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A performance evaluation of mainstream timber framed and traditional masonry housing in the UK

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Abstract

Within the UK traditional masonry construction techniques are struggling to deliver the quantity and ecological quality of housing required by an ever increasing UK population.

This research employs a case study review of a mainstream mixed timber frame and masonry housing development - Green Street, in order to explore the ecological viability of timber prefabrication as an alternative to the established masonry construction methods currently employed in the majority of British housing.

Four houses of each construction type in the Green Street development were outfitted with a number of environmental monitoring sensors for continuous monitoring. In addition the study incorporates fabric testing in the form of air permeability testing, Co-heating analysis, thermography, and a life cycle analysis. Building Use Survey, project management and design team interviews and an industry questionnaire form the final part of the evaluation protocol.

The study revealed that heating the timber dwellings ultimately required less energy per degree difference between inside and outside temperatures. During the summer the timber housing displays a greater diurnal temperature swing, while on average the temperature remains consistently lower than the masonry housing. The masonry housing was found to be both more air tight and exhibiting a lower heat loss coefficient, despite that, the performance gap between design and reality for space heating is less in the timber prefabricated housing. The life cycle analysis revealed that the timber walls have a lower impact on climate change.

BUS methodology results found that construction type had little to no impact on occupants. The design team review highlighted the need for a greater level of prefabrication in timber housing to increase precision and work around a serious skills shortage. An industry questionnaire suggested that timber construction in the UK can often suffer from poor construction practice, predicated by a gap in specialized knowledge.

The research concludes that in this instance, the timber prefabrication technique produced dwellings that perform ecologically on par with their masonry counterparts. In answering the research question, the evidence suggests that at this stage the technique would be better employed on a case by case basis and supported by specialists in timber fabrication, rather than implemented as a blanket alternative for existing masonry construction.

Already a number of insights from this research have filtered into industry practice and will continue to better inform both industrial and academic partners in their decisions regarding the use of timber prefabrication in mainstream UK housing.

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List of Acronyms

BPE – Building Performance Evaluation
BRE – Building Research Establishment
BSRIA – Building Services Research and Information Association
BUS – Building Use Survey
CIBSE - Chartered Institution of Building Services Engineers
DCLG – Department for Communities and Local Government
DECC - Department of Energy & Climate Change
DER – Dwelling Emission Rate
DTLR – Department for Transport Local Government and the Regions
EARM - Energy Assessment and Reporting Methodology
EST – Energy Saving Trust
HLC – Heat Loss Coefficient
ISO – International Standards Organisation
MMC – Modern Methods of Construction
NHBC – National House Building Council
OSM – Off Site Manufacture
PIR – Personal Infrared
POE – Post Occupancy Evaluation
POST – Parliamentary Office of Science and Technology
RGU – Robert Gordon University
RIBA – Royal Institute of British Architects
SAP – Standard Assessment Procedure
TER – Target Emission Rate
TPC – Timber Prefabricated Construction
TSB – Technology Strategy Board
UKTFA – UK Timber Frame Association
WHLC – Working Heat Loss Coefficient

1 Introduction

The timber prefabrication construction technique is seen by many as a viable solution to the challenges faced by the UK house-building industry, as provoked by the government's sustainable housing agenda, significant economic pressures and inadequate production levels, particularly within the public housing sector. However the techniques' alleged characteristics of rapid, inexpensive and sustainable construction are based primarily on foreign precedence with little information available on successful, practical examples within mainstream UK housing developments (Berge, 2009). The research that does exist is often fragmented (EST, 2008) and focused on the design and delivery phase, rarely incorporating post occupancy evaluation and life cycle analysis. With so little comprehensive evidence industry uptake understandably remains slow, with large developers reluctant to invest heavily in a historically stigmatised technique.

This significant gap in research has prompted the following study which closely examines the quantitative and qualitative post occupancy performance of a mixed timber frame and masonry housing development in the UK with the novel purpose of establishing standardised and comparable benchmarks for each style.

1.1 The Problem

The average home within Europe, and particularly the UK, is not conducive to the sustainable living standards that are required by modern environmental ideals, as necessitated by the advent of climate change (Pan & Garmston, 2012). The UK government has identified the housing sector in particular, as one of its greatest contributors of greenhouse gasses with energy consumption accounting for nearly a third of all carbon emissions within the UK (Swan & Ugursal, 2009). Innovation and a fundamental shift towards more environmentally responsible dwellings is essential in meeting this challenge to deliver more sustainable construction (Pan, 2010). This is not simply a moral duty that we have to future generations, it is quickly being adopted in legislation and sustainable policies throughout Europe (Council of EU, 2009) and in the UK (Communities and Local Government, 2006).

