achieve the required CO_2 reductions has therefore become very clear.

The investigation of the present status of sustainable construction is central to this chapter, which highlights the balance being struck between the three strands of sustainability. Although there have been many reports, reviews and statements made about the importance of improving the industry's long-term sustainability, it is debateable how effectively private UK construction companies have responded to the challenge of re-evaluating the influence of environmental performance against the short-term financial realities and societal demands of the economy within which they operate. The review presented here considers first the demands being placed on the industry from each corner, followed by an introduction to just some of the fundamental and more-sustainable construction methods that could be used, and the developed means of appraising improvement. In addition to the environmental and energy consumption of construction, the economic and societal barriers that must be overcome are also considered where appropriate.

2.1 The environmental impacts of construction

To enable closer examination of the current situation, it is useful to define environmental impacts related to construction in four areas of consumption: energy, materials & waste, water and land. These are the same key issues that the SBTG was set up to promote improvement within.

2.1.1 Energy Use

Buildings are major consumers of energy and therefore major contributors to atmospheric pollution and climate change. The primarily fossil fuel based energy that provides heat, light and power in our buildings accounts for nearly half of the nation's total energy consumption and for a similar proportion of our CO_2 emissions, with domestic buildings accounting for almost 30% and non-domestic for 20% [13]. Energy efficiency is expected to provide more than half the required savings to meet the Government's stated target of a 20% reduction of CO_2 emissions on 1990 levels by 2010.

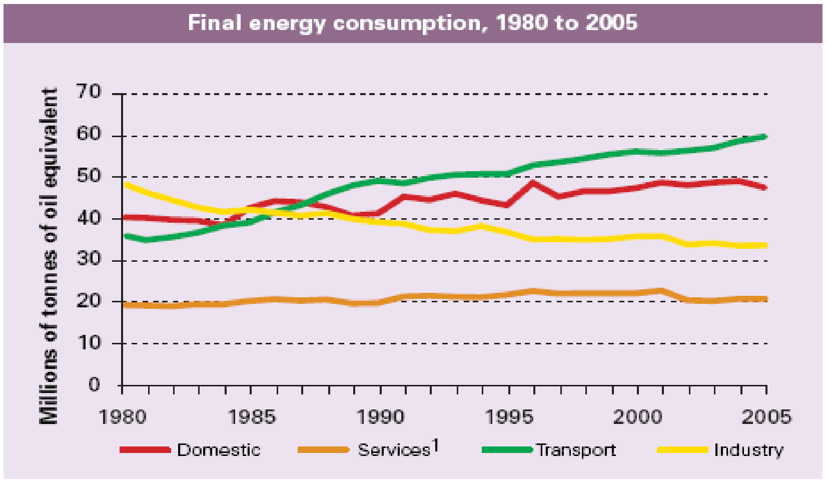


Figure 1: UK rate of energy consumption by final users, by sector [14]

Within the average home, the energy used can be broken down into four distinct categories [15]. Space heating is the largest, requiring 62% of the primary energy demand. Water heating follows at 23%, then the electricity for lighting and appliances at 13%. Cooking makes up the final 3% of domestic demand. These very pertinent figures often get overlooked in discussions on domestic energy use, which typically focus on the electricity for lighting and appliances even though space and water heating are accountable for 85% of the total. These figures vary depending on the age and size of house of course, and the resulting carbon emissions depend strongly on the fuel used, but it is only in a minority of modern homes that the space heating demand has been reduced by a significant degree.

Energy efficiency is undoubtedly poor throughout most of UK housing. 65% of our dwelling stock was built before the introduction of Building Regulations in 1965 [13] and were built to very different standards from today. While these dwellings will typically be robust structurally and built with low-impact materials, they are often difficult to adequately heat and expensive to renovate to modern standards. Compounding their poor performance is the near negligible rate at which they are being replaced. At present there are around 25 million dwellings in the UK, with about 200,000 more being built each year but only 20,000 being demolished [16]. This demolition rate of less than a tenth of one percent of the stock means it will be many decades before the improved performance of new homes has a noticeable effect on the overall performance. The challenge of upgrading the energy efficiency of the existing stock is perhaps the greatest obstacle to achieving a sustainable built environment, and is addressed indirectly by the work in this thesis.

A further distinction should be made between a building's use of energy during its operational phase and the energy that was embodied in its construction, through the sourcing and processing of materials, transportation, installation and mechanical labour. There is not agreement on how significant the embodied energy is compared to the lifecycle total, since this depends much on where the boundaries of the calculation are set, but estimates vary between 10% [17] and 50% [18].

2.1.2 Building Materials and Construction Waste

Construction materials account for over half of all raw materials used in the UK, the equivalent of 7 tons per person each year [19] and most are made from non-renewable resources. The quarrying of 250-300 million tons of material each year for aggregate, cement and bricks imposes significant damage at a local level and embodies much of the energy required to build each new home.

Construction and Demolition (C&D) waste accounts for 35-40% of the nation's total waste generation, amounting to 72 million tons per year. This is about four times the rate of household waste production, which is usually the focus of so much more attention. A 'hierarchical' approach to waste management was developed by the DETR based on the environmental benefits of the various options: minimisation; reuse; recycling; downcycling; incineration (heat recovery); landfill (methane recovery) [20]. Unfortunately there are often obstacles that prevent the reuse or recycling of materials: their availability; quality assurance; practical and programme constraints; and the prevailing culture that 'new' is always 'best'.

2.1.3 Water Use

Water treatment is an energy intensive process, yet only 10% of the water we use is consumed for drinking or cooking. Reducing water use would help conserve the groundwater reserves, reduce the threat to rivers caused by over-abstraction, decrease the energy demand for purifying and transporting water, and improve the effectiveness of sewage treatment. Water conservation and supply metering would be the cheapest options for handling the growing nationwide consumption of drinkable water.

2.1.4 Land Use

The UK Government wishes to accelerate the program of construction of new homes to meet the excessive demand that at present is preventing many first time buyers or other economically restricted groups from entering the market. Each additional home built will increase the pressure on the land and infrastructure resources of the country however, and the trend will be for new homes to consume more land per person if the acceleration in supply continues to be greater than the growth in the population. In response the Government have targeted that 60% of housing development would by 2008 be on previously developed land, to restrict the demise of our greenbelt areas, but it has also been recognized that compromise must be found here between the objective of environmental protection for sustainability and the societal and economic realities, as will next be discussed.

2.2 Socially responsive design

The UK's housing stock is often depicted as being thermally inefficient, badly maintained and unprepared for a time when environmental crises will be even more acute. Most of all however it is deficient in number, which has led to the excessive demand that the industry is struggling to meet.

The Office for National Statistics has reported that the population of the UK grew by 7% in the period of 1971 to 2005; however, during this same period, the number of households increased by 30% because of a reduction in the average household size from 2.9 to 2.4 [21]. There has been a shift away from the conventional two parents with children household towards an increasing number of single parents with children, adult couples without children and single people both young and old who want independent accommodation. These demographic shifts are not expected to falter so long as the additional homes are made available; however in 2001 the industry achieved the lowest number of new-home completions for 50 years. In response the Government is overseeing a resurgence to accelerate the program of new home construction so that 50,000 more than the present 150,000 net additions will be built in England each year by 2016 [22].

It is essential to respond to the excessive demand because house prices have risen in many areas like the South East beyond what can be afforded by first time buyers and key workers such as teachers and nurses [1]. For this reason, a common stipulation for new developments is that a certain percentage of the homes should be affordable to these vital groups. 'Affordable housing' is defined by each local authority within its own context and in line with the guidelines in National Policy PPG3 [23], although a typical definition could be of ‘low-cost or subsidised housing that is made available to those who are identified as not being able to afford a purchase in the open market of the locality’. The target percentage of affordable homes in each development can be set within the council’s Local Plan and usually ranges from 20-50%.

The need for more affordable homes to buy or rent is also driven by the estimated 2 million households who still live in what is termed ’fuel poverty’ [24]. This is a vicious cycle of deprivation, whereby people on low incomes tend to live in inefficient, difficult-to-heat homes; so those who can least afford to pay their bills actually pay the most relative to the size of the home to achieve a comfortable temperature. Fuel poverty officially exists if more than 10% of a household’s disposable income is spent on heating. The problem is intensified by the elderly age of most of the building stock and so providing more affordable, energy-efficient homes is one way of curing this social ill.

Of course despite the social benefits, each new home that is built will add increasing strain to the land and infrastructure resources of the country, which is already causing concern in particular regions earmarked for expansion. To restrain the advancement onto greenfield land, the Government targeted that 60% of housing development in England would be on previously developed land by 2008. By 2004 the nationwide average figure had already climbed to 70% [25] so there is now much interest to see if this high level of regeneration can be maintained across all UK regions.

The combination of these three factors (demographic changes, the need for affordable housing and the limitation of ‘greenfield’ expansion) has resulted in increasing pressure on planners to develop sites to greater densities and to take maximum advantage of each square hectare made available while still retaining the overall value of the site. In line with PPG 3 recommendations, the average density of new developments has risen from 25 homes per hectare in 1997 to 40 per hectare in 2004 [25], though it has been suggested by others that densities of 80 per hectare are necessary to trigger the infrastructural provision of shops, schools and public transport that are necessary to facilitate community growth and cohesion [26]. One means of achieving these higher densities has been by building smaller homes for smaller households. One or two bedroom dwellings had by 1991 become 51% of the UK’s annual build [25] and, despite being built on smaller plots of land and having a reduced usable internal floor area, their reduced occupancy led to a rise in the average living area available to each person, from 38m^2 in 1991 to 44m^2 in 2001 [27].

Market forces have made it more profitable however to sell larger suburban properties with additional space both indoors and outdoors. By 2002 the percentage of smaller properties had fallen back to 35% of the build total, while the fall at the larger end of the market in the number of 3 bedroom homes built from 1971 to 2002 almost precisely matches the rise in the number of 4 or more bedroom homes [25]. While there may be a real marketplace need for an extra child’s bedroom or an alternative function room, it is also suspected that a house with a greater number of smaller bedrooms will bring more profit than one with fewer but larger rooms [28]. Speculative private developers currently build 85% of all new homes annually and they must respond to the market to remain economically competitive and ultimately sustainable as a business, at the expense of the social needs and environmental protection of the nation.

This presents the compromise that is currently being made between the three branches of sustainability in new housing. Changes in our society and population are resulting in almost 10 new homes being built for each that is demolished and while much of the demand could be satisfied by high density urban flats that would still provide an increase in the average usable interior space per occupant, consumer preferences are reverting the market towards larger suburban homes that encroach further onto greenbelt land, although built at higher densities than before.

Whichever end of the market is looked at therefore, new homes are being built to contain smaller spaces than in previous decades, making it increasingly important that the overall floor area that they contain is allocated effectively. The number of daily activities our homes will have to cater for is expected to increase in future with home-working and telecare becoming more frequent, which brings greater significance to the efficiency of space subdivision. Land and space consumption is just one of the four aspects of environmental sustainability considered by the SBTG of course, the others being energy, materials and water. More energy efficient homes have in particular been called for as one of the most practicable means of improving the sector’s sustainability, especially as there are many design alterations that can be made that have very little effect on the construction cost, perhaps none more so than passive solar design.

2.3 Sustainable methods of construction

In the light of government commitments to reduce CO_2 emissions, abolish fuel poverty and improve the efficiency of the construction industry, it is clear that a ‘Business as Usual’ scenario is no longer an option. It is not a question of if, but of when and how the techniques for more-sustainable construction will be applied in mainstream practice. The primary goal of any sustainable design is to provide healthy and comfortable interior spaces, in structures that are both energy and resource efficient in the long-term. In practice, decisions have to be made early on that influence the construction method, materials used, durability, recyclability and the lifecycle energy use of the whole project.

2.3.1 Thermal mass and insulation

The first choice to be made is between a heavyweight or lightweight building. A heavyweight building will tend to be of monolithic construction with fully loadbearing walls that cannot be moved or pierced without supporting the structure above. The structure provides thermal mass, sound insulation and impact resistance. Lightweight buildings use a frame made from timber, steel or concrete posts and beams to provide all the necessary structural support. The infill walls are non-loadbearing, can incorporate higher levels of insulation, and offer a greater degree of flexibility in spatial arrangement.

The walls of heavyweight buildings are made using dense materials of high thermal mass, such as mass concrete, bricks or stone. Lightweight building wall materials are of low thermal mass and tend to be plant-based or renewable, e.g. timber or straw. The advantage of using high thermal mass materials is they will absorb excess heat (from solar or incidental gains) and release it when the surrounding temperature drops. This stabilises internal temperatures and can reduce the winter heating and summer cooling demands. A heavyweight building will however heat up and cool down over a longer period ('slow response') than a lightweight building ('quick response').

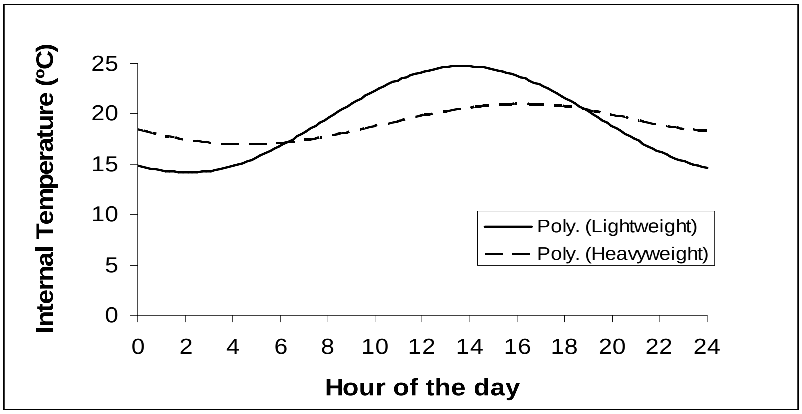


Figure 2: Temperatures on a hot day in buildings of high and low thermal mass [29]

Super-insulation

Materials of poor thermal conductivity (insulators) are used to reduce the heat lost through the building's external envelope and their installation is the single most important measure that can be taken to reduce the annual CO_2 emissions. Most energy saving is achieved in the first 100mm of insulation, then half as much with the next 100mm etc. Super-insulation is generally 300-450mm, depending on the insulation material. The best materials are light and fluffy, as entrapped air is an extremely good insulator. Renewable materials such as cork and sheep's wool or recycled materials such as cellulose fibre are preferable for sustainable purposes as they have very low embodied energy.

2.3.2 Passive solar design (PSD)

The solar energy falling on the earth in just one hour is equal to mankind's annual demand for fossil fuels. By harnessing a tiny proportion of solar energy we can make a huge difference to our impact on non-renewable resources. PSD uses the fabric of the building to admit and store solar heat, using the building itself as a solar collector, which is known as a 'Direct Gain' system. Given a good, holistic, energy efficient design, solar energy can make a 10% contribution to the space heating demand at no additional cost [30].

Orientation

In the northern hemisphere, the majority of glazing should be orientated to within 30º of south, with a preference to south-east to maximise early morning heat gain and minimise afternoon overheating. Glazing to the north should be minimal. Main living and dining spaces should be located on the warmer, southern side of the home, with bathrooms, utilities and bedrooms to the north.

Glazing

As the windows will be an area of relative heat loss, their performance requires particular attention and investment in a passive solar design. The ability of glass to admit solar radiation from the outside while trapping long-wave (heat) radiation inside is what makes solar heating possible. A minimum standard should be double glazed units with a low-E (low emissivity) coating, and an inert gas in the cavity, which gives a U-value of 1.8-2 W/m^2K; roughly equivalent to ordinary triple glazing.

Building form

Minimising the ‘surface area : volume’ ratio will minimise the building’s heat loss, which in practice means building a cube. However, to maximise the areas receiving direct solar radiation it is better to have a long shallow plan, like the houses at the Hockerton Housing Project that are only 6m deep [4].

Daylighting

Artificial lighting is responsible for 10% of domestic energy use, but this can be reduced by good daylighting design. Thoughtfully placed windows will offer pleasing views as well as admitting daylight and well daylit rooms have a ‘feel good’ factor and lift the spirits of the occupants, compared with dark or artificially lit rooms. Care should be taken however to avoid ‘glare’ or excessive contrast caused by a single, overly bright light source. Roof windows concentrate the daylight more than vertical windows and large spaces should have windows on more than one side to improve the light distribution.

Shading

In winter, the south façade of a building will receive nearly three times more solar radiation than the other sides; while in summer, south facing windows will admit a third less radiation than east and west facing glass. This is because the low position of the sun in winter allows deeper penetration into the building, whereas the midday sun is virtually overhead in mid-summer. Shading devices such as roof overhangs, reflective blinds, louvres or shutters can be used to further screen out summer sun while admitting winter sun, should the rooms be at risk of overheating during the summer.

2.3.3 Ventilation and air-tightness

Air leakage is not the same thing as ventilation. The former is uncontrollable, inefficient and can reduce the effectiveness of the insulation by up to two thirds [31]; the latter should be well controlled, operate effectively with minimal energy input, and improve indoor air quality. Air leakage, or 'infiltration', is caused by pressure differences between inside and outside air and has a number of typical entry points, as shown in Figure 3.

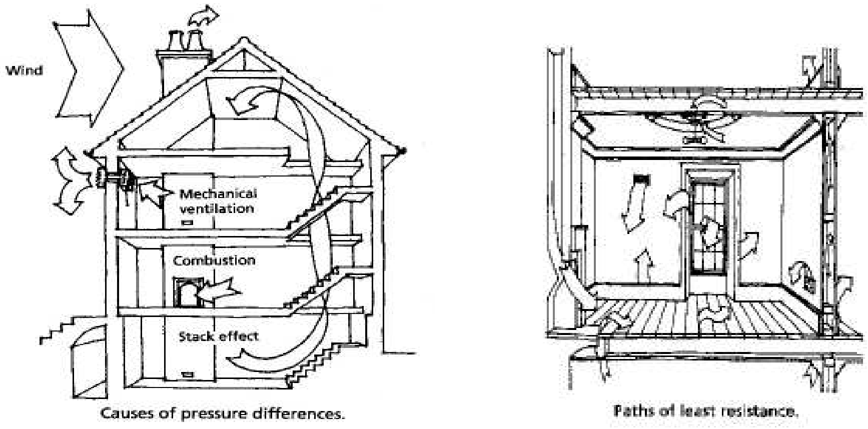


Figure 3: Causes and paths of passive air leakage [32]

Adequate ventilation must still be provided to an airtight building. Trickle vents in window frames can provide background ventilation. Humid areas can be vented at source, using ‘passive stack’ ventilation or mechanically driven fans. In airtight houses, mechanical ventilation with heat recovery (MVHR) systems can provide a high standard of draught-free comfort, and in very low-energy houses they can in fact serve as the main heating system. In an MVHR system, the outgoing air is used to preheat the incoming fresh air that is ducted to living areas, which can recover up to 70-80% of the outgoing heat.

2.3.4 Efficient heating system and controls

The form of heating system is integral to the building's energy performance and can impact upon the choice of structure, materials and internal finishes. If a traditional heating system is to be included, condensing boilers linked to a hot water storage tank currently perform best with seasonal efficiencies of approximately 85%. Combination boilers that provide heat only on demand and do not incur storage losses can still be less efficient overall because the water in the system is heated from cold every time. The 'cleanest' of the fossil fuels should be specified. This is mains natural gas, which at present is fortunately also the cheapest.

The heating system should be controlled with the objective of delivering only as much heat as is required for a particular pattern of use. Timers and programmers tell the boiler when to switch on/off and are available with 7-day memories. Optimisers can be fitted that take into account the outdoor temperature and the heat-up time for the building so that unoccupied buildings are not heated unnecessarily. The use of individual thermostatic radiator valves (TRVs) and whole room thermostats can save 10% of energy use compared to manual controls [4]. For further refinement a house can be 'zoned' for different heating regimes depending on the pattern of use.

For distributing the heat into the house, 'underfloor heating' is inherently the most efficient because it runs at lower temperatures. Alternatively, steel radiators should be sized according to room area, climate and heating demand.

2.3.5 Renewable Energy Technology

Planning authorities across the UK are following the lead of the London Mayor's Energy Strategy to make it a common requirement for major developments to source at least 10% of its energy needs from renewable energy technology. The introduction of this target was followed by the publication of a Renewables Toolkit document that, as well as discussing the passive measures covered previously in this thesis, advises on which technologies would be most suitable to use in the urban environment along with the costs and benefits that could be expected. The technologies considered most suitable for domestic use are:

Solar water heating (SWH)

Once the space heating demand has been reduced to a minimum, domestic hot water represents the largest energy savings possible in the average home. A $4m^2$ solar thermal system will typically produce 50-70% of the hot water demand in an average house, via panels mounted on a south facing roof [33].

Solar electricity

Photovoltaic (PV) panels generate electricity directly from sunlight through arrays of semi-conductor cells. The main barrier to using this technology at the moment is cost, at approximately £6,000 for a 1kW peak output, roof-mounted system [34]; however it is anticipated that costs will fall with increasing levels of subsidy and economies of scale.

Wind

Wind power has traditionally been seen as less applicable to individual buildings as it works more efficiently at a much larger scale of installation. The claim is made that a 600W model could provide sufficient electricity to cover the annual domestic demand; however there is significant concern that the turbulent and unreliable wind conditions around urban buildings would drastically reduce the average wind speed and turbine efficiency [35].

Biomass

Biomass stoves and boilers can be used in individual homes to provide carbon neutral heating by burning locally produced wood chip or pellets. The estimated £2,000 cost for a domestic biomass boiler and the ongoing costs of delivered fuel make economic savings unlikely, plus the occupant has to be willing and able to manage their fuel supply and ash disposal.

Ground Source Heat Pump

The stable temperature of the ground at approximately 11ºC makes it a reliable sink for free heating in the winter and cooling in the summer. Water (or another fluid or air) is pumped through pipes embedded in the ground to absorb heat in the winter, which is then upgraded by a heat pump to a suitable temperature for domestic heating. Although 3 units of energy can be expected for every 1 supplied to the pump, the CO_2 savings relative to a typical natural gas boiler can be reduced by the carbon intensity of the electricity used, and the expensive of drilling boreholes for the pipes can be prohibitive.

2.4 Housing assessment techniques

In order to turn the theory of sustainable construction into mainstream standard practice, more specific and rigorous criteria are required before ‘environmental impact’ can have a chance of outweighing other determining factors at the design stage. As well as providing tools to business and industry to assess the costs and benefits of each product, trustworthy indicators are required that will inform the public in an easy to understand way how they can use their power as consumers to play a part in creating a sustainable economy. Various indicators for housing have existed for some years already but have had limited impact for a number of reasons; however, this aspect of the Building Regulations is being strengthened and home energy ratings could become a key driver for energy efficiency in both new-build and the existing stock.

2.4.1 European Performance of Buildings Directive (EPBD)

EU Directive 2002/91/EC became European law on 4th January 2003 and the UK Government had three years from that point to implement it. The Directive’s objective was to promote improvements in the energy performance of residential, commercial and public sector buildings, through:

- A common framework for calculating a building’s energy performance.
- Setting minimum energy performance standards for all new buildings and renovated buildings with a total surface area over 1000m^2.
- Energy performance certificates that should be made publicly available.
- Regular inspection and assessment of boilers and air-conditioning systems.

2.4.2 The Building Regulations, Part L

Part L of the UK Building Regulations is devoted to the '*Conservation of Fuel and Power*', and the latest edition took effect from April 2006 in order to bring the Regulations into line with the requirements of the EPBD. Part L has been split into four categories: L1A – New dwellings; L1B – Existing dwellings; L2A – New buildings other than dwellings; and L2B – Existing buildings other than dwellings. Another fundamental difference in the 2006 edition is that each building is now to be assessed on its carbon emission intensity, with a pass only being provided if the result is found to be a certain percentage (typically 20%) less than that of a similar building built to the 2001 Part L.

2.4.3 The Standard Assessment Procedure

The Standard Assessment Procedure (SAP) is the approved procedure for calculating if a home's carbon intensity meets the requirement of Part L [36]. It is a basic, non-geographically specific rating that in the latest 2005 version considers electrical lighting as well as the space and water heating, using assumed average factors for construction detailing, shelter and solar strength. While a new house can at present be expected to reach 75, the average for the England's existing stock is 46 and it has been said that,

"*A 5 point rise in this would achieve our CO_2 targets for the foreseeable future*." [37]

Part L of the Building Regulations has required since 2001 that the SAP score be displayed in all properties being sold. This was praised as being the first time that providing such information to the consumer had been made a legal requirement of the seller. However, an extensive field survey in 2002 found that there was very poor compliance with this obligation and that the public were still being ill informed on energy efficiency [38].

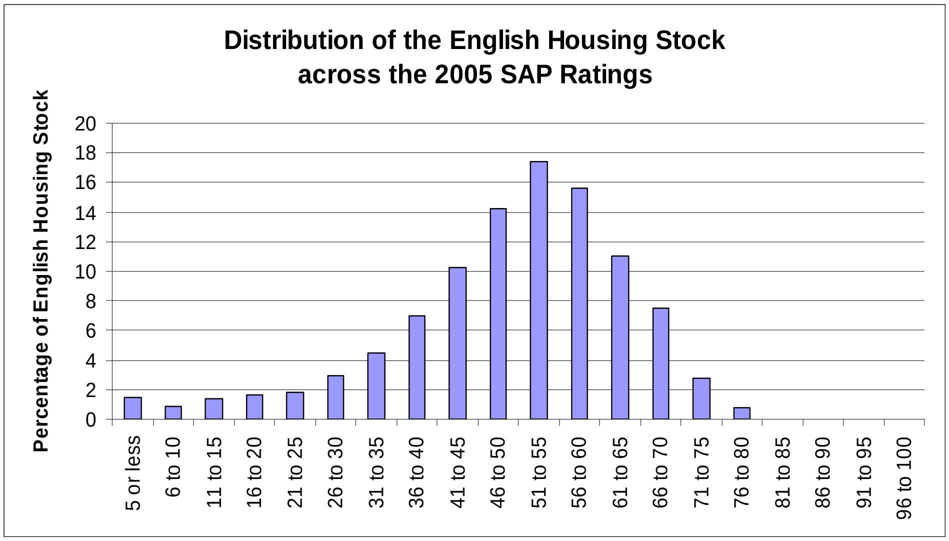


Figure 4: Distribution of the UK's housing stock on the 2005 SAP Scale [39]

The Reduced Data SAP (RDSAP) has been developed to make assessments possible on existing homes, where much data will inevitably be missing or unobtainable when undertaking an energy survey [40]. For new homes, SAP 2005 was brought up to date with some of the newer energy saving technologies, as well as becoming more detailed and accurate. It has also been decided that the rating should use a colour-coded A-G scale format, similar to that used for white good appliances, so that it receives greater attention from the public when it is used in the proposed Home Information Pack (HIP) that will meet the EPBD's certification objective for homes.

Home Information pack

As of June 2007, a compulsory part of the home selling process will be the creation of a Home Information Pack (HIP) that will include an Energy Performance Certificate (EPC) and a voluntary Home Condition Report (HCR). The mandatory EPC will enable compliance with the certification requirement of the EPBD, which is envisaged to include the new colour-coded SAP rating, CO_2 emissions, expected annual running costs and the five most cost-effective improvements for that dwelling [41]. A significant benefit from the packs could be a much raised awareness of the energy performance of the properties on the market and the emergence of a premium for those with a verified environmental benefit. Unfortunately however, it is not clear at present if energy efficiency really can become a differentiating factor in the mass housing market, which is something the Government hopes to tackle using a voluntary code that was based on the EcoHomes scheme.

2.4.4 EcoHomes

EcoHomes is the Building Research Establishment's (BRE) environmental assessment method for dwellings at the design stage, which awards a number of EcoPoints in each of seven categories depending on how it is predicted to perform [42]. Each category score is weighted to give the dwelling an overall grading of Pass, Good, Very Good or Excellent. The seven categories that the dwelling is assessed under are: energy; transport; pollution; materials; water consumption; ecology and land use; and health and well-being. Benchmarked figures are used where appropriate and the SAP is used within the energy category to calculate the home's CO_2 emissions.

Various estimates have been made on the cost to achieve each of the four grading standards available. These have been summarised elsewhere [5] [43], however a typical value for achieving ‘Very Good’ could be as low as £1,500 - £2,000 or 1-3% of the build cost. WWF-UK has argued that this could be reduced further still, to the point where it becomes comparable to or even cheaper than building to the 2001 Building Regulations, by offsetting the additional construction cost by ‘planning gain’, which allows developers to increase a development’s size in exchange for meeting environmental targets [44], and by placing a small premium onto the price of the homes.

2.4.5 The Code for Sustainable Homes

In relation to sustainable construction in general, the SBTG recommended the development of a unified national code for sustainable standards for buildings, which it labelled the Code for Sustainable Building (CSB). In their response, the Government are launching a Code for Sustainable Homes (CSH) that will be broad-based, in a similar fashion to the BRE EcoHomes scheme, in terms of its sustainability reference and will consider materials and products based on their entire life cycle environmental impacts. The CSH is to be a voluntary rating scheme that goes further than the Building Regulations and the Government hopes it will become influential in the private housing sector by creating a price premium for more-sustainable homes in response to consumer demand. There has been little indication however of how the public will be made aware of the scheme to ensure it becomes more integrated into the private house building sector than has EcoHomes.

2.5 Chapter conclusions

The objective of this introductory chapter was to describe the difficulty of establishing better sustainability standards in the UK housing sector when faced with the demands of the house buying public and the reality of market conditions. It is recognised that the energy used by the built environment is significant and presents one of the cheapest and easiest sources of greenhouse gas reduction. In fact the Government's most recent Energy Review appears to firmly emphasise the urgent need to implement the best energy efficiency improvements, with the expectation that the built environment will deliver half of the UK's targeted 15-25 MtC savings by 2020 [45]. The challenge is to transform an industry that is already having difficulty meeting the excessive demand for the finished product, that suffers from a chronic skills and labour shortage due to a lack of training [46] and that operates primarily through private enterprises that consider the financial cost of sustainability improvements to be greater than the benefits.

It was argued in this chapter that the technical means of achieving the target reductions have already been developed, and that new-build can rely largely on passive improvements to the space and water heating requirements of each home that would be maintenance free in operation. However, since the benefit of each eco-renovation in the existing stock would be less significant and more expensive to achieve than the advancement of new-build, the focus moves away from the 25 million homes that are already occupied in the UK and onto the estimated 200,000 that are to be built each year for the next ten. One of the means of encouraging homeowners to make improvements in energy efficiency to the existing stock is to demonstrate the benefits in improved comfort and lower running costs that can be achieved in new-build homes by relatively simple technologies that will continue to fall in cost as their market develops first in new-build.

Methods of building more-sustainable homes are proven and relatively cheap already when integrated into the design from the start, as shown by research on the EcoHomes scheme that goes as far as suggesting the additional build cost can be recouped through the planning process or using a small premium on the house. However the buying public first need to be made more aware of the benefits of sustainability in housing, so that they can take action through their choice of purchases. The SAP and EcoHomes schemes were intended to help shape the demands of private homebuyers but unfortunately failed to gain market penetration, though it is hoped that an advantageous differentiation may still be created for more-sustainable builders by the inclusion of energy certificates within the Home Information Pack and the introduction of the voluntary Code for Sustainable Homes.

It is becoming clear that there could be longer-term financial benefits to those businesses who take changes onboard at this early stage, though it is yet to be assessed which elements of sustainability would be most readily welcomed by the public and which would most strengthen the builder’s brand reputation and bring the most assured financial rewards. It is clear that the additional build-cost can be matched in the owner’s fuel and maintenance bill savings over not very many years of occupancy; however, builders are not confident that this attracts the premium that it deserves. The wider benefits of living on a more-sustainable development should also be promoted therefore, such as an increased sense of community, improved access to local amenities, reduced dependence on the car and enhanced health and well being. At present though, there is still a lack of exemplar projects across the country that could reduce the perceived risks to developers of taking on this approach and an almost complete absence of reporting to the public of the benefits felt by the occupants of the few pioneering schemes that do already exist.

It has been said that there is insufficient evidence of public willingness to pay a premium for the various improvements that could be included in a more-sustainable house. The next chapter will discuss the work of others to address this situation through homebuyer surveys, including one that was carried out as part of this thesis using a select sample of occupants of homes that have already been judged as being more-sustainable. However, it is also reviewed why this survey like most others has many limitations on what can be concluded from the collected data, which is why a new means of assessing the performance of new homes and occupant satisfaction is required.

The approach of post-occupancy evaluation is introduced in Chapter 4, as the emerging technique for assessing the performance of buildings, the satisfaction of their users and their relative sustainability. First however it is important to understand what can be learned from applying the traditional approach of household surveys.

3 Opinions of Households on Sustainability

A typical claim that represents one of the principal barriers to more-sustainable housing is that mainstream buyers are not concerned by energy efficiency so it does not make business sense to build to a better standard than the competition and be required to charge a price premium. The additional build-cost must be recouped if the economic case for improved sustainability is to be competitive.

Some have suggested that a scheme's environmental credentials could lead to faster or more generous progression through the planning process, which has economic rewards for the developer [5] [47]. The economics will remain uncertain however until the planning guidance is clarified. In the meantime it is argued that consumers would cover the premium if the financial and environmental benefits of the home were marketed appropriately to them, although many believe this is not possible as buyers do not consider the on-going, uncertain costs of fuelling a home when making a purchase. An initial step in strengthening the business case for sustainability is therefore to assess the willingness of the market to cover the build-cost premium, so they might benefit from the full range of benefits that a more-sustainable home brings.

This chapter reviews the research previously published on this issue, which leads onto a survey that was conducted as part of this thesis to advance the knowledge on the motivations and experiences of a particular group who undoubtedly have much insight to offer proponents of sustainability - those who are already living in a more-sustainable home.

3.1 Previous surveys

The Halifax Building Society has regularly conducted household surveys. In 1998 it reported energy-efficiency to be the top reason why buyers bought a new rather than second-hand home [48]. Then in 2000, the third most common motivation for making home improvements was to 'Reduce Fuel Bills', only behind to 'Add Value to the Home' and 'Improve Standard of Living' [49].

Also in 2000, a Gallup survey reported that 70% of consumers would pay more for an energy efficient home [50]. Consumers also wanted energy ratings to become standard for homes, which was of course the government's intention when the display of a home's SAP rating was made compulsory in 2001.

More recently, a British Gas survey produced a figure of £3,200 as the additional amount homebuyers would pay for an energy efficient home [51]. This figure was £900 more than they were prepared to pay for a modern bathroom or landscaped garden and £1,200 more than the highest estimated premium for building to the EcoHomes 'Very Good' standard [5], which is a very positive indication of what could be achieved commercially.

A study conducted by Mulholland Research & Consulting [52] on behalf of the Commission for Architecture and the Built Environment (CABE), WWF-UK and HBOS (the bank formed from the merger of the Halifax and the Bank of Scotland) consisted of an online survey of 912 intending home buyers who were questioned on their attitude towards design issues, aspirations in terms of quality and their decision making processes. Their findings that relate directly to the research in this thesis were:

- By averaging the rankings given to 8 particular qualities of a good home, having ‘Spacious rooms’ was concluded to be the most important factor. ‘Good natural light’ was the second most important and ‘Energy efficient / low running costs’ was equal third, tied with ‘Good sound proofing’.
- Energy efficiency was rated as very important by 74% of those aged 45 or more and 68% of those in less well to do social grades, which are of course the groups most likely to suffer from fuel poverty and could therefore benefit from the financial savings that energy efficiency brings.
- The provision of an EcoHomes assessment rating on their home would be welcomed similarly across all groups and by 87% of all those surveyed.
- Rankings were also given to 8 sustainability features, with the order of importance found to be: energy efficiency; lower running costs; health and well-being; water efficiency; renewable energy; environmentally friendly materials; ecologically friendly construction; and a sense of community.
- When asked if they would be prepared to pay a higher price for an energy efficient home, 84% said yes, with the average amount being 2% extra. A percentage figure is more appropriate than an absolute figure, since it takes into account the varied income and market price range of those surveyed.

Despite these strong feelings towards energy efficiency in the initial research, the focus in the final report moved to housing development planning, design policy and architectural detail [53]. The issue of energy sustainability was only indirectly mentioned in the desire for improved window design for more daylight in interior spaces. This is considered to be a missed opportunity for CABE to disseminate their important findings on the market place’s desire for sustainability to the design professionals who read their reports, and also to the wider public since the earlier study had received some press attention [54].

The most recently reported survey has illustrated the consistency of public opinion on the issue. The Energy Saving Trust (EST) reports that 70% is still the proportion who would pay more for an energy efficient home, but now it is claimed that almost half would pay an extra £5-10,000 [55]. The rise in the claimed premium may be evidence of a broader understanding of the hardship homeowners will face in future, as fuel prices continue to move upwards.

The figures for this up-front aspect of the business case therefore appear to be reliable and encouraging. Buyers overwhelmingly say that they want more energy efficient homes and most are prepared to pay a premium that is greater even than the additional build-cost of meeting the best EcoHomes standard.

The business case should not be argued only on up-front costs however, but also that on an on-going basis these homes are appreciated in a way that creates an advantageous distinction between the brand of ‘sustainable housing’ and the typical new-build development. To achieve this, evidence is required from the occupants of more-sustainable homes of an appreciated improvement in their satisfaction and well-being that makes the sustainability premium seem ‘value for money’. If this appreciation exists and is actively reported to the market, it might provide catalyst to consumer-led improvements in mainstream house builds.

An opportunity arose in 2004 to collect evidence to this effect, by conducting a postal survey of the residents of a variety of sustainable homes in the East

Midlands region. The East Midlands has been recognised by others as a prime location for trialling such research, as it is a region that features a varied range of more-sustainable dwellings as part of private or housing association developments, individual home-owners and demonstration projects of sustainable energy technologies [4] [56] [57].

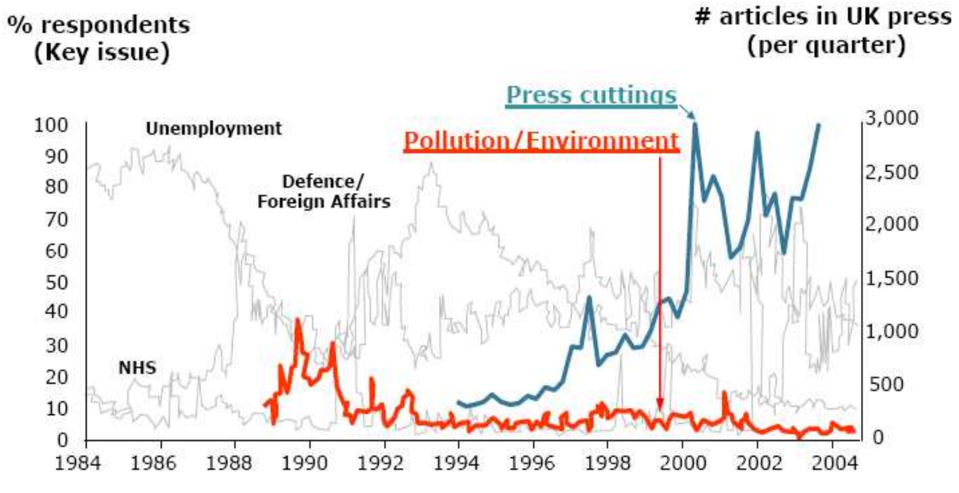
Since this was a targeted survey for a specific group of people, a reasonably direct line of questioning was deemed possible. It was expected that most of those who would respond would already have knowledge of the issues at hand, either as a prerequisite of their decision to move into or indeed build one of these more-sustainable homes, or consequently following the receipt of information from the developer of the benefits that their home could bring them. It was hoped to gain insight into the motivations behind their decision to live in a more-sustainable home, what they saw as the aspirational features for any home, and how the homes and the technologies they featured had performed during the time they had lived there. However, before the findings are reported on, it is important to understand the limitations of such a surveying methodology and the context in which the results should be read.

3.2 Discussion of the survey methodology

Although the collective findings from homebuyer surveys suggest a willingness to pay for energy efficiency improvements, the classic response is that the reported good intentions and belief in the somewhat abstract notion of being eco-friendly rarely gets translated into action being taken when the time comes to make the financial purchase for real. There are many reasons why this may well be the case, some of which are now discussed.

It is commonly appreciated that the wording and sequence of each question and the overall impression that a survey gives to the respondent can lead to an over-exaggeration of positive or negative responses that when aggregated do not truly reflect the whole of public opinion. For example, if a survey were to begin with emotional questions on the effects of global warming then it would not be surprising to discover a fairly polarised view on a following question regarding the construction of a nearby wind farm. The context in which the question was answered had been primed by those that preceded it. For this reason, the best indications of concern for the environment perhaps come from surveys where the public are asked what they think the most important aspects of house design are without any prompts beforehand on the research agenda. A series of focus groups conducted in this unprompted manner were reported on recently with the disappointing result that energy efficiency was not mentioned once [58]. What may be revealing however is that while only 25% of the group claimed they would be prepared to pay extra for an energy efficient home when asked directly, 64% said that they expected energy efficiency to come as standard.

The implication that the public expects not to have to take action to promote energy efficiency themselves, that it should come as standard, corresponds well with the growing disparity between the public's awareness of global warming (as measured by the level of media reporting it receives) and the relative concern the environment receives when ranked against the likes of the NHS and defence [59]. Figure 5 has been presented previously to show how the environment remains a low issue on the public agenda, even though the press coverage it receives has increased sharply. To speculate on what is shown by this graph, perhaps it is the case that the public has been told so repeatedly of the nature and scale of the difficulties ahead with little follow-on advice related to what they could do about it, they have come to assume either that there is nothing that can be done or that it is the sole responsibility of governments and big business to do all that is required.



Source: Factiva, UK press mentions including global warming, climate change, greenhouse effect or greenhouse gas, MORI
Base: c. approx 2,000 British adults

Figure 5: Charting the public's response to environmental press coverage

The media is often accused of being overly powerful in ability to manipulate public opinion, which is used by many climate change sceptics to ignore the reported urgency for greater environmental protection. It is said that an on-the-spot survey can often provide better indication of what was on television or in the newspapers in the most recent days than what the population truly believe in. An example given by CABE is that ‘security against crime’ emerged as the most important factor for housing design in a 2002 poll whereas a previous survey of 11 factors had positioned ‘safety’ halfway down the list [53]. Although this first highlights concern on comparing results from questions that use statements of just a few words to embody sometimes abstract concepts, for ‘safety’ could mean any of a large number of things, it may also indicate that the attention of the public was on different events at the time 4 years apart that the surveys took place. It is often voiced that people have become more fearful of crime because it is more frequently reported, even though the same does not appear to be true for environmental protection.

It has also been suggested that although a willingness to be more eco-friendly is often rated highly in surveys this is because the respondent is giving what they believe to be the morally correct response, but in actual fact, when the time comes to hand over their money, eco-friendliness falls much further down the list of priorities. This phenomenon has been termed the ‘value-action gap’ and a large body of previous work has been devoted to it [5]. The suggestion may in this case be unfair to the consumer however. Housing is a market skewed towards the builders at present, where the demand in many regions far outstrips supply. This means consumers are not offered the true range of choices that they would like, and so the emphasis moves away from what they would like to buy ideally and onto what they have to choose from in reality, within the general location and price range that applies to them. Interestingly, this scenario has been suggested by others as a primary cause for the steady rise in popularity of self-build housing in this country [4].

There are of course some examples where developers have built more-sustainable homes and have managed to sell them, often at a premium. In certain locations developers have come up with solutions that are very different to the norm across a whole range of issues, so that they represent a sustainable lifestyle that includes reduced energy consumption. Examples of this are The Hockerton Housing Project [60] and BedZED in Sutton [61], though it is subsequently impossible to identify the influence of increased energy efficiency on each buyer's and tenant's decision to live there, since these outstanding schemes offer a whole package of sustainable improvements. Gusto Construction's developments [62] and The Green Building in Manchester [63] are two examples where energy efficiency could be described as the prime factor that differentiates them however, so would make more suitable case studies to take this issue further.

Returning to the survey at hand, it needs to be borne in mind that the method used to gather opinions often introduces an unintentional selection process on the kind of person who will respond and the responses that they give. The location, timing and technique used for the actual act of surveying can bias a sample and prevent a true representation of the study population. For instance, questioning randomly selected people in a busy city centre on their shopping habits could be expected to gather a contrasting set of data than if the same set of questions were asked to people in their homes. The survey population will differ markedly as the latter approach will include data from more people who do not enjoy or perhaps are unable to shop in the city centre. Similarly differences may exist between the geographical regions of the population that prevent responses gathered from one particular sample region to be reported as representative of the population as a whole, unless it can first be proven that location is an unrelated factor to the issues under study. Where the act of responding is voluntary, a polarising effect is introduced to the opinions gathered, as it will generally be the people who have strong opinions at either end of the scale who will inconvenience themselves to respond.

When all of the various issues over sampling representation were taken into consideration, it seemed that the best means of gathering data from sustainable home occupants at present was to canvas as many as possible within the East Midlands region, since their population is still small in number and the distinguishing factors that could be used to identify an appropriate sample are as yet unknown. The survey that was posted out as original research for this thesis was sent only to those homes that have featured in a number of substantial reports on sustainability, with no incentive provided for them to respond other than kindness. There is therefore a considerable amount of research still required to be undertaken in this area, as this is a very challenging objective, though the indicative results from the pilot survey undertaken are now presented.

3.3 Indications from sustainable home survey

The survey was posted to the residents of 19 housing developments that had featured previously as sustainable home case studies for the East Midlands region of the UK [4] [64]. These represented a full mixture of speculative housing developments of all sizes, housing association developments and a number of homes that had been built or renovated by individuals or groups specifically for sustainability purposes. In total, 214 questionnaires were sent out in January 2005, along with a letter explaining why they were being contacted and a prepaid return envelope. No incentive to reply was included other than our gratitude and 65 responses were received; giving a return rate of 30%. Appendix A includes the questionnaire, details the origin of the 65 respondents and tabulates the answers for each question.

There had been no attempt to take account of the defining characteristics of the population of sustainable home occupants before the survey was distributed. Indeed even the very definition of ‘sustainable home’ had not been defined any more rigorously than the inclusion of each case study in various other reports. As such, it could not be predicted what the distinctive characteristics of any subset within the respondents would be. However, the responses were received from two groups of reasonably comparable size: 37 Tenants and 28 Owners. A preliminary investigation was made into whether these two groups displayed general differences in opinion, since their home ownership status may be used as a proxy for their financial situation and commitment that they have made to their home, which are likely to be crucial factors in a household’s decision to spend money to improve the building’s sustainability.

The low response rate of just 30% from a sample of people who already occupy more-sustainable homes suggests that this pilot application of the postal survey methodology suffered from the shortcoming that those who responded were already more concerned by the subject matter, i.e. energy efficiency. This also appears to be the case when inspecting the origin of responses, as the highest response rates came from those who were owner occupiers and had therefore already paid a premium to live in their more-sustainable home. It is only because 3.7 times as many surveys were posted out to housing association (HA) residents as were to private home owners that the 65 responses were more evenly divided between the two groups.

The lowest response rates came from HA tenants, 27% of whom responded that they were not aware of the energy efficiency of their home when they moved in. Over a third of those who were aware stated that this was not an influential factor for them. Some commented that they had much more pressing needs than cheaper bills at the time. In comparison, all of the owner respondents were aware and the majority were ‘very much’ influenced to buy or build their home by its energy efficiency benefits. It was also found that home owners planned to live in their homes for more additional years than tenants, though only by approximately four years more on average. This nevertheless indicates that tenants would not have as strong a financial commitment to their homes and the speculative assumption that ‘tenants’ and ‘home owners’ will differ in their opinions on sustainability may be an appropriate subdivision to investigate further.

What makes a good home?

Q7: How important is it for a good home to have each of the following qualities?

	Extremely			Not at all
Large, spacious rooms	4	3	2	1
Comfortable indoor environment	4	3	2	1
Modern entertainment facilities	4	3	2	1
Good level of natural light	4	3	2	1
Security from intruders	4	3	2	1
Attractive appearance from outside	4	3	2	1
Low gas and electricity bills	4	3	2	1
Peace and quiet from outside	4	3	2	1
Modern kitchen and bathroom	4	3	2	1
Parking space for a second car	4	3	2	1

The respondents scored these ten features by circling where they fell on the scale of 4 to 1. This enabled average scores and ranking positions to be calculated for each feature. The list was adapted from a similar question asked in the research of Mulholland [52], so a comparison of the results could illustrate how typical the aspirations of people already living in these more-sustainable homes are. The top 4 features were:

1. Comfortable indoor environment
2. Low gas and electricity bills
3. Security from intruders
4. Good level of natural light

This is broadly in agreement with Mulholland, who also reported that energy efficiency and natural light rank most highly. Differences between the tenants and owners are of note. These HA tenants placed security as their top concern whereas owners instead put more importance on having car parking for two. Some suggestions made for other qualities that could have been included in the selection list were: a garden with privacy; friendly neighbourhood; low maintenance; and ease of access and suitability for the elderly.

Energy efficiency features

Q9: How important do you feel it is for a home to have the following features?

	Extremely			Not at all
Well insulated walls and roof	4	3	2	1
Well insulated windows	4	3	2	1
Efficient water heating	4	3	2	1
Modern heating controls	4	3	2	1
Low energy lights & appliances	4	3	2	1
Water saving appliances	4	3	2	1
Its own electricity generation	4	3	2	1

When asked to then rank a list of energy efficiency features, water and space heating improvements were top, with electrical improvements next. This may indicate an appreciation of where the energy used in a home goes since the majority is indeed spent on water and space heating. Distinctly separate in last place was having ‘its own electricity generation’, illustrating the disparity between the media exposure given to the likes of photovoltaic panels and micro wind turbines and the accurate belief of these respondents that basic improvements to the walls, roof and windows are more rewarding.

Provision of energy efficiency information

Q10: If you were looking to move into a new home, how much information would you prefer to be given concerning its energy performance?

☐ I would prefer to be advised IN DETAIL on its energy performance

☐ I would prefer to be advised BRIEFLY on its energy performance

☐ I would NOT BE INTERESTED in knowing its energy performance

Four out of five of the respondents would prefer to be told in detail about the energy efficiency of their next property, with almost all others preferring to be told in brief. This ratio does not differ remarkably from that found in the housing market in general by Mulholland [53], which weakens the argument made by many builders that they cannot market homes for their sustainability since mainstream buyers are not as interested as the devoted niche.

Living with energy efficiency technology

Q11: Have you found the energy efficient features of your home to be disruptive to your life at home?

☐ Yes, very much so	☐ Yes, a fair bit
☐ Yes, a little bit	☐ No, not at all

The majority of both tenants and owners found it not at all disruptive living in their more-sustainable home; however, a third reported some disruption.

Unreliability of complex technological equipment was the most frequent complaint, with the consensus being that passive systems were more satisfactory and smarter investments to make. Often a traditional back-up system had to be provided for times when the renewable alternative failed, which seriously hampers the economic case for using the technology. Another concern was that the residents often still had no idea where their energy spending was going and what contribution the sustainability systems in place were making. Performance feedback, when provided appropriately, can be a very strong motivator for further improvements and indeed it is hoped that the next generation of ‘smart’ electricity meters can fulfil this purpose [65].

Environmental Purchasing

Q14: Would you be prepared to spend money on a piece of equipment that would save you money on your household fuel bills, and at the same time help the environment?

☐ Yes ☐ No

If you answered “No” to this question you may skip the next two.

Q15: What would be the maximum number of years that you would be happy to wait for the money you save on your fuel bills to equal the price you paid for the equipment?

☐ 5 years ☐ 10 years ☐ 15 years ☐ 20 + years

Q16: Would the fact that you are helping the environment make you less concerned about how fast you recover the cost of the equipment?

☐ Yes, very much so ☐ Yes, a fair bit

☐ Yes, a little bit ☐ No, not at all

The final part of the survey attempted to reveal their attitudes to spending money on energy efficiency equipment as an investment that would save them money in the long-term. 90% responded that they would spend money on energy efficiency equipment, which is perhaps not surprising seeing as many already had by moving into their current home.

The payback period was then assessed, as it is the simplest economic measure of an investment's value. Although the payback period is a crude measurement that takes no account of risk or the size of the ongoing financial savings once payback has been achieved, it is a concept that could be worded in everyday language so that the meaning could be easily grasped. Tenants required their investment to pay back sooner than homeowners and there are probably many reasons for this. For instance, their expected shorter term living status means they may not still be there to reap the financial benefit once the payback period has been reached. This would lead to a more short-term frame of mind when it came to making investments such as this.