Evidence from Schmuecker, (2011) Bell, et al., (2010) and Ball (1996) suggests that traditional masonry construction methods are simply unable to cater to the quantity, quality, and sustainability standards required of the modern-day industry without significant advances in building practice and materials. Based on a substantial body of work by Bågenholm, Yates, and McAllister (2001), Barlow, et al., (2003), Hartman (2010), (Mullens and Arif (2005), Pan et al. (2008), Roy et al. (2003) and TRADA, (2008) detailing the innate merits of timber prefabricated construction (TPC), this study suggests that the large scale assimilation of innovative TPC could inherently increase the productivity and ecological standing of the residential construction sector while working in partnership with the ever evolving masonry practices.

However any significant step towards the mass integration of TPC would require the backing and active participation of large house builders such as Taylor Wimpey, Barratt, Persimmon, Bellway and Berkeley which, out of the top 20 House Builders in 2011, garnered over 70% of new build turnover (The Construction Index, 2011, p. 1), and without whom this movement would forever remain on the periphery. "For timber frame to become more than a niche construction method, (in England) requires that the construction industry's experience of timber frame construction reach a certain "critical mass", i.e., the main material specifiers; architects, developers and construction engineers, start to regard timber frame as a real alternative when deciding on structural material." (Jonsson, 2009, p. 4) However traditions and cultural inertia in the UK generally place TPC in the negative framework of poor quality, light construction, and temporary structures (Craig et al. 2000; Bågenholm et al. 2001; Vale, 1995; Davies, 2005; Ball, 1999).

1.2 The Gap in Knowledge

The assumptions however are generally uninformed ignorance and based on the historical reality of post-WWII prefabrication (POST, 2003; Gillian, 2002) and its associated media coverage (Jonsson, 2009), rather than a reflection of the current process and available materials Wingfield et al. (2011, p.5). in speaking about the well documented Elm Tree Mews Project, published by the Joseph Rowntree Foundation, noted that:

> *"It is recognised by the housing industry that, despite the fact that solutions exist for the construction of very low and zero carbon housing, there is considerable concern that many of these solutions are untried and untested within the context of mainstream housing production in the UK. The lack of published performance data also shows that many schemes do not undergo comprehensive monitoring and evaluation to check whether the approaches chosen have achieved their designed performance targets."*

Essentially, the suppositions and evidence put forward by Bågenholm, Berge, Hartman and Roy outlining the potential benefits of TPC are based for the most part on foreign precedence and theoretical, applications.

Information pertaining to successful, practical examples of sustainable TPC within medium to large scale (greater than 20 houses) mainstream UK housing developments, not research housing or purpose built eco villages, is incredibly rare (see Section 2.7) and the research that does exist is often fragmented (EST, 2008) and focused on the design and delivery phase, rarely incorporating post occupancy evaluation and life cycle analysis.

What Wingfield is suggesting is that without a substantial body of UK based evidence that TPC actually works, there is no incentive for the mass house builders to adapt their practices and invest in what is historically a heavily stigmatised construction technique (POST, 2003; Ball, 1996; Goodier and Gibb, 2007; Johnson, 2007).

1.3 Novelty and Justification of the Research Directives

In recognition of the gap in knowledge discussed in section 1.2, but with respect to the somewhat narrow scope of this research project, the aim is to begin to fill that gap knowledge through the generation of post occupancy evaluation data from a specifically mainstream UK development of TPC dwellings. Adding to the novelty of this work, the thesis presents this data within the context of a previously undocumented type of case study in this field of research. A case study uniquely suited to the task of TPC evaluation in that it was constructed in multiple phases using a mixture of timber frame and masonry construction techniques all built by the same contractor. The dwellings were designed along the same environmental standards and even maintain a similar layout throughout.

These uniquely similar operating parameters represent an ideal opportunity to directly compare the timber and masonry building methods through post-occupancy performance monitoring of the dwellings and their occupants. Usually the lack of standardisation among dwellings means that a direct comparison is considered too inaccurate to generate significant data. This study therefore offers the potential to contribute a significant amount of representative (Section 9.5) novel information to help better inform industry, policy, and the general public as to the current standards of TPC mainstream dwellings in the UK.