Although 57% of the owner respondents expect to live in their home for over 20 more years; only 11% would wait this long for the equipment to payback.

In the final question, the issue of payback was compounded by asking to what degree a care for the environment would make the respondent less concerned about the payback period. The home owners were evidently most concerned, since none of them replied 'Not at all', unlike 26% of the tenants. There was an overall positive response to this issue, with only 16 of the 65 respondents (25%) replying that they would not be less concerned by helping the environment; however, perhaps this finding is to be expected to a morally loaded question such as this.

3.4 Chapter conclusions

This chapter set out to demonstrate the application of an appropriate means of countering one of the most often stated objections to accelerating the progression of the house building industry towards sustainability. The experience at present of most builders is that achieving improved environmental standards adds a premium to the build-cost, which must be recouped if they are to be economically competitive. They therefore believe it would be commercially unsound to distance themselves from the mainstream by building more-sustainable homes, since an insufficient number of consumers are willing to pay a premium for this.

This chapter first reviewed a range of published surveys that go some way to discredit this argument; however, to convince the builders, the reported enthusiasm needs to develop into consumer action, which in the current market is nearly impossible to discern since the demand for housing is so high and the supply of more-sustainable homes is so low. It is argued that evidence of a discernible on-going appreciation of living in these homes and the financial and lifestyle improvements that they provide must be reported on more often, to raise awareness of the ‘sustainable home’ brand and reassure prospective buyers that they can represent better value for money and possibly an improved lifestyle. This would in turn hopefully lead to mounting pressure on the builders to improve the range of choice in the market, which is required before the premium that buyers are willing to pay for a more-sustainable home can be fairly assessed.

A survey carried out to demonstrate what could be researched by a more rigorous study into this aspect of sustainable homes was also reported on. Although the sample population was restricted to a particular geographical region and the response rate was varied across schemes, the initial indications give further support to the case for more-sustainable housing. The benefit of obtaining feedback from users of new technology was demonstrated through the survey, as an information source for designers who wish to improve the quality of their products and their customer satisfaction.

Surveys and resident focus group interviews are quite often organised by housing developers who wish to keep their customers happy, so that they will spread the good word; however, these are usually sporadic and informal affairs that focus on individual problems of snagging and site development. If occupant feedback is to be used to strengthen the case for more-sustainable homes then the industry requires a standard method for this, so the collected data can be compared across schemes and the benefits of any single factor can be separated out from the full package that more-sustainable homes can offer.

In the next chapter a concept will be discussed that could establish a consistent method of collecting feedback for achieving this aim. Post-occupancy evaluation (POE) is emerging within the commercial sector as a means of comparing the effectiveness of the methods and outcomes of each new development or use of technology; although it is yet to take off within the housing sector. It will be argued however that POE could also provide considerable catalyst to the housing sector, by sharing information on the best practices as a means of accelerating improvements in its sustainability.

4 Housing Improvement through Feedback

It is clear that the construction industry is required to undergo a major transformation if it is to play its part in shaping our sustainable future, which is often described as the biggest challenge it has ever faced. It is also apparent from the scope of the Egan Report [46] that its ability to face up to this challenge will be seriously confounded by the poor quality control of finished product that is the current standard within the industry. Among other things, Egan called for the creation of a quality driven agenda that should be guided by performance measurement and targets for continuous improvement. Part L of the Building Regulations exists as the legally demanded set of minimum performance targets for heating and power use within the home; however, even though it is only comparable in thermal efficiency to what was built in Scandinavia before WW2 [66], an estimated one third of new housing does not achieve what is required in Part L [67]. Praiseworthy eco-schemes and case studies with super-insulation and exceptionally low air infiltration do of course exist in the UK, but they will remain as token, demonstration gestures until quality control is dramatically improved across the industry as a whole.

The more progressive manufacturing industries have accepted for many years that feedback from users on the performance of the finished product should be seen as a key part of their quality control regime. If the most is to be made of the existing knowledge base, in order to improve the next version of the product, then it must first be discovered which elements of the design were successful and which were not once it entered the marketplace. Otherwise, there is a risk of the next upgrade being one that replaces the good aspects and maintains the bad; not because the designers are incompetent, but because different criteria can be used by designers to predict the product's performance than are used by customers. Designers will often spend a long time solving the wrong problems very effectively, leaving untouched the problems that matter to the user, which will clearly have a significant effect on their brand loyalty. This scenario is especially true of the electronics or automotive industries where product renewal can be frequent, but it is also true of the construction industry, even though the period between 'upgrades' is considerably longer. A negative response can also often be delayed when the actual users of buildings are not the same group who paid the construction company to build it; however, strong alliances do exist between clients and contractors that can be damaged. So it is in the interest of all parties to listen to what the users of buildings have to say and use this to continuously improve the product; to remain competitive and to better control the quality and direction that the product development takes.

The act of gathering user opinion in order to continuously improve our buildings has been established within the construction industry for over forty years and Stage M in the Royal Institute of British Architects (RIBA) Plan of Work for Design Team Operation (1963) is named 'Feedback'. Currently however, this stage is omitted from the Standard Form of Agreement that architectural services are normally procured under, meaning that it rarely gets completed. Nevertheless it has developed in concept and reach and presently goes by the name of 'post-occupancy evaluation', or 'POE'.

According to Leaman [68], POE aims to assess a project from two fundamental points of view: "*How is this building working?*" and "*Is this what was intended?*". The attributes of design that are evaluated depend almost entirely of course on the desires of the funding party, and it is generally the same group who decide the boundaries of the time period under evaluation. A POE can focus either on the design & construction stage, the early occupancy period, or both. There are a number of qualities of a building that a POE can assess and the importance attached to each is often context dependent.

- Space – the physical capacity and how it fulfils the users' demands.
- Operations – the usability, manageability and flexibility of the building.
- Environment – indoor conditions (thermal, lighting etc) and their impacts.
- Users – opinions of the occupants, usually gathered by questionnaire.
- Image – both the building's styling and the signage for route finding.
- Cost – 'perceived value for money' is often the number one priority.

Full POE studies have traditionally focussed on commercial sector buildings, since this portion of the industry is more competitive and revolves upon quantifiable achievements such as efficiency and productivity. The same approaches can be adapted for residential studies, with the opinion of the occupiers taking a central role. The measurement of occupant satisfaction is more complex however than it sounds, although the advocates of POE claim this is where will come the majority of improvements that it can bring.

4.1 The benefits of building occupant satisfaction

The ultimate beneficiaries from a POE study should always be the building occupants, with any negative feedback that they contribute being acted upon where possible to improve the conditions for them and future occupants. Stating it like this will rarely provide sufficient reason for a commercial organisation to take on the cost of undertaking a study however, and so it is important to appreciate the full range of benefits to each of the various parties, especially as the funding could come from any of them. BRE have produced a concise table of costs and benefits to aid designers to obtain the necessary funding for POE [69]. The costs are broken down in a way that summarises the procedure for a study as: questionnaire design and distribution; data analysis; feedback reporting; and remedial action. The benefits fall into four categories:

1. Improved staff satisfaction and well-being, leading to raised productivity and reduced absenteeism, churn (staff turnover) and training overheads.
2. Improving the effectiveness of the facilities – building services, space allocation and obtaining early warnings of potentially serious problems.
3. Reduced energy & maintenance costs through improved service operation.
4. EcoPoints that are awarded for measuring staff satisfaction and acting on the information gathered under BREEAM for offices [70].

For advocates of POE in commercial buildings it is vital not to underestimate the potential increase in staff productivity that can come through comfort improvements. A range of studies using various methodologies has shown productivity gains of 20-25% following improvements to the work place, such as better use of daylight and lighting design [71] [72]. There is some uncertainty over certain aspects of the data, such as the measurable definition of productivity and the means of separating the influence of environmental factors from all others; however, this uncertainty can easily be countered by an appreciation of the magnitude of the potential gains compared to the costs of owning and operating a typical building. This has been reported on by others [73] and summarised by CABE for running an office for 25 years as: 6.5% on construction cost; 8.5% on furnishing, maintaining and operating; and 85% on worker salaries. Or in ratio terms:

Construction : Building running : Business running = 1 : 1.5 : 15 [71]
Alternatively, according to another reputable source = 1 : 5 : 200 [74]

Whichever set of ratios is correct, the figures illustrate the greater significance of the indirect benefits of productivity increases compared to the conventional means of justifying M&E equipment upgrades by their more direct benefits, such as a reduction in energy use or improved styling. Case studies from around the world have reported how payback periods have in this way been slashed from years to months on upgrades that were scheduled originally to improve energy efficiency and reduce maintenance and repair costs [73]. So here lies the message for the energy conscious designer. By focusing not only on the relatively minor energy and fuel savings but also on the considerable productivity gains that could come about, the business case for sustainable energy technology in commercial properties can become a win-win situation.

POE studies at present tend only to be done by the best companies on the best buildings, which forms a virtuous chain that assists others to obtain the resources required to conduct and publish studies of their own. In this way, POE has become a rich source of factual evidence to use to convince investors that environmentally beneficial strategies are already proven and reliable.

Returning to the housing market, it is possible to relate the first three of the four benefit categories to a similar benefit that the application of POE would bring to a housing development. Unfortunately EcoPoints are not yet available in the EcoHomes scheme for consulting the occupants of other homes; however, the financial and environmental aspects of space usage and building services provision have traditionally been significant for housing just as for commercial property, and a home's on-going energy and maintenance costs are becoming increasingly significant at present, as discussed in Chapter 2.

Where the difference lies is that while the benefits of occupant satisfaction in commercial buildings can be measured tangibly in terms of the staff costs and productivity, no such measurement exists for the satisfaction of a home owner. People use their homes for a multitude of various purposes and each of us has our own unique opinion on what an aspirational home is. No over-riding function exists for modern homes to which a figure or target could be assigned and so developers instead target their housing broadly to socio-demographic groups, usually without a good understanding of how the lifestyles of the occupants should influence the design in question.

4.2 Existing POE techniques

The number of methods developed over the 40 years that POE has existed has grown to such magnitude that it is itself one of the reasons that POE has not become mainstream. Over 150 possible methods have been reported previously [75] and, for this reason, one of the primary objectives of a recent program that researched the UK construction industry's perceptions on POE was to greatly streamline the methods into a recommended 'Portfolio of Feedback Techniques' [76]. The aim for this Portfolio is to make it much more clear which method should be used by those interested in conducting a POE, depending on what stage of the construction process they wish to study. The Usable Buildings Trust website presently hosts the Portfolio [77], which contains just 10 techniques, grouped into 5 stages of application and the 5 methodological categories of: Audits; Discussions; Questionnaires; Packages; and Process Changes.

Certain aspects of the Portfolio stand out clearly. The first is the importance placed on discussions and surveys as the most effective means of gaining information. Apart from the CIBSE TM22 Energy Assessment and Reporting Method (EARM), which is the only entry in the Audit category and is also incorporated into two of the other nine techniques, the focus is very heavily on what can be learnt descriptively both pre- and post-build on the expectations and opinions of the occupants and those others most involved in the process. A second aspect that stands out is the complete absence of a technique for households, as all in the Portfolio are targeted at offices, schools, retail and other commercial properties. Personal communication with Building Use

Studies (developers of the BUS Occupant Survey, as used in Probe series of POE studies) has revealed that several attempts have been made before on developing a standard POE questionnaire for housing but none have yet grown beyond the boundaries of the company that designed it. Currently the Construction Industry Council (CIC) is developing a housing version of its Design Quality Indicator (DQI) questionnaire [78] that features in the Portfolio, which is a very positive observation since the lack of a standard method has impeded the practice of surveying households, provoking CABE to remark,

"The fact that there is very little post-occupancy research conducted by anyone in this sector is a problem that we must all address." [79]

The prime reasons for the lack of a standard POE approach for housing have been suggested as commercial confidentiality, limited resources and a 'not invented here' mindset, meaning that techniques do not get picked up by other companies who instead develop their own. Additionally, since housing does not have an over-riding purpose, the surveys are often tailored to a specific development and research agenda, with limited application for the housing industry as a whole. Sustainability has in the past been described one such agenda, a lifestyle choice that is out of sync with the many personal aspirations for modern housing that must be seen as being non-sustainable, such as parking for a third car or a heated swimming pool. Many recent surveys of the homebuyer market as a whole have told a different story however, with a predominantly positive attitude towards sustainability coming through clear.

4.3 Overcoming the barriers to conducting a POE

The barriers to integrating POE into the construction process are complex and varied and, as one commentator has remarked, have resulted in a situation where POE has "*many advocates but few practitioners*" [68]. The barriers fall under the headings of corporate uncertainties and the difficulties of preparing, completing and reporting a study. A significant list with the means of overcoming each has been compiled elsewhere [80] and so only the main barriers are now reviewed.

Corporate uncertainties

- POE is perceived to be of low value, especially by some clients who see it as an exercise for the construction industry to solve its own problems. This makes it very difficult to obtain the required resources when the pressure is normally to work at reducing financial budgets and costs.
- It is also often seen as a risky exercise that could lead to reduced property values, higher Professional Indemnity (PI) insurance or even litigation if faults are exposed and blame is subsequently placed.

Process difficulties

- Clients may have difficulty defining what they want before a project starts, making it difficult for the practitioner to know what data to collect.
- Many POEs presently undertaken are single-building or single-project studies and so are often assessed using bespoke techniques with little thought for how the method and results could be applied in future.

- Identifying causes and effects in a building’s ability to help or hinder the activities that take place inside of it is an extremely complex challenge.

Post-study complications

- The report is required to be of more than limited benefit to everybody, whilst maintaining a balanced view that meets the expectations of each of the multi-disciplinary parties involved.
- If recommendations are to follow a POE study, it is usually necessary to benchmark the building against others in its particular class. This calls for some database handling, which is often underestimated and under-funded.

Solutions

The solution to most of these barriers is to maintain communication and transparency at all stages of the POE process. Trust should be developed by holding regular open discussion forums with all parties, to first of all introduce the concept of POE, formulate the brief, scope and benchmarking requirement of the present study and possibly to draw up ‘No fault agreements’ to clarify what falls outside the contractual obligations. In this way, the involvement of all parties should be more positive and helpful throughout, and the finished report should be one that is both fairer to all and positive on the benefits that the study has brought. This will make it more likely that the report gets published, and it is through increased publication of the success stories of POE methods that awareness of their existence and benefits will improve.

4.4 Chapter conclusions

The housing stock of the UK was depicted in Chapter 2 as being deficient, unsustainable and lacking in its ability to support 21st century style living. The accelerated program of house building that is currently underway is to tackle the often proclaimed shortage, but little is being done to assess if best use is being made of the limited land resource that we have or if what is being built is of sufficient standard to meet the difficulties that the changing climate will bring. This chapter has argued that housing should follow the lead of the commercial sector's adoption of post-occupancy evaluation (POE) and develop a common technique for assessing a dwelling's performance in terms of its energy and land consumption and its ability to satisfy the occupants' needs.

The value of the land footprint that a dwelling is built on may not be as important to the homeowner as the features that the house contains, but it is extremely significant to the developers who are required to build at a higher density and do not wish to lose overall market value on the development site.

Occupant satisfaction should be seen as a critical business function of a commercial building's performance, which must be understood by any energy conscious manager who wishes to apply POE within the commercial sector. The over-whelming magnitude of workers' salaries relative to the overall operating costs of a business means that even if the thermal, ventilation or lighting improvements made following a POE study result only in a small percentage rise in worker productivity, the implementation of the study can still become undeniably advantageous.

Unfortunately house builders do not gain such an immediate financial benefit from assessing dwelling occupant satisfaction. However, since POE has shown that energy efficient commercial buildings are also very often the most comfortable and satisfactory to work in [6], it is reasonable to hypothesise that the same will be true for homes; that more-sustainable dwellings are also more pleasurable to live in. Anecdotal evidence suggests this to be the case, although no conclusive studies of the possible correlation have been reported because of a lack of comparable data. While collections of sustainable home case studies have been assembled by others [81], the methods used have not yet been developed into a standardised POE procedure, although attempts are being made [78]. A standardised procedure is required so that data collected on the full range of mainstream and more-sustainable homes by independent assessors could enable comparisons on their achievements and occupant satisfaction.

As was also argued throughout Chapter 3, evidence of an enhanced on-going occupant satisfaction could be used to assure prospective buyers that they will be happier and economically better off in a more-sustainable home. This may ultimately lead to market differentiation for the builder and add a premium onto the market price of the more-sustainable homes that they build, contributing towards the additional build-cost of the home. Promotion of the findings from housing POE surveys may well create the market differentiation that is required to enable the mainstream to build more-sustainable homes.

5 Space Use Efficiency

Previous chapters have argued for the development of a standard and objective means of gathering data on the performance of more-sustainable homes, so that they can be promoted in the marketplace as offering benefits that warrant a price premium. As was discussed in Section 2.2, the land devoted to housing is becoming a significant issue, as the number of households continues to rise beyond the growth of the population. Smaller homes are being built and to a higher density, to reduce the need for expansion onto greenbelt land and to develop communities that can support the local services around them. The definition of a more-sustainable home should therefore include the efficiency with which the space it contains and the footprint of land it is built on is used.

Space usage is already one of the most frequently requested aspects of post-occupancy evaluation (POE) in the commercial sector, where the efficiency with which a business makes use of the buildings it operates from is of tangible financial value. These buildings are often rented by the square metre, which creates a financial focus that encourages the facility manager to assess the allocation of floor space very carefully, however the methods used for these assessments can often be inaccurate and labour intensive. In this chapter a new technique is proposed that links the present work with the fields of computer science and architectural design. The discussion will explain how these areas of research overlap and can complement each other in many ways, through the application of an occupant tracking system. First though it is important to appreciate why domestic floor space is allocated as it is today.

5.1 Internal space division

The architect’s conception of the activities that will take place within each room has always been fundamental to the overall form for housing, as this implies what size each room needs to be and where it should be positioned relative to the others. It is the space subdivision and layout created by the architect that provides the canvas onto which prospective buyers try to imagine superimposing their own lifestyles; picturing where they will place the functional, symbolic and sentimental objects that turn a house into a home [82]. This is a complex task for the architects, illustrated by the fact that there are 100 separately identifiable activity categories for daily time consumption that could be taken into consideration [83]. It is also one that has deep roots in the historical structure of the whole of society, reflecting why in modern housing the layouts will differ from those of the past, as housing responds to the changes in culture and society happening all around us.

First it is necessary to stress the well documented demographic changes that are taking place within UK homes and creating a demand in excess of the level of new housing provision. The rate of annual house building is to rise by approximately a third by 2016 due primarily to the reduction in the number of occupants within each household, which has brought an enlargement in the usable living area available to each occupant [27], placing ever greater pressure on the land resource that we have available as a whole. The Ecological Footprint (EF) is a measure of the area of land needed to provide all necessary food, materials and energy for a society and to absorb all of its waste. The EF of the UK is already more than 3 times the land area that it occupies [47] and each new house built to the current regulations steadily increases this level of mismatch. For the purpose of damage limitation, it is therefore important that full use is made of the footprint area of each new home built. The traditions and historical legacy of house design that have led to their current forms explain why this may not be the case at present.

5.1.1 Historical development of floor plan arrangements

The arrangement of space within the home has much to do with the historical shaping of our society and the way our culture functions. The most significant aspects of these transformations are now discussed, focusing on the evolution of the two most regarded living spaces in contemporary house design – the kitchen and living room - and the more topical distinction being made in recent times between the segregation of distinct rooms and the flexibility of open-plan design for living spaces.

The segregation of domestic living spaces began in C19th with the separation of cooking and washing from eating and living on the ground floor, with bedrooms on the floor above. The next marked change to this came with the industrial revolution at the turn of C20th, as those who made up the new social class moved outwards from the inner cities to the suburban environment, placing a geographical divide between the workplace and their more exclusive homes. The architecture of these large middle class homes came to emulate that of semi-public medieval halls, with the space inside coming to be organised and named according to their location, use and social status, such as "*front/back, clean/dirty, day/night, public/private, sacred/profane*" [84].

Territorial divisions were made firstly according to the social status of family members and household staff and then for the particular needs of family members, which included providing rooms for the lady to entertain in while the man was out at work. The creation of the front parlour as the household's primary room of social status has been the focus of much previous discussion [85]. Objects of significance were displayed here and it was where non-kin guests were entertained, although it was also the least used room. Under the modern criteria of efficiency that domestic architecture may be judged by, this makes the historical parlour a very ineffective use of space for a family home.

After the Great War, much attention was placed by the government on bringing working class homes up to a standard befitting the nation's war heroes. The Tudor Walters Committee of 1918 recommended 3 standard house plans that provided increased space and airiness, a minimum numbers of rooms and the location of living rooms that maximised the amount of natural light. In suburbia meanwhile, due to the reduced availability of domestic staff in the growing economy, the housewife was required to take up duties such as cooking, cleaning and washing. Thus the well laid-out, modern day kitchen developed out of the scullery and came to be a focus of household activity.

The post-WW2 years brought rapid advancement in living standards, thanks in particular to electrical appliances such as washing machines and televisions that respectively provided and filled leisure time at home with the family. The front parlour had until now been regarded as a room only for status use; however with its evolution into the 'living room', due to the new technology located within it, it quickly became a new centre of attention for family life.

Shortly after this in 1961 the concept of the ‘adaptable house’ was introduced by the Parker Morris Report, which recommended for social housing the use of larger open-plan rooms, to enable the use of all ground floor space at all times. The implication was that by removing the sub-dividing walls between the traditionally defined rooms, new larger spaces would be created whose use could be defined through the everyday activities that actually took place within them, whatever the occupants deemed most suitable. This was a contentious issue for some, who regarded the open-plan nature of modern domestic architecture as requiring management rather than as something that could be exploited. In fact the current trend for new-build housing is to build in the divisions, although a common suggestion on many of the home-improvement television shows now shown is to create more space and light by knocking these same divisions down. As such, the trend towards open-plan spaces has been in a period of fluctuation for some time, as internal walls are invariably built up or knocked down according to the current owners’ taste and needs.

The spaces created by the divisions within a house will clearly not be regarded with equal significance by each occupant, nor will their relative importance remain the same as the occupants go through generational changes or the house passes to another family entirely. The research of others [28] has identified that there are at least four distinct consumer groups for housing, who attach different significance to factors such as price, location, neighbourhood, property type, room layouts and the provision of gardens. The value they place on each factor was found to be primarily based upon the needs associated to their lifecycle stage. This therefore highlights the unfeasibility of designing a ‘one size fits all’ solution to family housing that will meet the changing requirements placed on it over time. It suggests that offering a greater range in room layout and specification is instead required to better meet consumer demand. The feedback obtained has shown homeowners not to like overly prescriptive house plans, full of pre-defined spaces that they are forced to pigeon-hole their individual behaviours into. Designers continue to include multiple space divisions in new build homes that could be avoided however, and make various assumptions on how important each space will be. This is due to the unfortunate fact that the marketplace gives a higher profit margin to a house with a greater number of small, inflexible rooms than to one with fewer rooms but larger and more adaptable spaces. Unless the UK market were to follow the example of the Continent and North America by marketing speculative homes primarily by their floor area rather than number of rooms, it will be difficult to move the marketplace economics in favour of open-plan.

With this historical legacy in mind, house designers now look to the new requirement of improved efficiency and conclude that space divisions will inevitably be made differently from in the past. Change occurs slowly in house design however, as developers are naturally risk-averse when their products are expected to have a 60+ year life and represent the most expensive purchase for many people in their lifetimes. At the same time many builders would like to be more progressive, to change the image of modern housing of box rooms with windows. It is therefore appropriate that they consider the work of others such as technologists and sociologists on the means to study the activities that take place within domestic spaces.

5.2 Space use assessment

The efficiency with which physical space is used is a frequently requested measurement in POE. A literature review conducted by CABE found that the efficiency with which office space was utilised was the second most extensive POE topic [71]. Of course, space in commercial properties often has a tangible financial value attached to it in the form of rental costs that are marketed by the square metre. Increased productivity through improved use of the available floor area can reimburse for the cost of conducting the study. This direct financial connection does not exist for housing; however if sustainable homes are to be marketed using POE findings, it is important to understand which spaces are most important in a house, what takes place within them and how these can vary according to the context of the occupants and time.

The concept of 'regionalisation' describes how time and space becomes zoned in routine social activities [86] and analyses into this regionalisation have made use of different frameworks to identify the activities themselves [87]:

Spatial

Zones of space used for various activities. For example, 'Command & Control', 'Hangout', 'Private', 'Social' and 'Work' [88]. These zones may map neatly onto a floor plan of the house or they might overlap across rooms.

Temporal

The subdivision of time for domestic activities has been studied, with the finding that it consists of small blocks that are constrained by external factors.

Goal-orientated

Certain activities will span several spatial zones and blocks of time, but they are tied by a common goal; for example, arranging a party.

Communicative

Communication as an activity has been singly identified as important when looking at how occupants use space within the home.

Architects also have attempted to develop frameworks that can be used to assess what activities take place in certain spaces and what similarities in design make some spaces successful and others not. Perhaps the most successful of these is the Design Pattern Language, which attempts to present "*the interaction of the space and the events, in a clear and unambiguous way*", in order to encourage technical design creativity towards "*concrete user situations*" [89]. The Design Pattern Language has been used to solve multi-disciplinary problems in a variety of fields, and its particular benefits have been noted by others designing the future home environment because of the importance of patterns and routines in structuring domestic life [90].

5.2.1 The importance of domestic routine

The significance of the accomplishment of activities within the home is a topic that has long attracted the attention of many researchers from multi-disciplinary fields. The gender divisions on the completion of household labour have featured in feminist literature for many years. Technologists and economists are presently very keen to learn more on the means by which new items of information communicative technology (ICT) are taken up in the domestic environment. Meanwhile sociologists have made much of the break-up of the 'nuclear family' and the effects this could have on relationships in and outside the home. The common thread is the importance of daily routines to maintain the smooth operation of domestic activities, and the significance of what can be learnt through their study and how they can evolve over time.

Also known as 'norms', routines have been described as the "*well-established, unwritten rules guiding someone's behaviour*" [91], or more succinctly, "*the glue of everyday life*" [92]. They play a central and dependable role in keeping order and stability and for completing the often mundane concerns of domestic life. Although they are often complex tasks, "*produced through the practised exercise of complex skills*" [93], routines are continually completed without need for explanation or someone else's attention, thereby making them 'unremarkable'. Routines can also become bound to locations due to a reliance on the technology found there, though most routine behaviours are distributed throughout the home in a way that varies between households in either subtle or sometimes obvious ways [94].

This focus of social scientists and technologists on the structure and locations of domestic routine has given rise to quite a number of techniques for studying the behaviour of building occupants [95] [96] [97]. Space use has also been assessed by POE practitioners using one or more of these techniques, with the objective of collecting comparable data often being significant in their selection.

5.3 Assessment methodologies

The most effortless techniques for the researcher are hands-off approaches that are self-completed by the occupants. Interviews, direct observation and in-situ participation are more complicated, time-consuming and costly, but usually also much more revealing.

Recall surveys

Asking the occupants to fill out surveys post-activity can seem like a quick and easy method of gathering the data required; however, it should be expected that the data collected will be inaccurate. The reliability depends first on the preparation of a survey method that will not introduce bias to the responses, second on the participants' ability to effectively communicate their opinions through the survey medium and ultimately on the participants being able to fully and accurately recall the scenario and context under question when they were most likely not aware of its significance at the time. It is also argued that the attempt of many surveyors to convert qualitative events into quantitative values that can then be aggregated and analysed as a whole cannot provide an account of group behaviour, since the act of answering questions is very different to the events being surveyed and the aggregations lose the rich detail of individual responses in favour of averages and majorities [94] [92].

Time diaries

As a response to gaps in the participants' memory of events post-activity, it may be preferable to ask them to complete diaries at more regular time intervals throughout the period of study. The diaries could be recorded on paper, Dictaphone, camcorder or even PDA. It is tempting to state that this method is more accurate since it will usually generate a larger quantity of data; however, it can also result in emphasis being placed on an individual participant's perception of events when they may be incorrect. Time diaries are also more disruptive for the occupants, who may forget or forgo their entries if it becomes laborious or tedious.

Interviews

Interviewing the occupants individually or in focus groups can often be very effective when handled by a competent researcher who can probe deeper into interesting answers without introducing bias to the questions. In this way, a standard interview format can be adapted to better suit the particular circumstances and to gain more relevant details. Similar to recall surveys, the limitation of interviews is that the data quality depends ultimately on the interviewees being able to remember the sequence of events accurately and to articulate their impressions effectively.

Direct observation

Real-time observation by a researcher can overcome much of the problem of partial or selective recall by the participants; however, the researcher may themselves interpret the behaviour incorrectly, because of their own assumptions or subconsciously imposed agenda. Recording of the activity using photographic or video technology can allow for later corroboration of the analysis by other researchers or even the participants. Direct observation is much more costly and time consuming than other methods, especially if recording devices are used for later review and analysis. Plus, it may be expected that the behaviour of subjects in the normally private setting of their home will be influenced by the presence of observers or cameras, although some researchers think not [98].

Ethnography

This form of direct observation deserves to be mentioned in its own right as one of the oldest methods of social research that has come to prominence as one of the most reported on for studying the natural behaviour of people in social situations. Ethnography, "*seeks to present a portrait of life as seen and understood by those who live and work within the domain concerned*" [99]. In order to do this, the researcher will immerse him/herself in the social situation, becoming directly involved to observe the situation both in-situ and in-vivo. They report objectively on the events afterwards, providing qualitative descriptions that are rich in detail and "*prior to the point at which they are subjected to reconceptualisation in terms of the postulated requirements of one or more of sociology's theoretical and methodological constructions*" [100]. Ethnography does not allow generalisable theories or hypotheses formed elsewhere to be used, as they can cloud what, it is argued, should remain as purely empirical findings in new domains of study. A disadvantage to this is that ethnographic studies do not often provide easy answers to designers, especially since the extensive yet highly specific details provided through one study can differ markedly from those reported in another. This has led to criticism of direct observation studies that are overly rich in descriptive detail, since design decisions often cannot be made based on what they report;

however, they have shown that the flexibility required to suit the spatial variation between different households' routines should be added to the specification for any domestic technologies developed.

Mapping

During the course of a POE exercise conducted in Japan, the technique of mapping the activities, timing, movements and communication events onto a copy of the building floor plan proved to be very effective at gathering extensive data on office space use [101]. This exercise was an enhancement of the ethnographic approach, as it relied on an in-situ observer recording the details whilst following employees around their workspaces but it presented the findings in a more objective way that could also be more instructive to designers wishing to improve the allocation of office space.

The consequence of the unremarkable nature of routine activities should be a concern towards any study that makes use of recall surveys, time diaries or interviews alone to gather detail on domestic behaviour that is habitually undertaken without any thought given to its significance. An element of direct observation should be included since, "*users doing routines is different from users describing routines*" [92]. At the same time however, becoming an active observer in the home is much more challenging than in other social situations, such as the workplace or public spaces, as it goes far beyond what is customarily deemed appropriate in the proverbial Englishman's castle. The forced social situation of a domestic ethnography or movement mapping could therefore be expected to alter the very behaviours under study [102].

5.4 Chapter conclusions

The internal floor plans of dwellings have been continually reshaped as architects responded to changes in our society that cause them to reconsider what activities will take place within each space and how this implies the location of one with regards to another. This gradual evolution has led to the rise in prominence of certain rooms such as the modern-day kitchen and living room, and the conflict between design theories such as open-plan versus segregation. Architects are now under further pressure to design for more efficient use of internal space, to take full advantage of the limited land resource that is available for each new home. For this reason POE practitioners have turned to the methodologies of domestic sociologists and technologists for a suitable means to study the behaviour of building occupants and to assess how their designs enhance or diminish occupant satisfaction.

While a range of such methodologies are practised, each is lacking in some important aspect. They may rely on the occupant’s subjective and often inaccurate recall of unremarkable routine events, unduly disturb the occupant by interfering at inopportune moments, or alter the very behaviour under scrutiny simply through their presence. POE practitioners have adapted these techniques further to overcome some of their limitations; however not to the satisfaction of those wishing to conduct research in the domestic environment. Computer scientists have now become attracted to the field of research, and the advances they have made in developing specialised sensors to track the movements of people inside buildings is of particular relevance.

6 Occupant Location Tracking

The technology to track people inside buildings was developed in the field of computer sciences so that occupants could take advantage of ‘context-aware computing’ systems. ‘Context-awareness’ developed from the idea that a computer that used sensors to become more aware of its surroundings would be able to automatically adjust whatever it controls to better suit the context. Additionally, the trends of increasing power, production and miniaturisation of electronics enable designers to foresee the day when environments could be populated with context-aware computers that no longer required a dedicated human-computer interface. Instead, their services would be provided direct to the user as they move freely in the environment. It was realised that to do so effectively, a context-aware computer would require the same unremarkable characteristic as the human routines it was supporting, and an awareness of the location of the people within the environment. This vision was given the name ubiquitous computing (UbiComp) and is the focus of many researchers.

It became apparent during this project that the same sensors that UbiComp designers were working with could be used to collect data on the use of the space within a home to be established for a post-occupancy evaluation (POE). A remote tracking system could provide the quantified data that most other methods of space usage assessment lacked, without being disruptive to the occupants’ behaviour or routines under study. This form of POE study would provide a more reliable basis from which to assess how the space was being used and whether it could be allocated more effectively.

6.1 Personnel locating sensors

UbiComp will make use of a multitude of various sensors to gather enough data to infer the activities taking place within their environment. Sensors for location, orientation, light, sound, temperature, pressure and electrical state are all commonly used. For the space usage study discussed in this thesis however it is only the locating and tracking of occupants that are of interest, which rely on the sensor subset that was least developed when the UbiComp application was established. Now that a range of sensors is available, researchers focus on improving capabilities such as their accuracy resolution and coverage range, their miniaturisation so they can be embedded directly into the environmental fabric, and reducing their power consumption and cost. Sensors for discerning the location of people can be classified at the highest level as being either ‘tagged’ or ‘untagged’ [103].

Tagged sensors deduce the location of a person by wirelessly locating an electronic tag that they are required to keep with them at all times. The electronic nature of the tag makes its identification accurate and reliable, as well as providing a communication interface between the person and the tracking system. These systems use a network of base stations distributed through the environment, although the exact purpose, size and distribution of the base stations vary between each technology.

Untagged sensors locate the people themselves rather than any object they carry. This form of tracking is clearly less disruptive and potentially more accurate than using tagged sensors since it is not difficult to imagine how an occupant could forget or forgo to keep their tag on them at all times. At present however it takes a lot of computer processing power and expensive sensors to make an untagged tracking system and their performance at identifying individuals is still not as good.

Further classification within each group is possible, relating to how the raw data is measured. The distinction now described is between three methods of data interpretation: proximity, triangulation/trilateration and scene analysis.

- Proximity sensors locate a person to being within a zone when they move into the sensor’s known range of view. The location resolution can only be improved by using more sensors with smaller zones of coverage.
- Triangulation and trilateration use the readings from at least three sensors that can detect the person in order to calculate by trigonomics a much more accurate location.
- Scene analysis sensors follow temporal changes in their vantage point view of the environment, to infer the movement of objects within the view.

Many forms of locating sensor have been developed using various detection and communication technologies. Those that are most suitable for tracking individuals are now described, with the particular benefits or disadvantages highlighted. Several are not yet available commercially, so a full cost to performance comparison cannot be provided.

6.1.1 Tagged sensors

Infrared tags

Two commercial systems, the Active Badge and ParcTab, use networked base station readers that detect infrared (IR) signals sent out by a tag that is carried by the person being tracked. While Active Badges are principally for location purposes [104], the ParcTab was designed to have mobile computing capabilities for offices such as temperature and lighting control [105]. The 'Locust Swarm' system differs in that the tags contain the IR detectors and the transmitters are the stationary base stations in the environment. This secures the privacy of the tag location to the user since the tag does not transmit this data itself [106]. The IR technology used by these three solutions is cheap and the walls of each room constrain the signal, which can improve inference reliability. The proximity range can be as high as 30 metres although detection may be affected by direct natural daylight and fluorescent lighting [107].

Radio Frequency Identification (RFID)

RFID tags come in two forms, 'active' or 'passive', with the defining characteristic being that active tags use an onboard power source to transmit a signal to silent readers, whereas passive tags induct the power to respond from a signal transmitted by the readers. The transmission wavelengths can be from roughly 130 kHz (low-frequency) to 928 MHz (ultra high frequency) depending on the application and licensing laws of the country. Although passive tags are expected to become commonplace on construction sites [108] and are extremely cheap at under $0.10 in bulk, they are not suitable for tracking people in a home since their read range is measured in inches because of their power limitation. However, active systems can have read ranges as high as 1000 metres [109] and are the preferable solution on cost consideration as well. Providing full coverage in a typical house will require many more readers than tags, and although active tags are more expensive, the readers are less expensive than for passive systems. Commercial active tag systems are already available for building access and vehicle tracking [110] [111] and the size of battery-powered RFID tags is favourable since they are available in forms similar to a security card or wristwatch. A difficulty with using RFID is that the signal is not constrained by physical barriers such as walls and floors, so careful configuration of the reader network is necessary to avoid 'bleed-through' between zones. Triangulation is possible to achieve location accuracies of 2-3 metres [109] but this requires a denser network of readers and costs excessively more than operating on proximity only. In addition, the RF signal strength can vary due to the environmental conditions and human body interference, making the performance inconsistent at times.

Ultrasonic

Ultrasonic signals operate at a much lower frequency than RFID, which has both benefits and disadvantages when used for indoor tracking. The 20 kHz signals do not suffer from interference from nearby metallic bodies, however they do require near line-of-sight between the tag and receiver. Two technologies have been reported on extensively - the AT&T Bats and the MIT Cricket. Both operate using a matrix of base stations located at ceiling height. The Bat base stations detect an ultrasonic signal emitted by the battery-powered Bat and triangulation of the three earliest received signals reliably gives the location to as fine as 3cm in three dimensions [112]. Crickets achieve a similarly impressive accuracy but the ceiling mounted grid consists of beacons rather than receivers, which provides privacy control to the user but places greater computational power demands on the tags that must carry out their own triangulation [113]. The large network of stationary base stations used by both systems would have a high visual impact where mounting above a suspended ceiling is not possible. Additionally, neither system is available commercially for easy deployment with user-friendly, front-end software.

6.1.2 Untagged sensors

People counters

Inexpensive people counters are commercially available that count the number of times an infrared or radio beam shone across a doorway is broken by people walking through [114] [115]. The counters cannot identify the person who passes through, but instead provide the one-way, two-way or aggregate total. Accuracy of the count relies on people walking single file and not swinging their arms or carrying other objects that would break the beam more than once.

Pressure pads

The ‘Smart Floor’ uses a matrix of load cells under a metal plate as a pressure sensitive floor tile that can identify the person walking over them reportedly with 90% accuracy based on their unique footstep pattern [116]. Structural alterations are required to fit the floor plate flush, which would be required at the junctures between every zone of interest, making this a poor choice for temporary installations in a complex building.

Optical systems

Systems that attempt to identify the people in an image have attracted much attention for research in multiple applications, perhaps the most topical of which is video biometrics for use at security checkpoints. In a house, cameras could be mounted in vantage points to record activity when motion is detected within their field of view, such as above doorways [117]. This is called an 'outside-in videometric scheme' [103] and requires sufficient cameras to cover every area of interest, which could be expensive in a complex building. Automatic identification between people is at present unreliable, which implies the footage must be watched through manually, which is a very time-consuming procedure that still may not guarantee their identification [89].

An alternative is to mount the camera on the person and use a set of targets at known positions to calculate the person's location using an 'inside-out videometric scheme' [103]. Some mobile robots make use of this technique but it is unrealistic to think an active person could maintain the camera in the required vantage position. In addition, these routines require substantial processing power and have great difficulty with complex scenes and variable lighting. To perform a manual review of the recording would take even longer with this technique, because of the real-time recording that would be required.

Ad hoc UbiComp network

A number of research groups are developing miniature tags that can be distributed in the environment as a cluster network that communicates within itself to calculate their relative positions as well as transferring any other data collected. MOTES [118], Smart-Its [119], SpotON [120] and MITes [121] are all examples. These tiny tags provide the basic building blocks of a ubiquitous network that could make use of various sensors to gather data such as temperature, noise or light levels, to enable a context-aware system to infer scenarios and activities. They can be used to infer the location of people by following the various interactions that they have with the environment and could be trained to identify individuals through their routines [95]. Although ad hoc tags may offer a low-cost approach to location sensing that is easily scalable to include many objects or people, they are all still at the research stage and require intimate technical knowledge of their operation to deploy.

It is clear that a combination of sensors will be required to bring the visions of UbiComp to fruition. Researchers continue to develop the capabilities and implications of each using sensor technology and many are being developed with the domestic environment specifically in mind. Several groups have taken this approach to the level of building tracking laboratories or even ‘Smart Homes’ as showcases and research centres into human living.

6.2 The ‘Smart Home’ vision

The objective of providing a dwelling with context-awareness has been developed into the marketable product of a ‘Smart Home’. This is a residence that makes use of an embedded network of sensors, tags and readers that communicate wirelessly and,

“*anticipates and responds to the needs of the occupants, working to promote their comfort, convenience, security and entertainment through the management of technology within the home and connections to the world beyond.*” [87]

Improvement of the domestic environment’s sustainability may therefore also be possible in a Smart Home. Much has already been written on the futuristic appliances that a smart home could bring [122] [123], which is understandable given the revolutionary nature of the concept. Several successful applications have already been developed however, based on research of the activities of the present and the market truism that products must focus on the real problems that people face today. These broadly fit into two categories: automation and informational [124].

Automation

The automation of particular appliances in the home can bring benefits in terms of comfort, convenience, security and entertainment. For many people these may be of minor significance; however, the benefits of automated lighting, cooker safety, window opening, door locking and even medication provision can bring noticeable improvements to the sense of security and independence felt by the disabled or elderly, and hence improve their enjoyment of life [125] [126] [127].

Automation also makes occupancy linked controls possible for heating, cooling, air-conditioning and lighting systems. Energy savings and hence sustainability improvements can be achieved by targeting the provision of these services only to the spaces that are occupied. Systems have been successfully implemented in hotels, where there is often a large number of bedrooms with intermittent occupancy and space heating accounts for up to 50% of the total delivered energy [128]. Research is ongoing for providing solutions in offices also; for automatic environment control in infrequently used conference rooms, or window blinds and ventilation strategies that respond dynamically to internal and external conditions. The economics appear impressive when these systems are implemented fully [105].

Informational

The functionality of the home can be greatly enhanced by further linking it to the outside environment, to bring in additional information and services to improve the smooth operations of daily life. The benefits will again be simply convenience and entertainment for some, however the provision of remote healthcare monitoring and assistance for those who work from home are two informational solutions that could have profound impacts on the requirements for the domestic environment [124] [129].

6.3 Occupant tracking case studies

Smart Home projects that track occupants to advance the vision of a context-aware environment are a rich source of information for those who may use the same sensors for alternative ends, such as data collection for space use POE.

Georgia Aware Home

RFID tags have been applied to commonly mislaid objects in the house. The ‘Smart Floor’ was invented here. They are developing video recognition interfaces for local digital control using a mobile camera on a pendant [130].

MIT House_n

MITes and a multitude of other sensors and interface devices are being used to assess human behaviour in the home and how computers can assist and motivate the occupants to maintain a healthy lifestyle [131].

Duke Smart House

This yet to be built smart house will use active RFID to locate the 10 occupants to a room-sized granularity, although no specific indication is given as to what the data will used for except for a possible intercom system [132].

The Adaptive Home, Colorado

This house uses a neural network program to learn the statistical regularities in domestic activity and context. This improves its ability to infer the activity underway and predict what will be wanted next. The stated aim is to make the dwelling more comfortable whilst conserving energy [133]. Non-identifying motion detectors are used, with internal and external light and temperature readings, sound levels, and the open/closed status of doors and windows.

Gloucester Smart House

This is a collaborative project to design a house that gives people with dementia greater independence. Technologies include a RF ‘Locator’ for misplaced items and an infrared motion sensor that gives verbal messages when it is inferred that the person is about to wander out of the house [134].

Orange-at-Home

Orange sponsored a project where 3 families lived for up to 2 weeks in a functioning smart house for ethnomethodological research on domestic technology. The researchers used motion activated video recording, in-situ ‘shadowing’ and interviews before and after each family’s stay [135].

Much good research has come out of each of these case studies on the abilities of each sensor technology. Two points made repeatedly are the importance of not developing technological curiosities just because they’re possible, as solutions should be designed for real problems that people are having, and to take due regard of the concerns that some have with the Smart Home concept of being tracked in their own house. To address both of these, the importance is stressed of taking an holistic approach to domestic research and of using these new tools to discover more about the behaviours of people in buildings before attempting to support them. The common concerns of being tracked are looked at now, along with how they can be addressed.

6.4 Tracking concerns

In Edwards and Grinter's influential paper [136] they listed seven points for the UbiComp designer to keep in mind when designing any system. These represent many of the worries held by potential users and how the designer should consider them to formulate the solutions. They incorporate fears of complexity, unreliability, unpredictability, lack of administration, future expense due to incompatibility and ultimately disruption to the users' everyday lives. Designers rightly argue that most of these worries are manageable using industry standards and considerate design, just as in any other field where control is entrusted to technology. However, some fundamental issues remain that deserve a more detailed discussion as they could be the issues that shape the future direction and market potential for Smart Homes and UbiComp.

A commonly repeated fear is that by allowing an electronic system to track your movements, you are potentially generating data that other parties could use for unsolicited purposes. Taking advantage of the benefits of location-aware computing unfortunately must entail some loss of privacy, but the risk can be minimised by collecting as little data as necessary for the purpose and by protecting the database from outside enquirers [137]. Tags that triangulate their location themselves are more secure, such as the Locust Swarm and MIT Cricket (see Section 6.1), however they suffer on physical size and computing power. The use of a tagged system retains more privacy than an untagged one, since the user can simply not carry the tag when the benefits are not required. A new threat may arise in the future if tags become interoperable across enterprises, since this would involve some sharing of data, but database security is hardly a new concern for the computer sciences [138]. The loss of privacy must also be seen as context specific, as tracking a patient with dementia could lead to them having increased freedoms and independence. Similarly, the ability to obtain cash instantly using ATM machines, commute safely under the watchful gaze of CCTV cameras, and to communicate anywhere using mobile telephones and are considered to provide expansions of freedom, even though the user is providing the phone companies and banks with data that could be used to track them down to a number of metres. Businesses that exploit precisely this potential have also been successful [139] because the benefit/cost ratio falls very strongly on the side of the benefits for the users, which is how location-aware computing must also be promoted to alleviate the needless fears held by many.

The UbiComp concept also makes some afraid that there will come a point when we will lose control over the technology that we take for granted in our society. UbiComp designers already accept however that no matter how many sensors and algorithms they include, they may never fully understand the context in which decisions are being made and so the systems should not be over-automated [140]. The benefits have been noted of developing a system to explicitly provide advice at appropriate moments on how the user could change their behaviour for the better, rather than to take the decisions away by implicitly making inferences that could be inaccurate or disruptive [141]. In this way, user control would be fully retained, even if the implementation is automated for convenience. In the words of the first to use the UbiComp term, *"Whereas the intimate computer does your bidding, the ubiquitous computer leaves you feeling as though you did it yourself."* [142]

In terms of the practicality of introducing location-aware technology into people's homes, what is not so evident in many of the applications suggested to date is the need to design solutions that fit in with the historical legacy of our domestic environment, instead of designing from a year-zero mentality. The ability to retro-fit solutions to the home should be a requirement for the designers to meet for two reasons. First because the new-build marketplace is so small in comparison to the existing housing stock, and second because one of the applications that could represent the first gains into commercial success is the provision of telecare in the home for the elderly or disabled, who are two of the least likely social groups to be buying new-build homes.

Finally, domestic routines have been described as "*stable and compelling*" and "*the glue of everyday life*", yet previous studies have reported that there is no normal week and that routines vary between households, change over time and can be altered quite dramatically by new technology [143]. Following UbiComp's implementation, there could be "*social consequences that cannot be predicted from studies*" [136], so some solutions could be destined to fail even if their design followed many years of ethnographic study. These serve as a warning to the rapid market introduction of solutions that do exist but where the use of current technologies does not provide the answer. Hence the importance of prototypes and pilot studies to technological design.

6.5 Chapter conclusions

In this chapter the commonly requested aspect of post-occupancy evaluation (POE) studies of assessing how effectively the space within a building is utilised has been linked to another research field that could impact on the domestic environment's sustainability - location-aware computing systems that form a subset of Ubiquitous Computing. UbiComp provides the commercial application that may make personnel tracking sensors commonplace within buildings. In doing so, they would enable the collection en-mass of the data required to make detailed assessment on the effectiveness of various internal floor plans, which would be a marked improvement from the current situation of unfulfilling consumer surveys and demanding, one-off ethnographic studies.

UbiComp could also provide more direct sustainability benefits through the automation of heating, lighting and ventilation that could be tailored precisely to the routines of home life acted out everyday by the occupants. The financial savings of such a system may potentially be significant and represent just one of many solutions under development where tracking technologies bring real benefits and convenience to the user. Research is still underway on the best means of implementing these solutions; however, there is no disagreement that for some user groups the need for assistance with routine life is very real and that the number of disabled or elderly people requiring home assistance will only increase in years to come. Telecare for these homes could provide the first avenue to market for UbiComp, to establish the technologies and gain further experience before launching products of more a convenient nature.

The technology being developed for personnel tracking comes under the categories of tagged and untagged. While untagged systems are potentially more user-friendly, they are at present excessively expensive, unreliable or unable to identify one person from another. Tagged systems require the user to carry a tag artefact with them wherever they go, but of the two methods this is by far the further developed, more dependable and commercially competitive. The relative benefits of infrared, radio frequency and ultrasonic sensors have been reviewed, along with case study examples of their implementation.

This chapter also included a discussion on the importance for designers to be aware of and address face-on the concerns often held about location tracking and context-aware computing. The technology brings no new threats to the issues of human-computer control or digital security and the relatively minor loss of privacy is something that will be overlooked if the benefits are made clear enough, just as they have been for mobile phones and ATM cards.

This chapter also concludes the literature review of the thesis. A full background discussion has been provided on why increasing significance is being placed on space use efficiency in housing, the importance of using a standard and comparable technique such as POE to collect the data required, and how personnel tracking technologies from the field of UbiComp can be used to gather accurate data on where people spend their time within buildings. The next chapter introduces a project where the implications of this review were put into practice in a real situation, by conducting a unique space usage study on a real family using a tracking system in a new-build home.

7 The Experimental Application

David Wilson Homes Ltd (DWH) is one of the ten most prolific speculative house builders in the UK. In 2005 they coordinated an exercise in one of their properties that was given the name 'Project:LIFE' and that focused on:

- How some progressive house design concepts would work in practice.
- How the space within modern-day homes is used by everyday families.
- How designers might meet future regulations on energy and sustainability.

The project grew out of a DWH advisory committee meeting in 2003 where it was recognised that more needed to be learnt about how the changing lifestyles of the families buying and living in DWH homes could affect the success of their marketed designs. DWH had no in-house understanding of post-occupancy investigation, so they required a research partner to conduct these aspects of the project. The School of the Built Environment was selected on the strength of our established research programs and previous collaboration with DWH, most notably with the Millennium Eco-House [144].

The Project:LIFE experimental study enabled a typical family's behaviour to be evaluated in a real domestic environment, to assess how their lifestyle was catered to by the house design and how it could be improved to enhance their living experience. It was in effect to be a post-occupancy evaluation (POE) of a concept design that focused on the allocation of space within the house.

7.1 The house and the family

The 5-bedroom home was designed as a testing ground for new concepts in layout, materials and equipment from suppliers. It is a 4-storey structure with approximately 340m^2 floor area that incorporates a top floor built into the roof space and an inverted dormer balcony. A large external decking area with a hot tub is featured on the first floor directly above the ground floor kitchen that is directly above a sunken basement with a floor area of approximately one third of the ground floor. As shown in Figure 7, the staircase between all floors is located in the middle of the floor plan, central to all living spaces.

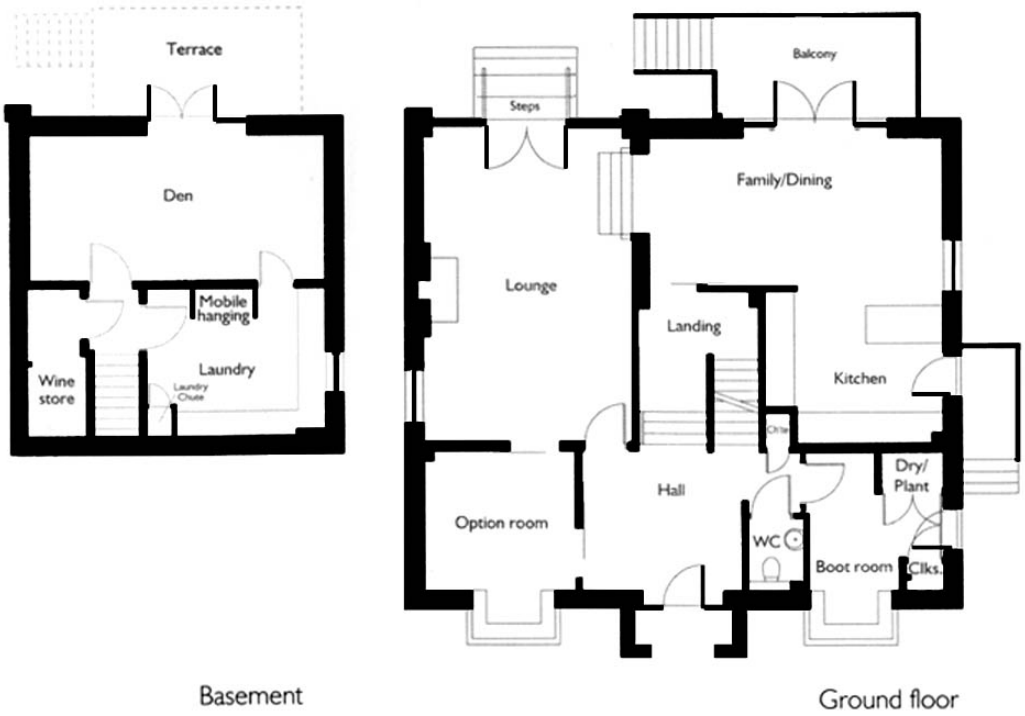
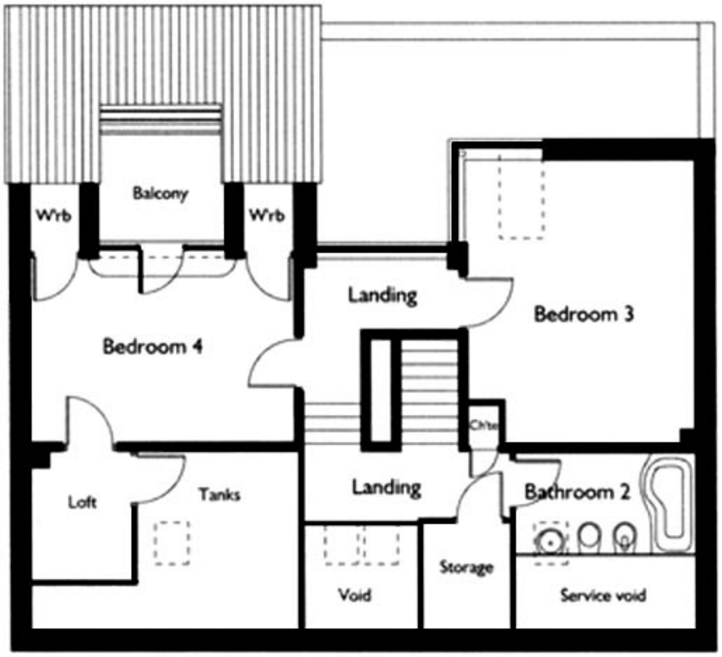


Figure 6: Schematic of the basement and ground floors

First floor



Second floor

Figure 7: Schematic of the first and second floors [145]

Figure 8: The vernacularly styled front and heavily glazed rear elevations

The split level floor design is created by the sunken basement that is made from pre-cast concrete slabs that rise part way above the ground floor level, lifting the kitchen above the rest of the ground floor and facilitating an unusually high ceiling in the neighbouring lounge. Much of the ground floor is open-plan and the whole house was designed to appear spacious and well lit.

The home's orientation is in line with the neighbouring houses on the brownfield site's layout, which take advantage of the outstanding Peak District hillside view offered by the location. As a result, the home's heavily glazed rear elevation, which is 69% glazed in area and incorporates 63% of the total glazed area, looks 30° NW.

The house is built using traditional stone and block masonry that is consistent with the vernacular architecture. Aircrete blockwork, rated A in the BRE Green Guide [146], improves the wall thermal efficiency. The wall, roof and floor U-values meet those suggested in the 2006 edition of the UK Building Regulations Part L1A for new homes [147]. Pilkington low-e double-glazing with an Activ™ self-cleaning outer-pane is used extensively on the house.

Within the design's development, many sustainable technologies came under consideration for inclusion: superinsulation, microCHP units, ground source heat pumps, combined solar ventilation and water heating systems, solar thermal ridge tiles, whole house mechanical heat recovery ventilation, sunpipes and rainwater collection. Budget and market-led decisions meant however that most of these did not make it into the constructed house.

The more energy efficient measures included in the final design were:

- Insulation U-values better than Part L of the 2001 Building Regulations.
- Underfloor heating and a SEDBUK A-rated condensing boiler.
- External air source heat pump to feed into underfloor heating system.
- Daylight enhancement in living spaces using large areas of self-cleaning, low-e double-glazing. [148]
- Heat-exchanging ventilation units in the kitchen and upstairs bathrooms.

Table 1: Details of the home's external envelope

Element	Construction detail	U-Value ($W/m^2 K$)
Walls	100mm Forticrete stone, Kingspan TW50, 50mm air gap, 150mm Aircrete blockwork	0.30
Roof	180mm Kingspan TP10 to horizontal roofspace	0.15
Floor	75mm sand/cement screed on 75mm polystyrene	0.30
Windows	Pilkington K Glass™ with Activ™ coating	1.70

DWH began a national media campaign in June 2004 to find the right family to thoroughly test-drive the house. Over 70 families applied from across the UK and following a short-listing procedure a series of home visits were made to the remaining families. This vetting process was aimed towards finding a family that met a number of requirements:

- Could articulate well their opinions on house design, with the same being true for any children that they had.

- Fell into a consumer group who could realistically live in such a house.
- Were open to the idea of having their lifestyle looked into by researchers.
- Would not be taking an alternative agenda to the national media coverage.

The selected family came from an existing DWH development and were visited and interviewed in their home before they moved into the study house. This was to ascertain how the family's daily routines and interactions had already been shaped by the design of their existing home. The ability to compare the family's behaviour in both houses was of interest as it would clarify whether a home's design shapes family life or whether a family makes their individual lifestyles fit as best they can into whatever home they live in.

The Parnell family was selected, consisting of a mother, father and two daughters aged 13 and 16 years old. They would live in the house for 6 months (June – December 2005), during which time they were specifically asked to live as normally as they could. The 6 month time span would allow the family to truly settle into the property and assess how they felt about its various design novelties over a range of seasons and conditions. They were made fully aware of the POE aspect of the project and were very willing to assist wherever possible. Even so, the data collection was required to be non-disruptive and discreet, allowing them to move around the house as naturally as any other, yet still accurate and detailed enough to enable a quantitative assessment on the way floor area had been allocated between the different spaces in the design.

7.2 Energy POE equipment & commissioning

The research undertaken as part of this unique study fell into three categories:

1. Energy focused assessments on the home's form.
2. Electrical energy usage of common household appliances.
3. Space use evaluation of the home's internal layout.

7.2.1 Energy focused assessments on the home's form

The considerations and criteria for a building's social and economic sustainability are broad, complex to measure and can change considerably over the lifespan of the home. However, in terms of environmental sustainability and in particular a building's in-use energy demand, the long-term consequences of some fundamental choices made very early in the project can be assessed objectively. There will still be some assumptions involved even for the most astute of environmentally aware designers, as advances in technology and changes in the local climate will inevitably impact on the relative merits of the chosen design; however this does not question the fundamental and long-lasting influence of decisions made on the home's orientation, construction materials or façade design. As well as influencing the up-front capital and on-going running costs of the home's mechanical and electrical plant, these decisions can often be used to speed the approval of a design through the Building Regulations. In fact, the incoming European Performance of Buildings Directive is to make the use of techniques to predict energy usage mandatory for most buildings (see Section 2.4).

Just a few of the available means were used in this part of the study to assess three of the most important aspects of a highly glazed home's on-going energy demand: the space heating requirement, risk of summertime overheating and its daylight performance. It is important that assessments like this are carried out early in the design process, as fairly fundamental alterations that can be crucial to the home's on-going energy performance are best made when they will have little financial consequence on the overall project. These three assessments were made first from a predictive viewpoint before the house had been constructed. Their accuracy was then evaluated wherever possible, using measured data of environmental conditions within the home, enabling a POE specific to each of the aforementioned aspects of house design.

Environmental monitoring

The project was originally scheduled to be carried out over March - September 2005 and since this did not cover the heating season it would have been a fruitless exercise to attempt an assessment of the underfloor heating system or the contributions made by the heat-exchanging ventilation units. Nevertheless, this was a significant opportunity to study the effects of design on a dwelling's energy use and it was still beneficial to monitor the internal temperature distribution throughout the house. By linking the data to the external weather conditions and the home's glazing design, it was hoped that a cost effective assessment could be made on two common means of predicting the effect of solar gains and the risk of summertime overheating.

Due to unforeseen delays to the build, in particular because of the harsh weather at the exposed site, the study actually took place from June to December. This became apparent when it was too late to alter the research program to include a means of assessing the heating system. Construction was almost complete and the specified monitoring systems were in the commissioning process. The internal temperatures were monitored using 10 thermistor-based sensors and the external conditions and seven of the potential 'wet' areas inside the home were monitored using combined temperature and humidity sensors. The measurement of relative humidity (RH) was to assess the effectiveness of the air ventilation units at maintaining a healthy internal environment. The sensors were distributed throughout the house on all floors to give a complete and continuous profile of the internal environment.

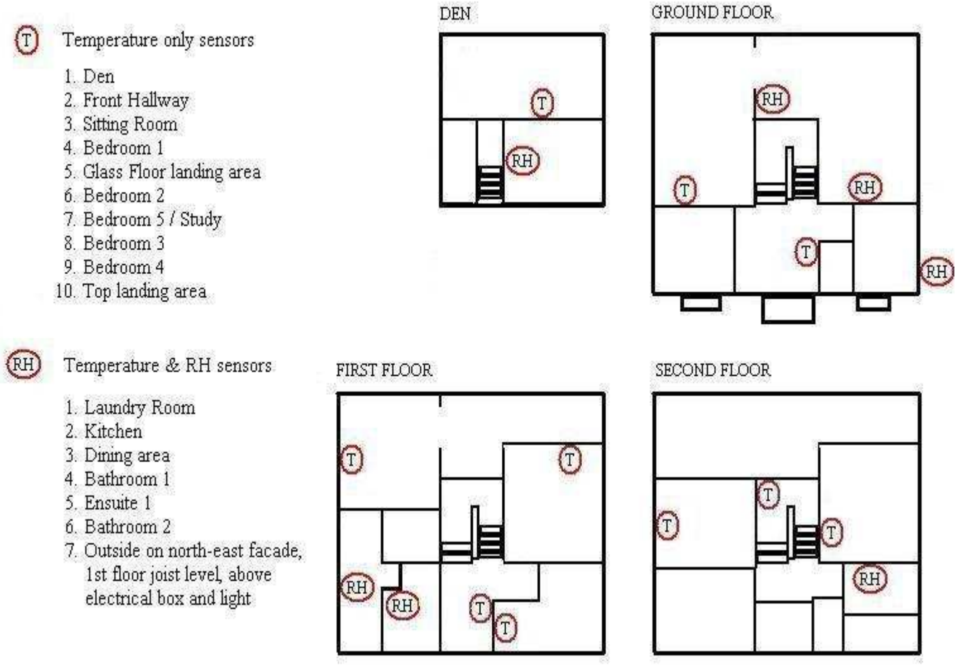


Figure 9: Locations of the temperature and humidity sensors

All of the sensors made use of monolithic integrated circuits with capacitance measurement of humidity and PT100 thermistors for measurement of temperature. They operated on a 24V DC input signal and provided their output as a 0-10V signal that required conversion into the appropriate reading range. Each was individually connected to a server PC through 3 USB LabJack data takers [149], which are also illustrated below.

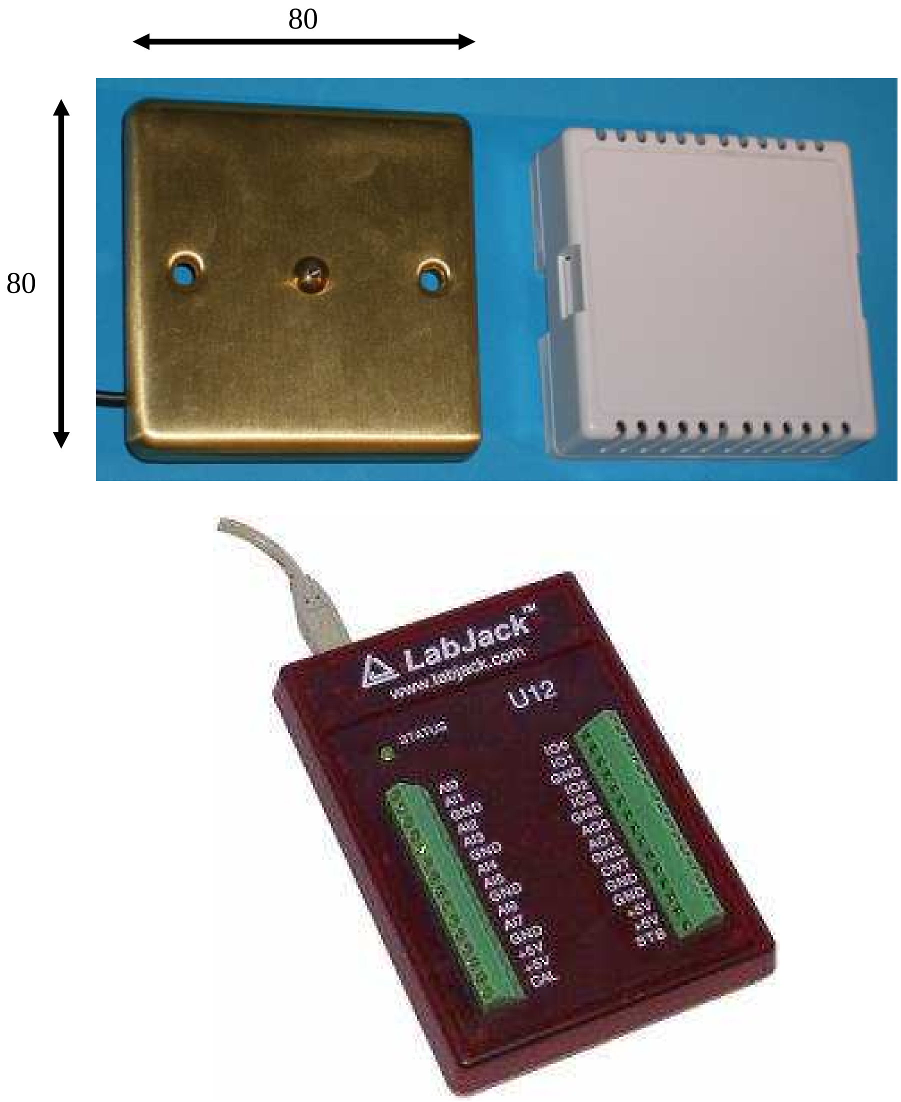


Figure 10: Top-left: Temperature only sensor.

Top-right: Combined temperature & humidity sensor. Below: LabJack data-taker

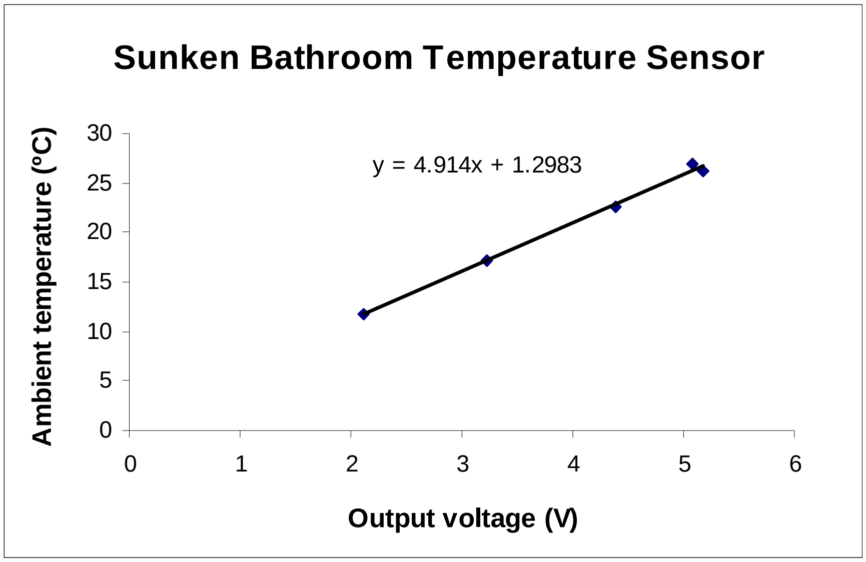
Before they were installed in the house, all 17 sensors were tested under controlled conditions in an environmental chamber, to confirm there was a linear relationship between the ambient temperature and humidity and the output signal. This was confirmed, but each sensor had its own pair of linear equation constants and the length of the signal cable was also found to have an effect on the calibration equation because of its resistance. Within the house, the cabling required to connect each sensor up to the server PC in the study room was as long as 30 metres, so the calibration constants were recalculated once the sensors had been brought online.

This calibration exercise was undertaken by plotting the output voltage recorded on the server PC by the DAQFactory software [150] against the actual internal temperatures and humidity measured using a handheld environmental meter like that shown in Figure 11. By completing this exercise during the winter and springtime house build, while the heating system was turned off and turned on, it was possible to consider a full range of ambient temperature and humidity conditions to find the appropriate linear equation constants. Despite the repetition within this calibration exercise there could still have been up to 2.8ºC or 7% RH error in each measurement as a result mainly of the possible inaccuracy of the handheld meter, as shown in Table 2. An example of the calibration graphs and equations produced for each sensor is shown in Figure 12.

Figure 11: Image of a Peak Tech 5035 Environmental Meter

Table 2: Environmental sensor details [151] [152]

Sensor Type	Model	Range	Accuracy
Temperature	TPBS	-10 to +70 ºC	± 0.2 ºC at 70 ºC
Temperature & humidity	TPRVHT	0 to 50 ºC 0 to 100 % RH	± 0.2 ºC ± 2 %
External temperature & humidity	TPVOHT	-20 to +50 ºC 0 to 100 % RH	± 0.2 ºC ± 2 %
Handheld environmental meter	Peak Tech 5035	-20 to +700ºC 25 to 95 % 20 to 20,000 Lux	± 3 % + 2 ºC ± 5 % ± 5 %



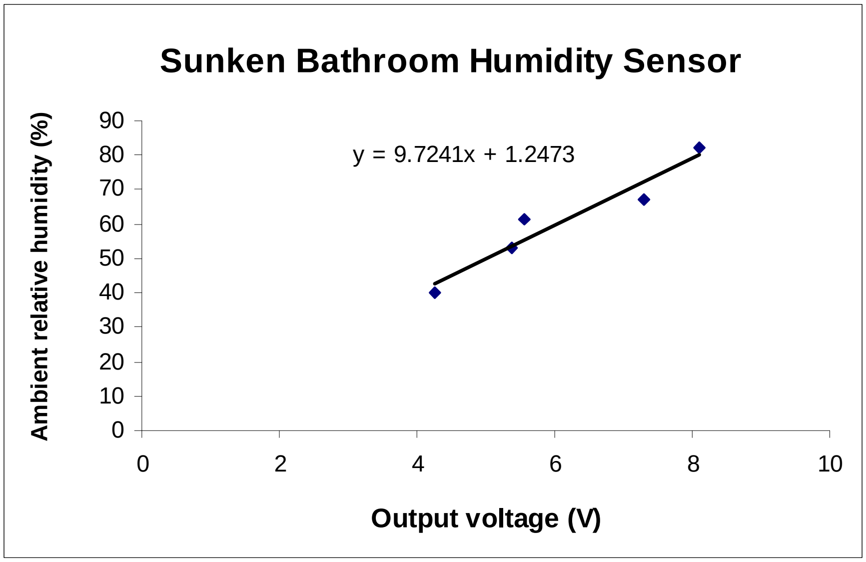


Figure 12: Calibration of the Sunken Bathroom's environmental sensor

7.2.2 Electrical appliances energy use

Whichever months the project took place over, it would have been feasible and beneficial to conduct an electrical appliance energy use assessment. The purpose of this aspect of the study was to investigate which kitchen and laundry room appliances required the most electricity and how that correlates with the incentives of the EcoHomes scheme to provide more energy-efficient models to new-home buyers. This is also considered to be an aspect of how modern lifestyles affect our use of energy to which the mass audience can relate easily. The intention was to capture information on which appliances should be upgraded or even forgone in order to make our homes more sustainable.

The options available for monitoring electrical use are a whole house continuous monitoring kit connected to a server PC running dedicated software [153], individual AC current transducer (CT) clamps connected to a data logger, or individual socket meters such as available from CREATE [154] and Brennenstuhl [155]. Budget and time considerations led to the choice of the simplest and most economical of these proposals; the metering of a selection of electrical appliances using individual socket meters, shown in Figure 13.

The meters were fitted to all the appliances in the kitchen and laundry room, the air purifiers located in the entrance hallway and top landing, and the monitoring equipment installed to collect the tracking and environmental data for this thesis. In addition, a single phase meter [156] was fitted to the induction hob that had the capability of drawing up to 7kW of power, which is well beyond the maximum 3kW rating of the socket meters and so required an alternative solution. The only electrical heating within the house was for the external hot tub, which was not metered since it is far from being a standard feature in a new-build house.

Figure 13: The socket meters and single phase meter used for the research

7.3 Occupant tracking system selection

With the fairly open brief given by DWH on investigating how the occupant family made use of the space within the house, a number of solutions with varying budgets and capabilities were proposed. They represented the full range of solutions discussed in previous chapters, with those not proposed having been disregarded because of their cost, non-availability commercially, the alterations they would require to the home's fabric or visual appearance, the disruption they may have caused to domestic life or their excessive demands on researchers' time. Those proposed were:

- Tabulated time keeping forms that the family would mark each time they moved from room-to-room. The cost of this solution would have been negligible; however, it would have been prone to significant error and unreliability as it relies completely on the family's accurate recall and compliance with a fairly intrusive process in their daily routine.
- Infra-red beam counters that keep count of the number of people who pass by them could have been positioned across each doorway. The cost of parts required for a complete system was estimated at £2,800. These too would have been prone to error as they as they miscount when two people pass side by side or when a person breaks the beam more than once by swinging their arms. In addition, they do not identify the person who walks into the room, which was a layer of detail favoured for this study.
- A wireless tracking system based on active Radio Frequency Identification (RFID) technology that would record the family's movements as they moved between proximity readers built into the fabric of the house. The system parts required were estimated at £10,000 and RFID was initially rejected because it was unfamiliar technology that had never been used before in a domestic environment and because of the possible angle that the media might have taken on its similarity with the curfew tagging of probationary prisoners, though the technology is different and the tags are smaller and much less remarkable.

- A video based recognition system that would record the passage of people through each doorway. For 16 doorways this system would have cost over £6,000. Aside from the obvious invasion of privacy that CCTV cameras would represent, meaning that the family may not have behaved normally when in the house, this solution has practical difficulties that include the lengthy analysis of real-time video footage required to manually timestamp and identify the person who passes underneath the camera.

With full consideration given to each solution it was agreed that although RFID tracking had never been used before in the confined environment of a dwelling and was the most expensive option, it was also the only means that held the potential for collecting the required data inconspicuously and with suitable resolution and reliability to make a detailed enough assessment.

The tracking system selected was an active RFID tag system operating at 434Mhz VHF from Wavetrend Technologies Ltd. [157] The family were required to wear an L-TG1200 wristband tag that broadcast its unique ID at 0.4 second intervals. These were detected by a network of L-RX201 readers fixed about the home within the stud partition walls and ceiling voids. The readers were daisy-chained using CAT-5 cabling, fed by a single power supply source and operated on a proximity basis. This meant that as a tag moved into the proximity range of a reader positioned strategically for the room, the reader would detect the unique ID of the tag and in turn update the tag's location with the dedicated SmartTag software that continuously ran on a server PC [158].

Figure 14: An L-RX201 reader and an L-TG1200 wristband tag

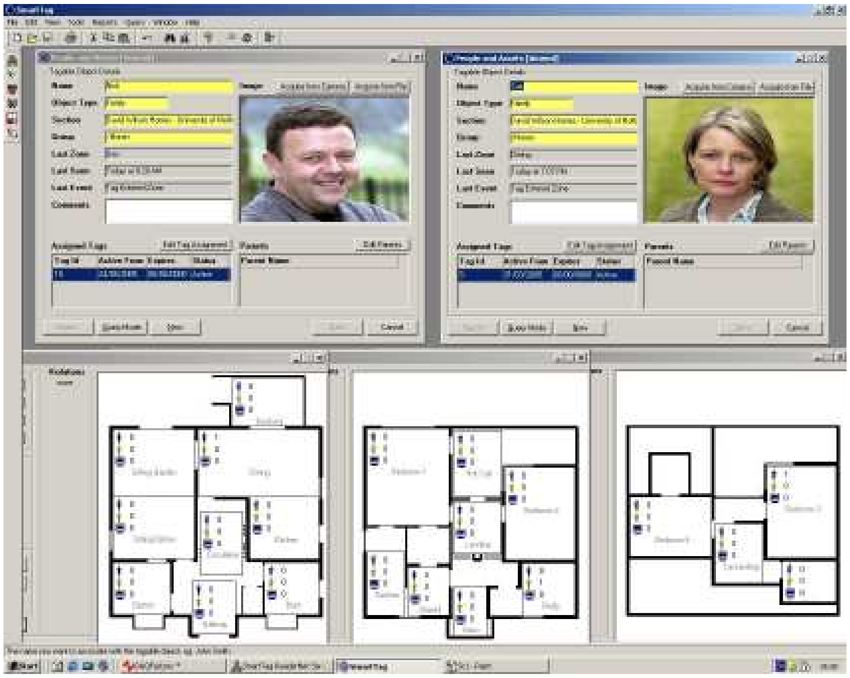


Figure 15: Screenshot of the SmartTag locating software

As well as being the first time the equipment had been used in a house, the Wavetrend system had never before been used to collect data for the specific purpose of space use POE. Its usual function was to passively observe for specific events that could trigger an alarm and to ignore all other data recorded, meaning that the SmartTag software provided limited functionality in terms of POE analysis. The analysis was therefore carried out manually during and after the tracking periods using a standard spreadsheet package. If the family had been tracked for their whole 6 month stay in the house, the amount of data collected could not realistically have been analysed without first developing dedicated software for this task. So to make the POE manageable, whilst ensuring it was still representative of their stay, the family were tracked for a total of 6 weeks: 2 weeks just after they had moved into the house, 2 weeks halfway through the project and 2 weeks just before the end of their stay.

The end of each of these tracking periods also provided the ideal opportunity to enter the house and conduct a de-briefing interview with the family. In this way, qualitative data was gathered on the experience of living in the house to substantiate the quantitative data collected using the tracking system. It was not known beforehand if the tracking would corroborate or refute the family's beliefs on how they spent their time, but the system would collect the data far more accurately than they could have possibly recalled after the events and it would do so in a very discreet fashion, which were the two most important criteria for the system. The wristband tags were light and comfortable to wear and the network of readers and antennae was hidden within the fabric of the building. This arrangement allowed the occupants to behave normally through the day, without drawing their attention to the study taking place around them in the house.

7.4 Occupant tracking system commissioning

The locations of the 23 RFID readers both in and outside the house are shown in Figure 16. They are labelled according to whether the reader was hidden in the stud partition walls (W), in the ceiling void (C), or under the floor decking (F). Many of them also had antennae fitted to alter their proximity range.

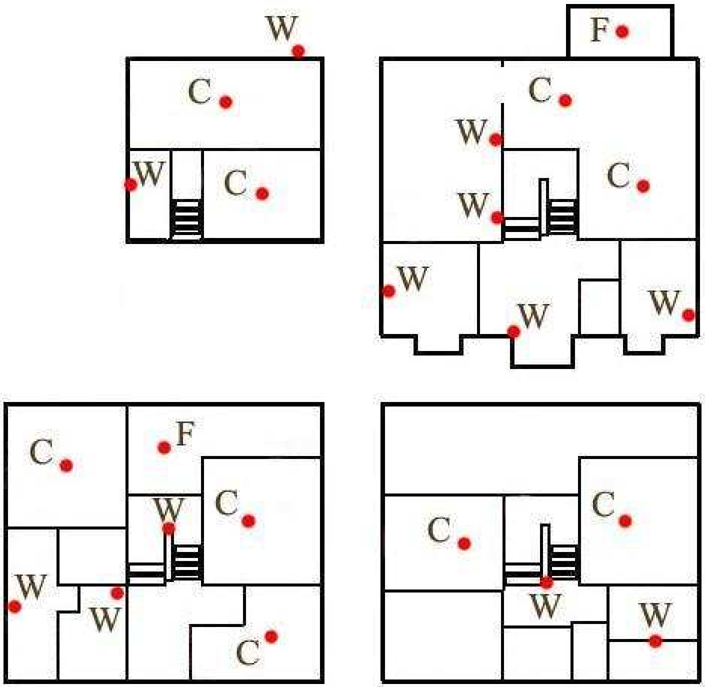


Figure 16: Locations of the 23 RFID readers

Before the system would be able to determine the location of each tag, each reader’s proximity zone had to be refined so that it would detect a tag as it passed into the space the reader related to and then ‘lose’ the tag when it was taken back out of the space. This is possible because the strength of the signal received from a tag weakens as its distance from the reader increases, so by setting a minimum limit to the signal strength that would be interpreted as a tag being within a particular space, the SmartTag software would be able to identify which tags were inside and outside each space. Refining the system settings in this way was a two person process. While one person wore a tag and repeatedly moved between the different rooms of the house, the other calibrated each reader's signal strength limit on the server PC. The two workers remained in constant communication using walkie-talkies. Although it is estimated that a domestic proximity-based system like this could in future be calibrated in one to two working days, for this experimental application it took over one week for a variety of reasons that each produced learning.

This was the first time that a proximity-based RFID system had been installed to continuously collect accurate and quantifiable data on how the spaces within a house were used by the occupants. Though the chosen system had been installed previously in offices, factories and warehouses, considerable difficulties were encountered during the commissioning process in the house. The suppliers concluded that this setup had stretched the system's capability to its limit and that some finer details of operation influenced the procedure in ways that had not been encountered before. Some of these were particular to the system in place, so are now discussed.

1. The decision to hide the readers within the building fabric had the knock-on effect of complicating the commissioning procedure. Tracking systems using the same components have been set up many times before in offices, factories and warehouses, where the space between each reader is far greater and the importance of refining the boundary of each zone is far less. In the domestic environment, precision in boundary definitions is highly

significant since each zone is so closely related to all others. The majority of spaces of interest directly join onto another without a dividing corridor and most also had a neighbour directly above, below or both above and below. The potential for ‘bleed-through’ was therefore greatly increased, which is where a tag’s signal is detected by a reader that is not assigned to the space the tag is actually in, resulting in a false location identification on the server PC. The capacity to refine the proximity ranges was weakened however by the inaccessible nature of most readers that had been sealed within the stud partition walls of the house, which made the commissioning procedure more cumbersome and lengthy.

2. The 23 readers were connected in daisy chain fashion to the same COM channel of the server PC that interrogated each reader in sequence to enquire which tags could be identified within its proximity range. Since the timing of these interrogations would not match the timing of each tag’s broadcast, each reader contained sufficient memory to store the last five broadcasts it had received. These five memory slots were reported back to the server PC in the order of oldest first and just one slot per interrogation. The upshot of this sequential procedure was that a delay of up to 2 seconds could be created between a tag entering a space and the tracking software reporting its presence, even though the relevant reader would have detected the tag with the first signal broadcast within range. Within this two second delay, the wearer could have walked from the doorway right to the middle of a room and the initial ignorance of this operating process resulted in much time being wasted trying to refine the point of tag detection to an impossible degree. The delay in detection cannot be considered influential

however to the results contained within Chapter 9, as not only would a delay on entering a space often be matched by a delay on leaving, but the editing of the raw data into a format where it could be analysed effectively illustrated the insignificance of any occasional 2 second error when spaces were being occupied for many minutes or hours at a time.

3. The orientation of the tag and where it was worn on the body was found to have a significant effect on how strongly the emitted signal was detected, due to the position of the tag antennae within the plastic wristband housing. This had not previously been of concern to the suppliers as the tags had been developed to maintain a quarantine procedure in a hospital between wards that were far apart, so fine-control over signal strength had not been important. The RFID system had never before been used in a situation where the reader sensitivities were as crucial to fulfilling its purpose. Plus, this signal variation was initially obscured by further interference caused by the human body and nearby metallic objects, which could render a tag undetectable under certain circumstances, though brief in duration as the tag would be redetected once the wearer moved again.
4. It is thought that the ambient environmental conditions in terms of both temperature and humidity had an influence on the strength of signal received by each reader. Varying conditions were suspected of altering the performance of the system so that the complex and highly refined boundary limits could alter day-to-day, particularly in rooms where humidity could accumulate, such as the bathrooms.
5. The conclusion from the previous two points is that a proximity-based system may not be the most appropriate in the domestic environment where

> there can be many regions of interest in close location to each other in all three dimensions, which makes the potential for signal bleed-through and erroneous tag detection significant. Triangulation of multiple signals is recognized as being more accurate, with a much improved resolution and the near elimination of bleed-through mistakes as a matter of course. Over the course of this research a product that operates on a triangulation-basis using an ultra-wide bandwidth has in fact been launched in the tracking industry. Ubisense claims the ability to locate tags to 10cm using just four readers per room, or to 30cm using just one reader [159], although at present the UWB frequency is available for research purposes only.

In addition to these technical complications, the cost of the RFID system also presents a significant barrier to its future deployment. The full cost was £12,150, with £6,150 accountable to the components and £5,990 to the installation labour. The SmartTag software adds a further £1,000.

However, despite their quite considerable cost, the decision was made to conceal the majority of the readers and antennae used in this experiment within the fabric of the house, which effectively turned them into disposable items since the labour and materials cost of their retrieval was greater than their value. It is recommended that in future the components are installed in accessible locations in a retrievable manner, visible to the eye if necessary. This would aid and shorten the commissioning procedure and strengthen the financial case for conducting space POE using occupant tracking systems, as the components could be reused across studies to develop the benchmarking data that provides the full benefit of POE.

7.5 Chapter conclusions

In summary, the POE undertaken for this research fell into 3 categories:

Energy assessment of the home's constructed form:

- Computer modelling of the home's winter heating demand and assessment using the Government approved method.
- Prediction and continuous monitoring of the risk of overheating from solar gains during the summer months.
- Computer modelling and actual measurement of the daylight levels.

Metering of the electrical resource usage:

- Energy metering of a range of kitchen and laundry room appliances.

Monitoring of the household's use of space:

- First time application of an RFID tracking system to study the movements of a family for three 2-week periods during their 6 month stay: shortly after they move in, halfway through and just before leaving.
- Qualitative interviews with the household at the end of each tracking phase on their experiences of living in the house.

This was the first time that data had been collected using an RFID system on the continual use of space within a dwelling. The study was an experimental application of the technology in an environment that stretched its capabilities to its limits because of the confined and complex geometry of the spaces that it was required to report on. Many lessons were learnt during the commissioning process on the complications of using a proximity-based system in such a confined environment and the system supplier has since upgraded the system specification and installation procedure as a direct consequence of the experiences that were reported on in Section 7.4.

The proximity-based RFID system was nevertheless considered to perform adequately once commissioned and it was stated with confidence that the POE study would focus the attention of DWH designers on the rooms that were most used and the features that would add most value to the home. The data would of course also highlight the rooms used the least, which could inform an evaluation of their importance in homes where space is more limited. A paper that presents an overview of the study and the conclusions reached is in the process of review for publishing [160].

Each aspect of the research very clearly contributes towards a better understanding of how a house performed in actuality compared to how it was expected to perform pre-construction, which is the fundamental essence of a post-occupancy evaluation (POE). The limited time-span of the study unfortunately negated the feasibility of a full POE energy survey using CIBSE TM22 as mentioned in Section 4.2, though the particular elements tackled are done so in a more rigorous fashion, as seen in the next chapter.

8 Energy Focused Assessments of the House

This chapter describes the research undertaken on some of the available means of predicting three aspects of the on-going energy demand of this highly glazed home: space heating requirement, risk of overheating in the summertime and daylighting performance. The predictive methods used for this study were the building services computer package HEVACOMP (v19), the government approved Standard Assessment Procedure (SAP) and Ecotect (v5.2b), a complete building analysis computer package. To assess their validity, the predictions made are compared against each other and against data measured in the constructed house wherever that was possible. Each of the three aspects assessed are often included in post-occupancy evaluation (POE) of buildings, when assessing their energy use, comfort and task lighting conditions. It is significant that the prediction methods can now be validated, as the opportunity to perform this analysis is not normally available to the building designer, despite the increasing importance being placed on their findings.

This chapter concludes with the results of a metering exercise carried out on the electrical appliances found in the kitchen and laundry room of the house, which are compared against the implied importance that the EcoHomes scheme places on different appliances. This exercise captured information on one of the aspects of how modern lifestyles affect our use of energy that the mass audience can relate to most easily, to illustrate which appliances we should upgrade or could perhaps forgo in order to improve the sustainability of our homes.

8.1 Space heating demand

8.1.1 Steady-state heat loss

The first step was to calculate the heat loss through the home's building fabric during a winter's day, which is often used to estimate the capacity of heating system required. It is important to use an appropriately sized heating system that does not fall short of the peak demand placed on it during the coldest time of year, yet does not stray far from its most efficient conditions during periods of partial load. The efficiency improves towards peak output, so one that can output not much more than the peak demand should be specified, bearing in mind domestic hot water requirements as well as space heating.

The building service engineering software package HEVACOMP was used for this calculation. The building was zoned into sensible areas of equal conditions and the internal temperatures and natural infiltration rates shown in Table 3 were taken directly from CIBSE Guidelines for dwellings [161].

- In the model, the exposed roof areas took account of the 40° pitch angle.
- Due to the semi-underground nature of the basement, the external temperature for the submerged walls was set as the constant ground temperature of 11ºC.

Table 3: Temperature and air infiltration values for HEVACOMP model

Outside	Kitchen	Living spaces	Bedrooms	Bathrooms	Communal areas
-1ºC	18 ºC	22 ºC	18 ºC	26 ºC	20 ºC
	60 L/s	0.5 ac/h	0.5 ac/h	15 L/s	1.5 ac/h

- The steady-state heat loss for a -1 ºC day was calculated as 12.3 kW.
- 54% is accountable to air infiltration and not through the building fabric.
- The glazing was the largest source of fabric heat loss, at 23% of the total.

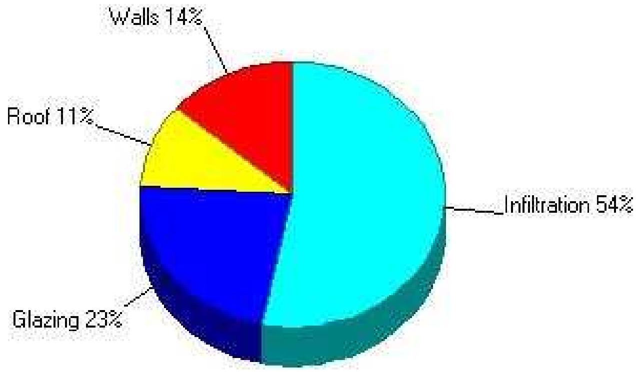


Figure 17: Breakdown of space heat loss from the home

Air infiltration has become more significant to the energy performance of modern homes as the fabric heat loss has steadily fallen with improvements to the Building Regulations. The steady-state result can also be used to evaluate the annual heating demand and its sensitivity to the U-value of each construction element, which could lead onto a cost - energy saving assessment.

8.1.2 Annual demand and relative sensitivities

The steady-state heat loss was entered into the HEVACOMP Energy program to predict the annual heating demand for the home. The program settings were for a dwelling of medium thermal weight that is continuously heated 7 days a week, 16 hours a day. The domestic hot water requirement and the internal heat gains should also be included to provide a more complete perspective on the energy use and potential savings. However, HEVACOMP has limited functionality to compute these for a domestic situation, so they were not considered at this stage. By analysing the sensitivity of the annual demand to alterations that could be made to the construction elements, it was also possible to discover which held the most scope for reducing the heating requirement. The elements looked at were the external walls, the window glazing and the air infiltration rate, which are responsible for 90% of the combined heat loss. Each element was varied between other realistic values and Appendix B contains the full table of results and design values; however, to summarise:

Overall annual demand

The 12.3 kW winter steady-state heat loss is expected to lead to an annual demand of 27.3 MWh, equating to 79.0 kWh per m^2 of floor. Although there is no agreed typical figure for the UK, 50.0 kWh per m^2 has been suggested by others for a mid-terrace that meets the 2000 Building Regulations [162], which the experimental house fails to meet as it is a detached house with large areas of glazing. The space heating component of this gas fuelled home's annual bill was predicted as £530, with CO_2 emissions of 5,177kg.

Infiltration rate

As air infiltration is responsible for 54% of this home's predicted heat loss, building a more air-tight house would seem to hold most scope for improvement. Improved air-tightness increases the need for controlled ventilation however, as discussed in Section 2.3.3, which could be mechanical with heat recovery (MVHR). Although an appropriately designed system should bring overall energy savings back to the owner, MVHR introduces new build costs and requires electrical energy to operate. It was therefore more viable to investigate the effect of increases in air infiltration from the already good practice figure of 0.5 air changes per hour (ach). If a well-sealed design became an averagely-sealed construction, 0.5 would be added to the infiltration rate, resulting in about 23% additional heating requirement. A leaky construction with 1.0 additional ach could result in a 46% increase, which translates annually into £250 extra on the bill and 2,370kg additional CO_2.

Window glazing

63% of all the home's glazing is on the rear elevation, which is 69% glazed in vertical area. The glazing results in disproportionately more heat loss because it has a higher U-value than the walls. The use of low-e coated glazing with a U-value of 1.7 W/m^2K rather than standard double-glazing of 3.0 W/m^2K will result in an 18.5% reduction in the annual heating requirement, reducing the annual fuel bill by almost £100 and its carbon emissions by almost a ton. The use of argon filled, low-e coated double-glazing of 1.3 W/m^2K would have resulted in a further reduction of 5.7%, giving a further £30 saving each year.

External walls

Building to a wall U-value of 0.30 W/m^2K rather than the 0.35 W/m^2K asked for in the 2001 Building Regulations resulted in less noticeable energy savings of 2.3%. Achieving the Best Practice value of 0.25 W/m^2K would have led to a further 2.3% reduction, saving £12 and 116 $kgCO_2$ annually.

8.1.3 Points of discussion on space heating results

At the level of thermal efficiency that the present Building Regulations require it appears more important to 'build tight and ventilate right', as goes the well-known motto within the low-energy building industry, than to upgrade the fabric elements any further. It is therefore significant that the BRE found approximately a third of new homes failing to meet the air-tightness requirement of the Regulations [67] and compliance testing on this is to become commonplace under the latest Part L1A for homes [147].

1. The embodied energy of insulation may also question the advantage of small improvements to fabric U-values that do not result in large energy and cost savings elsewhere. For example, by achieving the PassivHaus wall standard of 0.15 W/m^2K, combined with exceptional air-tightness and MVHR ventilation, there is a vastly reduced requirement for the expensive central heating system, which makes achieving the standard much more economically competitive [163].
2. The additional daylight that larger glazed areas provide can offset the need for artificial electric lighting and in this way save energy. Good natural daylight also brings improved well-being and is consistently found to be one of the most important considerations for homebuyers (see Section 3.1).
3. Extending this form of analysis could assist in an investigation of the means of overcoming the price premium barrier to more-sustainable homes by evaluating the additional build-cost of the improvements against the predicted energy savings to the occupants and the premium that could be added to the purchase price as a result.

8.2 The effect of solar gains on space heating demand

HEVACOMP (v19) is a useful tool to quickly assess the steady-state and annual heating demand early in the design process; however, to factor in solar gains requires data on the local solar strength and the ability to link the home's orientation and glazing distribution to the path of the sun.

A primary objective of this analysis was to present the data in a way that the benefits of passive solar heating became more relevant to builders. The Standard Assessment Procedure (SAP) is the Government's mandatory assessment tool, as discussed in Section 2.4, and takes account of the home's orientation, glazing distribution and the strength of solar gains from each orientation. A way of encouraging development layouts that takes advantage of passive solar heating is therefore to calculate the potential improvement in the SAP rating. The experimental house was rated in each orientation using the 2005 SAP worksheet, which also takes account of electricity for artificial lighting also and how it can be offset by more glazing [36]. Table 4 contains the primary results for three representative orientations for the heavily glazed rear façade: North, Actual and South. The actual orientation of the home's rear is 330º but SAP only considers each 45º, so the data is given for 315º.

Solar insolation is a combination of an orientation independent diffuse component and an orientation specific direct component. During the winter months in the northern hemisphere, solar gains from the north are diffuse only. Calculating the SAP using the northern flux for all orientations therefore gives an estimate for diffuse only light, enabling a full assessment of direct gains.

Table 4: Representative SAP 2005 Ratings

	Orientation of the glazed rear elevation			
	North, 0º	**Actual, 330º**	**South, 180º**	**Diffuse only**
Solar gains, W	1370	1458	2150	1015
Space heating, kWh/year	26793	26400	23438	28561
Total annual fuel bill, £	797	790	735	830
SAP Rating	**75**	**75**	**77**	**73**
Annual kg CO_2	**8,047**	**7,961**	**7,308**	**8,437**

Considering only diffuse gains, SAP predicts a 28,561 kWh annual space heating requirement. In the actual orientation, direct solar gains reduce this by 8% to 26,400 kWh; however, an 18% reduction to 23,438 kWh was predicted for a south-facing orientation. The benefits of this extra annual reduction are a £55 (7%) saving in the fuel bill, an additional 2 SAP points and a 653kg (8%) reduction in this gas-fuelled home's CO_2 emissions. The fuel bill predicted by SAP was £790, which includes £94 for hot water, £161 for lighting, £12 for pumping and £34 for standing charges on top of the £489 estimate for space heating. These figures for space heating demand and cost closely agree with those found previously using HEVACOMP of 27,250 kWh and £530 (see Appendix B), even though HEVACOMP made no consideration for solar gains or gave a detailed breakdown for internal gains and costs.

8.2.1 A computational approach to predicting solar gains

Computational analysis packages have been developed that offer various sets of tools to the building designer. These typically include 3-Dimensional CAD modelling, thermal analysis, HVAC design, solar shading and radiation calculations and the prediction of natural and artificial light levels. By sharing data and resources between the applications, analysis packages can offer a relatively quick and simple means for producing detailed and holistic assessments that can have influence at the early design stage. A tool included in the Ecotect (v5.2b) package predicts the solar irradiation that will fall on the external surface of a building for any hour, day or month of the year [164]. This can be calculated for a range of locations using a database of weather files, containing hourly climate data on the ambient thermal, solar and wind conditions. One of the weather files is for Sheffield, England - the city that the experimental house was built nearby.

Figure 18, Figure 19 and Figure 20 illustrate the 3-dimensional model that was created of the house, which includes detail on the surrounding buildings and landscape to improve the calculation accuracy and visualisation of results.

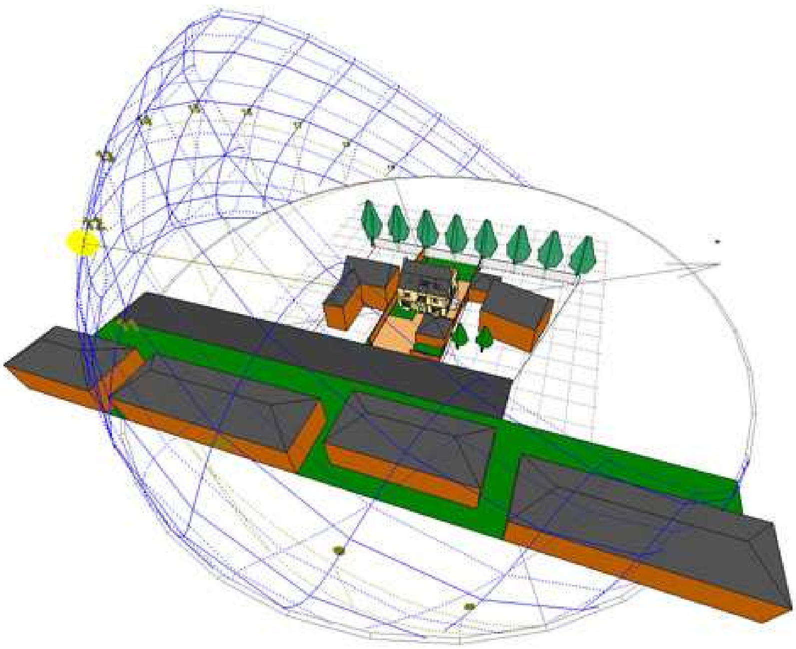


Figure 18: Perspective view of the site, front of house and the annual sun path

Figure 19: Closer view of the vernacularly styled front elevation

Figure 20: The heavily glazed rear façade (trees in foreground removed)

By summing the annual total predicted by Ecotect for each area of glass, the optimum orientation was found to be when the rear elevation is facing south-east, with the left-right axis of the house following NE-SW. Figure 21 shows that the glazed areas are predicted to receive 4,650 kWh (18%) more annual solar insolation in this orientation than in the actual orientation of 300°.

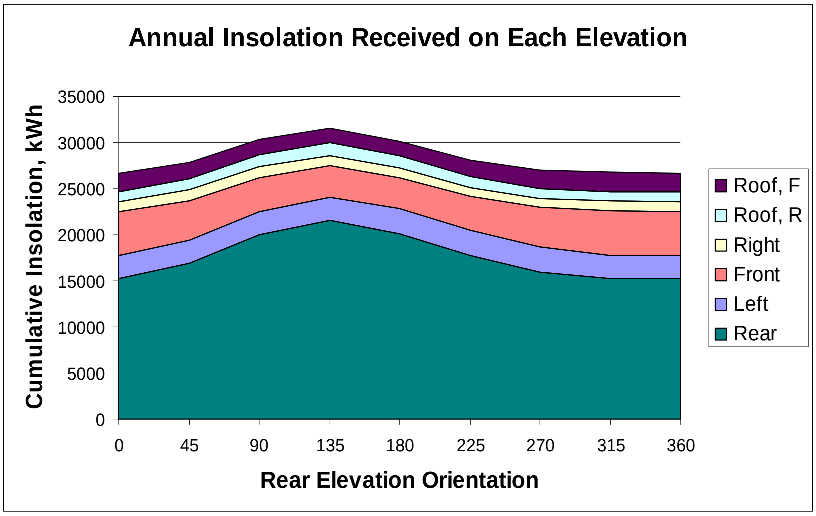


Figure 21: Total annual solar insolation for each orientation of the home

Ecotect can report the diffuse and direct solar components separately on a daily basis and Figure 22 shows the direct insolation received by the whole house during a representative October - May heating season. This season was chosen as it marks the start and end of the period when the average monthly temperature falls below 15.5ºC, which has been suggested as the temperature at which the contribution of internal gains is sufficient to heat a home [165].

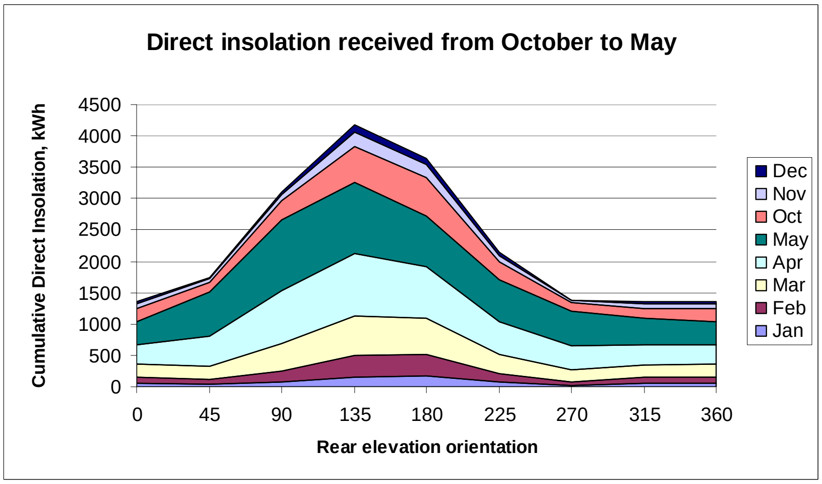


Figure 22: Cumulative direct insolation over an assumed heating season

Figure 22 illustrates more effectively the relative benefit of a south to south-east orientation. The optimum orientation of 135° (SE) was predicted to receive an additional 2,827 kWh of direct solar insolation during October - May to that received in the actual orientation.

The purpose of this exercise was to calculate the additional solar insolation that a house orientated for passive solar gains would receive on its glazed elements, which could be fed into a further calculation on the contribution this could make to the home's annual heating demand. To investigate the validity of progressing in that manner, the predicted solar insolation was compared to the previous SAP results, to test for agreement between the two techniques.

8.2.2 Comparison between SAP and Ecotect

The Ecotect model predicted the dwelling's glazing to receive an additional 2,827 kWh of solar insolation over an October - May heating season in a SE orientation. Previously, the SAP had suggested a 2,962 kWh reduction in the annual space heating demand could be achieved by a southern orientation that in the calculation received an extra 692 W of instantaneous solar gains.

At first it appears that there is close agreement between the additional solar insolation predicted by Ecotect to fall on the windows and the SAP calculation for the reduction in the heating demand. The discrepancy is just 4% of the SAP value; however, a realistic transmittance factor of 0.7 should be applied to the solar insolation as the glass provides an obstruction to its passage. This reduces the Ecotect prediction to 1,979 kWh, which is 33% less than the SAP result. From the information available it is not possible to conclude why such a large discrepancy exists between the two results; however, two initial points of discussion are worth considering.

Whereas the SAP uses the same set of solar flux values wherever the house is built in the UK and whatever the local climate conditions, Ecotect takes the insolation values from a weather data file that has continuous data for every day in the locality. It is unknown how accurately this data reflects a typical year for the locality, though its use is convenient as it enables a cumulative summation of the insolation strength as the sun path angle changes throughout each day. Further analysis of the data found that the direct component comprises between 26-53% (depending on the orientation) of the total gains calculated by the SAP, whereas it comprises just 10-23% of the total insolation predicted by Ecotect. Figure 23 shows how the direct components vary with orientation for each methodology.

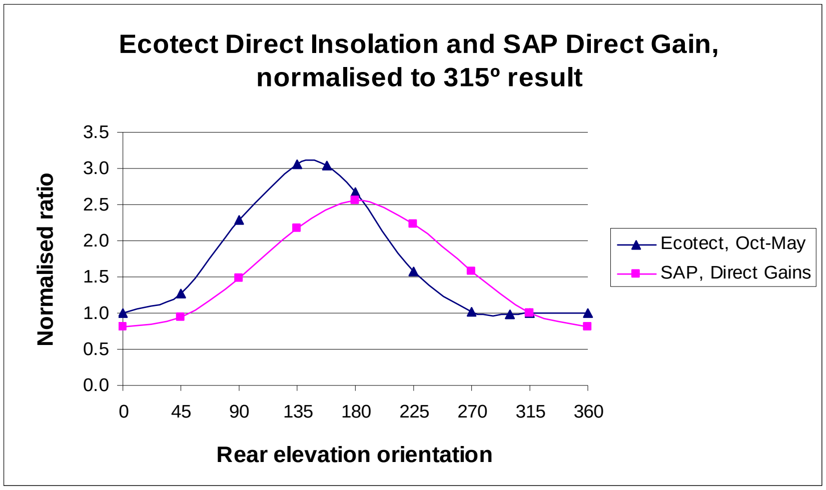


Figure 23: Direct components in each orientation normalised to 315°

The results in Figure 23, normalised to that of 315°, show that Ecotect predicts a 210% peak increase in direct insolation at 140° east, whereas the SAP predicts a 157% peak increase in direct gains on a due south facing orientation. So, although the Ecotect data set leads to a direct solar component that is less significant to the overall gains, the variation in direct gains is relatively greater and more orientation dependent using the Ecotect data set than in the SAP.

The Ecotect figure was a summation of the monthly solar insolation from October through to May as an assumed heating season. The SAP worksheet uses average solar flux values for each of the 8 cardinal and inter-cardinal orientations given for an unknown heating season length. A second possible error source is that the two heating seasons are not the same period. Yearlong, Ecotect predicts a SE orientated house will receive an additional 4,650 kWh solar insolation, or 3,255 kWh when the 0.7 transmittance value is factored in. Ecotect does predict it possible therefore to receive the insolation required to match the SAP calculation by using a longer season than October - May. Alternatively, it may be that the SAP solar flux values and hence the calculated contribution are too high because they were averaged from a heating season longer than it should be. Lengthening the heating season would increase the average flux value since the solar strength would be greatest at the start and end of the period. A combination of the two is of course also possible.

Unfortunately a POE analysis against the actual heating demand was not possible due to the time and resource constraints of the project. It was however possible to investigate the risk of the home overheating in the summertime, which is an aspect that the SAP can also be used to predict.

8.3 Summertime thermal analysis

Both the SAP and Ecotect package were used to assess the risk of the home overheating in the summertime. These predictions were then compared against the actual air temperatures monitored continuously in the home.

8.3.1 SAP

Appendix P of the 2005 SAP worksheet is to be used to predict the likelihood of a dwelling having problems from overheating due to solar gains [166]. The prediction uses a second set of solar flux values to assess the home's average internal temperature during the hottest summer days in the UK. Using this procedure it was predicted that the risk of overheating in this low to medium weight, multi-storey home depends on one aspect in particular: the effective air change rate achieved by opening the windows.

Figure 24 shows the temperature predicted in the home, assuming it is in the Midlands region of the country, but built in all orientations. The background fill depicts the four bands of overheating risk. The overheating risk is 'Medium' or 'High' (threshold temperatures of 22ºC and 23.5ºC respectively) only when the effective air change rate is below 2 ach. It can also be seen that the orientation of the house adds a maximum of 1.5ºC to the summertime internal temperature at low ventilation rates, which is the same effect as had the house been built in the warmer South of England or Thames valley.

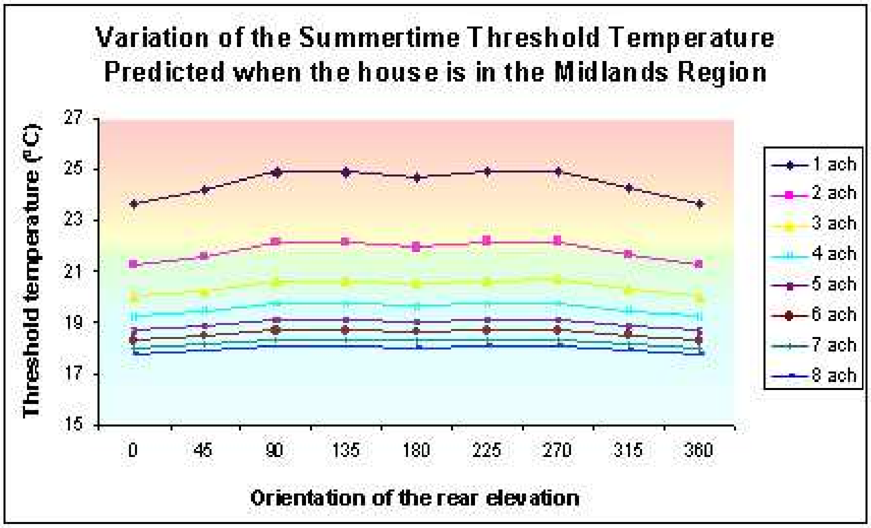


Figure 24: Threshold temperatures in Midlands region

Maintaining a ventilation rate of 2 ach is clearly expected to be the key factor in keeping such a heavily glazed home cool in the summertime. This means that the occupants should be able to open the windows past 50mm, according to Table P1 in the 2005 SAP. This should not be difficult in the safe, quiet and pollution-free environment in which this home is built, but it may provide issue if the design was transferred to an inner-city development.

8.3.2 Ecotect (v5.2b)

By looking at the monthly totals for the largest area of glazing of the house, the lounge patio doors, it is seen that although a southerly orientation would receive the most insolation, much of the additional comes during the summer, when the heating system would be turned off and it is likely that the windows would be open to ventilate the house. Figure 25 shows the monthly figures for four orientations for the doors: due north (0°), that of the maximum annual insolation (135°), due south (180°) and the actual orientation (300°). In the actual orientation, it is seen that the additional solar gains are predicted to be small, even in the peak months. If the house had been built with a more southerly orientation, the model predicted a peak monthly additional solar insolation of 250 kWh in May, or 45% of the total.

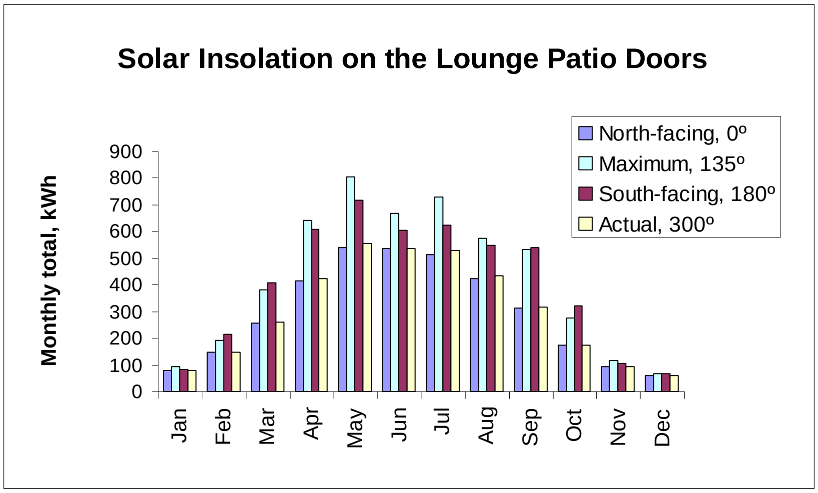


Figure 25: Monthly insolation totals on the lounge patio doors

This extra insolation may introduce a requirement to using shading techniques such as overhangs or brise soleil to prevent summertime overheating. These add to the build-cost of the house, would need to be particularly wide to shade a significant proportion of the large windows and require a means of being unfurled when the sun is strong and stored away when not required. Alternatively, the occupants may have felt the need to install an electrical energy intensive air-conditioning system for summertime cooling, especially in the years to come as climate change increases the summertime temperatures of the UK. It is therefore possible that the actual orientation of this house is sensible, since the rear elevation is 69% glazed and there is no means to cool the home other than opening windows and doors.

8.3.3 Temperature Monitoring

A network of temperature and relative humidity (RH) sensors had been installed as described in Section 7.2.1, to investigate two aspects in particular:

1. Whether a correlation existed between the glazed areas of each room and the average temperatures recorded in them during the summer.
2. Whether the SAP prediction could be corroborated that the risk of overheating was ‘not significant’ so long as the house was well ventilated.

External summertime conditions

In addition to the calibration described in Section 7.2.1, the temperature and RH readings of the external sensor were assessed against those of the Norton Lees weather station in the south of Sheffield city [167]. Figure 27 illustrates that the temperatures measured during the summer months of June, July and August typically differed to the weather station’s by 2ºC, although by as much as 5ºC. The experiment house was built at an exposed location at altitude on the edge of the Peak District, which would account for some of the discrepancy. Figure 28 shows that there is even less consistency between the two sets of RH data, and includes the moment on August 23rd when the external RH sensor ceased to function. The excessive discrepancy in RH measurements suggests that the handheld meter was not particularly accurate, as this was the source of the calibration constants that were applied to the continuously recorded voltage signal to provide the reading. The external RH sensor was calibrated over 4 readings, as shown in Figure 26, and the manufacturer’s claimed accuracy is ±5% (Table 2 in Section 7.2.1). However, it appears in Figure 28 that the sensor reading only reached 80% when it rained and the nearby station recorded 100% RH. In fact the 20% difference appears throughout, suggesting that the handheld meter required recalibration, though there was insufficient time to carry this out and repeat all of the measurements.

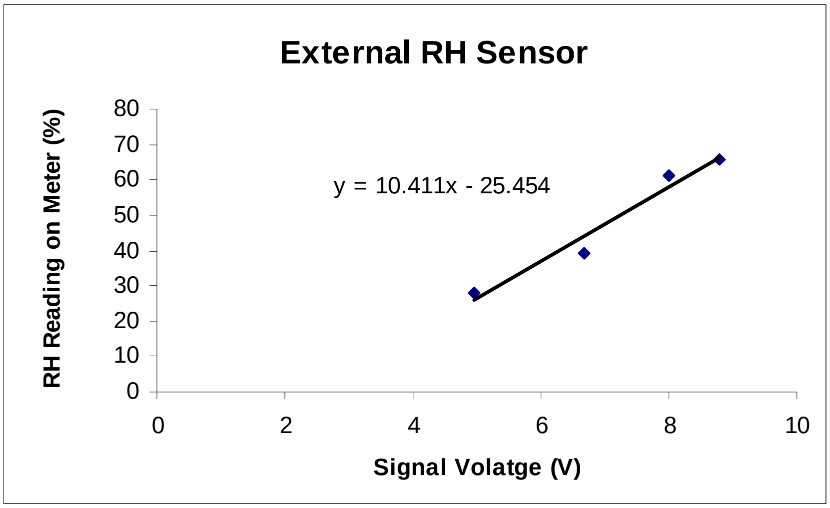


Figure 26: Calibration chart for the external RH sensor

Relative humidity in individual rooms

CIBSE Guide A recommends that the RH should be maintained at 40-70% for general comfort conditions [161]. The average RH each month for all monitored spaces within the experimental house was between 37-60%, except for the shared and top bathrooms during an occasional winter morning and evening when the RH fell below 25% while the room temperatures approached 30ºC and it was 0ºC or less outside. However, if it is correct that the handheld meter was providing readings that were 20% too low, then these conditions are also within the CIBSE guidelines.

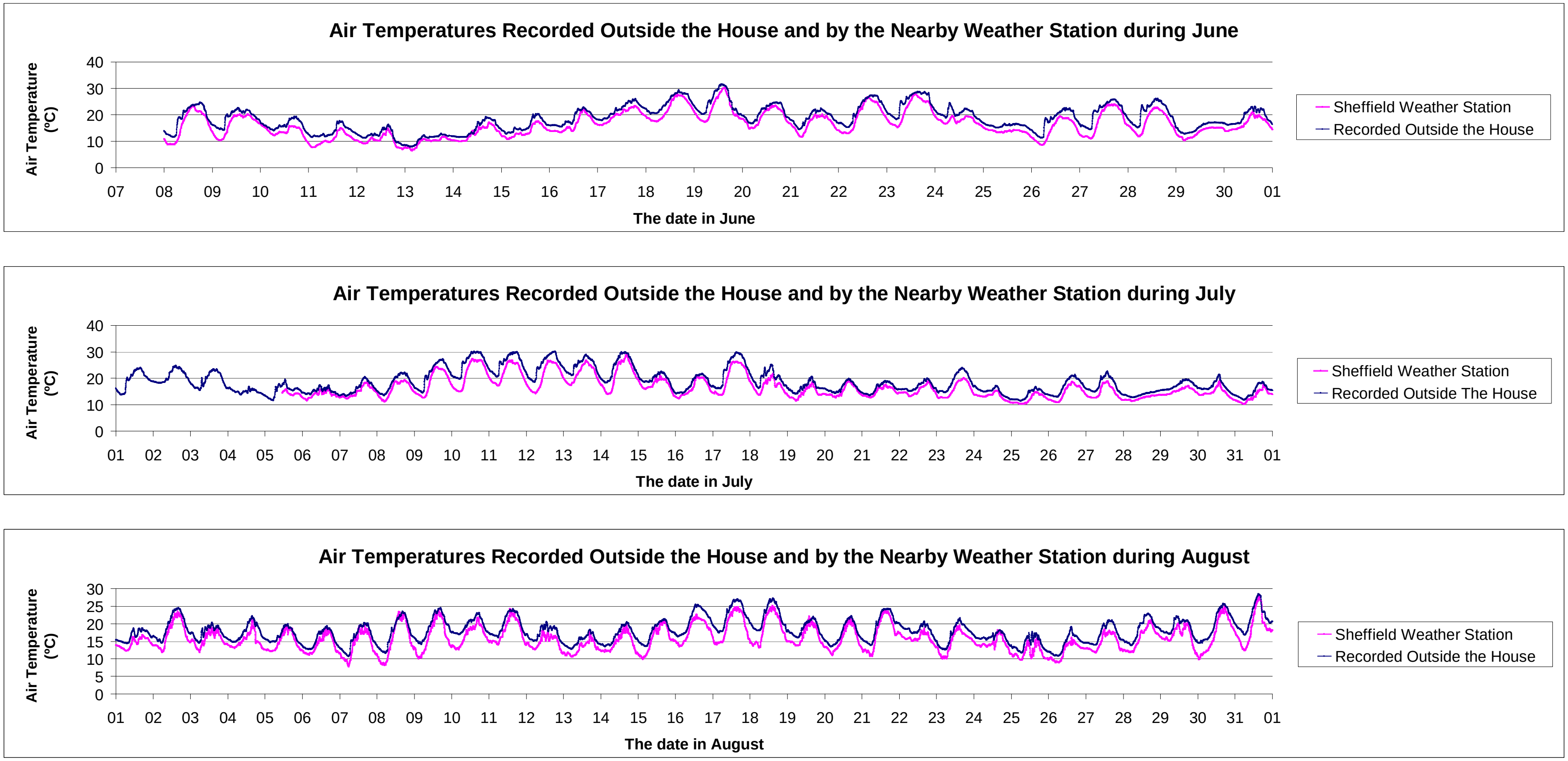


Figure 27: External air temperatures during the summer months

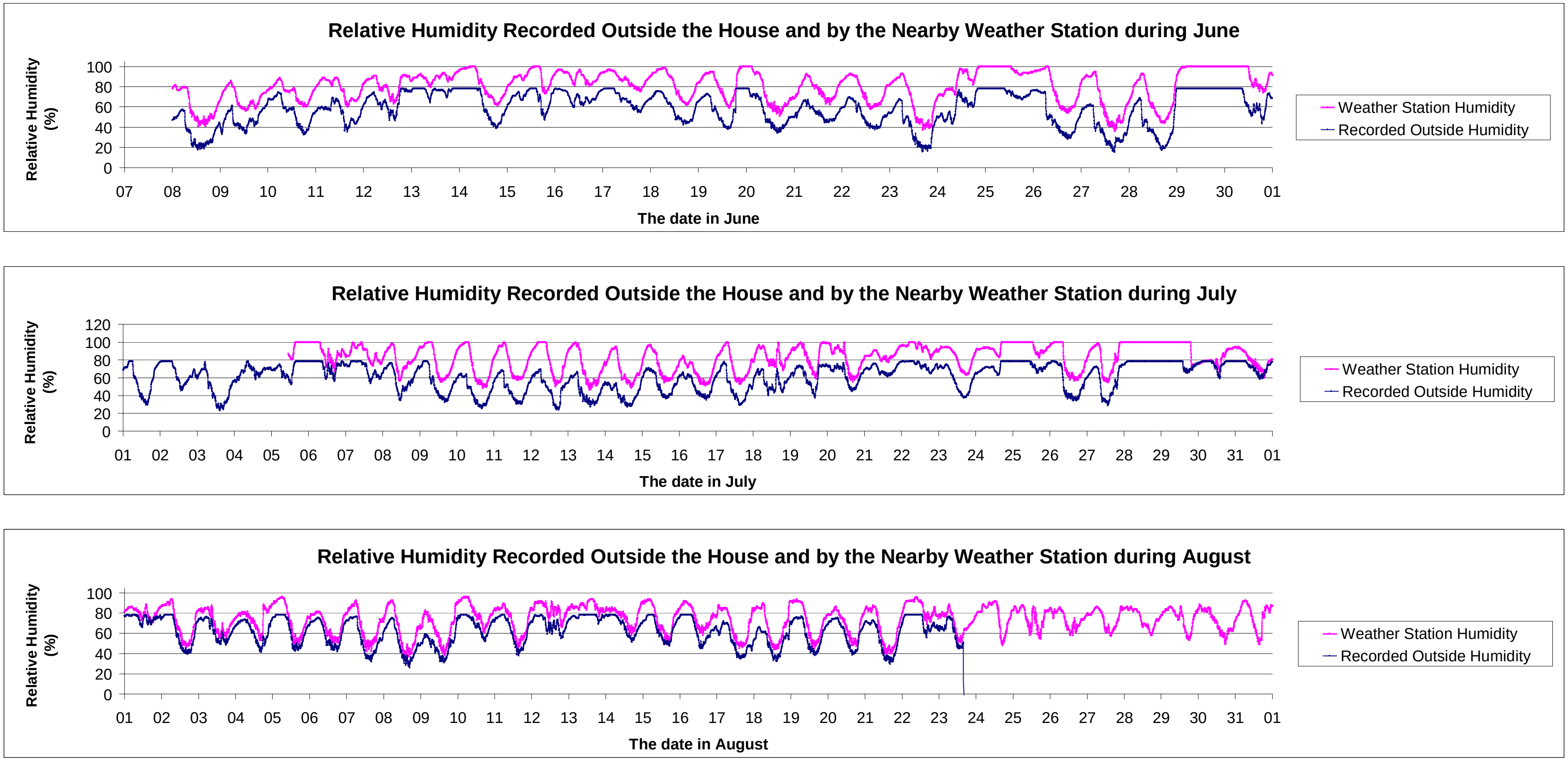


Figure 28: Graphs of external summertime relative humidity

Summertime temperatures in individual rooms

Appendix C contains the analysed and tabulated data from that collected continuously from June 8th to December 31st. It was found that:

- The average monthly temperatures recorded day and night in all areas of the house were comfortably warm, ranging from 21.7 to 26.1 ºC.
- The Standard Deviation and skewness shows that although temperatures in most rooms were maintained at a relatively steady temperature above 20ºC, they were not of normal distribution, so upper and lower quartile figures were calculated for a confidence range.
- The upper quartile values show that bedrooms 1 & 2 were worst affected by overheating, each being in the upper 20 degrees C for a quarter of the summer months and on occasion above 30ºC while outside was 15ºC.
- The highest temperature recorded was in bedroom 3 at 39.6ºC. High temperatures were recorded here regularly at 7-8pm in June and July. The CAD model showed that the low-lying sun may have been shining directly on the sensor on the back wall. A 32ºC maximum is likely more realistic.
- Table 5 summarises the range of seasonal average air temperatures for each type of room in the house and compares them to the operational temperatures in CIBSE Guide A. In a well-insulated, convection heated building, the air and operational temperatures are closely related; however, in a building with a lot of glass, the solar gains and higher surface temperature of the glass during sunny periods can cause discomfort during the day, though its enhanced heat loss and cooler surface temperature can also aid sleeping at night. Bedroom 3 may corroborate this as it was the

most comfortable bedroom at night during the warmest periods, cooling close to 25ºC while others remained near or above 30ºC.

Table 5: Comparing the guideline and recorded seasonal temperatures (ºC)

	Kitchen	Living spaces	Bedrooms	Bathrooms	Communal areas
Guideline summer *	21-23	23-25	23-25	23-25	21-25
Actual summer	26	23-24	24-27	24-25	22-25
Guideline winter *	17-19	22-23	17-19	20-22	19-24
Actual winter	19	22-24	19-24	23-29	19-22

* Guidelines are for the operative temperature and not the air temperature.

- During the summer, the bedroom average temperatures were above CIBSE guidelines, but only by 1ºC in Bedroom 1 and 2ºC in Bedroom 2, which was unoccupied at the time. Through the winter heating season, Bedrooms 3 and 4 averaged 4 to 5ºC warmer than the CIBSE guidelines [161] and the shared and top floor bathrooms were 6 to 7ºC warmer. The top floor bathroom was not actually in frequent use during these months, but for the shared bathroom this must have been the users' preferred temperature.
- The ratio of the area of glazing for each room to its volume was calculated and related to the average summertime temperature recorded. Appendix C also contains this data and Figure 29 shows that it may be possible to suggest a maximum glazing/volume ratio to avoid excessive summertime temperatures, as the linear trend line crosses 25ºC at a ratio of 0.15 m^{-1}.

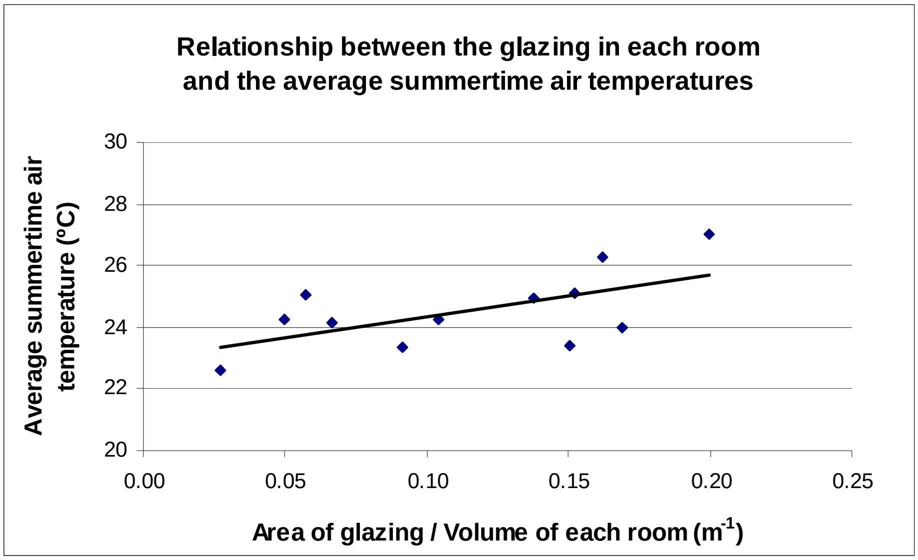


Figure 29: Comparing the glazing ratio and summertime air temperatures

8.3.4 Points of discussion on summertime thermal analysis

1. It is not possible to comment on the terminology chosen in the SAP rating that the risk of this home overheating is 'not significant'; however, it is of concern that the bedrooms had the highest summertime temperatures when bedrooms are usually considered to be maintained an equal or lower temperature than the rest of the house. Bedroom 2 was not in use at this time, so was likely not adequately ventilated on these days. However Bedroom 1 was used by the parents throughout the summer and must have been uncomfortable, especially at night. The parents revealed that they were not happy with the security arrangement of leaving the French doors open for ventilation and DWH subsequently fitted additional swing windows for this purpose, which did improve the conditions in the room.

2. The plotted graph of the glazing area / volume of each room has indicated that it may be possible to recommend a maximum design value for this ratio in order to avoid excessive summertime temperatures in the room. A value of 0.15 m^{-1} appears to maintain the average room air temperatures below 25ºC for this set of collected data; however, the only two rooms that exceeded this value on average were Bedrooms 1 and 2 that are suspected to have been poorly ventilated. In addition, Bedroom 3, the room with the second highest glazing/volume ratio, had an average summertime temperature of 24ºC and in fact benefited from its larger area of glazing by cooling more than other rooms during the night.

3. The implication of this is that it is not possible to provide a straight-forward conclusion on this aspect of design. Although additional glazing will lead to an increase in the heat loss and energy use of the home during the winter, it may be that this can be compensated for by improvement to the comfort conditions during summer nights. The effects of climate change within the lifetime of this house are expected to noticeably increase the summertime temperatures in the UK, which could be expected to lead to rising use of air-conditioning to maintain comfort conditions [168]. This will require significant electrical energy use, which with our present energy supply mix creates three times more CO_2 per kW than gas does for heating.

4. To progress further with this analysis, the research would have to take account both of the mean radiant temperature to measure the operating temperature and the ongoing ventilation rate to assess the comfort conditions in each room, rather than considering only the air temperature as was done in this research.

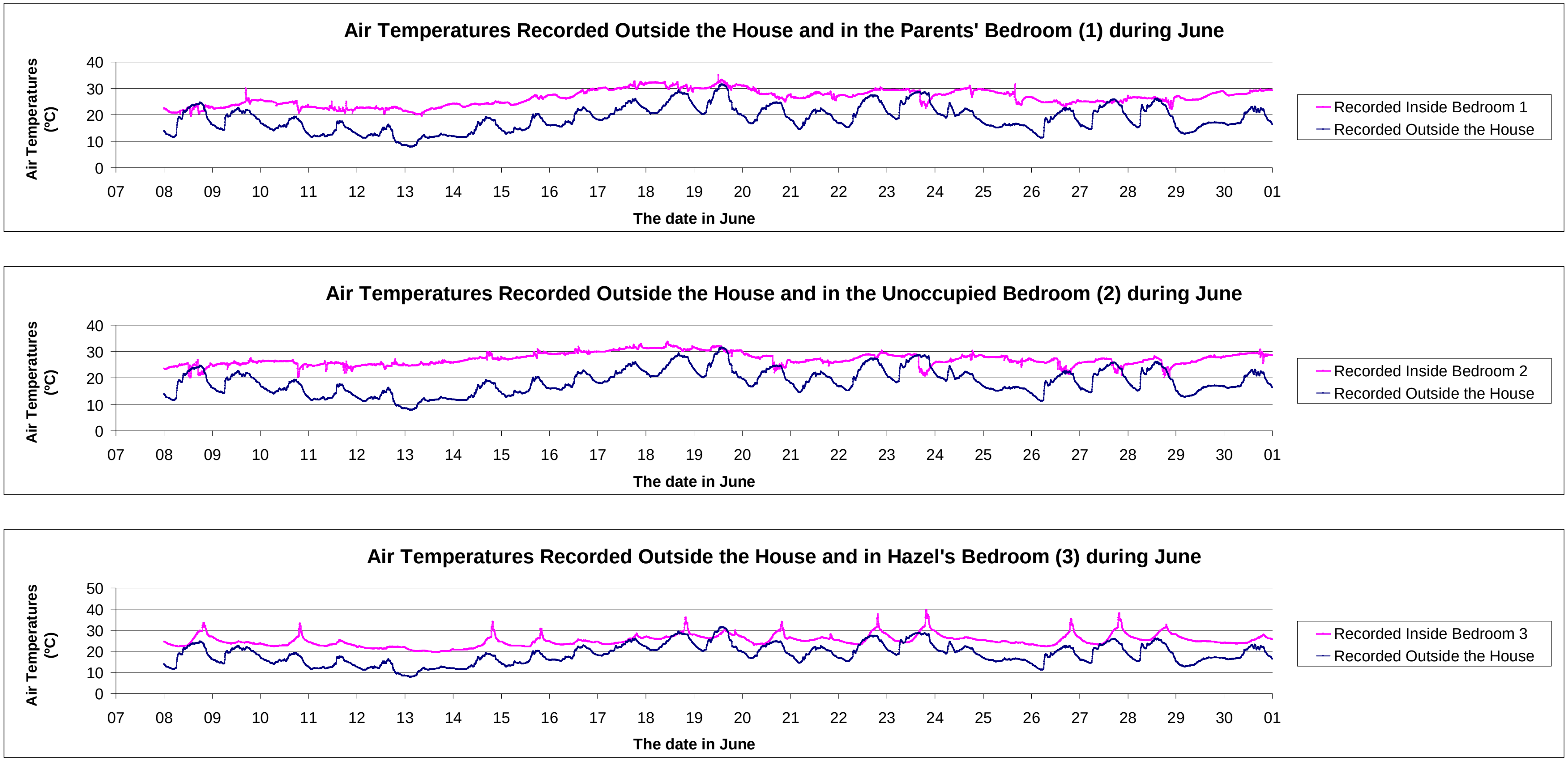


Figure 30: Air temperatures recorded in Bedrooms 1, 2 & 3 during June

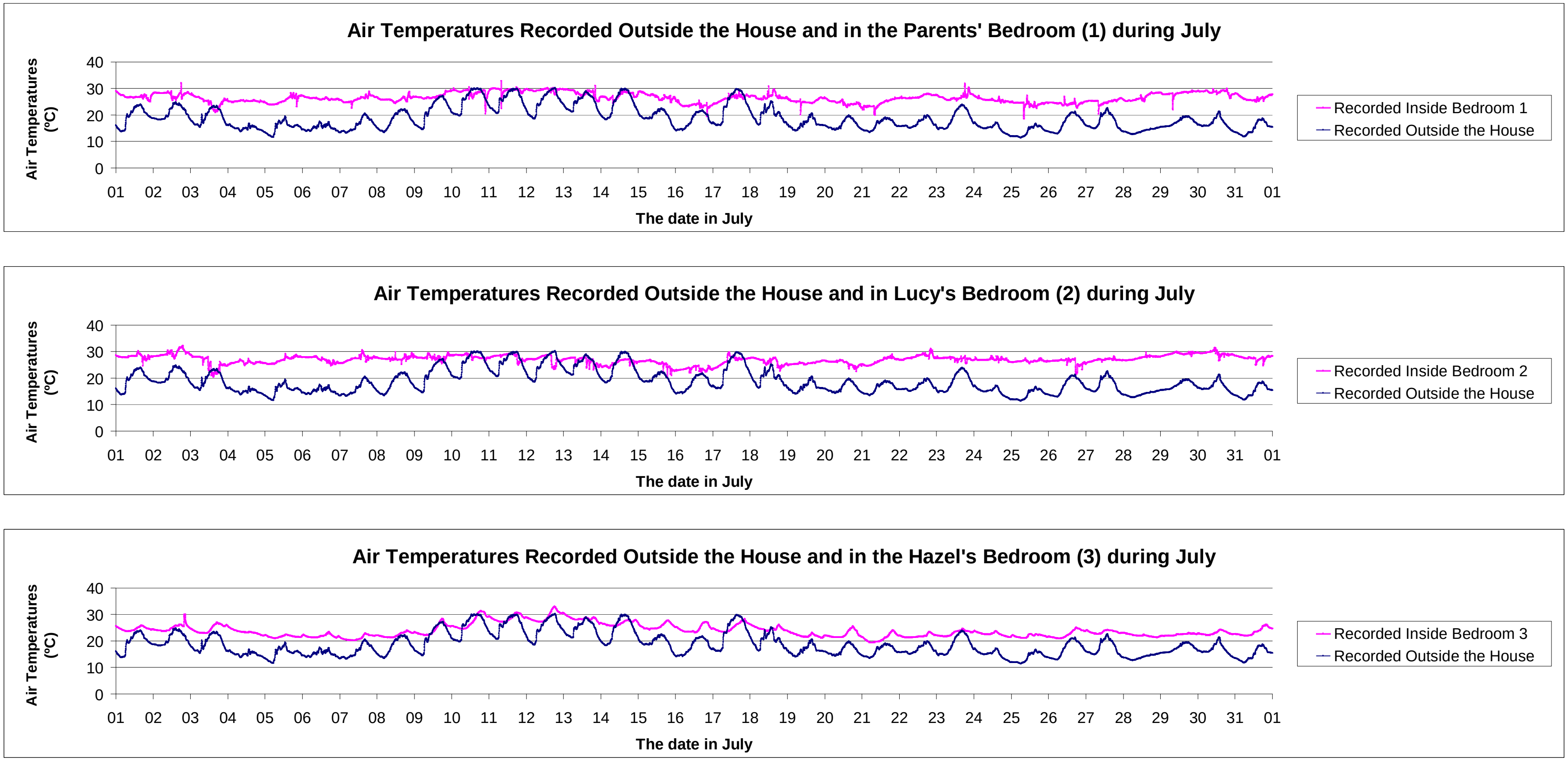


Figure 31: Air temperatures recorded in Bedrooms 1, 2 & 3 during July

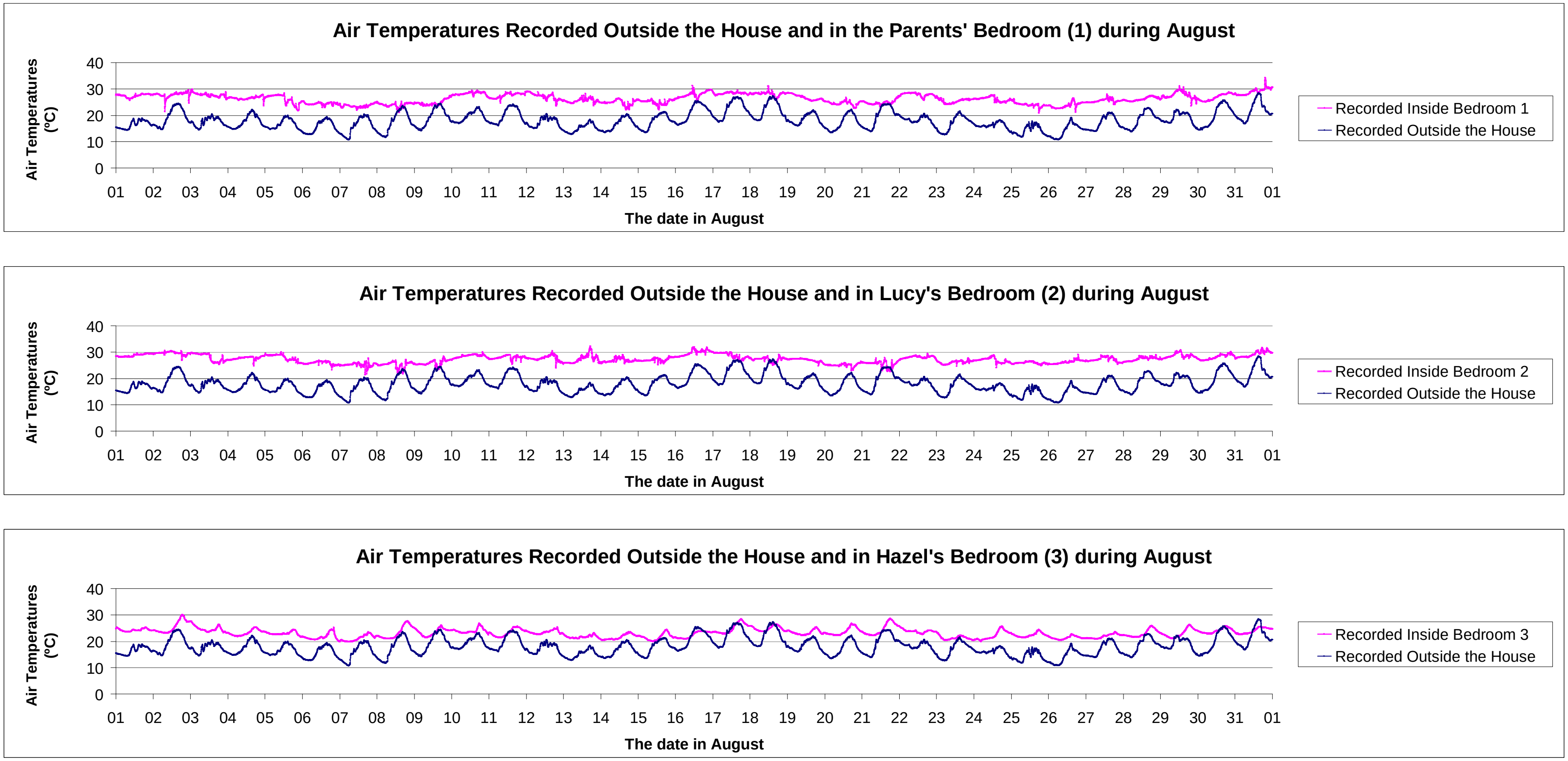


Figure 32: Air temperatures recorded in Bedrooms 1, 2 & 3 during August

8.4 Daylight levels inside the home

The enhanced diffusion of natural daylight within a building can lead to improvements in occupant satisfaction and energy efficiency. A good level of natural light is repeatedly cited as one of the most sought after features in a home (see Section 3.1) and it is often said to bring health and well-being benefits as well as improving the aesthetic views [169]. Enhanced daylight can also reduce the need for electrically powered artificial lighting and the absorption of solar thermal gains can reduce the demand for fossil fuel heating.

To assist designers, target daylight levels to achieve are set by DETR Best Practice Guidelines [170] and two measurements for receiving EcoPoint credits are given in Section Hea 1 of the EcoHomes assessment [42]. These are the ‘View of Sky’, which requires 80% of the floor area of select rooms to be able to see the sky on a 0.85m working plane, and the ‘Daylight Factor’. The daylight factor (DF) quantifies how naturally lit each room will appear on an overcast day. It represents the level of natural light that will enter the room as a percentage of the diffuse sunlight that is available for at least 85% of the time between 9am to 5pm over the entire year. The assessment is made for diffuse, overcast conditions, as the contribution from direct sunlight is unreliable in the UK’s climate. Calculating the DF early in the design process can be used to guide changes to the size and positioning of the windows in each room, in order to improve the lifelong lighting conditions in the home when there will be minimal design cost implications. Three different methods for assessing the DF were selected for comparison in this study.

1. A formula promoted by the Building Research Establishment (BRE) that has been used for over twenty years to provide an average value for each room to which it is applied.
2. Computer simulation of the natural light received at every point within a 3-Dimensional model.
3. Calculation of the percentage using simultaneous measurements of the external and internal light levels in the real building on an overcast day.

(1) The BRE daylight factor formula

$$DF = {TA_W \theta M} \Big/ \left\{ A\left(1 - R^2\right) \right\}$$ [171]

DF : Average daylight factor for the room.

T : Glazing transmittance value, which is taken as 0.6 for the low-e coated, double glazed units used in the experimental home.

A_W : Window area, not including the frame and sashes that typically take up 20% of the wall void area.

θ : The angle subtended by the sky. This is the angle above horizontal that you need to look at before seeing the sky from the window.

M : A maintenance factor that represents the window cleanliness. This was taken as 1 since the house has self-cleaning windows.

A : The total area of interior surfaces (walls, floor and ceiling).

R : Area weighted average reflectance of interior surfaces, which depends on their colour but a typical value of 0.6 was recommended [164].

(2) Computer modelling using Ecotect (v5.2b)

The Ecotect package can rapidly calculate the DF at every point on a nodal grid within the 3-Dimensional model, using the split flux method developed by the BRE. Calculating the DF for each point on a grid has the considerable benefit of providing an insightful graphic of how the daylight intensity will vary within each space, rather than providing an average value only. This can very effectively highlight whether the windows should be repositioned to prevent issues of excessive contrast or localised gloominess. The distribution can also be helpful to assess the risk of solar overheating and whether daytime luminaries may be required.

The Ecotect model was the same one as shown in Figure 18. The nodal grid spacing was set at 500mm on the horizontal plane, giving 21 nodes from the front to rear and 23 nodes from the left to right. A vertical spacing of 775mm gave 12 nodes from the z-axis basement floor to second floor roof - three nodal layers per floor. Figure 33 and Figure 34 demonstrate very clearly the graphical benefit of Ecotect. Both plan sections depict the DF on the 0.85m working plane of the ground floor. The kitchen floor is above this working plane height so the DF in the kitchen is not shown. The coloured linear scale represents 0-5% DF: 0-1% as blue, 1-2% as purple, 2-3% as red, 3-4% as orange and above 4% as yellow. Figure 33 shows the DF predicted at each node in the house as it has been built. Figure 34 illustrates the fall in natural light expected if three beneficial features are removed: a side window in the lounge (bottom-middle); the glass floor above the entrance hallway (middle-right); and the glazing in the side entrance door to the boot room (top-right).

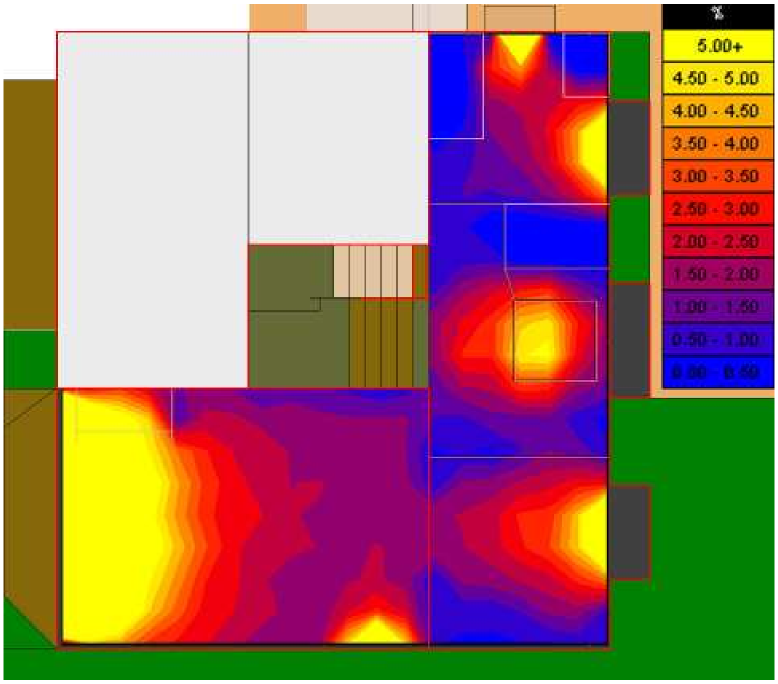


Figure 33: Predicted DF across the ground floor of the house as built

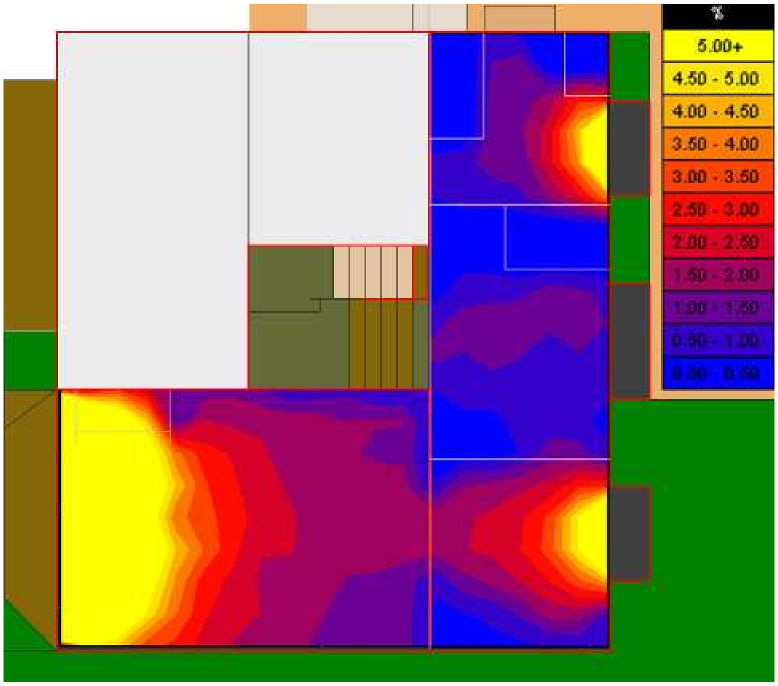


Figure 34: Predicted DF when the described alterations were made

(3) POE measurements taken in the house

The same environmental meter shown on page 106 was used to conduct a POE of the DF predictions. This was made by turning off all artificial lighting, removing any obstructions by the windows, opening the blinds and curtains fully, crouching down low at each nodal position with the lux meter held steady and horizontal at a working plane height of 0.85m, as per CIBSE guidelines [172], and only taking the reading on the digital unit once it had settled. This exercise required a day that had a uniformly overcast CIE sky and 7th March 2006 was just such a day. Figure 35 shows the external lux measurements that were taken frequently over the course of the test to enable a more accurate DF to be calculated later. It is seen that a linear interpolation between each of the measurement points provides a suitably accurate value of external lux. The only measurement that did not follow the trend was that taken at 13:27, although this introduces only an additional ±0.2% DF uncertainty to the results for Bedroom 1, Bedroom 2 and the First Floor Landing, which were assessed between the measurements at 13:16 and 13:27.

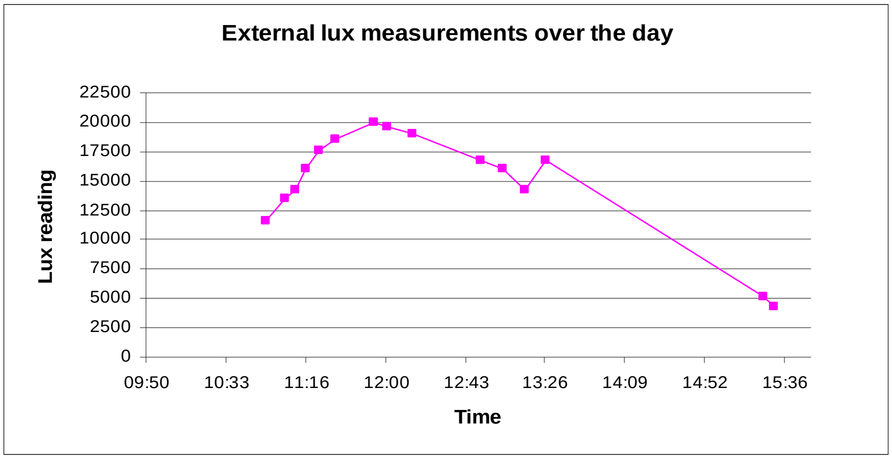


Figure 35: External lux measurements taken during the daylight POE

A large number of internal lux measurements were taken in a grid fashion within each room, as shown in **Appendix D**, which enabled the actual DF to be calculated at each point and compared to the other methodologies.

8.4.1 Comparison of results

Appendix E contains the results obtained using each of the three methods and the statistical comparisons between each set of results. Figure 36 depicts the findings ordered in the progressively increasing value found by method (3).

- The BRE formula cannot be applied to the open-plan hallway and stairwell spaces that are on split levels and have openings through to other spaces where there are windows providing additional light.

- The Ecotect modelling results are listed in three formats. (2a) is the average of every grid node value that lies within the room. (2b) is the average of a reduced set of values that correspond to the positions where the measurements were taken for method (3). (2c) is the value that the majority of the working plane in each room exceeds.

- For (2b), the node locations calculated for by Ecotect did not always match up with the locations where readings were taken, so the nearest Ecotect values were linearly interpolated to find a more appropriate set of values before the average was calculated.

- The DF obtained by method (3) is assumed to be the most accurate as it is the only one that used lux values measured in reality. However all methods are subject to methodical errors that are discussed later.

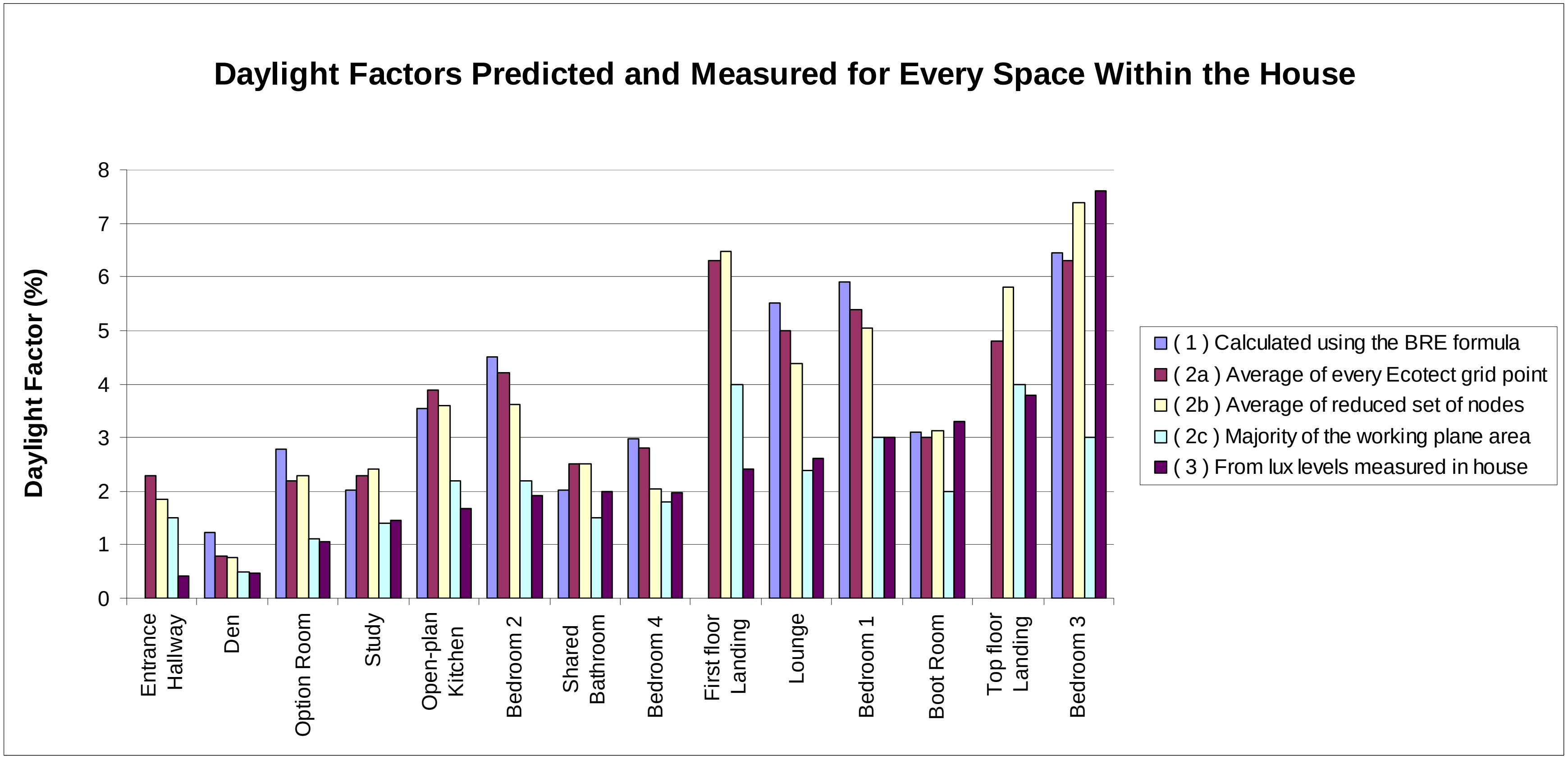


Figure 36: Comparison of the Daylight Factor results

8.4.2 Points of discussion on daylight factor results

There is a significant disparity within the sets of results for most rooms and it is difficult to identify a trend in Figure 36 on how they compared; however, some points of note are apparent from the analysis contained in Appendix E.

- The average DF found using the BRE formula (1) broadly agrees with those found using methods (2a) and (2b); however, none agrees with what was measured in the house (3).
- Reducing the number of Ecotect nodal points (2b) results in an average difference of only 0.4% DF to that calculated for the full nodal set (2a).
- The DF falls away quickly from a high value by the windows, which augments the average DF results (2a) and (2b) but is not considered by taking the majority DF on the working plane (2c).
- The remarkably high DF readings taken in Bedroom 3 gave it the only actual DF (3) that is higher than those predicted. This is the only room that has a skylight as well as vertical windows, which creates a very high concentration of sunlight in the glazed corner. The DF was measured as 33% in this corner and the lux level did not drop as soon as was predicted when the meter was moved further into the room.

These points indicate that the following conclusions can be made on the accuracy of the Daylight Factor prediction tools.

1. The value that Ecotect predicted for most of each room to have (2c) provided the best indication of the actual average DF value (3).

2. Almost all of measured values are not as high as those predicted, though occupant feedback was very positive. The actual average DF for almost all rooms was over 2%, as required in the DETR Best Practice Guidelines and meeting the ‘Daylight Factor’ and ‘View of Sky’ requirements of the BRE EcoHomes (2005) assessment. It is concluded therefore that the house design performed well in terms of daylighting.
3. There appears to be insufficient accuracy in the prediction methods to base detailed design decisions on the results that they give. This requires further consideration before concluding whether it was a case of measurement error or if something more fundamental is wrong with the prediction tools. As the focus of this thesis is not on solar design or daylight achievement, it is sufficient only to discuss some of the more likely sources of error.
4. A previously published paper had discussed the predicted results in further detail and progressed towards making design conclusions based on these [173]; however, the actual DF measurements had not been taken at the time that this paper was published.

8.4.3 Methodological concerns

It is beyond the scope of this research to investigate the theoretical or empirical basis on which the three methods were developed. Instead, some the main shortcomings of predicting the DF before a dwelling has been built and measuring it post-occupancy will be briefly discussed.

(1) The BRE daylight factor formula

- The formula required most values within it to be estimated or taken from standard or manufacturer's datasheets, as they could not be measured until the house had been built. The more significant of these were:
    a. The reflectance is to the squared power in the formula, making relative error in R the most significant to the DF error. However a value of 0.6 was used for all surfaces in each room, which is inaccurate as each was decorated in different finishes and tones. The need to assume a typical value cannot be avoided as the décor of a room is often one of the final decisions made and can also be changed easily by the occupants once they move in.
    b. Although θ, the angle subtended by the sky, was estimated from the 3-dimensional CAD model that included surrounding buildings, it did not take account of window overhangs or shelves, or that the skyline was uneven since the outside obstructions varied in height.
    c. The reduced percentage of window opening that was actually able to admit light was taken account of by introducing a 0.8 Frame Factor, as in the SAP; however, the blinds, curtains and window sashes varied throughout the house so this value should also have varied.

- The formula is unable to take account of open-plan doorways or translucent doors that allow daylight to be shared between neighbouring spaces, such as between the hallway, option room, lounge and kitchen in this house.

- Nor can it take account of non-rectangular rooms that create an internal obstruction that make some areas darker than the room's average.

(2) Computer modelling using Ecotect (v5.2b)

- Although a different value was used for the reflectance of the wall, floor and ceiling surface materials in the 3-D model, they were still estimated and set to be the same in rooms that had different décor in reality.

- The model has no detail on overhangs or shelves around the windows that can prevent daylight from entering or reflect it deeper into a room.

- Perhaps most significantly, it was apparent when the ‘void’ element or internal windows were used in the model that localised areas of a much higher DF than plausible were predicted, like the elements themselves were creating light. This could only have been the result of error in v5.2b of the Ecotect software package. In the previously compared results, this was accounted for by creating holes in the internal walls and floors where voids or glass would otherwise have been. Ecotect was then tested by modelling the external wall windows as holes also, with a varied outcome. The DF by the ‘window’ increased, as expected since there is no longer any obstruction; however, moving into the room, it was also predicted to fall more rapidly, giving a lower average DF and a much lower majority value for the room. Figure 37 shows the result for the lounge with double glazed window elements. The DF is 25% by the windows and the majority of the room is over 2.5%. In Figure 38 though, by replacing the windows with holes, the highest DF had risen to 34% but the majority value fell to just 1%, hence the large area of blue. There is a contradiction in these results since, when there is a hole in the wall, the DF is higher by the wall and should also be higher throughout the whole room, but instead it is lower.

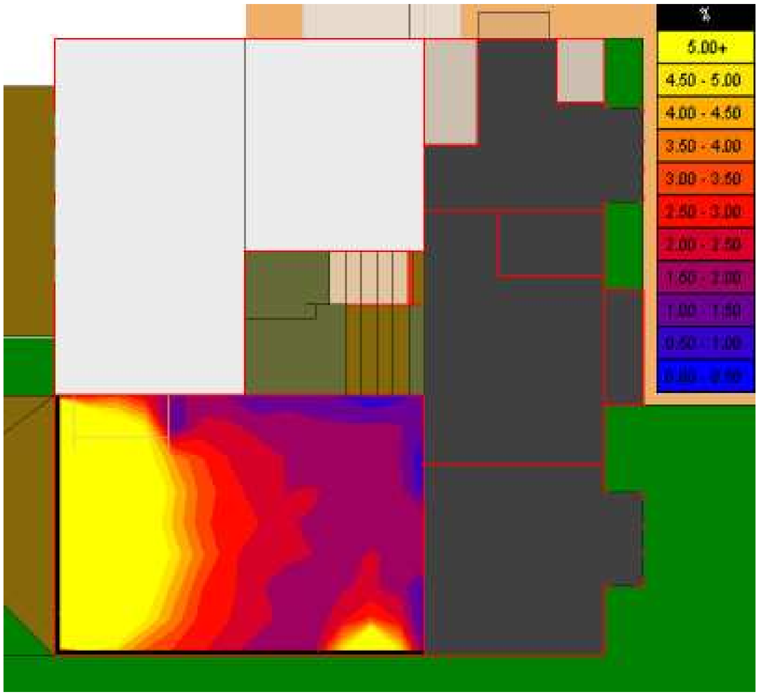


Figure 37: DF in the lounge with low-e, double glazed windows in place

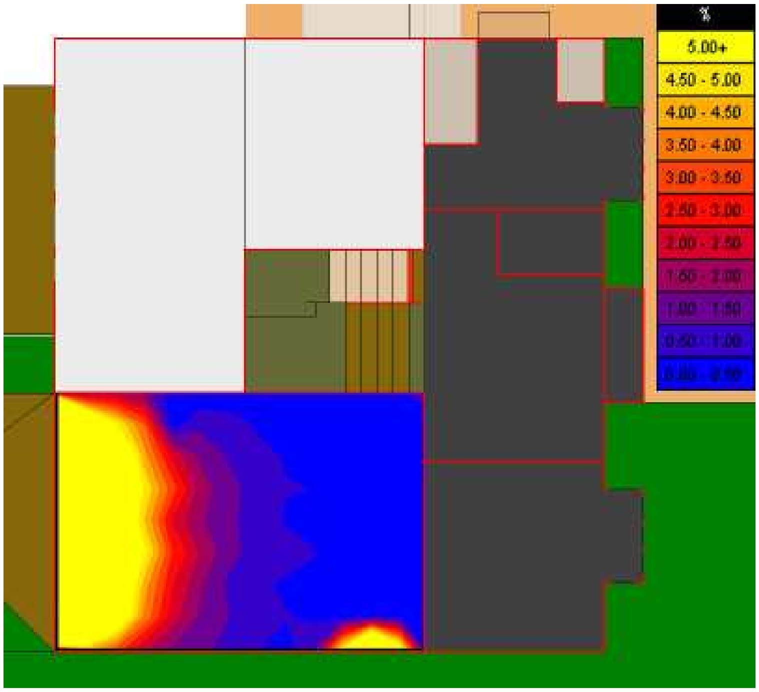


Figure 38: DF in the lounge with holes instead of windows

This contradiction was seen in the results for all of the rooms. In Figure 39 it is shown that the maximum predicted DF was greater for most rooms when they had holes instead of windows on the external walls. Figure 40 shows however that the average value was lower for the model with holes, by as much as 1.8% DF. The reduced averages are the result of the DF falling to a lower value within each room, as previously demonstrated, which is intuitively incorrect and causes concern on the modelling accuracy of Ecotect v5.2b.

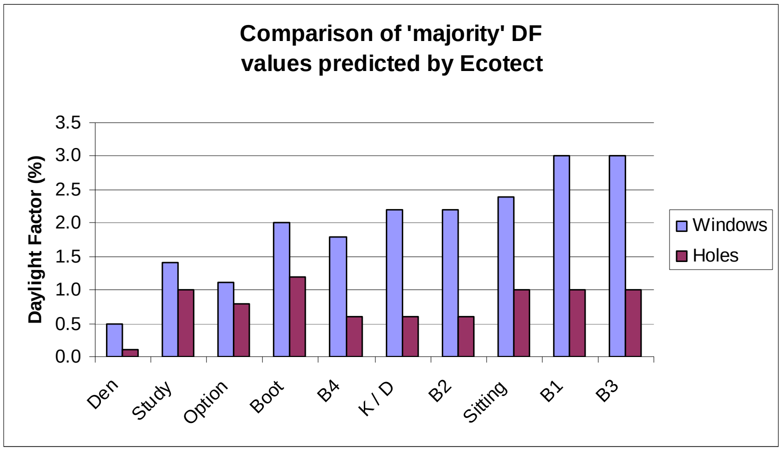


Figure 39: The maximum daylight factor predicted for each room

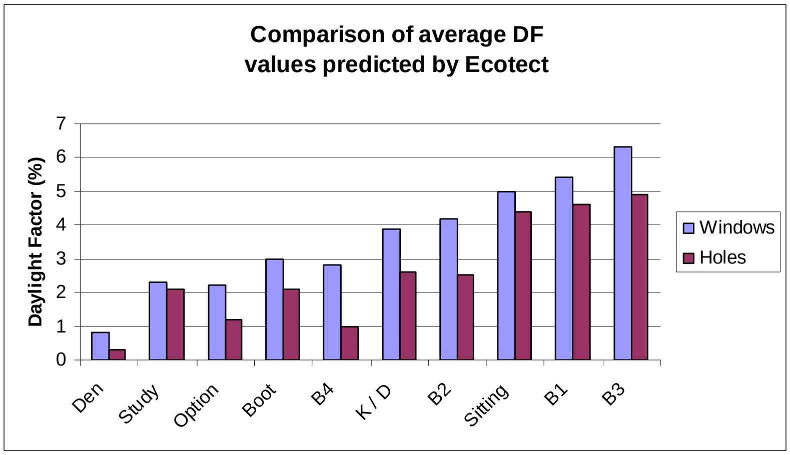


Figure 40: The majority daylight factor predicted for each room

(3) POE measurements taken in the house

- Manufacturer's data for the handheld lux meter states that it is accurate to ±5%. Since DF is the internal lux divided by the external lux, the error of each individual and average DF attributable to the meter is ±10%.
- The readings were taken at approximate grid positions within each room, so they may not provide a true area-weighted average since the high lux values near the windows may be over or under represented.
- By linearly interpolating between the outside measurements, the time gap between taking them and the inside readings should not be significant except that, in the interest of using time resourcefully, the external readings were taken outside in the street between the house and the neighbouring row rather than in a completely isolated location as strictly required.
- The intention of measuring the lux levels on an overcast day is to enable a consideration of diffuse daylight only, under a CIE overcast sky. Daylight is rarely completely orientation independent however as the clouds do not fully disperse the light, so it will be stronger in the direct line of the sun. The effect of this is that the external lux measurements taken throughout the day will have an unknown direct daylight contribution as well as diffuse. Likewise, some measurements taken inside the house will have been enhanced by direct sunlight, but in some rooms more than in others, as it would depend on the orientation of the windows and where in the sky the sun was positioned at the time of measurement. The overall effect of this and assessing the ideal conditions to obtain realistic DF readings is an active field of research that lies beyond the scope of this thesis.

8.4.4 Feedback of daylight factor results on the house design

DETR guidelines state that a DF above 5% could lead to issues of overheating from solar gains [170]. In the measured DF study, Bedroom 3 had a measured DF of 7.6% while all other spaces were less than 4% DF. It would seem possible and sensible to reduce the glazing in Bedroom 3 without losing its daylit appearance. It is suggested that the skylight portion of the glazed corner be removed from the design, though no attempt is made to model the outcome of this suggestion since the techniques were found through the POE study to generally be in poor agreement.

It was previously suggested however that there may be a benefit to the additional glazing in Bedroom 3 if it avoids the future summertime use of domestic air-conditioning systems for night-time cooling. This bedroom very effectively demonstrates the importance of taking an holistic approach to assessing building design, as the consequences and benefits of each decision will often have knock-on effects on other aspects of sustainability.

Returning to the measurement of the DF, despite the many hours spent modelling the properties of each room and analysing the data, methodological errors were still evident with some apparently unavoidable. It is concluded that the tested prediction methods are not accurate enough to warrant their use for making detailed design decisions, though it is also recognised that they nevertheless serve the purpose of focussing the designers' attention on daylight encouragement. The research and testing programs required to take this issue further is unfortunately beyond the scope of this thesis.

8.5 Electrical appliance energy usage

A further aspect of energy use that was studied was the electrical usage of the appliances in the kitchen and laundry room. These appliances are the most commonly provided in new build homes and 2 credits are available within the EcoHomes assessment if they are provided at a particular Eco-label standard. Fridges and freezers should be of ‘A’ rating or higher for one credit. The second credit is provided if the washing machine and dishwasher are of ‘A’ rating and the tumble dryer is of ‘C’ or higher. The EcoHomes scheme was described in more detail in Section 2.4.

The benefits of a study on the electricity consumption of domestic appliances when used in the context of a real family home and lifestyle were:

1. To corroborate the implication of the EcoHomes assessment that equal credit should be rewarded for the two categories given above.
2. To suggest any further categories that should be considered significant enough to be rewarded with further credits.

8.5.1 Points of discussion on appliance monitoring

As all of the kitchen appliances were built into the worktop furnishings of each room, the socket meters shown previously in Figure 13 had to be fitted on the date that the appliances were delivered to the house (07/04/05) and as such would not actually have been on zero readings when the family moved into the home (04/06/05). Each was used in a different fashion during this 2 month period, with some being switched off, some remaining on stand-by and some being used intermittently. There is no way of accurately estimating each reading for the date that the family moved in and so this lengthened time period should be kept in mind when comparing the results that are listed in Appendix F.

It is most appropriate to place energy limits on fridges, freezers, dishwashers and tumble dryers as these are the most energy intensive appliances in the home. The divide created by EcoHomes between the two categories of appliance also seems appropriate. One EcoPoint would have been awarded for the fridges and freezers that used approximately 140 kWh/month between them. A second EcoPoint would have been awarded for the washing machine, dishwasher and tumble dryer that used a combined 151 kWh/month.

At an electricity price of 8 pence/kWh, the two ESSA air purifiers used £6.75 of electricity per month between them. This figure should be higher as they were not operating as much during the start as later in the study period because the family were not aware of the most advisable way to use them. Their cost to benefit ratio will be dependent on each household’s circumstances, as this would be a small price to pay for some people for the alleviation of asthmatic or allergy symptoms that it is claimed the purifiers can bring.

The RFID network and central PC that was required to remain turned on for 24 hours a day used a combined £6.20 of electricity a month. This figure should be factored into any future assessment of the energy and cost implications of including an occupant tracking system like this into a Smart Home.

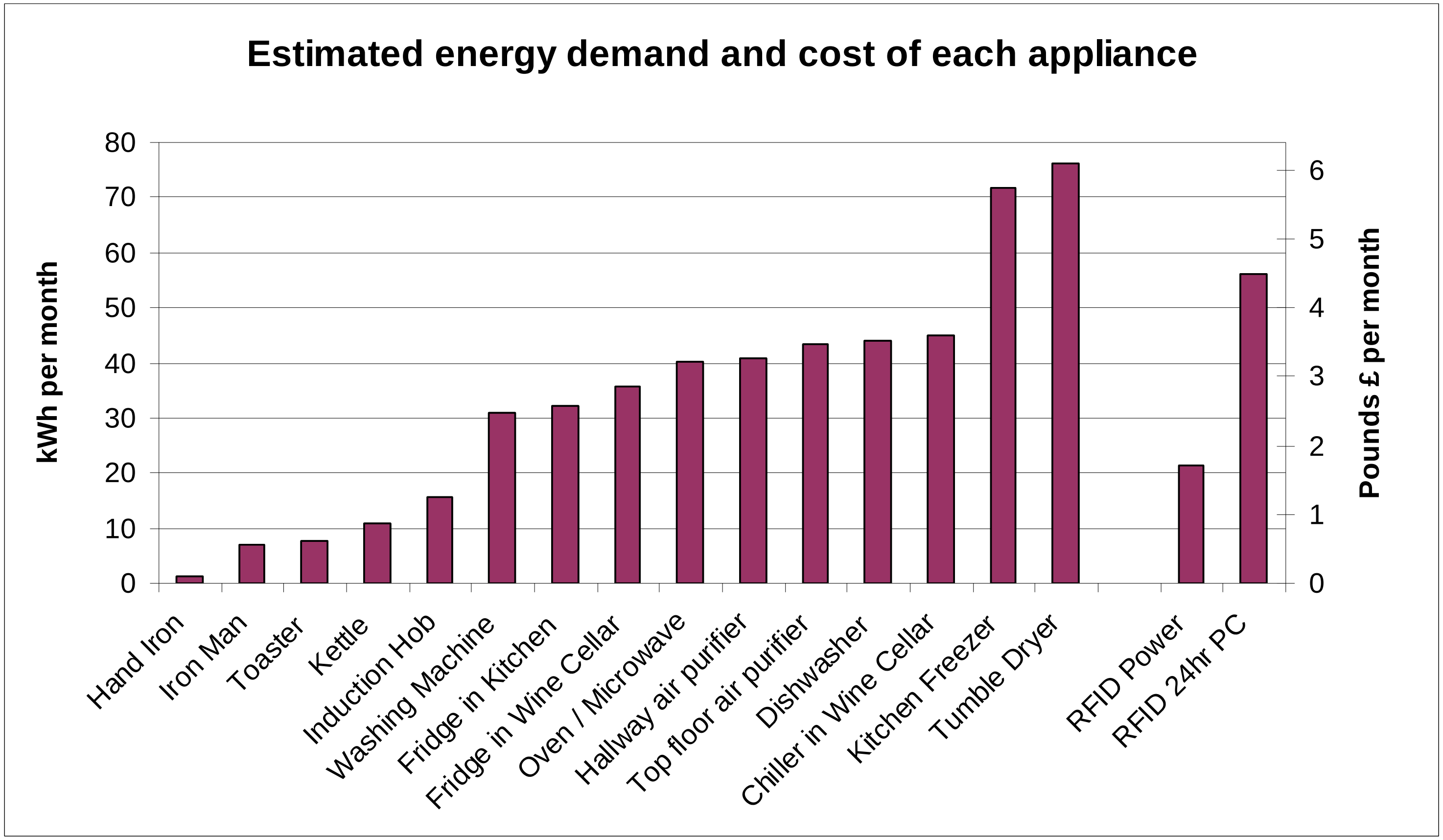


Figure 41: Average monthly electricity use and cost of each appliance

8.6 Chapter conclusions

The energy demand of the experimental house was considered on a number of fronts in this chapter to provide an assessment of the design and a post-occupancy evaluation of the prediction tools. The five aspects considered were the annual thermal heating demand, the contribution that solar energy could make towards this, the risk of the house overheating in the summertime, the daylight levels achieved inside each room and the electrical energy used by the main kitchen and laundry room appliances.

The thermal heating demand was assessed using the building services software package HEVACOMP v19. This predicted a peak demand of 12.3 kW and an annual requirement of 27.3 MWh, equivalent to £530 in natural gas. An analysis of the three main variables found an air-tight construction to be the most important, followed by improvements to the glazing and then to the walls. The analysis could be expanded in future to assess the sustainability benefit and economic viability of making such improvements, bearing in mind their embodied energy consequence and the disconnect between the additional cost to the builders and the fuel savings rewarded to the occupants.

The 2005 SAP and the Ecotect (v5.2b) package were used to factor in the influence of construction orientation and solar gains. The annual space heating demand and cost predicted using the SAP were in close agreement with those mentioned of HEVACOMP. It was also found that the home’s SAP rating could have been 2 points greater had it been orientated so the rear elevation that incorporates 63% of the total glazed area faced the south, reducing the annual fuel bill by £61 (7.7%) and CO_2 emissions by 752kg. In comparison Ecotect found the optimum orientation to be when the rear elevation faced south-east (135°), when the glazed areas received 4650 kWh (18%) more annual solar insolation, or 2,827 kWh over an October - May heating season.

It was discovered that the SAP and Ecotect package differ in the importance they place on the contribution of direct sunlight relative to diffuse gains and how dependent it is on the home's orientation. Two possibilities were suggested on why the SAP flux values and Ecotect insolation data gave different conclusions; however, the comparison cannot be taken further until it is known from where the design values used by each method originate.

Building a highly glazed house in a southerly orientation may bring a new requirement to block the summertime direct solar gains using shading techniques such as overhangs or brise soleil. Alternatively, HVAC technology could handle the cooling load, but this will have significant capital and fuel costs of its own. Appendix P from the 2005 SAP was used to show that the risk of this naturally ventilated home overheating should be 'Slight' or 'Not Significant' so long as the windows could be opened to provide an air change rate of at least 2 ach. The importance of ventilation was confirmed by the occupants who requested more openable windows to be installed as they were in discomfort during summer nights in particular. Interestingly, the highly glazed Bedroom 3 cooled the most during summer nights, which may indicate an ability of glass to aid summertime comfort in rooms that are unoccupied during the day and are desired to cool down during the night. Although additional glass would result in extra heat loss during the heating season, it might also negate the use of domestic air-conditioning systems if climate change raises ambient temperatures and night-time discomfort as expected.

The fourth aspect assessed was the diffuse daylight levels in the home that were expected to be enhanced by the large area of glazing in the design. It was predicted and then measured that the home exceeded DETR Good Practice Guidelines and BRE EcoHomes (2005) requirements, although the predictions did not match the POE measurements sufficiently accurately to encourage their use to make detailed design decisions. Further research is necessary before it could be estimated to what extent this is a fault of the prediction methods rather than a case of POE measurement error, although a seemingly obvious concern already exists on the daylight modelling tool of Ecotect (v5.2b).

Finally in this chapter, an electrical energy study was undertaken on the main kitchen and laundry room appliances. A breakdown of the estimated energy use and monthly cost of each was given and it was observed that it is most appropriate to place energy rating demands on fridges, freezers, dishwasher, and the tumble dryer as these were the most energy intensive appliances, which is inline with the division within the EcoHomes scheme of the two EcoPoints available for providing white goods with energy efficiency ratings.

It is hoped that this chapter has also demonstrated the importance of taking an holistic approach to assessing a building’s energy demand, as decisions made in order to satisfy individual requirements will often affect its performance at another time of day or season over the expected lifespan of the building. Demonstrating this was a secondary objective of this thesis however, and the next chapter returns to the primary concern of the domestic space use POE.

9 Monitoring the Household's Use of Space

David Wilson Homes (DWH) wished to discover how the family who were test running the Project:LIFE experiment house found living with the more unusual design aspects of the floor layout. As well as asking them direct questions about their thoughts on the design of spaces and rooms, it was requested that quantitative data be collected on how they spent their time in the house. In other words, DWH wanted a post-occupancy evaluation (POE) to be carried out on the allocation of space within the home. It was argued in Chapter 4 that POE should become commonplace within housing, which would lead to more effective home design with improved quality control, cross-industry sharing of best-practice methods during this innovative time and the promotion of more-sustainable homes if they are found truly to be more satisfying to live in and valued economically. An often requested aspect of POE is the efficiency of space allocation, as each square meter of a commercial property has a real financial value attached to it. For a dwelling, the value of the land it is built on may not be as important to the homeowner as the features the house contains, but it is significant to the developers who are required to build homes at a higher density and do not wish to lose any overall market value across the development site.

This chapter analyses the data collected by the radio frequency identification (RFID) network described in Section 7.3 in terms of how the spaces created by the floor plan design were used by the occupants of this experimental house.

9.1 Categorization of collected data

The family wore the RFID tags for three periods of two weeks that were spaced evenly through their 6 month stay. For the 6 weeks (42 days, 1008 hours) of study, just 6% of the data has had to be termed ‘unknown’, either due to a tag accidentally not being worn, or system failure. 94% of the requested data was therefore collected in this unique application of RFID technology, which is considered a success. Appendix G includes a sample of the collected raw data and explains the editing and analysis procedure it was put through. An estimated 150,000 lines in total of raw data had to be manually reviewed, edited to approximately a fifth in size and converted into a form that could be analysed and compared using a standard spreadsheet package. This process had to be undertaken manually as intelligent software has not yet been made available for this purpose. There was insufficient time to undertake this as it would constitute a major piece of work in its own right. As an overall average, it took two days to analyse each 24 hours of collected data.

Although the data was collected on an individual room basis, when summarising the findings it makes sense for it to be reported in terms of zones that are defined as groups of rooms that roughly share the same activity.

Outside: Anywhere outside and beyond the RFID system range.
Four bedrooms: Master (B1), Ensuite (B2), Glazed (B3), Balcony (B4)
Four bathrooms: Sunken, Shared, Top floor, Hot tub
Four living spaces: Lounge, Den, Decking by kitchen, Option Room
Open-plan kitchen: Kitchen, Dining table area
Four utility rooms: Laundry, Wine cellar, Boot Room, Study (B5)
Circulation areas: Stairs, Landings, Entrance hallway

By averaging the data collected over the six weeks, it was found that the family spent 28% of their combined time outdoors, 43% in one of the four bedrooms, 3% in a bathroom, 14% in a living space, 10% in the open-plan kitchen, 1% in a utility room and 1% in a circulation area.

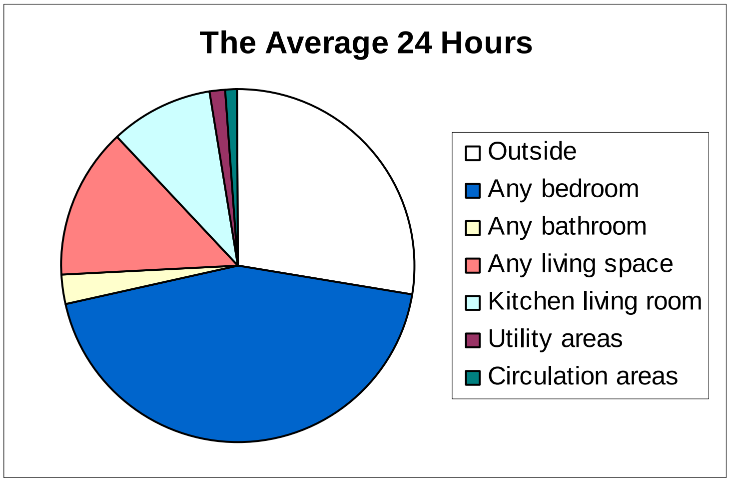


Figure 42: Breakdown of all the data collected over the 6 weeks

Subdivision of Data

The patterns in time spent in particular spaces were naturally expected to vary over the course of each day. To confirm this, the days were split into 4 time bands that represent the natural rhythm that exists in the daily routines of the typical household, the Parnell family included.

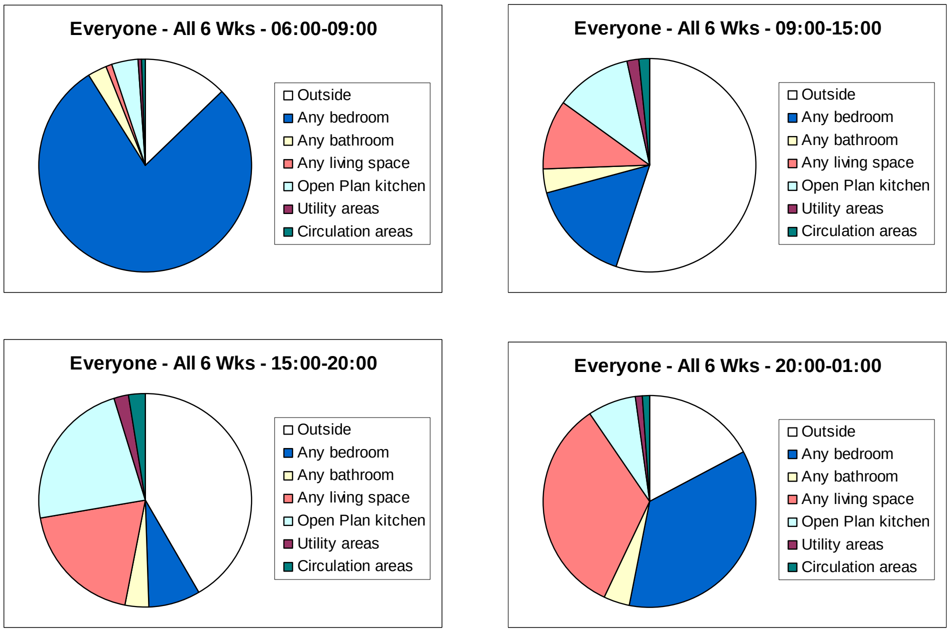
1) 6am to 9am (breakfast)

2) 9am to 3pm (lunch)

3) 3pm to 8pm (dinner)

4) 8pm to 1am (supper)

The average time spent by the whole family in each zone during each time band is shown in the charts that follow. Since each chart is distinctly different, it is clear that the pattern of room usage varies greatly according to the time of day, as of course was expected.


Everyone - All 6 Wks - 06:00-09:00

Everyone - All 6 Wks - 09:00-15:00

Everyone - All 6 Wks - 15:00-20:00

Everyone - All 6 Wks - 20:00-01:00

Figure 43: The division of each time band between each zone

The proportions also vary with the type of day being considered. Although a division between weekdays and weekends would seem a natural choice, for this study the division created was between the days when they had to go to work (or school for the daughters) and those when they did not. ‘Work days’ versus ‘Rest days’ is a more appropriate comparison since the 3 phases did not involve the same activities.

During Phase 1 everyone went to work or school (Lucy revised at home).

During Phase 2 everyone was at home on holiday for the whole 14 days.

Phase 3 was a mixture of one week at home and one week at work or school.

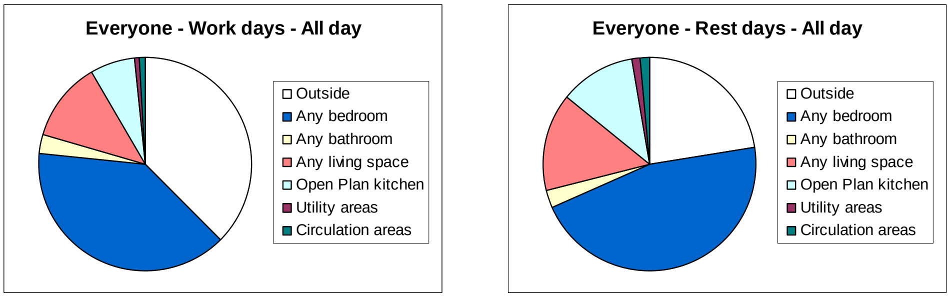


Figure 44: The average time spent in each zone on 'work' and 'rest' days

Of course the proportions also vary between the individual family members and so the data had to be considered from three perspectives:

1. Which individual it is (Sue, Nick, Lucy, Hazel, or the whole family)
2. What type of day it is (work days, rest days, or the whole six weeks)
3. What time of day it is (6-9am, 9am-3pm, 3-8pm, 8pm-1am, or 24 hours)

Appendix H contains the data that resulted from extensive analysis of the collected data. It would require a substantial number of charts to fully illustrate all of the information in these tables. An in-depth analysis report was produced for DWH just three weeks after the final phase of tracking had been completed [174], though only the most notable findings for particular rooms and zones are discussed in this thesis.

9.2 Where the family spent their time

9.2.1 Bedrooms

There were four bedrooms for the family to choose from. The master bedroom with access to both main bathrooms (B1), the first floor bedroom with en-suite shower room (B2), the top floor bedroom with a fully glazed corner (B3) and the top floor bedroom with a Juliet balcony (B4). Table 6 shows how much of the 24 hour day each of the family spent on average in each bedroom.

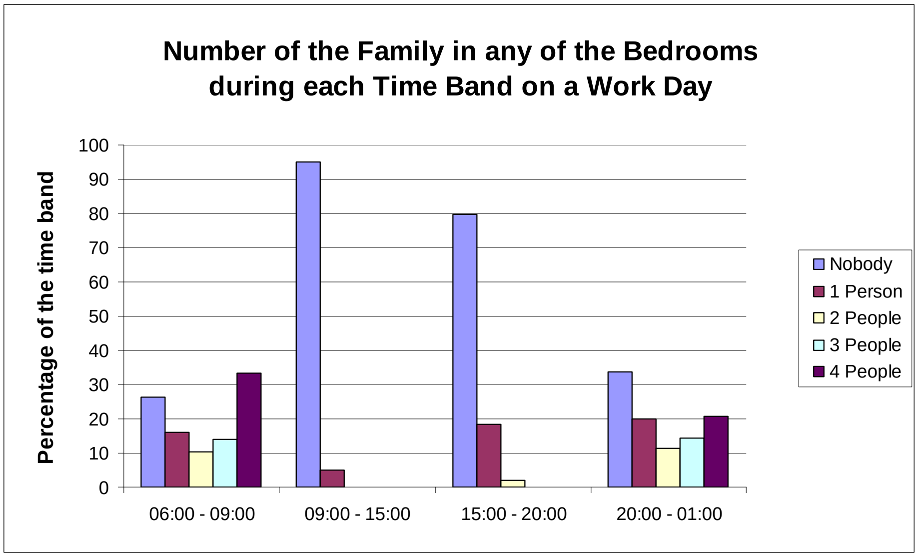
Table 6: Average hours spent by the family in each bedroom

	Work days				**Rest days**			
	B1	**B2**	**B3**	**B4**	**B1**	**B2**	**B3**	**B4**
Sue	8.4	0	0	0	9.8	0	0	1
Nick	7.9	0	0	0	8.4	0	0	0
Lucy	0	3.6	0.2	7.0	0.2	9.8	0.2	2.4
Hazel	0	0	10.1	0	0.5	0.5	11.3	0.2

The daughters spent roughly two hours more each work day and almost 3 hours more each rest day in their bedrooms than the parents did in theirs. Lucy swapped from B4 to B2 part way through Phase 2 of tracking, which explains why her results appear spread between the two. This meant that she began to use the en-suite in B2 as her bathroom and the time spent there is indistinguishable from the time spent in the bedroom space itself.

Most of the time in a bedroom they would have been asleep, so it is useful to look at how these rooms were occupied through the day. This is depicted by Figure 45 and the difference between work days and rest days is very clear.

Bedrooms were occupied longer in the mornings and less in the evenings on rest days and this was true for each of the family. Also, the bedrooms were used during the day by the daughters but not the parents.



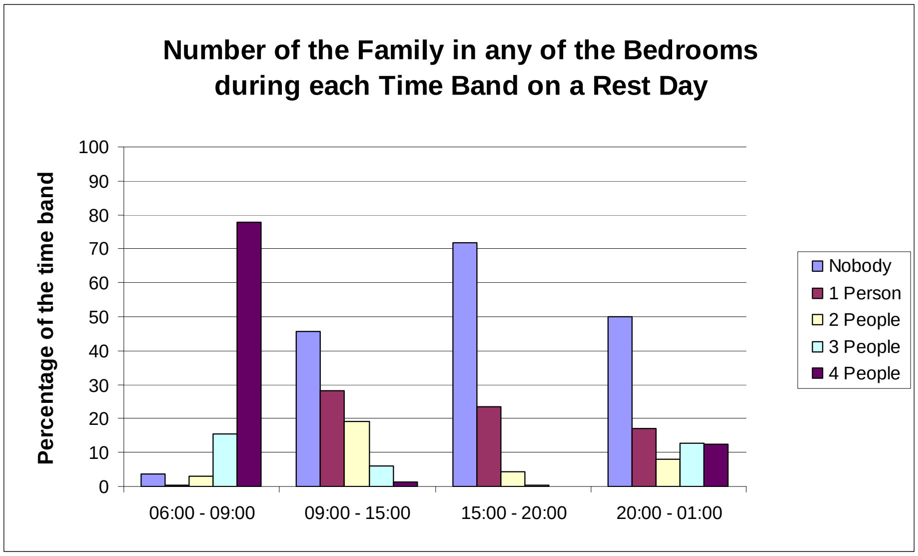


Figure 45: Bedroom occupancy on work and rest days

9.2.2 Bathrooms

The comparison of interest with regards to the bathrooms was to see how the family selected between the sunken bathroom that was only accessible from the master bedroom and the shared bathroom that was accessible through two doors; from either the master bedroom or the first floor landing.

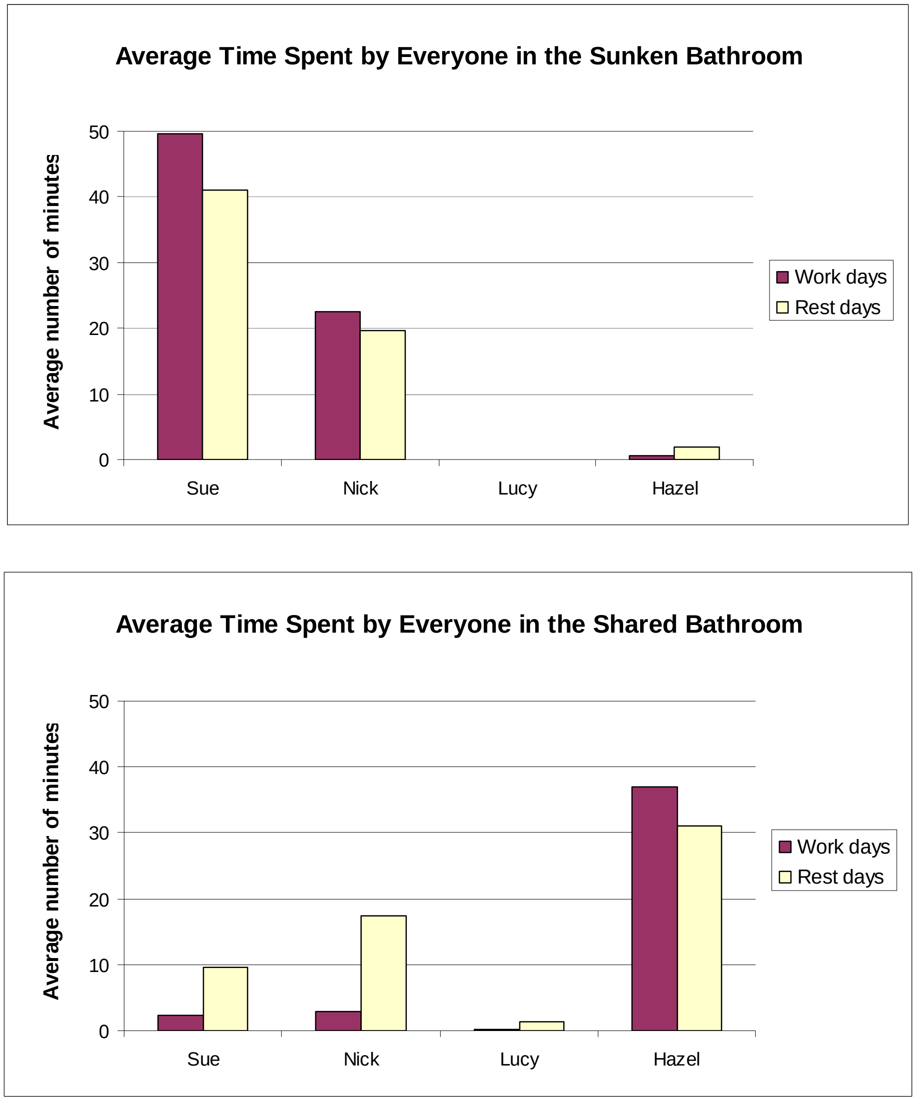


Figure 46: Time spent by each person in the sunken & shared bathrooms

As had been expected at the start of the project, it was Sue who used the sunken bathroom the most. She did not show a consistent pattern in her use of this bathroom, using it at all times of day when she was in the house, although generally more in the evenings than the afternoons.

Contrary to what had been predicted at the start of the project, it was Hazel who used the shared bathroom the most, even though she had to walk down three half flights of stairs to reach it from her bedroom. She used it fairly regularly throughout the day and evening although with an increasing trend as it got later in the day.

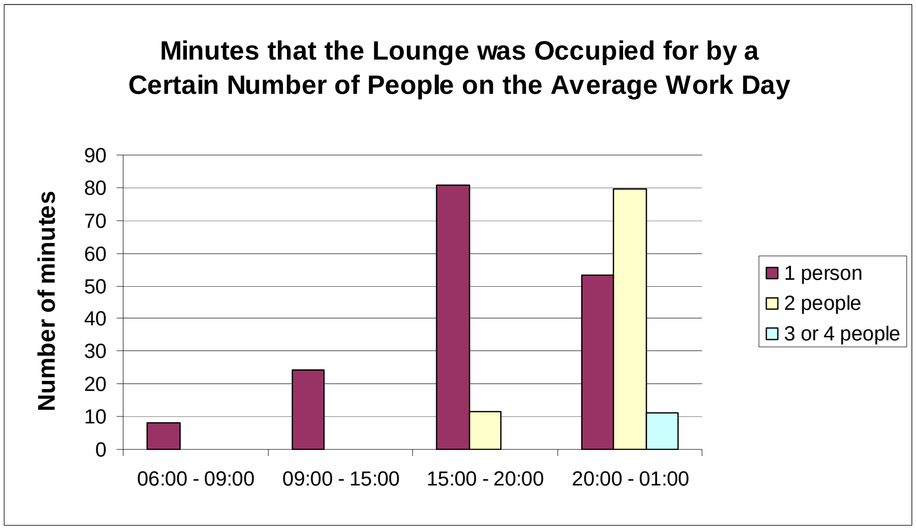
Nick showed a fairly distinct pattern in how he used the two bathrooms. On the days that he had to go to work, he primarily used the sunken bathroom in the morning and again, but for a shorter time, in the early evening when he returned home. On rest days however, although after rising in the mornings he still used the sunken bathroom more than the shared bathroom, he was more likely to use the shared bathroom in the afternoon and evening.

Lucy was the only member of the family to regularly use the top bathroom and this ceased to be the case when she moved to B2 which had its own en-suite. During the tagged spell that she was staying in B4, she was using the top bathroom at all times of the day, but especially in the late mornings of the days that she did not have to go to school. This bathroom subsequently became the bathroom for any guests who stayed in B4.

9.2.3 Living Spaces

The family spent a considerable amount of time in what have been called the living spaces (lounge, den, decking at kitchen level and option room). Of the six weeks of collected data, 14% of it was recorded in one of these four spaces.

Lounge



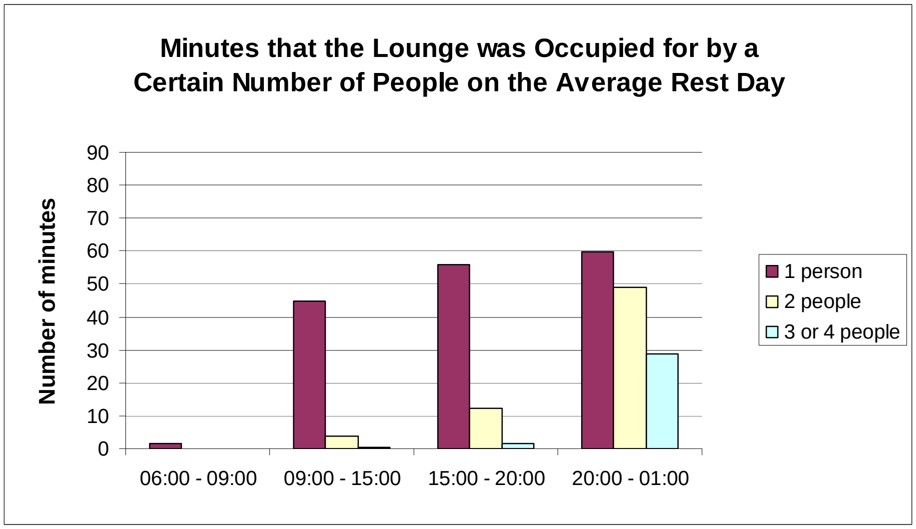


Figure 47: Average occupancy of the lounge on each work and rest day

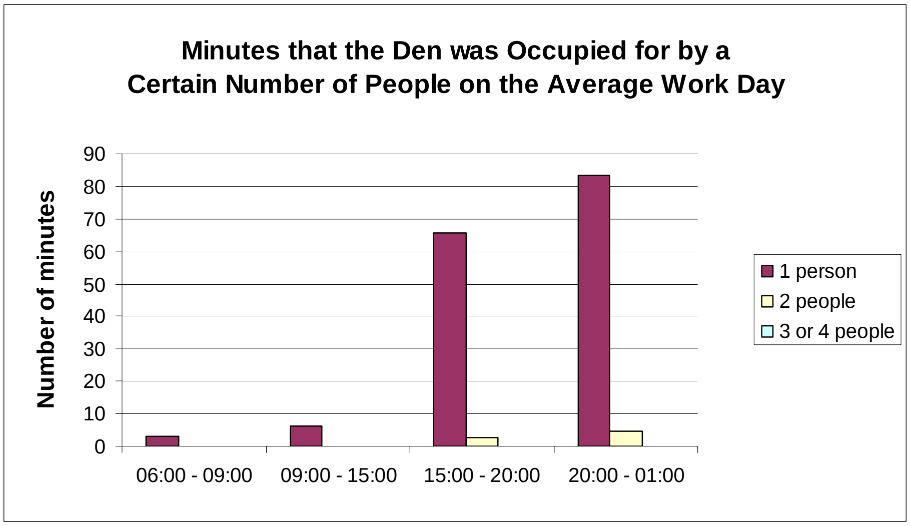
There was at least one person in the lounge for 19% of the study period, or 25% if you consider only the hours when someone in the house would normally be awake (6.30am to 00:30am).

Figure 47 shows that the lounge was used mainly by individual family members during the daytime. 60% of the time that it was occupied, it was by only one person, although it became a collectively shared room in the late evening; especially on rest days when 3 or 4 people would be in the room together for half an hour on average each evening.

Den

The den was more consistently used in terms of the length of time the family spent in it. It was occupied for roughly 20-30% of the day, apart from in the early mornings and during working days.

The den was a much more solitarily used room than the lounge and it was very unusual for more than 1 person to be in the room at the same time. Further investigation found that it was only being used regularly by two members of the family. For Hazel the den had become a regular alternative during the day and evenings to the lounge, which she did not use like the rest of the family. For Nick the den was a place to unwind alone in the late evening on workdays.



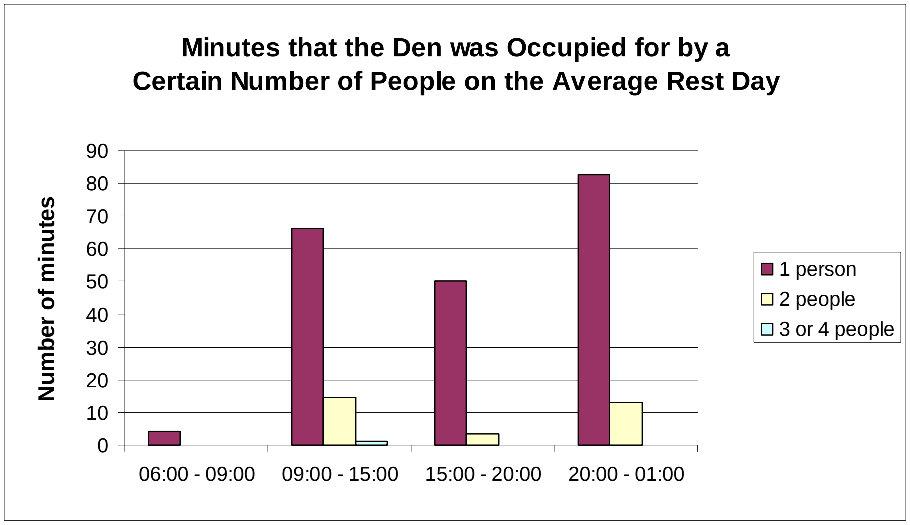


Figure 48: Average occupancy of the den during each work and rest day

Option room

Only Lucy made use of the option room to any extent during the six study weeks. She used it quite considerably on work days during Phase 1 and this was because she used the room to revise for her GCSEs. Subsequent to this phase, the family failed to find a use for the room.

9.2.4 Kitchen & Dining table area

Although the kitchen and dining table area were served by two separate RFID readers, it became clear during commissioning that there would be uncertainty when analysing the data as to which of the two areas a tag was actually in. Within the L-shaped, open-plan space there was an area where the proximity zones of the two readers would overlap and another covered by neither. An unknown degree of error was therefore introduced when analysing the raw data, as one area had to be selected over the other when it was actually unknown which the person was in. To overcome this error, the kitchen and dining table area are now combined into a single ‘Open-plan kitchen’.

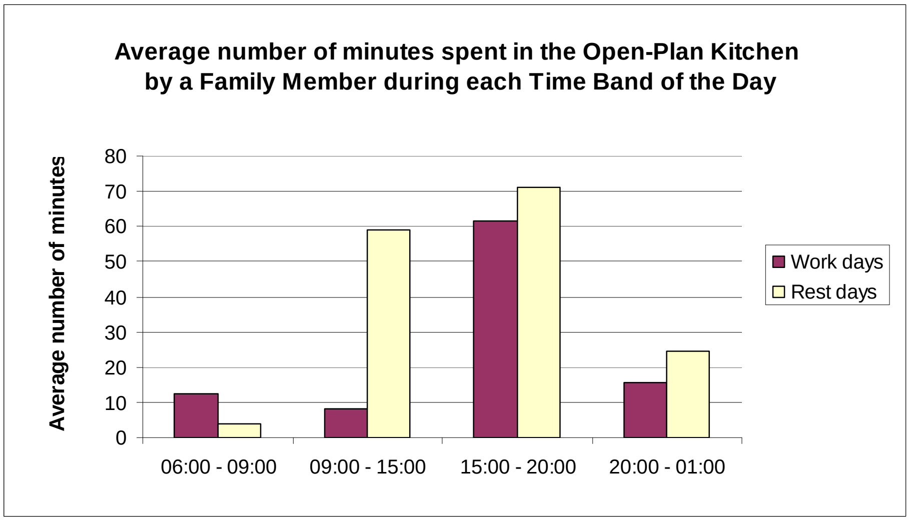
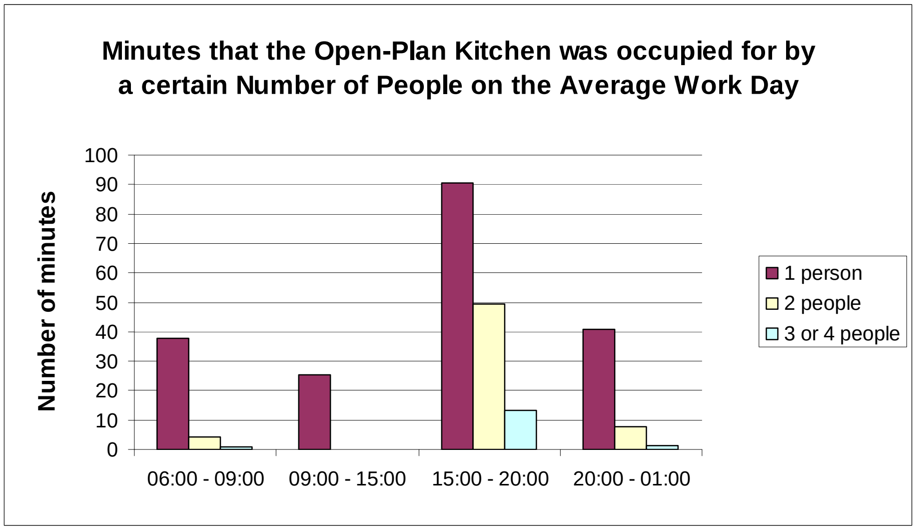


Figure 49: Average time spent in the open-plan kitchen

This pattern of use is formed as would be expected around meal times. The majority was in the early evening (dinner time), but also significantly in the late morning on rest days (late breakfast or lunch) and briefly in the early morning on work days (breakfast) and in the late evenings (supper).



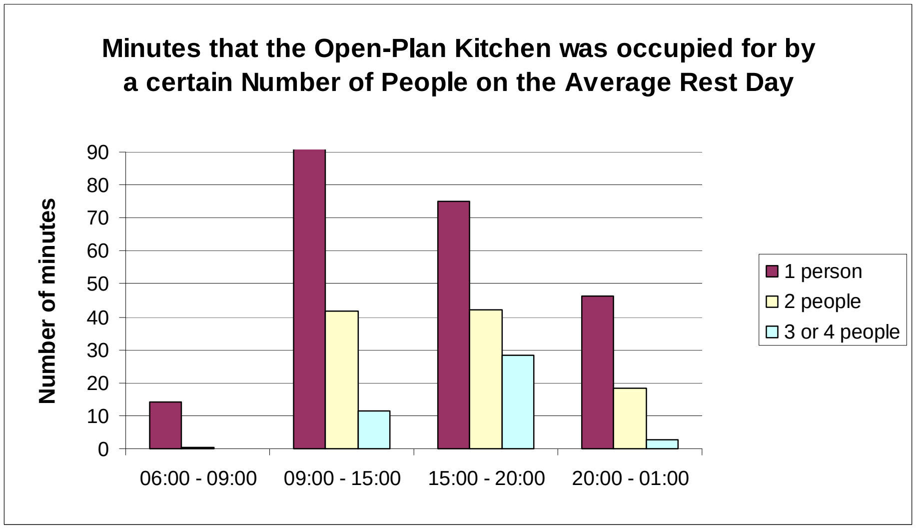


Figure 50: Occupancy of the open-plan kitchen on each work and rest day

Figure 50 shows that the open plan kitchen was in the main an individually used space. The family had staggered morning schedules, which meant they didn't use the space collectively in the mornings. They gathered here at lunchtime and in the early evening however, more than in any other room of the house. This study has therefore reinforced the commonly held belief that the kitchen, especially when open-plan, has become the hub of social activity and communication in the contemporary family household.

9.2.5 Utility Rooms

Laundry room

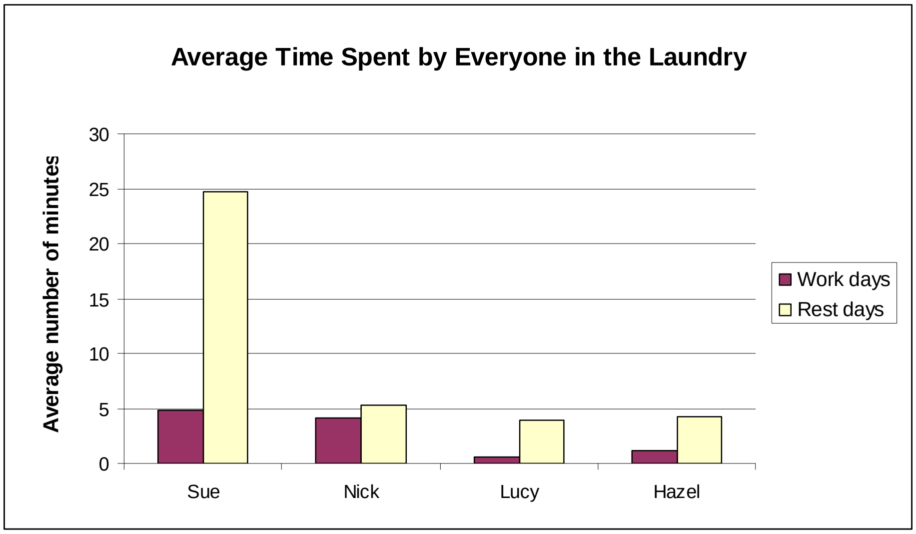


Figure 51: Everyone's use of the laundry room

Sue was in the laundry room for an average of almost 25 minutes per day on the days that she did not have to go to work.

Other utility rooms

Sue, Nick & Lucy made use of the boot room during the study but Hazel did not. This is partly down to the allocation of house keys, as Hazel had a key for the Kitchen side door but not for the Boot Room door.

Hazel made almost exclusive use of the Study. This was before they took the wireless laptop computer out of the room, from which point the only reason the family went into the Study was to collect print-outs.

9.3 Presentation of space use data

The pie charts and bar charts used in the previous section to depict the spreadsheet analysis of the collected data have enabled the family's behaviour to be compared on the basis of what kind of day, what band of time during the day and which family member was to be considered. The four chosen time bands represent the natural subdivisions of daily activity within the typical household, structured around the daily cycle of rising in the morning and taking breakfast, being away from the house at work or school, returning home and preparing for the evening meal and finally settling in to relax before bedtime. By grouping the data into these four bands, effective comparisons have been made on the general trends that lie within the household's use of space; however, this means of presentation cannot adequately convey the ability of an occupant tracking system to illustrate how the house is being used in real-time nor of how tracking systems could be used for the future applications mentioned in Section 6.2. The calculation of average room occupancies at a particular time of day across the study weeks cannot convey this information as, although domestic behaviour is made up of routine activities about the home, these routines do not necessarily take place at the same time each day. Calculating the average occupancy of each space has the effect of reporting all spaces as being partially occupied all of the time.

An alternative approach was trialled that could be used to investigate for the presence of routine movements. Figure 52 contains six frames of an animation created to convey the changing use of space within the house, according to the passage of time over a day when the family did not go to work or school. For this animation the occupancy data has been averaged over every 15 minutes of what was assessed to be a typical rest day. This assessment was made by choosing the day that had the most similar daily occupancy time of each individual room to the average for all 27 rest days in the study.

The animation of the typical rest day shows the following typical behaviour for this family: (time in brackets if a particular frame illustrates the point)

- There was a staggered start to the morning as the parents came down from their bedroom about one hour before their daughters. (09:45)
- Both of the bathrooms accessible from the master bedroom were used in the morning and evening.
- The top floor balcony was used to relax in privacy. (11:45)
- The den was used repeatedly for short spells throughout the day and in the evening it became an alternative to watching television in the lounge.
- The open-plan kitchen, dining area and lounge were used more consistently throughout the day than the den.
- The decking outside the kitchen was used as an extension to the open-plan dining area. (11:45 and 16:30)
- The house was usually vacant for a period of time each day. (14:00)
- The den, lounge and bathrooms were the typical spaces to relax in the evenings. (20:00)
- The father often went to bed later than the rest of the household. (23:15)

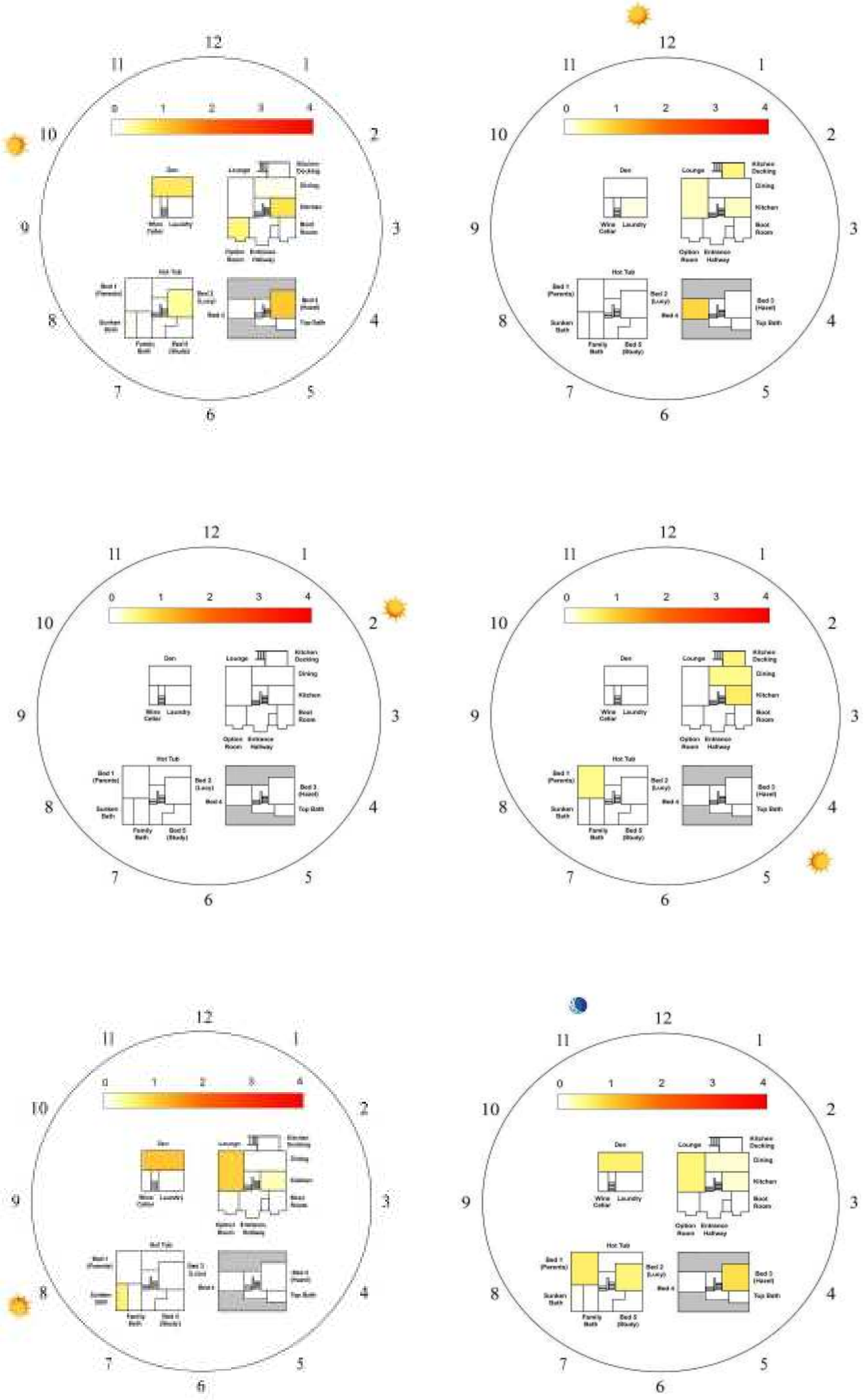


Figure 52: Animation frames - 09:45, 11:45, 14:00, 16:30, 20:00 & 23:15

Although the animation depicts the occupancy of rooms closer to real-time, the overall efficiency with which the space is used is of more interest when conducting a space allocation POE. In terms of a house, this efficiency could be defined between the floor area of a room and the time that it is occupied for, irrelevant of the number of people. This quantifies which spaces are most significant to the household routines and therefore most deserving of attention from designers to ensure they serve their functions well. Appendix I describes in detail how it was calculated and Figure 53 illustrates that the design mainly performed well since the larger spaces were also the most occupied.

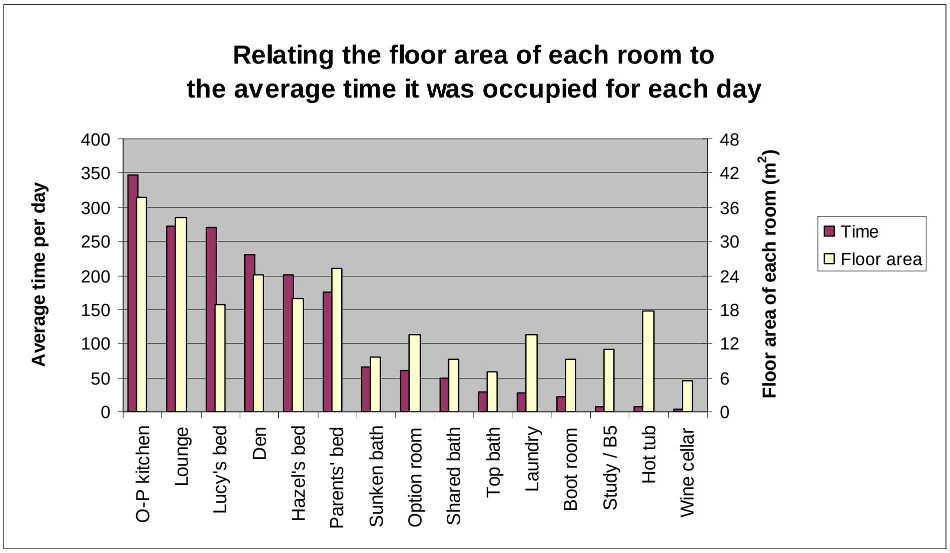


Figure 53: Comparison of each room's floor area and average occupancy

At first it appears that Lucy's bedrooms (B2 & B4) are too small and the parents' (B1) is too large; however, two factors have not been considered. B2 had an en-suite bathroom attached and the time that Lucy spent there was indistinguishable from the time that she spent in the bedroom itself, so they had to remain combined in Figure 53. Also, B1 is used by two people rather than one and so would naturally be expected to contain more space. Some other rooms do appear though to be excessively large relative to the time spent in them: the laundry, boot room, study, hot tub decking and wine cellar. It may be possible to combine their functions into a smaller footprint; however some further points must be considered:

- Many rooms performed functions even when unoccupied; for example, food and drink storage in the wine cellar and washing in the laundry.
- Additional space may be required depending on the function that is being served; for example, while computer monitors are best viewed at close range, televisions require there to be distance between screen and viewer.
- The time spent in a space may be determined primarily by the activity undertaken there and this may change considerably over future years due to technological development. For example, microwavable convenience meals can shorten the time spent in the kitchen and broadband internet may increase the time spent in the study, though a wireless internet connection can remove the tie to a specific location altogether.

The basic assumption that the rooms occupied the longest should also be the largest implies that the value of each unit of time spent in the house is equal, though the points above show that this clearly is not so. The occupancy time is just one dimension of a room's importance and is very often a reflection of the activity undertaken there rather than the financial value attributed to it by the household and designers. If space allocation POE is to be quantified using time, the need therefore remains to question the household on the qualitative importance of each space and how the time spent was subjectively perceived.

9.4 Qualitative interviews

It cannot be explained why the family spent their time as they did by looking only at the quantitative data. This was the first time that an occupant tracking system has been used to carry out a POE on domestic space use; however it was still necessary to use the more traditional techniques of qualitative research to substantiate the quantitative findings. Questionnaires, interviews and focus groups have for many years been used to gather subjective feedback from households, and the family was interviewed four times during this study. First in their own house before the experimental house had been constructed, to gather background information on the homes they had lived in previously and how they felt their current home met their needs and expectations. Then each of the tracking phases was concluded with an interview, to discuss how they felt they had spent their time in the home and what design features had been influential. Each interview was led by Dr James Fitchett, Reader of Consumption and Marketing at Leicester University, who conducted and recorded the interviews in the robust nature of social sciences. Extracts from the interviews were included in the report handed to DWH [174] and in their own published document [145], and a joint paper shall be published on this aspect of the project in the near future [175].

In the main, the information gathered from the interviews agreed with what was recorded by the RFID system. The family were very appreciative of the additional space and natural light that the house provided, commenting that this was what most visitors pick out first on entering the hall.

"When you walk in… you look up and there's that expanse of sort of light and space. It's a big wow."

They found that the additional space had a downside too however, as this led to the family very often doing their own things in their own separate spaces.

"We kind of lose people here... I don't really like that aspect of living here very much. That's not something we used to get in the old house, so there's that side of it, but then again on the other hand we sometimes got on top of each other in the old house."

Although the family appreciated that they no longer had to compete for spaces in the house, which made life more relaxing, they found to begin with that it was affecting their social behaviour as a family unit and in fact the parents felt the need on occasion to search for their daughters so that they could spend more time together as a family. This follows what was seen in the RFID data in that Hazel often used the den as an alternative to the lounge when others were there and Lucy spent more time in her bedroom during the day than everyone else. It cannot be confirmed if their behaviour changed after moving into the concept house, as no data was collected in their old home.

A further general point on the space layout was directed at the split-level design of each floor. While this was described as fantastic for people from teenage to middle age, the difficulties that having so many steps brings to the very young or elderly visitors was picked up on as an issue due to their reduced mobility and concern for safety. This issue is raised again in Section 9.5, where a possible solution is suggested.

The main points that the family raised about each room are now presented, starting from the basement level.

- The den was a very popular room although not used by everyone equally. They liked the fact it was a multi-functional ‘escape hole’, describing the times they spent there as, *“very much ‘go away, I want to be left to do this on my own’.”* The tracking data corroborated that the den was a solitarily used space. The den had also found use as a bedroom during the study, when a guest could not sleep in the study because of equipment noise.
- The laundry was also a well received room, with the laundry chute and extra space to sort the clean clothes both being appreciated. The lack of entertainment facility in the room was noted however, which made the chore of ironing even less pleasurable than it needed be.
- The open-plan kitchen and dining area became the heart of activity during parties as well as daily life, with the lounge sometimes not being used. More space was requested for the kitchen, for food storage and preparation.
- The family repeatedly mentioned the décor as being a main reason why they were not using the lounge as much as in their previous home. They would have changed much of the lighting and wall decorations, including the flat-screen television. They did not find the room to be cosy and the suggestion was made that this could have been due to the high ceiling.
- The split-level, rear patio decking areas were successful spaces to eat, relax or entertain guests when the weather was suitable.
- The family were never inclined to use the option room as a dining room, even though this was how it had been dressed before they moved in.

Instead the suggestion was repeatedly made that it would have been a better use of space had this room been kitted out as a proper study, since the upstairs study was rejected for various reasons.

- The study/bedroom 5 was considered a failure because of the noise generated by the centralised entertainment equipment and the server PC for research that were housed in cupboards in this room. Additionally, the room was reported to have an isolated feeling to it. Rather than seeking seclusion in a study, this family prefer to remain close to the living areas so that they can remain aware of other household activity as they work.
- What was said during the interviews about the use of the four bathrooms agreed with what had been found from the RFID data. Nick commented that he used the shared rather than sunken bathroom in the mornings if Sue was still in bed so as not to wake her up, which illustrates the benefit of having the flexibility of two luxury bathrooms.
- The family commented that all of the bedrooms were overheating in the summer months. This applies in particular to the master bedroom (B1) since the only possible ventilation was to leave open the French doors and also the glazed bedroom (B3) because there is so much glass and only one of the windows could be opened. These comments enhance the findings of Section 8.3 on thermal overheating.

9.5 Review of the house design

The purpose of the qualitative interviews was to corroborate the POE data collected by the tracking system and explain why the spaces had been used as they were. The tracking data could indicate which spaces had been the more or less successful, which could in future be fed into planning the interviews so they were more focused and less time consuming; however, the tracking data could not be used to judge how the design could be improved, as this depends on knowing what purpose and value the household gave to each space. By considering both sets of data, the following review could be made.

Successful spaces

The U-shaped open-plan living space created by the long, high-ceilinged lounge that went up the half flight of stairs into the dining area and kitchen was a great success. It was recorded that this was where the family spent most of their time, collectively making use of this combination of spaces and remaining within earshot of each other even though they were not in the same strictly defined room. DWH interpreted this as *"living together but apart"* [145] and the multi-functionality that it implies is one of the hallmarks of open-plan design.

The provision of the basement den was found to be the ideal complement to the open-plan ground floor when someone wanted to retreat to a more private space to relax alone. The additional sound insulation of this pre-fabricated concrete space was also well appreciated in the late evenings.

The bedroom and bathroom configuration worked well for this family and they have shown that the best approach may be to provide options and flexibility. While the parents appreciated and made use of the choice of two luxury bathrooms accessible from their bedroom, the daughters showed that individual priorities can count for everything. At first Lucy was staying in bedroom 4 and had claimed the top bathroom for herself, though she later moved to bedroom 2 for the added convenience of the smaller en-suite shower room it contained. Hazel meanwhile continued to walk down three half flights of stairs to access the shared bathroom, even though the more convenient option of using the top bathroom had become available. So convenience was more important than luxury for Lucy, but luxury came before convenience for Hazel. Designers cannot of course predict how these individual behaviours will play out and so they should instead include flexibility in the bedroom and bathroom hierarchal design if possible.

Unsuccessful spaces

The study was one of the least used rooms of the concept house even though the family had made good use of the study in their old home. The interviews revealed that the activities that took place in their previous study were now being carried out in places where they were more enjoyable, such as in the dining seating area. This was possible thanks to the wireless computer network and the additional space that was available in this house. Also, the family were not happy with the noise and uncomfortable conditions in the study caused by the large quantity of electronic equipment required for the central entertainment system and the server PC for the tracking and environmental monitoring systems. These conditions also resulted in this room failing in its second role, as a guest bedroom, when a household guest decided to sleep in the den rather than in this room.

Suggestions for improvement

There was no special requirement for the central entertainment equipment to be located in the study and the server PC would not normally be present either. If the equipment were moved elsewhere this room could be kitted out as a permanent bedroom, adding value to the home. The user of this bedroom would be expected to make use of the shared bathroom just across the hallway. Although the wireless broadband provided freedom from a desktop computer, the family still requested a dedicated space for study, printing and other office furniture. The ground floor ‘option room’ was suggested as the ideal location for this study, as this family’s preference was to be able to work while still feeling connected to the activities of the rest of the household. Plus the den was available for the times when seclusion was required.

The top floor bedroom featuring a rooftop balcony was vacated by Lucy halfway through the study, at which point the secluded balcony started to be used by other members of the family. If this bedroom were to be turned into an alternative function room with a sofa bed for example, then the house could be marketed as five bedrooms with a communal room featuring a balcony.

The father appreciated the boot room as a place to discard his wet or dirty outdoor clothes; however, the suggestion was made that had there been a shower cubicle nearby, he would not have had to walk up the carpeted stairs in a wet and dirty condition to one of the main bathrooms. A possible solution to this would have been to swap the boot room with the laundry room below and fit a shower cubicle under the stairs to replace the wine cellar that could be integrated into the new ground floor laundry room.

- The new boot room would have an entrance that was closer to the garden that both parents liked to tender. Previously, to avoid walking dirt through either the den or lounge, they often used the kitchen door as the convenient access from the garden, although this was not the most hygienic behaviour.
- This lower boot room would still be used by the household when they arrive wet or dirty from their outdoor activities and there should be more than sufficient space for indoor bicycle storage. The cellar space could contain a shower cubicle for when someone wished to wash before entering the main living space of the house and the existing ‘mobile hanging’ space should be maintained to store clean clothes for these occasions.
- The shower room could incorporate with ease a WC for those using the den and the boot room will still have plenty of space for the kitchenette equipment it already contains. In this way, the sunken basement could become a self-contained bed-sit should there be a time when someone who has difficulties with stairs is living in the house.
- A ground floor laundry room that would be used for irregular but quite lengthy spells would benefit from natural light, a view outside the front of the house and the ability to listen to the distributed sound system whilst doing the chores without disturbing any occupants in the den. Cleaned laundry would not have to be carried up the extra flight of stairs. If privacy

is required, net curtains or opaque glass could be installed and the position of the garage could also prevent prying eyes from looking in.

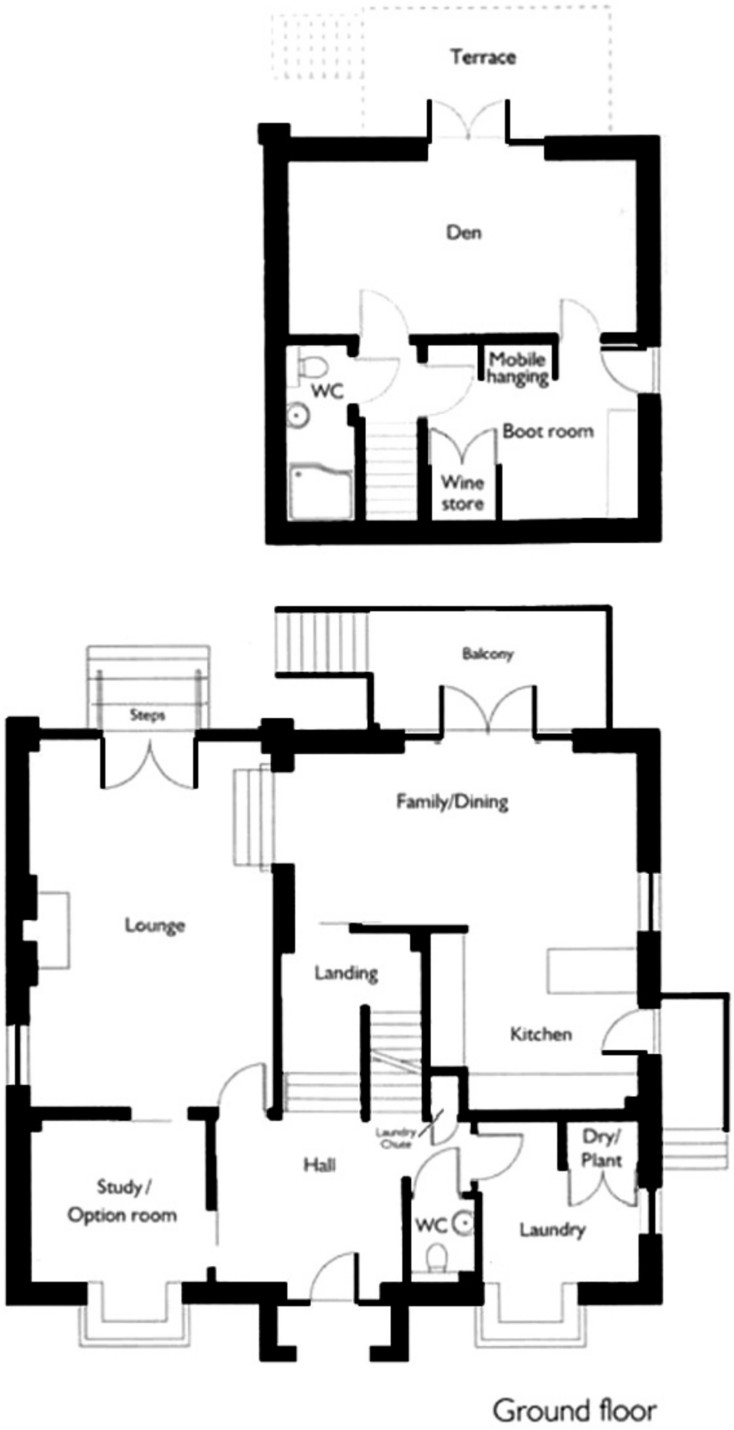


Figure 54: Adapted floor plans for the basement and ground floor

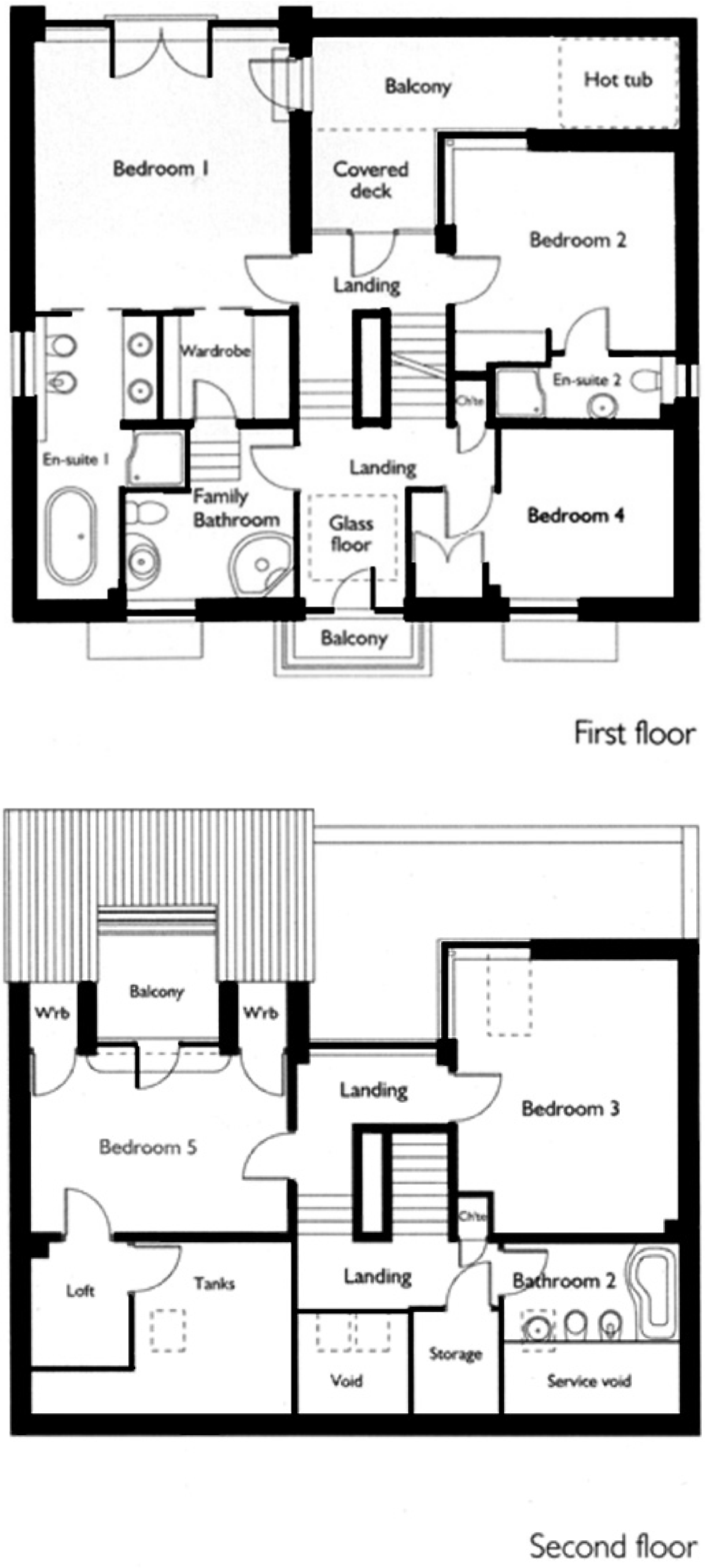


Figure 55: Adapted floor plans for the first and second floors

9.6 Smart Home Application

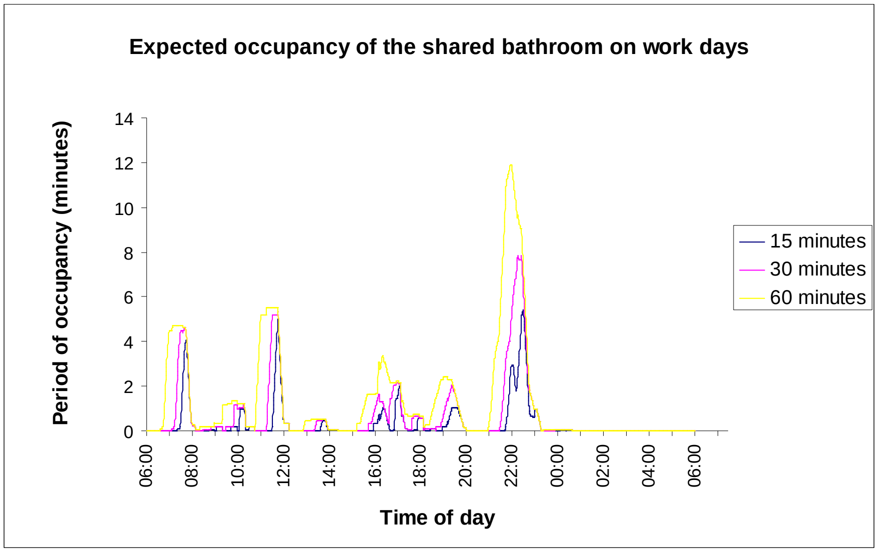
One of the often stated applications for occupant tracking systems is that a building management system (BMS) could respond dynamically to the movement of occupants and the general patterns of space usage in the building. This principle has been the focus of a number of research groups elsewhere, as discussed in Section 6.2. This thesis can contribute to that body of work by approaching an assessment on the potential for dynamic zoned control of the heating system, whereby if a defined zone is not in use then it does not need to be heated to full comfort conditions, saving both energy and money. Before a full assessment on this type of system would be possible, a number of factors would need to be taken into consideration, including:

1. The setback conditions to be used once each zone becomes unoccupied.
2. The acceptable time period for which each zone could acceptably be below normal comfort conditions, should it unexpectedly become occupied.
3. The response time of the heating system to heat the zone up from the setback condition to the required comfort condition.
4. The expected times of occupancy of each zone throughout the day.
5. The zoning regime that most favours energy efficiency and life cycle cost.

On first consideration, it is suggested that the setback temperature and acceptable time of sub-comfort conditions should be user definable, so that some default values can be changed depending on the occupants' needs and preferences. The heating response time and zoning regime depend largely on the specific context and installation, and as such, it is not possible to provide clear answers to these points at this stage in the research. The collected data can be used however to investigate the fourth point: the expected times of occupancy of each zone throughout the day. The objective is to illustrate if it would indeed be feasible to have a heating setback condition for certain rooms because they are regularly unoccupied for significant spells of time.

If space heating was instantaneous then the system could always be turned off when no-one was present, but this can not be so as there will always be a lag between the heating being turned on and the comfort conditions being reached. The faster the system’s response time, the more often it could be turned off to save energy and money. The response time would depend on the method of heat distribution, the volume and shape of the space and the materials present within the space, all of which are context specific.

The 6 weeks of collected data were re-examined for three arbitrary response times - 15 minutes, 30 minutes and 60 minutes - and a series of graphs show dynamically how long on average each room was occupied for during the response period that followed. The data was split into work and rest days since it is assumed that the system would be intelligent enough to distinguish between them. Rather than including all of the produced graphs, they are selected in order to illustrate some initial points of discussion that follow.



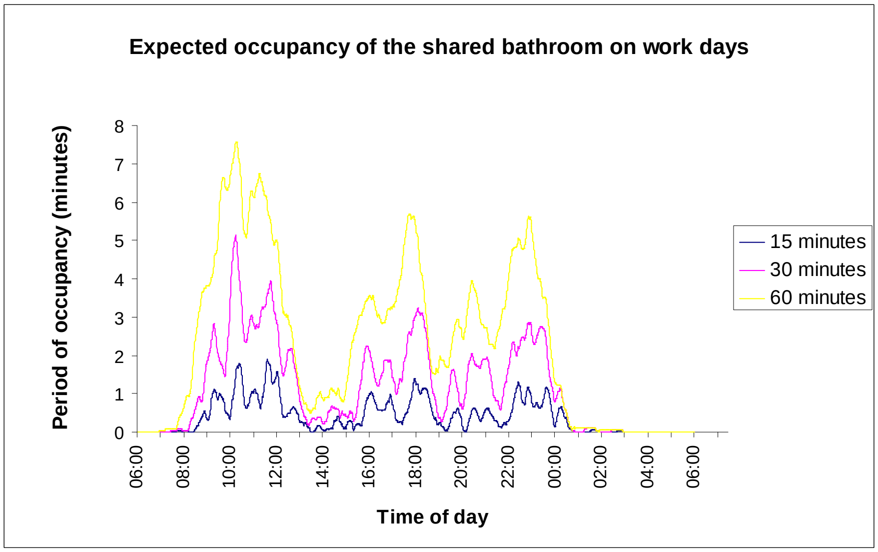
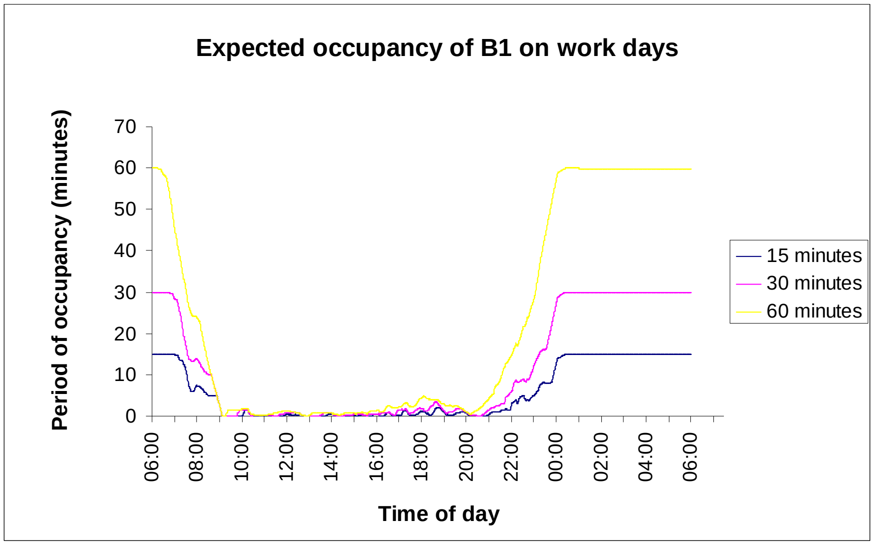


Figure 56: The occupancy of the shared bathroom over the 6 study weeks

Figure 56, which depicts the shared bathroom occupancy, makes two points:

- The time that activities take place at is more flexible on rest days and so the bathroom’s occupancy appears to be more continuous.
- If the heating system response time is longer, there are fewer opportunities to set back the environmental conditions. This is seen as the gaps between each spike are shorter and in some cases disappear for the 60 minute traces.



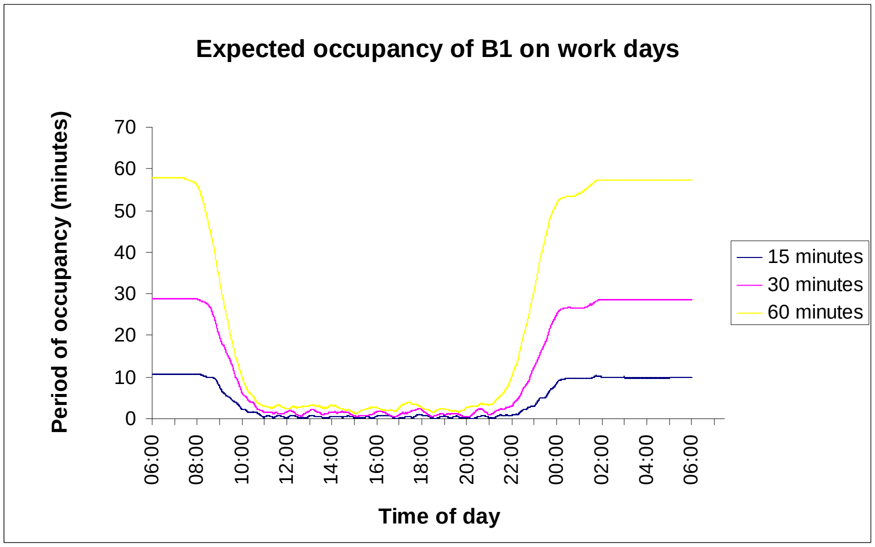
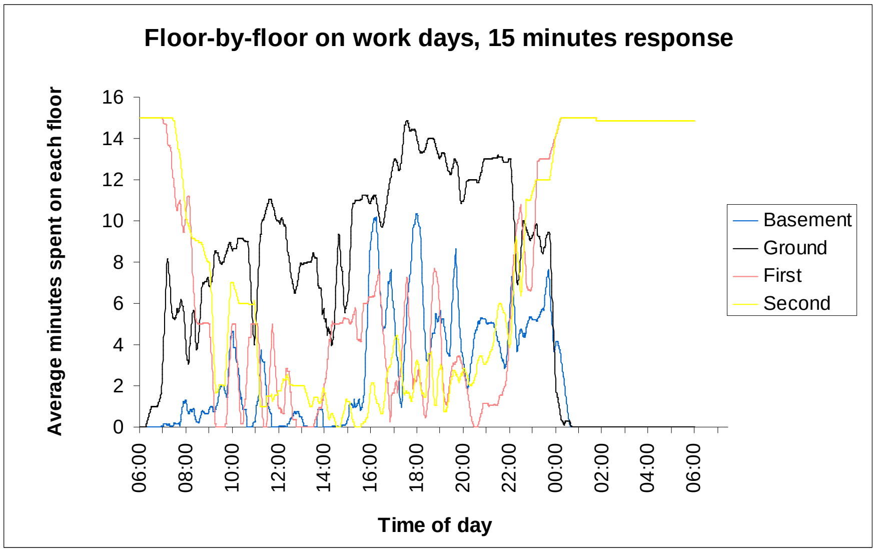


Figure 57: The occupancy on rest days of the master (B1) and balcony (B4) bedrooms

The vertical scales in Figure 57 differ because Lucy moved out of the balcony bedroom during the second phase; however, it illustrates clearly that different people will make use of what is essentially the same room in ways that are closely aligned to their activities, gender and life-cycle stage. These conditions cannot be predicted by house builders or heating system installers, which is why full adaptability is essential if this type of system is to be used.



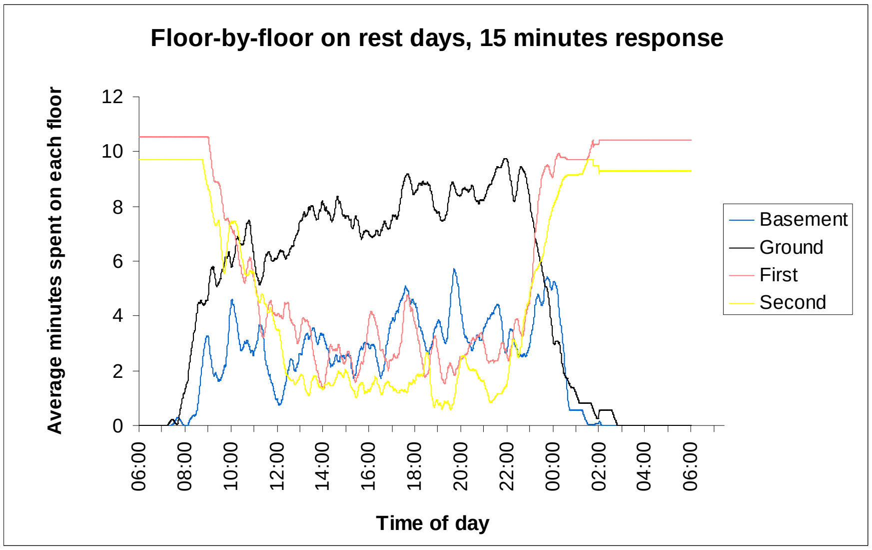


Figure 58: When each floor of the house was in use

Figure 58 depicts the occupancy on a floor-by-floor basis and the top graph illustrates very well why it would be necessary to provide responsive controls or a manual override. During the first phase, Lucy stayed at home to revise for her GCSEs and so the ground floor in particular shows steady use during work days. The rest of the family started these mornings with their normal work schedule and so the system might have expected everyone to be leaving the house, enabling it to operate at setback conditions. The system would have to respond appropriately to Lucy disrupting the pattern, which could be as simple as a default setting that provided full comfort conditions.

Individual room heating zones would provide the most frequent opportunities to set back the system and hence achieve the best fuel savings; however, the additional cost of system complexity might make another zoning regime preferable. Figure 58 shows that the ground floor is consistently used much more than the other floors, which would suggest that the heating could be focused here. All the traces have a significant number of spikes though, illustrating that the other floors were also used considerably but not for as long or as regularly day-to-day. On this evidence it does not seem appropriate to zone the system for this house on a floor-by-floor basis if comfort conditions are to be maintained using setback conditions.

Averaged data discounts the irregular occasions when time is spent in a room. A setback system that was controlled purely by averages would lead to a room always being cool if the occupants went into it frequently but irregularly day-to-day. This is unavoidable if the setback strategy is taken, but perhaps it could be effectively controlled if the system took account of weighting factors on the importance of comfort conditions being maintained and the probability of occupancy, which could be determined over an initial observational period when full comfort conditions would be maintained. If heating systems like this were installed in enough households, the data required for space use POE to improve the allocation of domestic space could be collected as a secondary concern to direct economic savings to the household.

9.7 Chapter Conclusions

This experimental project proved it feasible to use an RFID tracking system to monitor the time spent by a household in each region of domestic space. It was shown that such assessments can add value to a space use POE by corroborating and bringing a new level of detail and accuracy to the more traditional approach of interviewing the household to gather qualitative data.

Interviewing or surveying households suffers as a POE data collection technique from ultimately relying on the recall of the participants on their behaviour. Factors such as their liking of the décor in a space, the activity that takes place there and the level of interaction with other household members can all affect the subjective perception of the flow of time in a space, although as a topic this is beyond the boundaries of the present research. The supposition though is that interviewees can sometimes unwittingly give false information because they have perceived events to be different to how they actually were. This is assuming that they do in fact provide details, which can be difficult when conducting group interviews as particular members can come to control the conversation and provide their subjective version of events without others having the chance to voice their beliefs. Individual interviews are of course possible, but they are also more time and resource demanding and may ultimately lead to very little new information.

The use of a tracking system was shown in this chapter to provide information in a far greater level of detail than could ever have been recalled by any individual member of the family. Although the commissioning of the system raised some technical issues that may have affected the true accuracy of the information generated, the signal bleed-through and detection time lag were managed through developing an understanding of the system performance and manual review of the data. The data itself was objective, accurately time-stamped, gave equal weight to the behaviour of all four household members and is quantifiable in a way that enables comparisons on the use of each space within the home to form part of a greater POE data set.

The data was analysed and presented in a number of different styles. A room-by-room assessment was made in Section 9.2 that grouped each individual's behaviour according to the type of day and period of day being considered. This presentation method effectively conveys the general behaviour of each household member and how each room was used over the course of the average day. Since no two days were the same however, perhaps the computer animation represented in Figure 52 of Section 9.3 best conveys the constantly changing use of domestic space over a typical day, although the assessment of a typical day itself is uncertain as external influences are constantly changing the routines that make up the days. A third approach was then taken to investigate whether the largest spaces in the house were also the most significant to family life, measured by the time for which each space was occupied for over the average day. The assumption that the significance of each space is related only to its occupancy is clearly incorrect however when the multitude of functions that a room may serve even when unoccupied is taken into consideration. Each approach taken to present the data has its own limitations therefore and this could be an important area for further development if housing design is to be influenced by space use POE.

It is clear that data collected on occupant movements should not be analysed in isolation, for the patterns and regularities do not explain why one space is valued above another or even if those most occupied are also the most valued. The need remained therefore for the subjective opinions of the household to be collected as well, which were reviewed in Section 9.4 and completed the picture of how the family behaved within the home.

The benefit of gathering both sets of data was then developed in Section 9.5 through suggestions that were made on how the house design could be improved for the lifestyle of this particular family. The suggestions work within the existing fabric structure of the house and are considered to make a more marketable product overall through increasing the number of bedrooms, making more efficient use of space by bringing the ‘option room’ to life as a study, assisting in domestic chores by moving the laundry room and food store to a more convenient location on the ground floor and finally through making it adaptable should mobility impairment become a future issue within the household by making a self-contained accommodation possible in the sunken basement.

In conclusion, both sets of data, quantitative and qualitative, were discussed fully at the end of the study with DWH designers, which has had influence already. In the words of DWH development director James Wilson,

“These learnings are already forming the basis for design change in our homes and directing new areas of design within the product range.” [145]

10 Expanding on the POE Research

The data collected and reported on in the two previous chapters have provided David Wilson Homes (DWH) with detailed information on how the experimental house was used that has already been influential in their designs for future homes and that was unmatched in terms of its accuracy and resolution to any previous research found in the literature. The combination of quantitative data collected by RFID tracking and qualitative data from the traditional approach of face-to-face interviews has provided a more complete picture than achieved before of where a real family spent their time in a modern home and how that time was valued.

A valid criticism that remains on the research is that the experiment, in the nature of all pilot studies, was of an individual group of subjects whose behaviour may or may not have been representative of the population as a whole. Conclusions reached on the behaviour of the family within this one house can not be extrapolated to the housing market as a whole.

To address this issue, the ideal scenario would be to carry out a tracking research program of a large sample of families within their homes to provide some statistical benchmarks for comparison. The resources that such research would require are substantial however and far beyond what were available for this project. It may be that this scenario could develop unassisted through the gradual uptake of Smart Home technology, whereby the data is collected to enable the benefits of the applications described in Section 6.2, but this is not expected to occur in the near future. At this point in time therefore, despite the limitations discussed in Section 3.2, a text based survey still presents one of the most effective means of gathering a large sample of data on the subjective opinions of the wider population. The survey answers can be represented in a quantifiable way that enables benchmarks and trends to be distinguished.

In addition, as was also argued in Chapter 3, there is a great need to gather the honest opinions of households on the sustainable approach being advocated in this thesis. Section 3.3 reported on an investigative questionnaire developed using a sample populated by occupants of more-sustainable homes. While this postal survey was straight-forward to complete, it was targeted at a specific group who may not have been representative of all occupants of more-sustainable homes but were assumed to be knowledgeable of the issues at hand, so sustainability and energy efficiency were approached directly by the questions. To fully appreciate the responses received to that survey, the opinions of mainstream households is also required, to discover if there are any exceptional differences in the motivations or experiences of those who have already chose to live in a more-sustainable home.

This chapter addresses these shortfalls in data by first demonstrating that an individual POE study can have influence on housing research beyond its own group of subjects. Secondly, it shows a way that the opinions of mainstream households can be gathered and compared to the occupants of more-sustainable homes, to illustrate if there is a discernable difference. This is one of the key requirements before the market differentiation of more-sustainable homes could occur due to the positive living experiences that they may bring.

10.1 Development of the online survey

It is clear that not enough is known in general about what use people make of the spaces within their homes to enable the findings of an individual POE study to be compared against the behaviours of all households. A prime objective of this survey was therefore to demonstrate a means to assess where some basic activities take place within the homes of the general population.

Additionally, it was to demonstrate the sort of comparisons that could lead to a better understanding of the differences between mainstream households and those who already occupy a more-sustainable home. Sustainability as a topic was not to be approached directly however because of the influence that a direct line of questioning on environmentalism can have on the respondents (see Section 3.2). So more general questions were used on good and bad house design, with the intention that if sustainability issues were important to the respondent then they would be raised unprompted.

The survey reported on in Section 3.3 was conducted by mail and targeted at the residents of East Midlands homes that had previously been identified as sustainability case studies. The postal approach enabled this select population to be targeted, though it was labour intensive to prepare the 214 surveys sent out and to input the 65 responses into a database. Since a key requirement for the second survey was to gather a much larger response sample, from a population that could be expected to be even less enthusiastic to respond voluntarily, a randomised postal survey was deemed inappropriate given the time and resources available. Instead the opportunity was taken to launch an online survey immediately after the publication of the study findings and a media event held by DWH that received good coverage in the local and national press [176]. It was expected that this event would provide a level of exposure that could not realistically have been otherwise achieved and so to enable a rapid and appropriate response, this survey was conducted from a webpage linked to the Project:LIFE website that was promoted by the press coverage, DWH and using the University's email system.

The decision to conduct the survey in this manner meant that no controls were put into place by the sampling procedure to ensure or test if the respondents were representative of each social, demographic and geographical group of the mainstream house buying population. This survey has instead gathered responses only from those people with access to a PC and internet connection who had heard about the project and felt motivated enough to respond. There may be instances where the same person has responded more than once or even where the respondent is already living in a more-sustainable home.

The almost complete lack of sampling criteria means it must be stressed that the information contained in this chapter is not intended to reflect the opinions of all UK house buyers. The survey would have to be conducted in a far more robust fashion in the nature of the social sciences before any general beliefs of households could be identified. Nevertheless, the indications it has made are that it may indeed be possible to learn some lessons for general and more-sustainable house design through mass market surveys.

10.2 Findings from the online survey

614 responses were received in total and Appendix J reviews the questionnaire and the responses obtained for each question. The responses were heavily inclined towards the younger age groups, with 45% in the 18-34 age range and 34% in the 35-49 age range. Although these two age groups only represent roughly 22% each of the UK population [21], they respectively constitute approximately 67% and 25% of first-time buyers [177]. The average age of a first-time buyer has risen in recent years to 33 [178] and though they account for only 30% of new mortgage loans [177] they are the target market for the smaller and affordable homes that will most benefit from efficient use of space.

The mix of homes that the respondents live in compares reasonably to the national averages provided in the English Home Condition Survey [16]. Their homes fell into every band used in the online survey for construction year that were based on the work of others [179], though it is suggested that these should match the five bands used in nationwide data in future [25] that are broader, more evenly spread and would validate the sample representation. Only 8% of the responses received reported not knowing the age of their home. Most of the respondents had lived in their homes for less than 5 years and there was an average of 3.0 people per house, greater than the national average of 2.4 [21].

These findings are likely a reflection on the sample bias towards the younger age groups, possibly at University, for whom larger house shares in temporarily leased accommodation are popular. Future surveys should aim though to be proportionally representative of all home buyer groups.

What makes a good home?

6) Based on the experience of living in your home, please rank the following six aspects of house design in the order of importance that you place on them.

1 (least important to you) to 6 (most important to you)

You should use each value only once.

	1	2	3	4	5	6
Comfortable indoor environment	○	○	○	○	○	○
Good level of natural light	○	○	○	○	○	○
Large rooms and suitable layout	○	○	○	○	○	○
Well equipped kitchen / bathroom	○	○	○	○	○	○
Lower than average fuel bills	○	○	○	○	○	○
Good sized garden / outdoor space	○	○	○	○	○	○

In the same fashion as in Section 3.3, comparison of the overall order of characteristics could be used to indicate how the aspirations of occupants of more-sustainable homes differ from the mainstream. Lower gas and electricity bills, which is a defining characteristic of improved sustainability, ranked the second highest position previously whereas it came fifth in this second survey. This might indicate a correlation between living in a more-sustainable home and an awareness of the strong connection between environmental protection and what is spent on gas and electricity; however, the ability to use 'low fuel bills' as a proxy for 'environmental protection' requires careful consideration.

The options presented can be refined through iteration to improve the value of using this format of question by substituting in the most commonly suggested alternatives. There was a wide variety of suggestions in this second survey, most common being: location & views; adequate parking provision; sufficient storage; and privacy (noise and visual). Interestingly these are all issues explored in a recent CABE report [79].

When describing what was lacking in their current home the answers were varied though energy efficiency, eco-friendliness and improvements they would make to the room arrangements all featured, acknowledging the need for progress in the areas that the work in this thesis was aimed towards. The statistical significance of this is non-assessable though since the responses were not from a random sample of all households.

Where do various activities take place within the home?

8) What activities do you do regularly in the following rooms in your house?

You should tick as many activities that apply for each room.

You should tick "Do not have" only if your house does not have that type of room.

	Work	Eat	Relax	Socialise	Alone	Do not have
Bedroom	○	○	○	○	○	○
Living Room	○	○	○	○	○	○
2nd Living Room	○	○	○	○	○	○
Kitchen	○	○	○	○	○	○
Kitchen-dining area	○	○	○	○	○	○
Separate dining area	○	○	○	○	○	○
Study	○	○	○	○	○	○

Although the feedback from the POE study was unprecedented in its detail, DWH designers did not know how representative the behaviour of this family was of homebuyers in general. An objective of this survey was therefore to demonstrate how basic information could be gathered on how homes are used, to make some more general conclusions apparent on effective house design.

Only 57 of the 614 respondents (9.3%) had all of the suggested rooms in their home. This means most may have been using a less than ideal room for an activity because their home did not contain the preferable space; however, these compromises will become even more common as homes are built smaller to achieve the focus on increasing density. An objective of this question was therefore to illustrate which combination of limited spaces could be the most successful, highlighted through their multi-functionality.

It is inaccurate to compare where activities take place in two homes without first considering their differences in terms of age, type and the combination of rooms they have. For instance, within this restricted sample, a 2nd living room, kitchen-dining area, separate dining room and study were all progressively more common in the larger styles of homes, as is depicted in Figure 59.

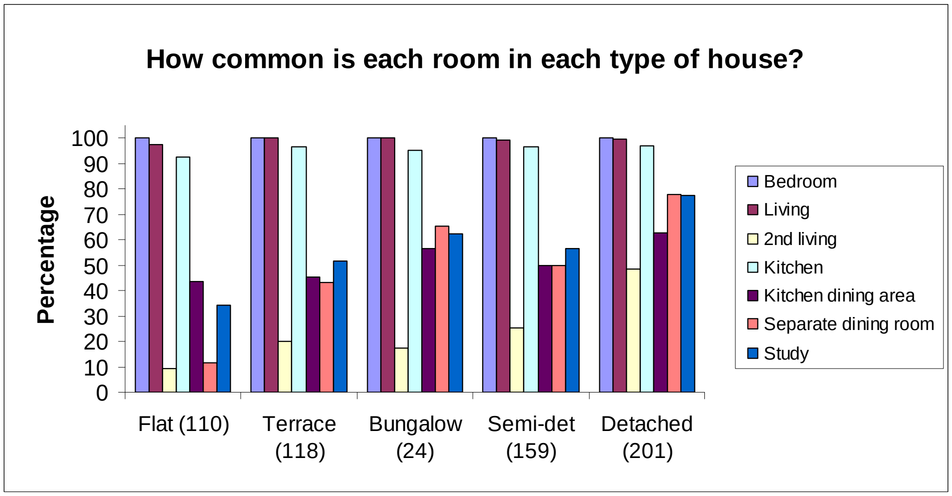


Figure 59: Rooms in each house type (number of responses in brackets)

The indications that came through from those that responded to the survey are discussed now on a room-by-room basis.

Bedrooms

As well as being the most common place to relax or be alone, 20% claimed to regularly use their bedrooms for work, although this varied considerably across the respondent age groups - from 64% of those aged under 18, to 6% of those aged 35-49. The differences in room use by each age group can be depicted as in Figure 60. It was also found that the average household size where work took place in the bedroom was 3.7, which is 0.7 more than the average of all responding homes. A possible explanation for the variation across this sample is the bias towards younger house sharers that was discussed earlier.

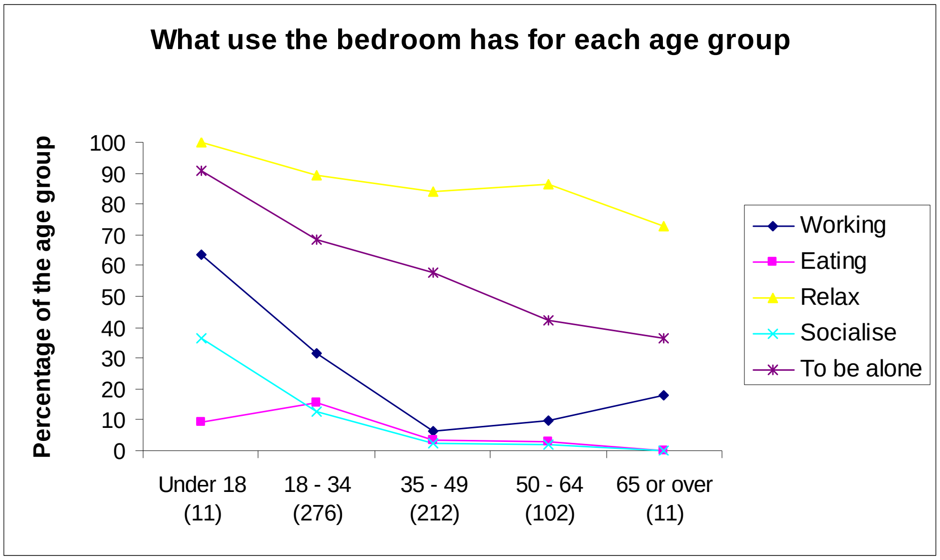


Figure 60: How the bedroom use varied with respondent age

Living room

The living room was by far regarded as the most sociable room by all age groups and the top place to relax along with the bedroom. It was also common for the respondents to take meals in the living room and to work there too.

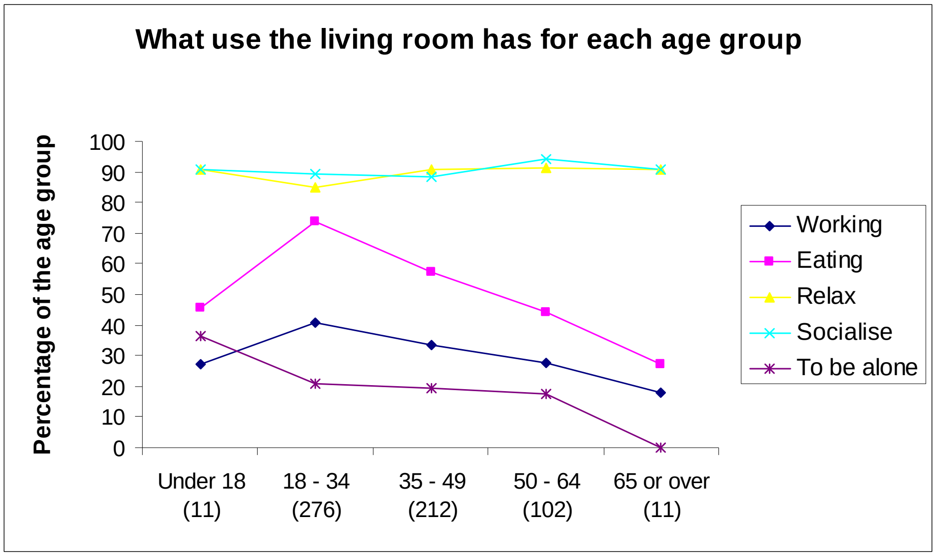


Figure 61: How the living room use varied with respondent age

2nd living room

If the respondent's house had a 2nd living room, it tended to be regarded as a less social and relaxing space than the main living room and was used more for working and to be alone. This is precisely how the basement den was used by the family who stayed in the experimental house.

A purpose for this question was to show how trends could be identified and developed into instructive conclusions for designers who at present have to imagine the functions that a room will be expected to serve in relation to the other spaces in the house. For instance, by comparing the responses from those living in a home with a 2nd living room to those without, it was found that this room above all others alleviated the need or desire to work and eat in either the main living room or the separate dining room, as reported in Table 7.

Table 7: The effect of providing a second living room (in percentages)

	Main living room		Separate dining room	
	Work	**Eat**	**Work**	**Eat**
If they don't have a 2nd living room	40	53	70	96
If they have a 2nd living room	29	47	35	85

A more robust implementation of this form of question could therefore be used to develop a statistically significant profile of the uses that each room is put to in relation to the number of occupants and which other rooms are available in the house, which would be very useful to designers and architects in their design conceptualisation process.

The kitchen, kitchen- dining area and separate dining room

The decision to provide a separate dining room or to make the kitchen larger to include space for the household to dine in is one that receives much consideration already from designers. DWH took of option of providing both in the experimental house, specifically to see which found favour with the occupant family, and found that they always dined together in the open-plan kitchen-dining area and rejected the alternative 'option room' that had been laid out as a dining room when they moved in. This was the decision of just one family however, which is why it would now be relevant to conduct a representative survey of the whole housing market on this issue.

As an indication of what might be found, of the respondents to the online survey who had just one of these two dining spaces, these were both very commonly used for dining - by 92 and 96%. It was also found that when their home had either of these two rooms that the living room(s) was used much less to work and to eat in and the kitchen became a more sociable space.

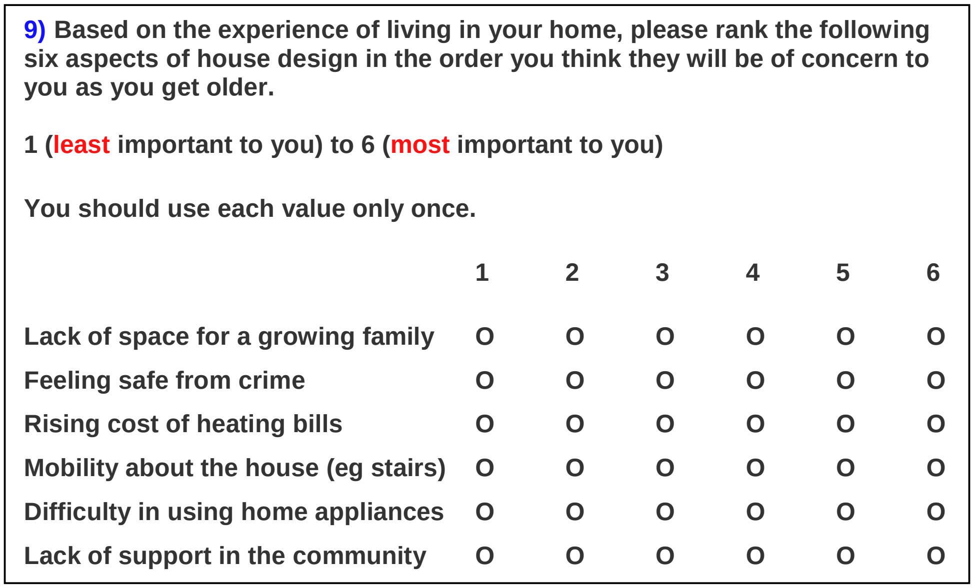
If the home had both a dining area and a separate dining room, they were reported as equally sociable spaces but the dining area was used to eat in by 91%; 10% more than for the separate dining room. For this indicative set of responses therefore, a separate dining room is a marginally less effective use of space for dining than having a dining area within the kitchen; however, it is still a much appreciated room that was the most commonly used space to work in when a house did not have a study.

Study

In the 59% of respondent homes that had a study, it was practically always used for working purposes (96%), which clearly indicates the failure of the 'Study/Bedroom 5' in the concept house to fulfil its intended purpose. Something that is not known however is how many of the respondents' studies were rooms originally intended for this purpose, or if they were spaces that had been adapted by the occupants themselves. For instance, the family in the experimental house would have converted the ground floor 'option room' into a study had they been living in there permanently. One of the benefits they stated for this arrangement was that they could remain in touch with what was going on around them in the house while they did their work.

Studies were reported through the online survey to be very unsociable rooms however and the most common place to go to be alone after the bedroom. It may be the case that the family's desires for a study differ from the desires of the market as a whole; however, this cannot be accurately assessed until a more robust sample is taken of the population that includes a question on whether their studies are in spaces originally intended for this purpose.

Concerns for older age



9) Based on the experience of living in your home, please rank the following six aspects of house design in the order you think they will be of concern to you as you get older.

1 (least important to you) to 6 (most important to you)

You should use each value only once.

	1	2	3	4	5	6
Lack of space for a growing family	○	○	○	○	○	○
Feeling safe from crime	○	○	○	○	○	○
Rising cost of heating bills	○	○	○	○	○	○
Mobility about the house (eg stairs)	○	○	○	○	○	○
Difficulty in using home appliances	○	○	○	○	○	○
Lack of support in the community	○	○	○	○	○	○

This question was to demonstrate how a survey may discover which additional benefits of more-sustainable housing should be emphasised in future to improve the marketing to different age groups. Many homes are unable to cater to the changing needs of their aging occupants, forcing them to make considerable alterations to the house or indeed to move. Figure 62 illustrates that while a strong concern within the younger age groups of this response set was with regards to a lack of space in the house, mobility about the home became more significant for the more elderly groups. The rising cost of fuel was of more concern to the older respondents, which is of relevance since they are also the most likely to suffer from fuel poverty (see Section 2.2).

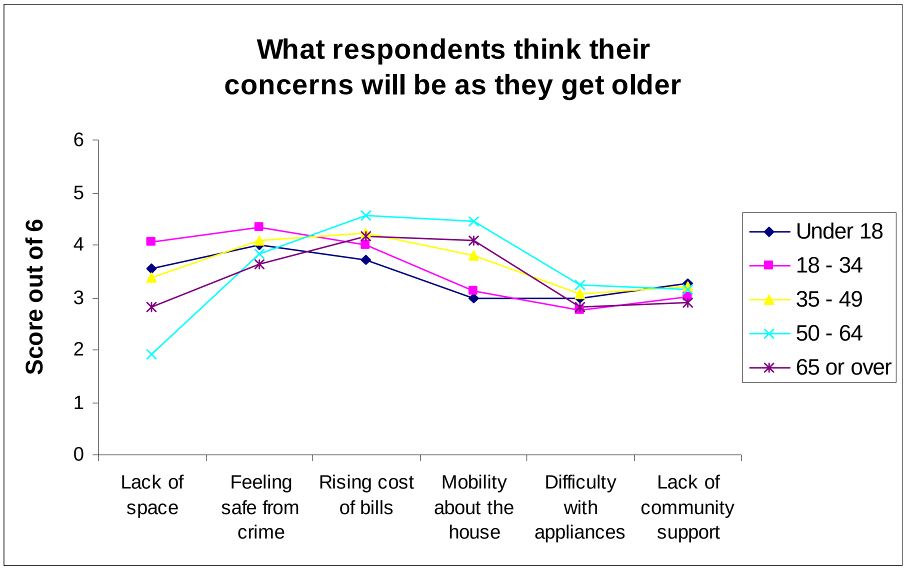


Figure 62: The respondents' concerns for older age

Energy Efficiency

10) Imagine that you have just spent a considerable amount of money on a piece of equipment that will save you money on your fuel bills and reduce your impact on the environment. How many years would you be happy to wait until the total money you save equalled the price you initially paid for the equipment?

O Less than five O 5-9 years O 10-19 years O 20 + years

11) Would the fact that you are helping the environment make you less concerned about how fast you recover the initial cost of the equipment?

O Yes very much O A fair bit O A little bit O No not at all

These were identical questions to those used in the postal survey to gauge the acceptable payback period for energy efficiency products. Comparing the opinions from occupants of more-sustainable homes and the wider population is important since they represent two different consumer groups and stages in the success of sustainability products in the marketplace. Many of those who have already purchased a more-sustainable home represent the early adopters and enthusiasts who can bring the invaluable first financial returns to investors; however, it is uptake by the mass-market that enables mass production techniques to be used that can markedly reduce the manufacture and retail cost and help make economical sense of energy efficiency products.

Figure 63 shows that while the clear majority (75%) of the tenant respondents of more-sustainable homes expected the equipment to have a payback of less than 5 years, only 38% of the online respondents felt the same way and just 27% of the owner respondents of more-sustainable homes. The median response to the online survey was in the 5-10 year band.

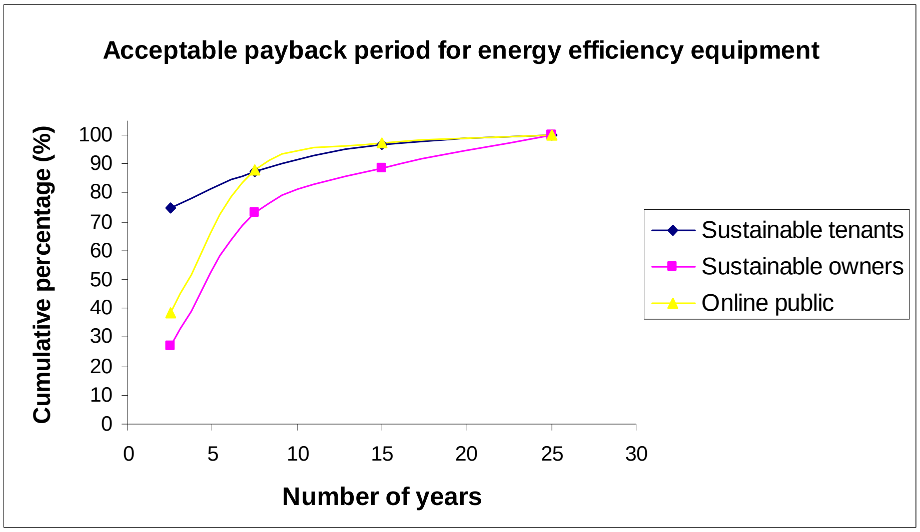


Figure 63: Comparison of payback period from different survey groups

Figure 64 depicts the answer to the final question that regarded the degree to which a care for the environment would make the respondent less concerned about the payback period. Although the indication is that the majority of all the groups would be fairly motivated or more, the influence of the 'value-action gap' discussed in Section 3.2 would have to be considered if a more robust survey was conducted in future.

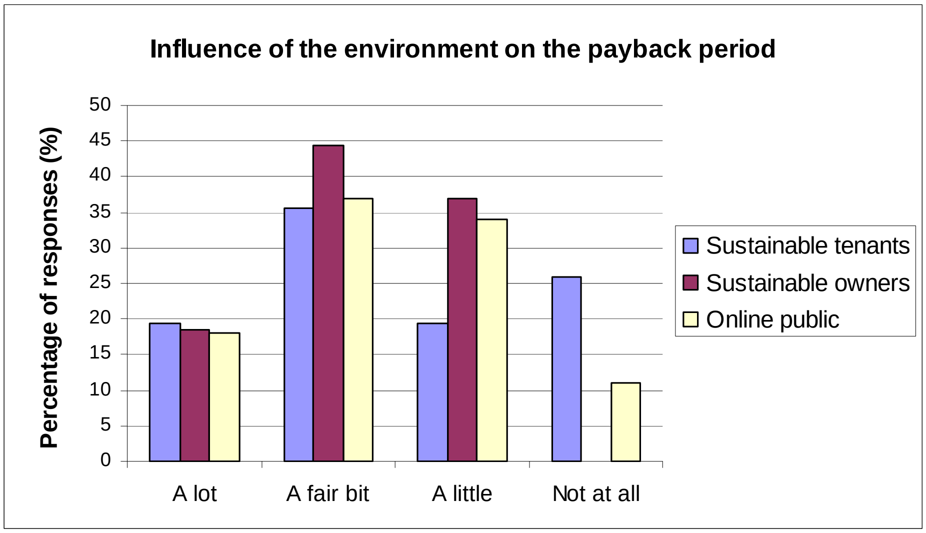


Figure 64: Influence of the environment on the payback period

Additionally, purchasing energy efficiency goods, of which more-sustainable homes are an example, can involve more considerations than financial gain and environmental protection. It would be beneficial therefore if future research were to look further into the process that those who already live in a more-sustainable home went through in making that decision.

10.3 Chapter conclusions

The objectives of the online survey were twofold and demonstrative in nature since the methodology chosen to gather responses negated the use of robust sampling criteria to ensure proper representation was made of the housing market as a whole. Therefore, no conclusions on the typical behaviour or comparisons between households could be drawn from this piece of work.

The first objective was to demonstrate how information could be collected that would assist designers through POE benchmarking of where in the home some fundamental activities took place. This was met through a question that asked where five activities (working, eating, relaxing, socialising, being alone) regularly took place within seven spaces of the home (bedroom, living room, 2nd living room, kitchen, kitchen-dining area, separate dining room, study). Although all of these spaces were present in the DWH concept house, this was the case in less than 10% of the respondents' homes and this was also factored into the data analysis. The analysis demonstrated the potential of how a future survey could be used to develop a portfolio containing the statistical regularity with which each domestic space was required to meet each specified use, with regards to the assortment of rooms in the house and the number and ages of the occupants. A benchmarked portfolio of this nature would assist architects and house designers when they are conceptualising where the regular activities of domestic life will take place, which is particularly crucial when they are limited for space within the dwelling and would like certain spaces to meet common multi-functional requirements. Of particular interest appears to be the play-off between the kitchen, kitchen-dining area and separate dining room since although these rooms are often some of the first to be discarded from the specification, they were also the most multi-functional rooms reported by the online respondents.

The second objective was to show how the aspirations on house design and attitudes towards energy efficiency of those who already live in more-sustainable homes could be compared to those of mainstream households. This was first tackled by asking the respondents to rank and discuss six important features for an aspirational home, one of which was intended as a proxy for energy efficiency without introducing a moral bias to the question, which as discussed in Section 3.2 can be influential in surveys on sustainability. It was later assessed however that the feature selected as the proxy was not sufficiently equivalent to enable this substitution to be made.

The final questions in the survey though turned directly to energy efficiency and a means of assessing and depicting the prevailing attitudes towards this critical feature of more-sustainable homes was illustrated through the use of the economic payback period. It was indicated that although there may be distinguishable groups who are prepared to wait longer than others to recoup the initial investment in energy efficiency equipment, there may not be as much variation between them in the concern they report for the environment. The suggestion being that it is willingness or ability to act on their concerns that may ultimately distinguishes the groups, to overcome the ‘value-action gap’, although more first should be discovered on what other motivators had effect on those who already occupy more-sustainable homes.

11 Conclusions and Further Work

The structure of this thesis was to begin with a conceptual and literature discussion and then follow with a review of an experimental application, with the overall purpose of demonstrating the potential of using occupant tracking systems to improve on the post-occupancy evaluation of homes. The primary objectives of the research were:

1. To explain the significance of making more efficient use of the land footprint and internal space within each new home, in order to achieve a more-sustainable and satisfactory built environment.
2. To clarify the need for a standard approach to gathering post-occupancy domestic feedback that involves the allocation of space within modern housing design.
3. To present the novel work carried out in an experimental house that highlighted the ability of applying a proximity-based RFID system to improve upon the existing techniques of space use assessment.
4. To demonstrate how the findings from such a unique experiment could influence housing design and future research within the built environment.

This chapter will discuss the findings of the thesis on each of these points, with an additional focus on reviewing the importance of taking a more holistic approach when considering sustainability, the performance of the RFID tracking system and suggestions for how this research could be taken further.

11.1 Achievement of the primary objectives

The significance of efficient space use

The pressure on speculative developers to build new homes to increasing density was mentioned repeatedly in this thesis. The Government has stipulated targets for a one third increase in the number of homes to be built annually and for 60% of them to be built on land that has been developed on previously. They have also empowered local councils to require a percentage of homes within each new development to be ‘affordable’, with 25-50% being typical. The purpose of these targets is to balance the need for the housing industry to expand, to meet the demand for more homes and to regain control in regions where prices have risen beyond what can be afforded by certain key worker groups, against the desire to protect our limited land resource from suburban sprawl. This balancing of social, economic and environmental goals is a clear demonstration of the principles of sustainable development being put into practice, and has resulted in a focus on the density of new developments that increased from 25 homes per hectare in 1997 to 40 per hectare in 2004.

The need for a new analysis technique

As densities and the need for affordability have increased, developers have to either build smaller homes or incorporate more rooms into the same building footprint. However, the spaces within these homes are not expected to cater to any fewer activities than in the past, so the allocation of space and multi-functionality of each room is becoming increasingly important. This has brought architects and designers to acknowledge their almost complete lack of information on how the spaces they create are eventually used, and the implication this has on how they may be improved. There is therefore a requirement for a means of collecting performance data in a consistent and comparable manner across the full range of designs, which in the commercial sector is being fulfilled by post-occupancy evaluation (POE). It was argued in this thesis that POE be developed within the housing sector as well.

POE is recommended as the framework for assessing the benefits of more-sustainable homes, including the efficiency with which the land resource is made use of. However, it has yet to be developed into a standard technique for dwellings and, in terms of space use analysis, has lacked a method that improves on subjective occupant surveys and in-situ observation exercises that are likely to affect domestic behaviour. With this in mind, an experimental application was described in this thesis where, for the very first time, a radio-frequency identification (RFID) occupant tracking system was installed within a dwelling to investigate its effectiveness for conducting a space usage POE.

Findings of the space use study

The decision to use an RFID personnel tracking system for this experiment came after first assessing the alternative means of studying occupant behaviour in buildings from the fields of social and computer sciences. These were rejected however as they were unable to identify the occupants individually or would be disruptive to the domestic life that was the subject of investigation. In contrast, the proximity-based RFID tracking system discreetly recorded the movements of each household member in far greater detail and accuracy than could ever have been recalled by the individual's themselves.

The experiment was not completed without difficulty. The finer technicalities of the system that were learned of one at a time during its commissioning were found to affect the performance in several unexpected ways. As a direct consequence, the manufacturers have made changes to the installation process to improve system reliability and shorten the commissioning procedure.

The conclusion is that although a proximity-base RFID system can be used to collect data for this purpose, there are at present several aspects of system performance that will hinder its uptake in dwelling research and design. Further research is required on the extent of signal interference and locating error caused by the environmental context in which the tags are to be detected, such as temperature, humidity, nearby metallic objects and the human body itself. Controlled laboratory testing is required to investigate this further and likewise for triangulation-based systems as these may be more appropriate for use in dwellings, where the potential for signal ‘bleed-through’ is high.

The data was analysed and presented in a number of different ways that investigated what could be learned first from the average day, the typical day and finally from an attempt to evaluate the effectiveness of allocation of space throughout the home. Each approach was found to have limitations however, and it is clear that data collected on occupant movements cannot be analysed in isolation, for patterns in the data do not explain why one space was valued above another or even if those most occupied were also the most valued. The need remains therefore to collect the subjective opinions of the household.

Potential influence in the built environment

The benefit of gathering both sets of data was developed by suggesting improvements that could be made to the room arrangement to better suit this particular family's lifestyle, which although helpful for the designers also illustrates the main limitation to the study. In the nature of all domestic POE research, especially where a novel technology is being piloted, there are no existing datasets to compare the findings against. While over time this situation may change, for now it illustrates the importance of maintaining a holistic approach to sustainability and POE in the domestic environment.

11.2 Maintaining a holistic approach

The research in this thesis also had some secondary objectives that could illustrate other important barriers to be overcome to improve the sustainability of our built environment.

Willingness of homebuyers to pay a premium for sustainability

Although it is argued by others that it may not necessarily be the case, it is generally considered that building to a more sustainable standard than is at present required in the Building Regulations adds a premium to the build-cost of the home. Several pieces of research have determined this premium in relation to achieving the different standards of the EcoHomes scheme, with others discussing how it can be offset by savings made through planning gains, a speedier passage through inspection and perhaps faster sales. Doubt remains over the figures however, so the focus remains on the willingness of the consumer to cover the premium by paying more up-front for the home.

The publicly reported surveys that have approached this subject were reviewed in Chapter 3, along with a demonstration of how this methodology could gather the information that might provide catalyst to further improvements to mainstream housing. The occupants of existing more-sustainable homes represent a rich source of comparable information on how they perform in practice and if they could be marketed on their ability to improve the standard of living as well as on energy efficiency and environmental protection.

Assessment of some energy use prediction techniques

The intention in Chapter 8 was to advance on the knowledge of some of the simulation tools that claim to be able to predict the energy use or other sustainability aspect of a particular building form. Due to the timetable of research in the experimental house it was regrettably impossible to assess those tools used most frequently to predict the space and water heating demand of the home. Additionally, a full assessment on the summertime environmental comfort conditions could not be completed due to a lack of data, although the recorded patterns in excessive air temperatures did corroborate the feedback received from the occupants. It was also possible to assess the two chosen means to predict daylighting performance. The conclusion reached was one of concern over the stress often placed on simulation results, as those evaluated appear to not yet be accurate enough to encourage their use for detailed design considerations. A more controlled repetition of this research would likely obtain more conclusive data, but this would be going beyond the scope of this thesis as the evaluation of simulation techniques was a secondary objective of the research.

Comparison of a POE study against the mainstream market

It is still unknown how influential the lifestyle of the household will be to the findings of each POE study. This is avoided within the commercial sector as quantifiable measurements for business success, such as absenteeism and productivity, can be compared across studies; though distinguishing the influence of building design on these factors is still a debated subject. The housing sector lacks a singular objective however, as it is more concerned with the complex and subjective idea of occupant satisfaction. Satisfaction has much to do with how the lifestyle of the household suits the design of the house and their lifecycle stage at the time of assessment, which is a stumbling block for any domestic POE method that cannot quantify these aspects as well as the house design.

An attempt was made in Chapter 10 to progress on this implication using a POE survey question that could provide architects with a new tool for the design conceptualisation process. A survey could be used to gather a portfolio of household behaviours that would provide an understanding of where activities usually take place within each style of home and of which spaces are most multi-functional and satisfactory to the occupants. For instance, in an housing development that is expected to be attractive to young families, would it be more appropriate to include a space for dining in the kitchen, a small study for the parents and expect the children to do their homework in their bedrooms, or would it be better to integrate the kitchen-dining space and study into a larger ‘option room’ that will be used only occasionally as an dining room, as the family normally eat in the living room, and so can still be used as the parents’ study and also by the children at homework time? The suggested portfolio would answer this with statistical value on how well each alternative would cater to the activities that are most important for the demographic and social group being targeted.

This thesis has successfully demonstrated therefore how the quantitative data collected on a small group of subjects could be related to the behaviour of the mainstream in a more resource-effective manner than repeating the tracking study across the full range of homes on the market at present, although the means of collecting both sets of required data still need much improvement. It is also suggested that future developments in tracking technology may bring further capabilities that will accelerate its implementation, such as accurate, untagged tracking and activity inference using an ad hoc network of wireless sensors, as has also been discussed in a recent CIBSE publication [180].

11.3 Suggestions for further work

Development of the domestic POE method

More could be learned in this project through purely qualitative interviews with the occupant family than by asking them to quantify their responses, since there is no publicly available data to compare their responses against. None of the available POE questionnaires have been developed for the domestic context. This means that while the household interviews investigated the important questions of why one space was used or preferred over another, they did not provide data that could be related to future studies in different households. Nor did they overcome the inaccuracy introduced through erroneous recall and responses biased towards the individual who provides the answer. However, this is where the strength lay in the quantitative RFID study that gathered time-stamped data that was directly comparable and gave equal weight to each individual's behaviour. This epitomizes the opportunity available for occupant tracking systems to become a standard tool for undertaking space use POE in all buildings, not just homes, though the systems are not yet sophisticated enough to be used in isolation for the purpose of domestic POE, as they cannot assess the activity underway or the degree of occupant satisfaction. There therefore still remains a requirement for the development of a domestic POE questionnaire, quantifiable, comparable and most likely text-based, which is a significant undertaking.

Before a POE questionnaire could be applied across mainstream and more-sustainable homes, an assessment must be made on what sampling criteria is appropriate to accurately reflect the full range of social, demographic and geographical groups who live in each form of house [16]. If these criteria are not determined beforehand, then it is unlikely that the established benchmarks will be scientifically robust, which could negate the benefits of POE and actually lead the housing industry in the wrong direction.

System performance testing

As discussed in Section 7.4, there were a number of areas where the tracking system's performance was unsatisfactory if the intention is to use the technology as a standard tool for space use research. Some of these should be assessed in controlled laboratory settings before embarking on a repetition of this kind of experimental application, as they would undoubtedly reoccur in a similar context and leave the same suspicions over the accuracy of collected data. Three aspects of system performance are suggested in particular:

- The effect of varying ambient temperature and humidity conditions on the signal strength and detection range of the L-RX201 readers should be investigated within a controlled environmental chamber.
- Repositioning or extending the antenna within the wristband tag's housing may improve performance by reducing the interference effect caused by the different locations and orientations that the tags can be worn in.
- An alternative solution to both of these points may be to locate each tag by triangulation of signals received by three or more readers rather than through the proximity to just one. Triangulation is thought to bring great advancement on locating resolution, with the claim from Ubisense being that they can detect their personnel tags to 10cm in 3 dimensions using just four readers per room [159]. This is using a different signal frequency (UWB) and additional readers, so the system cost may become even more significant. A performance to cost analysis of three system setups is therefore recommended: proximity-based RFID, triangulation-based RFID, and triangulation-based UWB.

In addition to these performance tests, some dedicated software should be developed to assess the stream of data as it is recorded, to effectively produce a real-time POE on how the spaces are being used. The vast quantity of junk data generated in this experimental application was discarded through many hours of manual inspection of the raw data (see Appendix G); however, this would not be commercially satisfactory and is a prime concern for the future implementation of the technology for POE. The most challenging aspect envisaged is the appraisal of what data is accurate and what is erroneous. It may be that the issue of bleed-through junk data will be resolved in the process of investigating signal triangulation; however, if not, the analytical software will require algorithms that provide it with some intelligence to decide which signals are accurate and which are not. When spaces are divided by physical barriers such as solid walls, then the software inference is straightforward; however, when the spaces are linked by doorways then it becomes a more complex and maybe irresolvable task.

Alongside the automation of data analysis, it is suggested that an improved method of presentation is required to convey the successfulness of the space design, bearing in mind that the house can be used differently one day to the next. Chapter 5 included a discussion on how routines form a significant function in domestic life; however, previous studies that were descriptive in the nature of ethnography paid little regard to the timing of the movements that lay behind the routines. It was realised in Chapter 9 that averaging the 42 days of data collected by this unique experiment had the affect of making all rooms appear to be partially occupied all of the time, and the other extreme of selecting a single typical day to depict as an animation was itself a complex task since each day's behaviour could be affected by a multitude of external influences, from the weather to the arrival of guests. There is therefore a need to develop a further means of presenting the data to both designers and social scientists, to illustrate the routine nature of behaviours within the home without losing sight of the fact that they do not necessarily occur at the same time each day. The work of others may provide inspiration for this development [85].

Finally, it would be advantageous to investigate further the application proposed in Section 9.6 of controlling a building's heating and ventilation systems using the patterns established over time in the occupants' movements. While this thesis was focused on a domestic study and indicated that the opportunities for introducing set-back conditions are few, it seems reasonable to speculate that this control would be more realistic practically and economically in a commercial setting, not least because the building occupants may already be required to carry a tag artefact on them for security purposes. The POE space use analysis could in this way become a spin-off of an economically beneficial introduction of an integrated building energy management, communications and security system that would provide real benefits to the building occupants at just a small cost to their privacy of movement in the workplace.

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Appendices

Appendix A. Survey of sustainable homes

The Cover Letter

Dear householder,

Please help us to improve our understanding of how people's views on energy efficiency affect their choice of home by answering this short survey. It should only take about 15 minutes of your time, and your answers will be kept in confidence.

You have been chosen as a recipient of this questionnaire because the house that you occupy is one of the best examples of energy efficient construction in the East Midlands.

This research is being conducted by the Institute of Sustainable Energy Technology, School of the Built Environment, University of Nottingham. The data collected will be used as part of a Doctorate thesis, and every completed questionnaire that is returned will be invaluable to making this an effective study that can be used to inform the house building industry.

Each of the questions should be answered by either:

Marking a box with a tick: e.g. ☑

Circling a number on a scale from 4 to 1: 4 3 2 [✓ 1]

Writing a few words on a line: ________________________

Please use the enclosed pre-paid envelope to return your completed questionnaire.

Many thanks,

Richard Holland

(PhD Research Student)

The Survey

In this first section, we wish to obtain some basic details about you and your home.

Name: ________________________________

Sex: ☐ Male ☐ Female

Age: ☐ Under 18 ☐ 18-34 ☐ 35-49 ☐ 50-65 ☐ Over 65

Address: ____

You are the:
- ☐ Tenant
- ☐ Home owner
- ☐ House designer / builder as well as an occupant
- ☐ Other (please specify) _____________________________________

Q1: What type of property do you live in?

☐ Flat ☐ Terrace ☐ Detached, Semi-detached or Bungalow

Q2: How many bedrooms does your home have?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 or more

Q3: How many people in each of the following age groups live in your home on a regular basis?

Under 18 ____ 18-34 _____ 35-49 _____ 50-65 _____ Over 65 _____

Q4: Were you aware of the energy efficient features of your home when you moved in?

☐ Yes ☐ No

If so, would you say that they influenced your decision to move in?

☐ Yes, very much so ☐ Yes, a fair bit ☐ Yes, a little bit ☐ No, not at all

Q5: How many years have you lived in your home for?

☐ 0 - 5 ☐ 6 - 10 ☐ 11 - 15 ☐ 16 - 20 ☐ 21 +

Q6: How many more years do you expect to live in your home for?

☐ 0 - 5 ☐ 6 - 10 ☐ 11 - 15 ☐ 16 - 20 ☐ 21 +

In this section, we want to hear your opinion of what makes a good home.

Q7: How important is it for a good home to have each of the following qualities?

	Extremely			Not at all
Large, spacious rooms	4	3	2	1
Comfortable indoor environment	4	3	2	1
Modern entertainment facilities	4	3	2	1
Good level of natural light	4	3	2	1
Security from intruders	4	3	2	1
Attractive appearance from outside	4	3	2	1
Low gas and electricity bills	4	3	2	1
Peace and quiet from outside	4	3	2	1
Modern kitchen and bathroom	4	3	2	1
Parking space for a second car	4	3	2	1

Q8: Are there any other general qualities that you consider to be particularly important?

____

____

Q9: How important do you feel it is for a home to have the following features?

	Extremely			Not at all
Well insulated walls and roof	4	3	2	1
Well insulated windows	4	3	2	1
Efficient water heating	4	3	2	1
Modern heating controls	4	3	2	1
Low energy lights & appliances	4	3	2	1
Water saving appliances	4	3	2	1
Its own electricity generation	4	3	2	1

Q10: If you were looking to move into a new home, how much information would you prefer to be given concerning the building’s energy performance?

☐ I would prefer to be advised IN DETAIL on the building’s energy performance

☐ I would prefer to be advised BRIEFLY on the building’s energy performance

☐ I would NOT BE INTERESTED in knowing the building’s energy performance

In this section, we would like to find out how living in an energy efficient home has affected your attitude towards renewable energy technology.

Please use the space provided overleaf if you would like to expand on any of your answers.

Q11: Have you found the energy efficient features of your home to be disruptive to your life at home?

☐ Yes, very much so ☐ Yes, a fair bit ☐ Yes, a little bit ☐ No, not at all

Q12: Has your interest in renewable energy increased since you moved into your home?

☐ Yes, very much so ☐ Yes, a fair bit ☐ Yes, a little bit ☐ No, not at all

Q13: Whenever you make an expensive purchase, how important would you say each of the following issues are in influencing your choice?

	Extremely			Not at all
Price	4	3	2	1
Reputation of the brand / model	4	3	2	1
Effect on the environment	4	3	2	1
Opinions of friends and family	4	3	2	1

Q14: Would you be prepared to spend money on a piece of equipment that would save you money on your household fuel bills, and at the same time help the environment?

☐ Yes ☐ No

If you answered “No” to this question you may skip the next two.

Q15: What would be the maximum number of years that you would be happy to wait for the money you save on your fuel bills to equal the price you paid for the equipment?

☐ 5 years ☐ 10 years ☐ 15 years ☐ 20 + years

Q16: Would the fact that you are helping the environment make you less concerned about how fast you recover the cost of the equipment?

☐ Yes, very much so ☐ Yes, a fair bit ☐ Yes, a little bit ☐ No, not at all

And finally…

We would like you to tell us of **any** concerns or praise you have on any renewable energy equipment you use, or indeed about any other aspect of energy efficiency in the home. We are especially interested if you chose to install a piece of equipment yourself, and whether it has performed up to your expectations.

Please don’t forget to mention the kind of system your comments refer to, for example ‘solar thermal panel’, ‘heat recovery ventilation’, or ‘wood fuelled boiler’.

As an existing occupant of an energy efficient home, your opinions are invaluable to the industry. The companies who design and specify energy efficient products are keen to hear how they could improve customer satisfaction, which will lead to increased environmental protection as well as promoting the image of renewable energy.

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That completes this short survey. Thank you once again for your time.

Please return your completed questionnaire in the enclosed pre-paid envelope.

The Responses

Project Name, Location	**Posted out**	**Returned**
Autonomous House, Southwell	1	1
Beaconsfield Street, Nottingham	6	1
Concept Cottages, Donnington	2	1
Corncroft, Green Lane, Clifton	22	5
DWH Millennium EcoHouse	2	2
Environ EcoHouse, Leicester	2	1
Fosse Estate, Newark	33	3
Garendon Road, Loughborough	17	4
Gusto Construction, Various	31	22
Hall Park Close, Littleover, Derby	71	9
Hollies Barn, Eakring	1	1
Hockerton Housing Project	5	4
Mike Teague's Home	1	1
Murray Frankland's Home	1	1
Nottingham EcoHouse	1	0
Plane Tree Court, Nottingham	10	4
Sinfin & Mapperley Energy Projects	5	2
Underhill Houses, Derby	2	0
West Beacon Energy Farm	1	1
Unknown addresses	-	2
Totals	**214**	**65**

The respondent demographics breakdown as follows:

Male	Female	Male & Female
25	36	4

Under 18	18 - 34	35 - 49	50 - 65	Over 65
0	2	26	18	15

Tenant	Owner	Builder & Owner
37	21	7

The group of 'Builder and Owner' includes those who have carried out or commissioned refurbishment work to an existing property. Combining them with the small group of 'Owner' gives the two groups of comparable size.

The responses to each question asked are now tabulated. Where figures are shown in brackets, these are the value as a percentage of the total number of respondents in the category, disregarding any invalid or blank responses.

Q1: Property Type:

Flat	Terraced	Semi or detached
9	4	52

Q2: How many bedrooms were in each respondent's property?

	One	Two	Three	Four	Five
Flat	3	-	6	-	-
Terraced	-	-	2	2	-
Semi or detached	1	27	4	15	5

Q3: How many occupants are there on average in each band?

Under 18	18 - 34	35 - 49	50 - 65	Over 65
0.57	0.28	0.59	0.38	0.35

Q4: Were they aware of the energy efficiency features before moving in?

	All Responses	Tenants only	Owners only
Yes	55 (85)	27 (73)	28 (100)
No	10 (15)	10 (27)	0 (0)

If they were aware, did this influence their decision to move in?

	All Responses	Tenants only	Owners only
Yes, very much so	25 (45)	6 (22)	19 (68)
Yes, a fair bit	11 (20)	8 (30)	3 (11)
Yes, a little bit	7 (13)	3 (11)	4 (14)
No, not at all	12 (22)	10 (37)	2 (7)

Q5: Number of years that they have lived there:

0 - 5	6 - 10	11 - 15	16 - 20	21 +
59	4	0	0	2

Q6: Number of years more that they think they will live in their home:

(Some of the more elderly tenants wrote beside their answer "*As long as I'm alive for*". These have been included in the 21+ category though in future a separate response option should be provided.)

	All Respondents	Tenants only	Owners only
0 - 5	15 (23)	11 (30)	4 (14)
6 - 10	6 (9)	5 (14)	1 (4)
11 - 15	7 (11)	2 (5)	5 (18)
16 - 20	3 (5)	1 (3)	2 (7)
21 +	31 (48)	15 (41)	16 (57)
D / K	3 (5)	3 (8)	0 (0)

Q7: How important is it for a good home to have the following qualities?

The table below contains the average values when each answer option is attributed a value from 1 to 4. The figure in brackets is the rank order placing of that quality within the group.

	All Responses	Tenants only	Owners only
Large, spacious rooms	3.2 (7)	3.1 (7)	3.3 (7)
Comfortable indoor environment	3.7 (1)	3.7 (4)	3.8 (1)
Modern entertainment facilities	2.5 (9)	2.6 (9)	2.5 (10)
Good level of natural light	3.7 (4)	3.7 (3)	3.6 (=2)
Security from intruders	3.7 (3)	3.8 (1)	3.5 (4)
Attractive appearance from outside	2.9 (8)	2.9 (8)	2.9 (8)
Low gas and electricity bills	3.7 (2)	3.7 (2)	3.6 (=2)
Peace and quiet from outside	3.5 (=5)	3.6 (5)	3.4 (6)
Modern kitchen and bathroom	3.5 (=5)	3.5 (6)	3.4 (5)
Parking space for a second car	2.5 (10)	2.2 (10)	2.9 (9)

Q9: Importance of energy efficiency features in a home

Average values in table below with rank order placing in brackets.

	All Responses	Tenants only	Owners only
Well insulated walls and roof	3.8 (=2)	3.9 (=2)	3.8 (=2)
Well insulated windows	3.8 (=2)	3.9 (=2)	3.8 (=2)
Efficient water heating	3.9 (1)	3.9 (1)	3.9 (1)
Modern heating controls	3.6 (6)	3.6 (6)	3.6 (6)
Low energy lights & appliances	3.7 (5)	3.7 (=4)	3.7 (5)
Water saving features	3.7 (4)	3.7 (=4)	3.7 (4)
Its own electricity generation	2.7 (7)	2.8 (7)	2.7 (7)

Q10: How much information would they prefer to be given about their home?

	All Responses	Tenants only	Owners only
In detail	51 (78)	28 (76)	23 (82)
Briefly	12 (18)	7 (19)	5 (18)
Not interested	1 (2)	1 (3)	0 (0)
Blank	1 (2)	1 (3)	0 (0)

Q11: Have the energy efficiency features been disruptive to their daily life?

	All Responses	Tenants only	Owners only
Yes, very much so	0 (0)	0 (0)	0 (0)
Yes, a fair bit	5 (8)	4 (11)	1 (4)
Yes, a little bit	15 (23)	9 (24)	6 (21)
No, not at all	43 (66)	22 (59)	21 (75)
Blank	2 (3)	2 (5)	0 (0)

Q12: Interest in renewable energy grown?

	All Responses	Tenants only	Owners only
Yes, very much so	9 (14)	3 (8)	6 (21)
Yes, a fair bit	25 (38)	13 (35)	12 (43)
Yes, a little bit	12 (18)	8 (22)	4 (14)
No, not at all	17 (26)	11 (30)	6 (21)
Blank	2 (3)	2 (5)	0 (0)

Q14: Would they be prepared to spend money on energy efficiency kit?

	All Responses	Tenants only	Owners only
Yes	58 (89)	31 (84)	27 (96)
No	5 (8)	4 (11)	1 (4)
Blank	2 (3)	2 (5)	0 (0)

Q15: If they answered yes to Q14, what is the acceptable payback period?

Up to…	All Responses	Tenants only	Owners only
5 years	31 (53)	24 (77)	7 (26)
10 years	16 (28)	4 (13)	12 (44)
15 years	6 (10)	2 (6)	4 (15)
20 or more years	4 (7)	1 (3)	3 (11)
Blank	1 (2)	0 (0)	1 (4)

Q16: Do they consider helping the environmental to be a bonus?

	All Responses	Tenants only	Owners only
Yes, very much so	11 (19)	6 (19)	5 (19)
Yes, a fair bit	23 (40)	11 (35)	12 (44)
Yes, a little bit	16 (28)	6 (19)	10 (37)
No, not at all	8 (14)	8 (26)	0 (0)

Appendix B. Annual heating demand sensitivities

Variable values	Steady State Heat Loss	Annual Energy Usage			Annual gas bill		CO_2 emissions	
W/m^{2}K, ach/hr	**W**	**GJ**	**kWh**	**kWh/m^2**	**£**	**+/-**	**kg**	**+/-**
Actual Case	12,275	98.1	27,250	79.0	530	-	5177	-
Infiltration = 0.5	15,153	121	33,611	97.4	654	+ 124	6386	+ 1209
Infiltration = 1	17,890	143	39,722	115	772	+ 252	7547	+ 2370
Windows = 3.0	14,548	116.3	32,306	93.6	628	+ 98	6138	+ 961
Windows = 1.3	11,576	92.5	25,684	74.5	500	- 30	4882	- 296
Walls = 0.35	12,555	100.3	27,861	80.8	542	+ 12	5294	+ 116
Walls = 0.25	11,995	95.9	26,639	77.2	518	- 12	5061	- 116

Design characteristics used in the HEVACOMP model

- Design temperatures: 20ºC inside, -1ºC outside, 7ºC seasonal average
- Set temperature rise from internal gains: 6ºC
- Degree days for Sheffield: 2300 [161]
- Floor area of house: 340 m^2
- Condensing gas boiler efficiency: 90 %
- Price of gas: 1.75 pence per kilowatt hour
- CO_2 emissions of gas: 0.19 kg CO_2 per kilowatt hour [181]

Appendix C. Environmental conditions recorded in the house

Sensor Location	$\frac{\text{Glazing}}{\text{Volume}}$	7 month Average	Summer Average	Winter Average	Standard Deviation	Skewness	Summer Lower Quartile	Summer Upper Quartile	Summer Maximum (month recorded)
External		13.8	18.4	6.5	4.5	2.1	14	20	31.5 (June)
Den	0.09	22.9	23.3	22.6	1.9	0.9	21	23	37.2 (June)
Laundry	0.03	22.3	22.6	21.8	1.1	1.0	21	22	31.7 (July)
Entrance Hall		21.7	22.1	21.1	1.3	1.0	20	22	33.2 (July)
Lounge	0.15	23.1	23.4	22.3	1.9	-0.4	21	22	30.0 (July)
Dining Area	0.10	23.7	23.6	23.7	1.4	0.2	22	23	30.3 (July)
Kitchen		23.8	26.1	18.9	3.9	-0.5	24	26	31.2 (June)
First Landing		22.8	23.1	22.5	1.6	0.4	21	23	29.1 (July)
Study	0.07	24.8	24.7	24.8	1.6	0.2	22	25	30.3 (July)
Shared Bathroom	0.06	26.0	25.0	28.2	2.9	0.0	22	26	33.1 (June)
Sunken Bathroom	0.15	24.5	25.1	23.4	1.7	-0.2	23	25	30.3 (June)
Bedroom 1	0.16	23.8	26.3	18.8	4.2	-0.4	24	27	33.0 (June)
Bedroom 2	0.20	24.9	27.1	20.2	3.8	-0.5	25	27	33.7 (June)
Top Landing		24.4	27.3	18.9	4.3	-0.6	25	27	29.3 (June)
Top Bathroom	0.05	26.1	24.2	29.5	4.2	0.8	22	24	36.8 (Dec)
Bedroom 3	0.17	23.5	23.9	23.1	2.1	0.9	21	24	39.6 (June)
Bedroom 4	0.14	24.6	25.0	23.6	2.4	-0.4	23	25	33.1 (July)

Notes to accompany the table of the environmental conditions recorded in the house

- ‘Glazing / Volume’ gives a measure of how much glass area there is in each room relative to its size. No values are given for the ground floor and landings as this cannot take account of their open-plan nature.

- The ‘7 month Average’ is the average temperature over June to December.
  The ‘Summer Average’ is the average over June, July and August.
  The ‘Winter Average’ is the average over November and December.

- ‘Standard Deviation’ is the measure of how the data is spread about the average. It can be used to calculate confidence intervals when the distribution is ‘normal’.

- ‘Skewness’ is a measure of how ‘normal’ the data distribution is. If the skew is close to zero, the Standard Deviation can be used to predict the temperature limits that contain 66%, 95% or 99% of the recordings.

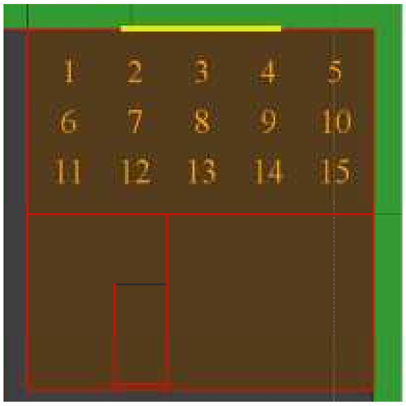
- Lower Quartile is the value that 25% of all the values was less than.

- Upper Quartile is the value that 25% of all the values was greater than.

Appendix D. Daylight Factor Recording

The number in brackets beside each room label is the number of measurements taken within the room. All of the windows are marked up in yellow.

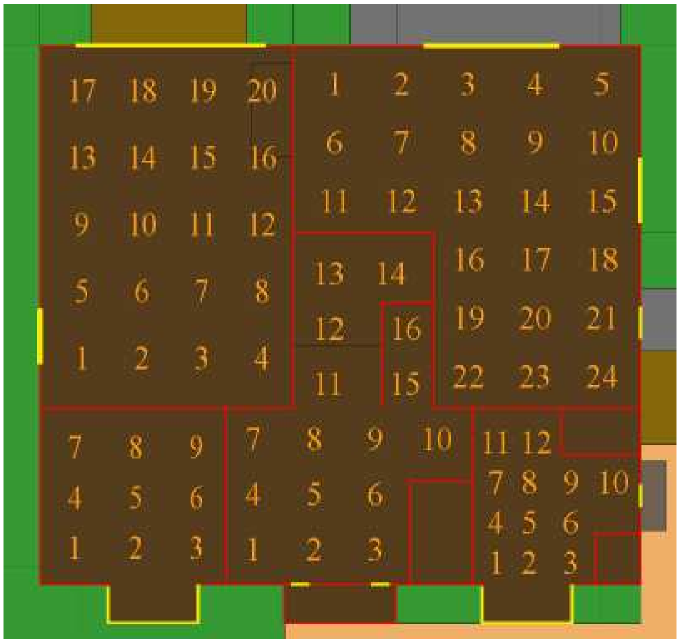
Basement Level



Den (15)

Ground Floor Level

Kitchen / dining area (24)



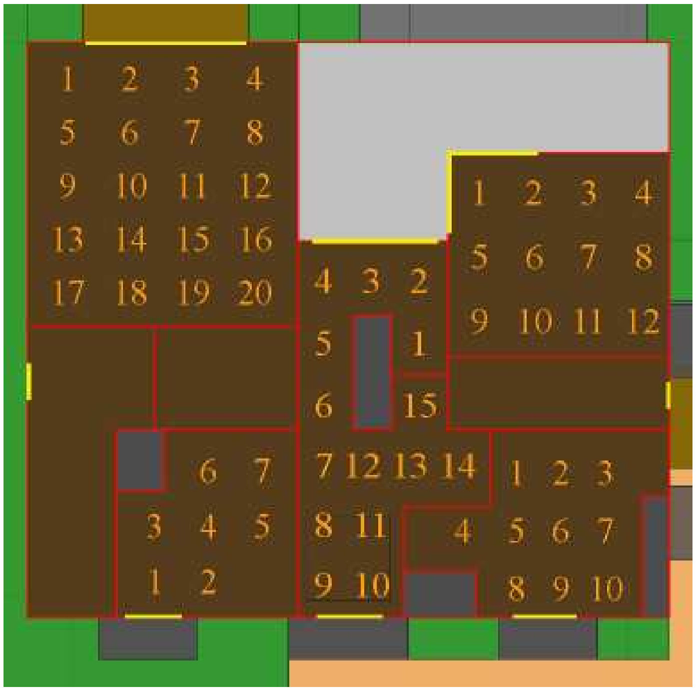
Lounge (20)

Option room (9)

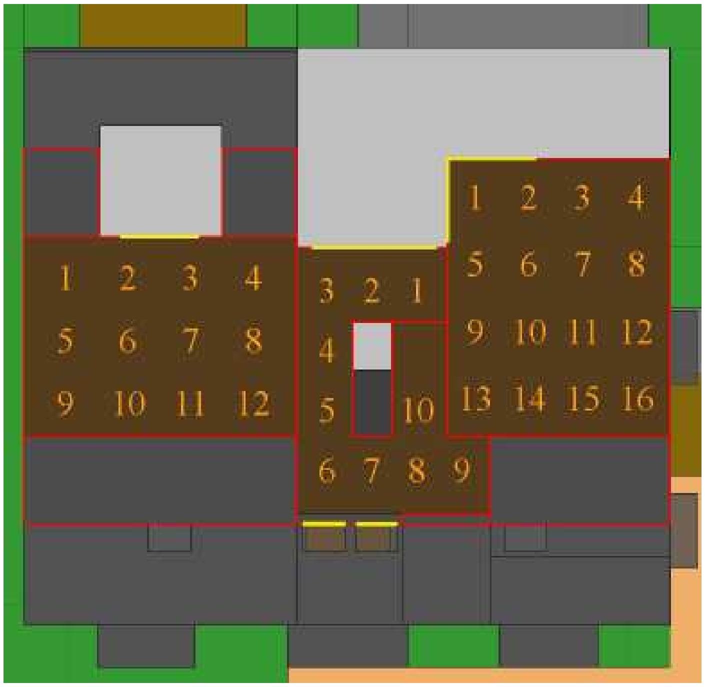
Boot room (12)

Entrance hallway (16)

First Floor Level



Top Floor Level



Recorded Daylight Factors

Room	Time	External Lux, Lux_e	Interpolated Lux, Lux_e'	Node Number	Lux_measured	DF_reality
Option	10:55	11600				
	11:03		12982	1, 2, 3	45, 300, 460	0.3, 2.3, 3.5
	11:04		13155	4, 5, 6	54, 90, 115	0.4, 0.7, 0.9
	11:05		13327	7, 8, 9	44, 54, 68	0.3, 0.4, 0.5
	11:06	13500				
Lounge	11:11	14300				
	11:12		14583	1, 2, 3, 4	117, 105, 103, 90	0.8, 0.7, 0.7, 0.6
	11:13		14867	5, 6, 7, 8	110, 140, 135, 112	0.7, 0.9, 0.9, 0.8
	11:14		15150	9, 10, 11, 12	200, 220, 240, 160	1.3, 1.5, 1.6, 1.1
	11:15		15433	13, 14, 15, 16	340, 460, 300, 200	2.2, 3.0, 1.9, 1.3
	11:16		15717	17, 18, 19, 20	800, 1500, 1350, 1300	5.1, 9.5, 8.6, 8.3
	11:17	16000				
Entrance	11:19		16457	1, 2, 3	5, 80, 150	0.3, 0.5, 0.9
	11:20		16686	4, 5, 6	53, 140, 135	0.3, 0.8, 0.8
	11:21		16914	7, 8, 9, 10	42, 130, 110, 18	0.2, 0.8, 0.7, 0.1
	11:22		17143	11, 12, 13, 14	35, 40, 50, 40	0.2, 0.2, 0.3, 0.2
	11:23		17371	15, 16	40, 15	0.2, 0.1
	11:24	17600				

Room	Time	External Lux, Lux_e	Interpolated Lux, Lux_e’	Node Number	Lux_measured	DF_reality
Boot Room	11:24	17600				
	11:29		18100	1, 2, 3	1200, 1400, 1100	6.6, 7.7, 6.1
	11:30		18200	4, 5, 6	450, 700, 450	2.5, 3.8, 2.5
	11:31		18300	7, 8, 9, 10	150, 215, 270, 1000	0.8, 1.2, 1.5, 5.5
	11:32		18400	11, 12	125, 125	0.7, 0.7
	11:33	18500				
Kitchen / Diner	11:54	20000				
	11:56		19886	1, 2, 3, 4, 5	230, 250, 1140, 980, 300	1.2, 1.3, 5.7, 4.9, 1.5
	11:57		19829	6, 7, 8, 9, 10	250, 310, 370, 330, 320	1.3, 1.6, 1.9, 1.7, 1.6
	11:58		19771	11, 12, 13, 14, 15	190, 250, 260, 280, 350	1.0, 1.3, 1.3, 1.4, 1.8
	11:59		19714	16, 17, 18, 19, 20	190, 250, 300, 120, 150	1.0, 1.3, 1.5, 0.6, 0.8
	12:00		19657	21, 22, 23, 24	500, 100, 130, 350	2.5, 0.5, 0.7, 1.8
	12:01	19600				
Den	12:12		19129	1, 2, 3, 4, 5	28, 50, 205, 200, 50	0.1, 0.3, 1.1, 1.0, 0.3
	12:13		19086	6, 7, 8, 9, 10	35, 70, 160, 133, 65	0.2, 0.4, 0.8, 0.7, 0.3
	12:14		19043	11, 12, 13, 14, 15	44, 90, 100, 90, 50	0.2, 0.5, 0.5, 0.5, 0.3
	12:15	19000				

Room	Time	External Lux, Lux_e	Interpolated Lux, Lux_e’	Node Number	Lux_measured	DF_reality
Bed 3	12:52	16700				
	12:53		16642	1, 2, 3, 4	5500, 2200, 615, 380	33.0, 13.2, 3.7, 2.3
	12:54		16583	5, 6, 7, 8	3600, 2000, 730, 460	21.7, 12.1, 4.4, 2.8
	12:55		16525	9, 10, 11, 12	1000, 900, 600, 450	6.1, 5.4, 3.6, 2.7
	12:56		16467	13, 14, 15, 16	460, 480, 430, 400	2.8, 2.9, 2.6, 2.4
Top Landing	12:57		16408	1, 2, 3, 4	880, 1080, 920, 660	5.4, 6.6, 5.6, 4.0
	12:58		16350	5, 6, 7	370, 800, 670	2.3, 4.9, 4.1
	12:59		16292	8, 9, 10	400, 175, 260	2.5, 1.1, 1.6
Bed 4	13:00		16233	1, 2, 3, 4	120, 900, 760, 130	0.7, 5.5, 4.7, 0.8
	13:01		16175	5, 6, 7, 8	190, 400, 400, 190	1.2, 2.5, 2.5, 1.2
	13:02		16117	9, 10, 11, 12	170, 210, 200, 150	1.1, 1.3, 1.2, 0.9
	13:04	16000				
Bed 2	13:16	14200				
	13:17		14436	1, 2, 3, 4, 5, 6	1270, 430, 120, 80, 560, 270	8.8, 3.0, 0.8, 0.6, 3.9, 1.9
	13:18		14673	7, 8, 9, 10, 11, 12	120, 60, 147, 138, 75, 65	0.8, 0.4, 1.0, 0.9, 0.5, 0.4
First Landing	13:19		14909	1, 2, 3, 4, 5	250, 620, 550, 450, 300	1.7, 4.2, 3.7, 3.0, 2.0
	13:20		15145	6, 7, 8, 9, 10	170, 250, 460, 810, 710	1.1, 1.7, 3.0, 5.3, 4.7
	13:21		15382	11, 12, 13, 14, 15	460, 180, 110, 70, 85	3.0, 1.2, 0.7, 0.5, 0.6

Room	Time	External Lux, Lux_e	Interpolated Lux, Lux_e’	Node Number	Lux_measured	DF_reality
Bed 1	13:22		15618	1, 2, 3, 4	1400, 1400, 1400, 1300	9.0, 9.0, 9.0, 8.3
	13:23		15855	5, 6, 7, 8	510, 530, 500, 700	3.2, 3.3, 3.2, 4.4
	13:24		16091	9, 10, 11, 12	220, 250, 250, 200	1.4, 1.6, 1.6, 1.2
	13:25		16327	13, 14, 15, 16	110, 130, 120, 110	0.7, 0.8, 0.7, 0.7
	13:26		16564	17, 18, 19, 20	100, 85, 80, 90	0.6, 0.5, 0.5, 0.5
	13:27	16800				
Study	15:25	5100				
	15:26		4940	1, 2, 3, 4, 5	30, 31, 15, 20, 70	0.6, 0.6, 0.3, 0.4, 1.4
	15:27		4780	6, 7, 8, 9, 10	65, 23, 200, 220, 26	1.4, 0.5, 4.2, 4.6, 0.5
Shared Bath	15:28		4620	1, 2, 3, 4	310, 150, 100, 50	6.7, 3.2, 2.2, 1.1
	15:29		4460	5, 6, 7	15, 8, 7	0.3, 0.2, 0.2
	15:30	4300				

Appendix E. Comparing the three Daylight Factor measurements

Room	(1) BRE formula	(2a) Average of every Ecotect grid point	(2b) Average of matching nodes	(2c) Majority for the room	(3) From lux levels measured in house
Entrance Hallway		1.7	1.8	1.2	0.4
Den	1.2	0.8	0.8	0.6	0.5
Option Room	2.1	2.2	2.3	1.8	1.0
Study	1.5	2.3	2.4	1.5	1.5
Kitchen / Diner	2.6	3.9	3.6	3.0	1.7
Bedroom 2	3.5	4.2	3.6	2.8	1.9
Shared Bathroom	1.9	2.3	2.5	0.8	2.0
Bedroom 4	2.6	2.8	2.0	1.8	2.0
First floor Landing		5.7	6.5	4.0	2.4
Lounge	4.6	5.0	4.4	2.5	2.6
Bedroom 1	4.9	5.4	5.0	3.5	3.0
Boot Room	2.3	3.0	3.1	2.0	3.3
Top floor Landing		6.2	5.8	4.0	3.8
Bedroom 3	4.9	6.3	7.4	3.0	7.6

Statistical analysis between the five sets of Daylight Factor results. **(See previous table for meaning of 1, 2a, 2b, 2c & 3)**

Room	Absolute Variations					Ratios				
	1 – 2a	1 – 2b	1 – 3	2a – 2b	2c – 3	1 : 2a	1 : 2b	1 : 3	2a : 2b	2c : 3
Entrance hallway				0.5	1.1				1.3	3.6
Den	0.4	0.5	0.8	0.0	0.0	1.5	1.6	0.6	1.1	1.0
Option room	0.6	0.5	1.7	0.1	0.1	1.3	1.2	2.7	1.0	1.1
Study	0.3	0.4	0.6	0.1	0.1	0.9	0.8	1.4	1.0	1.0
Kitchen / Diner	0.4	0.1	1.9	0.3	0.5	0.9	1.0	2.1	1.1	1.3
Bedroom 2	0.3	0.9	2.6	0.6	0.3	1.1	1.2	2.3	1.2	1.1
Shared bathroom	0.5	0.5	0.0	0.0	0.5	0.8	0.8	1.0	1.0	0.8
Bedroom 4	0.2	0.9	1.0	0.8	0.2	1.1	1.5	1.5	1.4	0.9
First floor landing				0.2	1.6				1.0	1.7
Lounge	0.5	1.1	2.9	0.6	0.2	1.1	1.3	2.1	1.1	0.9
Bedroom 1	0.5	0.9	2.9	0.4	0.0	1.1	1.2	2.0	1.1	1.0
Boot room	0.1	0.0	0.2	0.1	1.3	1.0	1.0	0.9	1.0	0.6
Top floor landing				1.0	0.2				0.8	1.1
Bedroom 3	0.1	0.9	1.2	1.1	4.6	1.0	0.9	0.8	0.9	0.4
Average	0.4	0.6	1.4	0.4	0.8	1.1	1.1	1.8	1.0	1.2
Standard Deviation	0.2	0.4	1.0	0.4	1.2	0.2	0.3	0.7	0.1	0.8

Appendix F. Electrical Appliance Metering

- Since the appliances were used in a variety of modes over the 2 months between when they were fitted and when the family occupied the house, it had to be assumed that each appliance was operated for 7 months in total.
- The cost of electricity was taken as 8 pence per kilowatt hour

Appliance	Total kWh	£ / month
Iron	9.73	0.11
Iron Man	48.64	0.56
Toaster	53.48	0.61
Kettle	75.12	0.86
Induction Hob	108.78	1.24
Washing Machine	217.15	2.48
Kitchen Fridge	224.32	2.56
Fridge in Wine Cellar	250.33	2.86
Oven/Microwave	281.06	3.21
Air cleaner in hall	286.03	3.27
Air cleaner at top	303.38	3.47
Dishwasher	307.56	3.51
Chiller in Wine Cellar	314.53	3.59
Kitchen Freezer	502.39	5.74
Tumble Dryer	533.28	6.09
RFID Power	150.50	1.72
RFID 24hr PC	392.97	4.49
Food Storage	752.7	8.6
Cooking + Dishes	826.1	9.4
Clothes Cleaning	810.8	9.3
Air Purifying	589.4	6.7

Appendix G. Conversion of the RFID data

The displaying of this sample of RFID data is to indicate the extent of manual analysis that had to be carried out just to discard the excessive ‘junk data’ that was collected due to the problems encountered with signal ‘bleed through’.

Two hours worth of data collected from a single tag is contained the 53 lines of the *‘Raw data’* table below, which was edited down to 15 lines of information in the *‘Edited data’* table that then follows. This manual, line-by-line editing process had to be carried out for an estimated 150,000 lines of data in total.

Raw Data

activity_log_datetime	activity_details
11/06/2005 09:29:16.5	Sue Entered the "Sunken" zone
11/06/2005 09:29:16.5	Sue Left the "Bedroom 1" zone
11/06/2005 09:45:51.686	Sue Entered the "Bedroom 1" zone
11/06/2005 09:45:51.686	Sue Left the "Sunken" zone
11/06/2005 09:45:53.126	Sue Entered the "Sunken" zone
11/06/2005 09:45:53.126	Sue Left the "Bedroom 1" zone
11/06/2005 09:46:16.5	Sue Entered the "Bedroom 1" zone
11/06/2005 09:46:16.5	Sue Left the "Sunken" zone
11/06/2005 09:50:46.563	Sue Entered the "Sunken" zone
11/06/2005 09:50:46.563	Sue Left the "Bedroom 1" zone
11/06/2005 09:51:13.686	Sue Entered the "Bedroom 1" zone
11/06/2005 09:51:13.686	Sue Left the "Sunken" zone
11/06/2005 09:52:28.186	Sue Entered the "Landing" zone
11/06/2005 09:52:28.186	Sue Left the "Bedroom 1" zone
11/06/2005 09:53:01.25	Sue Entered the "Dining" zone
11/06/2005 09:53:01.25	Sue Left the "Landing" zone
11/06/2005 09:53:24.563	Sue Entered the "Kitchen" zone
11/06/2005 09:53:24.563	Sue Left the "Dining" zone
11/06/2005 09:53:55.063	Sue Left the "Kitchen" zone
11/06/2005 09:54:09.626	Sue Entered the "Kitchen" zone
11/06/2005 09:54:49.313	Sue Entered the "Dining" zone
11/06/2005 09:54:49.313	Sue Left the "Kitchen" zone
11/06/2005 09:55:07.376	Sue Entered the "Kitchen" zone
11/06/2005 09:55:07.376	Sue Left the "Dining" zone
11/06/2005 09:55:12.563	Sue Entered the "Dining" zone
11/06/2005 09:55:12.563	Sue Left the "Kitchen" zone
11/06/2005 09:55:18.466	Sue Entered the "Sitting Option" zone

11/06/2005 09:55:18.466	Sue Left the "Dining" zone
11/06/2005 09:55:23.656	Sue Entered the "Hallway" zone
11/06/2005 09:55:23.656	Sue Left the "Sitting Option" zone
11/06/2005 09:55:56.876	Sue Entered the "Dining" zone
11/06/2005 09:55:56.876	Sue Left the "Hallway" zone
11/06/2005 09:56:24.563	Sue Entered the "Landing" zone
11/06/2005 09:56:24.563	Sue Left the "Dining" zone
11/06/2005 09:56:26.5	Sue Entered the "Top landing" zone
11/06/2005 09:56:26.5	Sue Left the "Landing" zone
11/06/2005 09:56:26.813	Sue Entered the "Landing" zone
11/06/2005 09:56:26.813	Sue Left the "Top landing" zone
11/06/2005 09:56:28.75	Sue Entered the "Top landing" zone
11/06/2005 09:56:28.75	Sue Left the "Landing" zone
11/06/2005 09:56:39.906	Sue Entered the "Bedroom 4" zone

Edited Data

activity_log_datetime	**activity_details**
11/06/2005 09:29:16.5	Sue Entered the "Sunken" zone
11/06/2005 09:51:13.686	Sue Entered the "Bedroom 1" zone
11/06/2005 09:52:28.186	Sue Entered the "Landing" zone
11/06/2005 09:53:01.25	Sue Entered the "Dining" zone
11/06/2005 09:53:24.563	Sue Entered the "Kitchen" zone
11/06/2005 09:55:12.563	Sue Entered the "Dining" zone
11/06/2005 09:55:18.466	Sue Entered the "Sitting Option" zone
11/06/2005 09:55:23.656	Sue Entered the "Hallway" zone
11/06/2005 09:55:56.876	Sue Entered the "Dining" zone
11/06/2005 09:56:24.563	Sue Entered the "Landing" zone
11/06/2005 09:56:26.5	Sue Entered the "Top landing" zone
11/06/2005 09:56:39.906	Sue Entered the "Bedroom 4" zone

The next step in the analysis procedure was to convert each of these 15 lines of information into a form that would enable statistical comparison using the MS Excel spreadsheet package. This was achieved by assigning the tag to a single room for each 30 seconds of each day. The *'Converted Data'* table below shows how this was achieved for the same period covered in the previous two tables, except while the previous tables had contained data only for Sue's tag, this one shows the comparable information for all four members of the household. Each letter or term used in the table represents a different room in the house; so for instance, SUNK = the sunken tub bathroom, K = kitchen, ST = on a communal areas such as the stairs.

Converted Data

Time	Sue	Nick	Lucy	Hazel
9:29:00	SUNK	SHARED	B4	B3
9:29:30	SUNK	SHARED	B4	B3
9:30:00	SUNK	SHARED	ST	B3
9:30:30	SUNK	SHARED	D	B3
9:31:00	SUNK	SHARED	K	B3
9:31:30	SUNK	SHARED	K	B3
9:32:00	SUNK	SHARED	K	B3
9:32:30	SUNK	SHARED	K	B3
9:33:00	SUNK	SHARED	K	B3
9:33:30	SUNK	SHARED	K	B3
9:34:00	SUNK	SHARED	K	B3
9:34:30	SUNK	SHARED	K	B3
9:35:00	SUNK	SHARED	K	B3
9:35:30	SUNK	SHARED	K	B3
9:36:00	SUNK	SHARED	K	B3
9:36:30	SUNK	SHARED	K	B3
9:37:00	SUNK	SHARED	K	B3
9:37:30	SUNK	SHARED	K	B3
9:38:00	SUNK	SHARED	K	B3
9:38:30	B1	SHARED	K	B3
9:39:00	B1	SHARED	K	B3
9:39:30	B1	SHARED	K	B3
9:40:00	B1	SHARED	K	B3
9:40:30	B1	SHARED	K	B3
9:41:00	B1	SHARED	K	B3
9:41:30	B1	SHARED	K	B3
9:42:00	ST	SHARED	K	B3
9:42:30	K	SHARED	K	B3
9:43:00	K	SHARED	K	B3
9:43:30	K	SHARED	K	B3
9:44:00	K	SHARED	K	B3
9:44:30	K	SHARED	K	B3
9:45:00	D	SHARED	K	B3
9:45:30	D	SHARED	K	B3
9:46:00	K	SHARED	K	B3
9:46:30	K	SHARED	K	B3
9:47:00	K	B1	K	B3
9:47:30	K	B1	K	B3
9:48:00	K	B1	K	B3
9:48:30	D	B1	K	B3
9:49:00	D	B1	K	B3

9:49:30	D	B1	K	B3
9:50:00	D	B1	D	B3
9:50:30	D	B1	D	B3
9:51:00	D	SUNK	D	B3
9:51:30	D	SUNK	D	B3
9:52:00	D	SUNK	D	B3
9:52:30	D	B1	D	B3
9:53:00	D	B1	D	B3
9:53:30	D	B1	D	B3
9:54:00	D	B1	D	B3
9:54:30	D	B1	D	B3
9:55:00	K	B1	D	B3
9:55:30	D	B1	D	B3
9:56:00	D	B1	D	B3
9:56:30	D	B1	D	B3
9:57:00	K	B1	D	B3
9:57:30	K	B1	D	B3
9:58:00	H	B1	ST	B3
9:58:30	H	B1	B4	B3
9:59:00	D	B1	B4	B3
9:59:30	D	ST	B4	B3

On average, it took a full day of editing to convert 24 hours worth of raw day from the household into the format of the table shown above, which is now in a format that could be analysed in a meaningful, statistical manner. MS Excel was used to sum the time each household member spent in each room over four periods of each day, which could then be further analysed by making comparisons across periods of the day, type of day and household member, as discussed and represented in Chapter 9.

The signal bleed-through was much more severe than had been expected and the provided software lacked the analysis tools required to conduct the POE study since it had not been designed for this purpose. If tracking systems are to be used to conduct space usage POE in future, the location accuracy and consistency must be improved and dedicated software should be developed for the analysis process.

Appendix H. Summarised RFID Data

Complete set of averaged data for the Whole Family

	Average for Work Days					**Average for Rest Days**			
	06:00 – 09:00	**09:00 – 15:00**	**15:00 – 20:00**	**20:00 – 01:00**		**06:00 – 09:00**	**09:00 – 15:00**	**15:00 – 20:00**	**20:00 – 01:00**
Outside	28	89	43	11		5	35	41	20
Bedrooms	53	2	6	46		91	25	9	31
Bathrooms	7	1	4	4		0	5	3	4
Living	2	6	22	32		1	14	19	34
Open-Plan Kitchen	7	2	20	5		2	16	24	8
Utility	1	0	2	1		0	2	2	1
Circulation	1	0	2	1		0	2	3	1

Complete set of averaged data for Sue

	Average for Work Days					**Average for Rest Days**			
	06:00 – 09:00	**09:00 – 15:00**	**15:00 – 20:00**	**20:00 – 01:00**		**06:00 – 09:00**	**09:00 – 15:00**	**15:00 – 20:00**	**20:00 – 01:00**
Outside	45	100	37	20		4	38	35	26
Bedrooms	40	0	3	41		94	13	6	32
Bathrooms	6	0	7	6		1	6	4	6
Living	0	0	15	26		0	9	12	26
Open-Plan Kitchen	7	0	31	5		1	26	35	8
Utility	0	0	2	1		0	5	4	1
Circulation	2	0	4	1		0	3	3	1

Complete set of averaged data for Nick

	Average for Work Days				Average for Rest Days			
	06:00 – 09:00	**09:00 – 15:00**	**15:00 – 20:00**	**20:00 – 01:00**	**06:00 – 09:00**	**09:00 – 15:00**	**15:00 – 20:00**	**20:00 – 01:00**
Outside	18	95	76	10	8	41	44	25
Bedrooms	53	1	2	22	82	6	2	16
Bathrooms	7	0	3	2	0	6	3	4
Living	3	2	5	57	2	20	19	43
Open-Plan Kitchen	11	2	12	8	7	20	26	9
Utility	5	0	1	1	0	3	2	1
Circulation	2	0	1	1	1	4	3	1

Complete set of averaged data for Lucy

	Average for Work Days					**Average for Rest Days**			
	06:00 – 09:00	**09:00 – 15:00**	**15:00 – 20:00**	**20:00 – 01:00**		**06:00 – 09:00**	**09:00 – 15:00**	**15:00 – 20:00**	**20:00 – 01:00**
Outside	16	63	22	7		4	26	36	14
Bedrooms	62	6	15	60		93	40	19	37
Bathrooms	9	2	2	4		0	5	3	1
Living	4	20	38	25		1	13	18	39
Open-Plan Kitchen	7	7	21	2		1	13	20	8
Utility	0	1	1	0		0	1	2	1
Circulation	1	1	2	1		0	2	3	1

Complete set of averaged data for Hazel

	Average for Work Days				Average for Rest Days			
	06:00 – 09:00	09:00 – 15:00	15:00 – 20:00	20:00 – 01:00	06:00 – 09:00	09:00 – 15:00	15:00 – 20:00	20:00 – 01:00
Outside	33	100	37	5	4	34	47	16
Bedrooms	59	0	6	61	96	40	7	40
Bathrooms	6	0	4	5	0	4	3	4
Living	0	0	31	20	0	13	27	30
Open-Plan Kitchen	2	0	18	6	0	7	14	7
Utility	0	0	2	2	0	0	1	3
Circulation	1	0	2	1	0	2	2	1

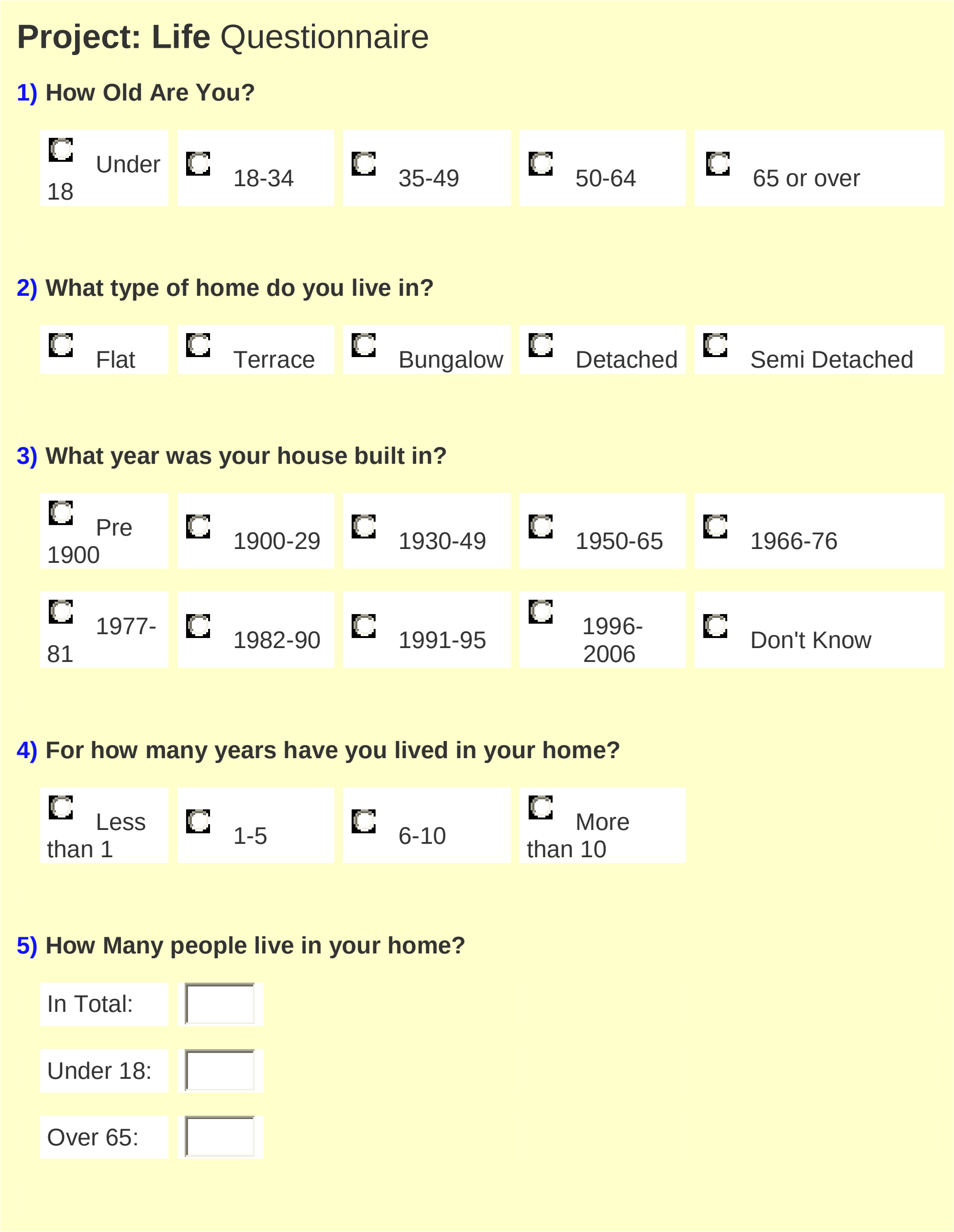
Appendix I. Efficiency of floor space use

Room	Average occupied time (minutes)	Floor Area	Time / Area
Den	166	24.1	6.9
Laundry	10	13.6	0.8
Wine Cellar	3	5.4	0.5
Boot room	22	9.3	2.4
Option room	87	13.5	6.5
Lounge	269	34.2	7.9
Open plan kitchen	271	17.7	0.3
Study / B5	7	17.6	21.7
Parents' bedroom (B1)	121	25.2	7.2
Shared bathroom	37	9.2	4.0
Sunken bathroom	72	9.7	7.5
Hot Tub Decking	5	17.7	0.3
Lucy's bedroom (B2/4)	163	18.8	8.7
Hazel's bedroom (B3)	131	20	6.5
Top bathroom	32	7	4.6

- The occupancy time is the average time per day that the room had somebody in it, whether that was one person or all four of the family.
- 7 hours has been deducted from the occupancy times for each bedroom since the family are assumed to be asleep for this period of time.
- Lucy's bedroom was a combination of bedroom 4 and 2 and the figures in the table reflect this also, being the sum of time and averaged floor area.

Appendix J. Online survey

This survey was linked to from the Project: LIFE webpage and gathered 614 responses as is discussed in Chapter 9.



Project: Life Questionnaire

1) How Old Are You?

○ Under 18	○ 18-34	○ 35-49	○ 50-64	○ 65 or over

2) What type of home do you live in?

○ Flat	○ Terrace	○ Bungalow	○ Detached	○ Semi Detached

3) What year was your house built in?

○ Pre 1900	○ 1900-29	○ 1930-49	○ 1950-65	○ 1966-76
○ 1977-81	○ 1982-90	○ 1991-95	○ 1996-2006	○ Don't Know

4) For how many years have you lived in your home?

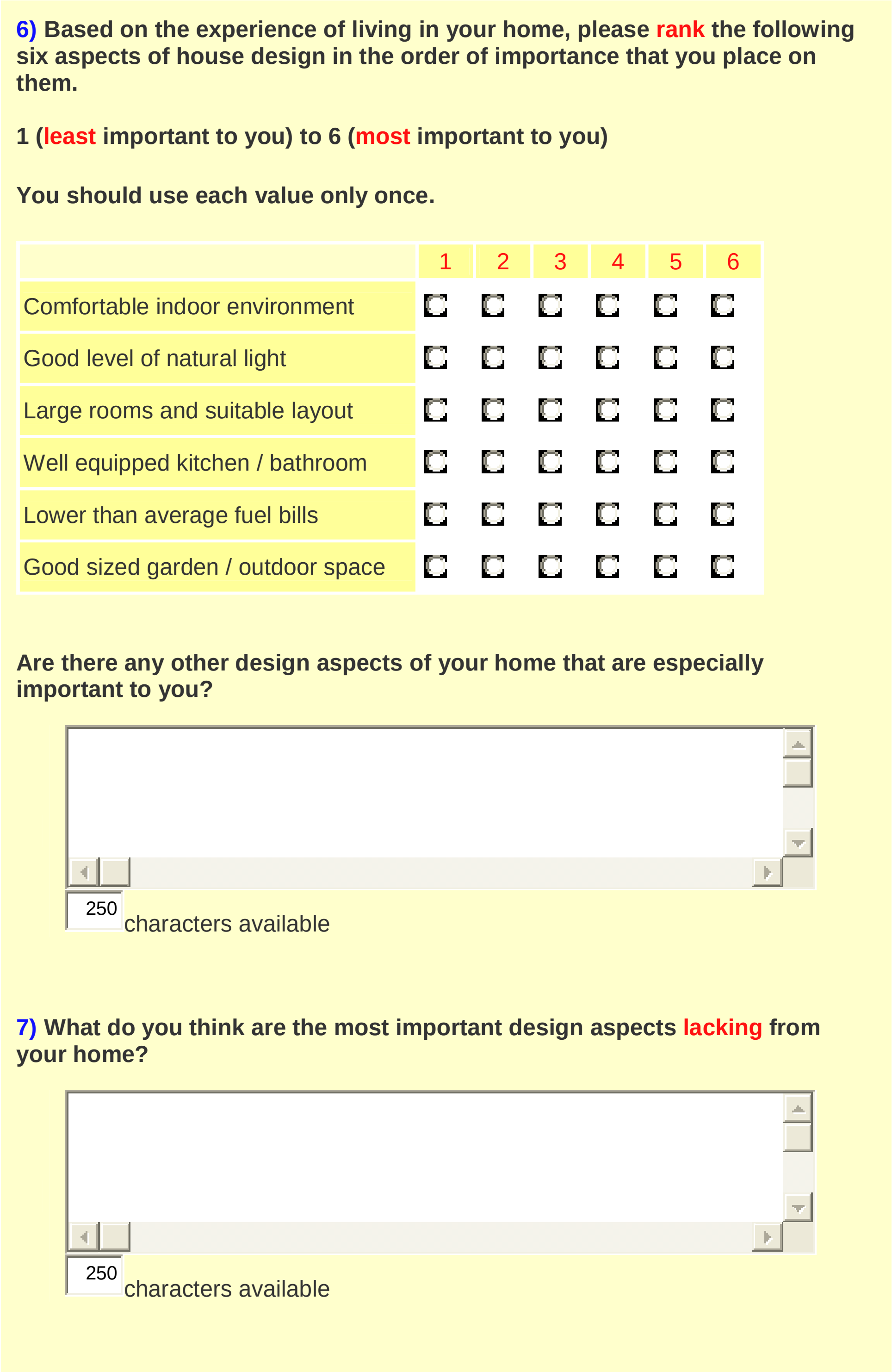
○ Less than 1	○ 1-5	○ 6-10	○ More than 10

5) How Many people live in your home?

In Total: ☐

Under 18: ☐

Over 65: ☐



6) Based on the experience of living in your home, please rank the following six aspects of house design in the order of importance that you place on them.

1 (least important to you) to 6 (most important to you)

You should use each value only once.

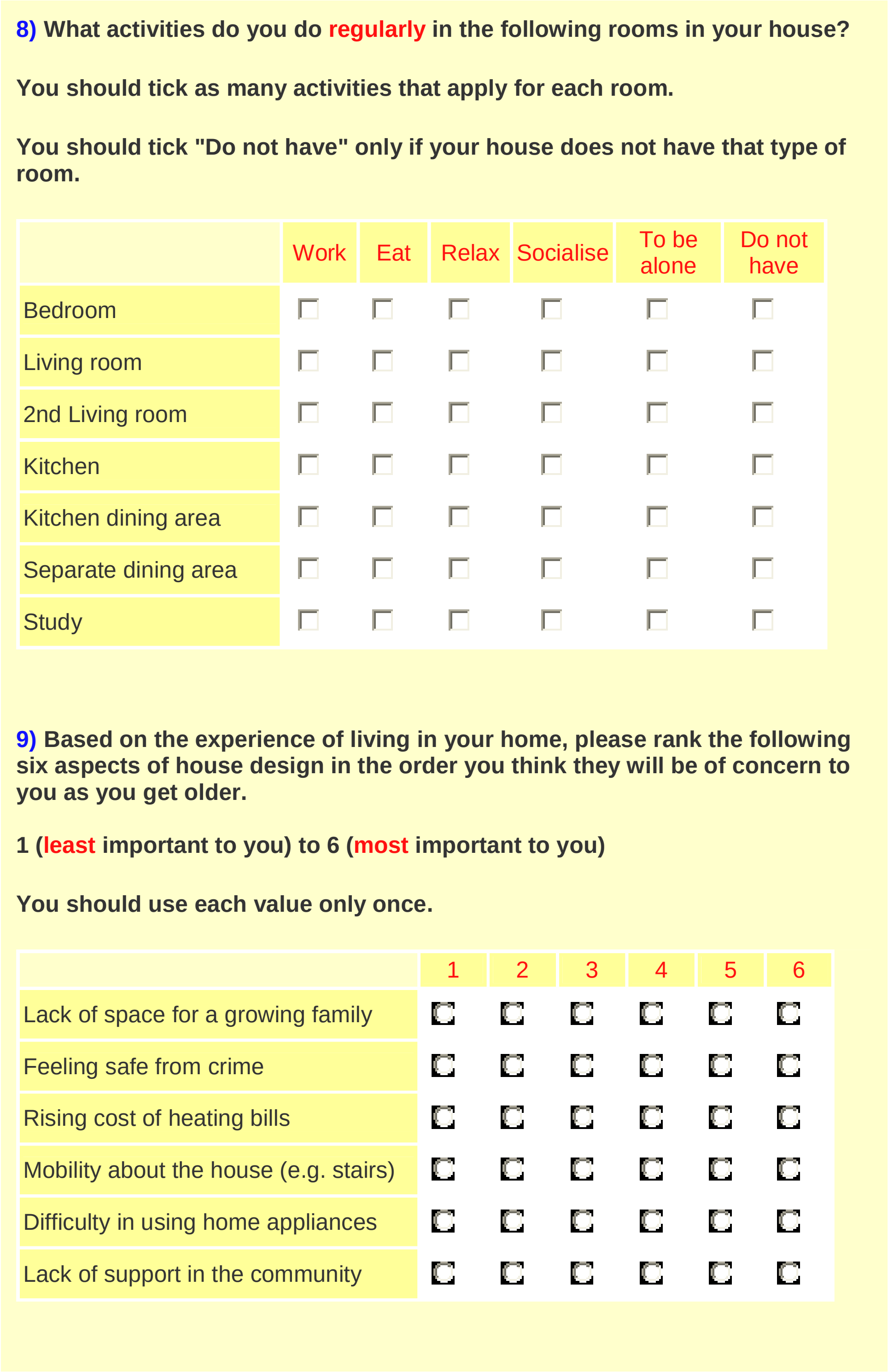
	1	2	3	4	5	6
Comfortable indoor environment	○	○	○	○	○	○
Good level of natural light	○	○	○	○	○	○
Large rooms and suitable layout	○	○	○	○	○	○
Well equipped kitchen / bathroom	○	○	○	○	○	○
Lower than average fuel bills	○	○	○	○	○	○
Good sized garden / outdoor space	○	○	○	○	○	○

Are there any other design aspects of your home that are especially important to you?

250 characters available

7) What do you think are the most important design aspects lacking from your home?

250 characters available



8) What activities do you do **regularly** in the following rooms in your house?

You should tick as many activities that apply for each room.

You should tick "Do not have" only if your house does not have that type of room.

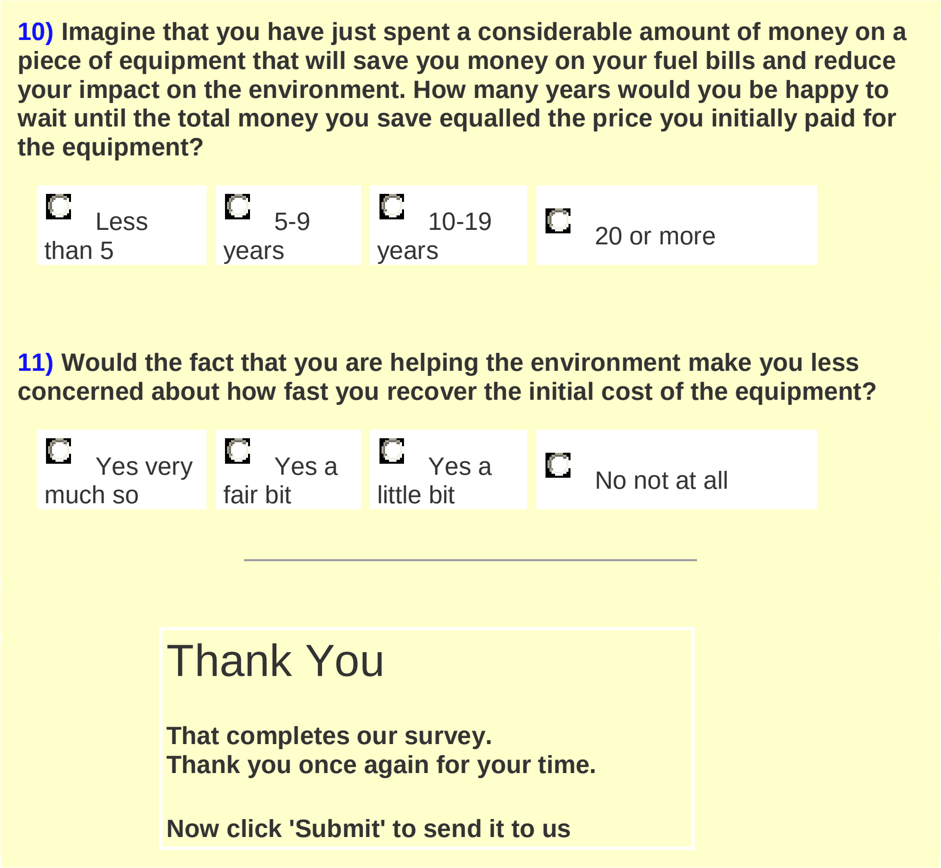
	Work	Eat	Relax	Socialise	To be alone	Do not have
Bedroom	☐	☐	☐	☐	☐	☐
Living room	☐	☐	☐	☐	☐	☐
2nd Living room	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐
Kitchen dining area	☐	☐	☐	☐	☐	☐
Separate dining area	☐	☐	☐	☐	☐	☐
Study	☐	☐	☐	☐	☐	☐

9) **Based on the experience of living in your home, please rank the following six aspects of house design in the order you think they will be of concern to you as you get older.**

1 (least important to you) to 6 (most important to you)

You should use each value only once.

	1	2	3	4	5	6
Lack of space for a growing family	○	○	○	○	○	○
Feeling safe from crime	○	○	○	○	○	○
Rising cost of heating bills	○	○	○	○	○	○
Mobility about the house (e.g. stairs)	○	○	○	○	○	○
Difficulty in using home appliances	○	○	○	○	○	○
Lack of support in the community	○	○	○	○	○	○



10) **Imagine that you have just spent a considerable amount of money on a piece of equipment that will save you money on your fuel bills and reduce your impact on the environment. How many years would you be happy to wait until the total money you save equalled the price you initially paid for the equipment?**

○ Less than 5	○ 5-9 years	○ 10-19 years	○ 20 or more

11) **Would the fact that you are helping the environment make you less concerned about how fast you recover the initial cost of the equipment?**

○ Yes very much so	○ Yes a fair bit	○ Yes a little bit	○ No not at all

---

Thank You

That completes our survey.
Thank you once again for your time.

Now click 'Submit' to send it to us

The Responses

In each of the tables that follow, percentage figures are given in parenthesis.

What age is the respondent?

Under 18	18 - 34	35 - 49	50 - 65	Over 65
12 (2)	289 (46)	218 (34)	103 (16)	11 (2)

What kind of house does the respondent live in?

	Flat	Terrace	Bungalow	Semi	Detached
Sample	115 (18)	119 (19)	24 (4)	211 (33)	164 (26)
Nationally	(18)	(26)	-	(32)	(23)

What is the age of their house?

D/K	Pre 1900	1900-1929	1930-1949	1950-1965	1966-1976	1977-1981	1982-1990	1991-1995	1996-2006
50 (8)	75 (12)	76 (12)	66 (10)	73 (12)	68 (11)	36 (6)	40 (6)	27 (4)	122 (19)

How many years have they lived in this home?

Less than 1	1 - 5	6 - 10	Over 10
109 (17)	242 (38)	103 (16)	176 (28)

How many people are living in this house? (average figures given)

In total	Under 18	Over 65
3.1	0.7	0.1

Q6: How important do they think it is for a good home to have the following qualities?

	Average	Rank
Comfortable indoor environment	4.7	1
Good level of natural light	4.3	3
Large rooms and suitable layout	4.5	2
Well equipped kitchen and bathroom	4.0	4
Low gas and electricity bills	3.4	5
Good sized outdoor space	3.3	6

Q8: What activities take place in each room?

	Do Not Have	Of those homes that have the room				
		Work	Eat	Relax	Social	Alone
Bedroom	0	20	9	91	8	63
Living room	1	36	62	89	91	20
2nd living room	72	42	31	66	65	26
Kitchen	4	34	69	22	53	8
Kitchen-dining	48	34	96	37	67	8
Separate dining	48	44	92	25	65	11
Study	41	96	8	38	4	53

Q9: What do they think will be their concerns as they get older?

	Average	Rank
Lack of space for a growing family	3.4	4
Feeling safe from crime	4.2	1 =
Rising cost of heating bills	4.2	1 =
Mobility about the house (e.g. stairs)	3.7	3
Difficulty in using home appliances	3.0	6
Lack of support in the community	3.1	5

Q10: What would be the acceptable payback period for them if they were to spend money on a piece of energy efficiency equipment?

	Average	Rank
Less than 5	246 (39)	2
5 – 9	304 (49)	1
10 – 19	59 (9)	3
More than 20	17 (3)	4

Q11: Do they consider helping the environmental to be a bonus that makes it less important to reach the payback period?

	Average	Rank
Yes, very much so	121 (19)	3
Yes, a fair bit	226 (36)	1
Yes, a little bit	211 (34)	2
No not at all	69 (11)	4