The "Overcoming Client and Market Resistance to Prefabrication and Standardisation in Housing" project from the Scott Sutherland School of Architecture and Built Environment (RGU, 2002) presents an interesting research model with similar research goals wherein a two stage process was used to generate data for the purpose of addressing market resistance towards prefabrication and standardisation in housing. Initially, they developed and tested predominantly financial models through which the resistance to pre-fabrication and standardisation in UK housing could be eased (RGU, 2002). The second stage involved the practical, on-site demonstration of both product and process developments looking to increase market penetration and confidence in the pre-fabrication and standardisation technique. Thus, in seeking to address the opposition to prefabrication and standardization, the project dealt with two very distinct lines of inquiry; the financial and practical viability of the process.

From a financial point of view the research concept is very simple - if it costs more to produce houses of similar standards using TPC methods then there is no industrial incentive to change existing practices. With the financial crash of 2007/2008 (Adair et al. 2009), an unreliable rate of profitability, and generally low margins in the residential market, companies can simply not afford to invest in financially unfounded and untested ventures. It must first be established that TPC housing can be built cheaper or on par with existing masonry methods.

From a practical perspective even if a house can be built more cheaply using TPC, if the final result is poorly constructed, and underperforms, there is no point in building it. Evidence must demonstrate that TPC housing can perform better than or on par with existing masonry methods.

Where the Robert Gordon University (2002) project displays a significant financial bias in its dual research directive, this project maintains a far narrower scope in its development of post occupancy data. Given the vast and somewhat diverse nature of the financial and performance based justification, it is only feasible to focus on one area of inquiry, financial or performance, within the narrow timeframe and financial constraints of this research project. Fundamentally, the focus of the study stems from the argument that it makes little sense to promote a technique or practice such as TPC, no matter what the financial benefits might be, without first understanding how it performs in the environment for which it is intended.

Based on this argument and the gap in knowledge presented in section 1.2, the research goals focus on developing a post occupancy performance evaluation of the TPC method in an effort to establish its ecological standing; as a prerequisite to future research projects that may delve further into the financial implications of building timber prefabricated housing.

1.4 Research Aim

Keeping in mind the significant gap in TPC knowledge discussed in section 1.2, the research goals are to provide a comprehensive, performance evaluation of an environmentally certified timber and masonry fabricated case study site as a representative proponent of TPC performance in the mainstream housing market of the UK. The performance characteristics and qualitative evidence gathered through this comprehensive program of Post Occupancy Evaluation (POE) will address the research question – is TPC an ecologically viable alternative to established masonry construction methods in mainstream British housing?

POE is the structured process of evaluating the performance of a building after it has been built and occupied. This is achieved through systematic data collection, analysis and comparison with predetermined or specified performance criteria (Menezes et al. 2011). The POE research program in this project consists of a retrospective evaluation of the design and construction process, fabric testing of the dwellings as constructed (compared with design expectations), the monitoring of energy and other performance characteristics of the dwellings in use and a host of qualitative testing on occupants and the team responsible for designing and developing the case study site. The final phase of the POE is a basic life cycle analysis of the structural envelope (See Chapter 6 for details). The post occupancy perspective is vital as it tests the actual performance of a building rather than relying on models and predictions. The role of design quality and functionality and the way in which this ultimately reveals itself through the building performance and occupant perceptions (Yates, 2003) informs both the long-term success of sustainable technologies/techniques and their relative efficacy in environmental terms.

As a fundamental component of the research aim, this project looks to overcome one of the greatest obstacles of building monitoring and POE - the fragmentation and singularity of results (Energy Saving Trust, 2008). With data inherently tied to the site/dwelling specific data often becomes incompatible with other studies from different locations and difficult to process on a large scale. As such, the overarching format of the POE data collection is dictated by the Technology Strategy Board's (TSB) Building Performance Evaluation (BPE) protocol (TSB (b), 2011). The rigorous and widely tested protocol inherently validates the methodology used within this study and creates a set of data and conclusions that are easily comparable to the benchmark performance characteristics and context of the majority of current research.

Once data and performance statistics are collected via the TSB BPE protocol they are analysed, wherever possible, within the context of the "gap between design and reality" (Colmer, 2012; Herring & Roy, 2007; Johnston, 2010; Taylor et al., 2009; Wingfield, 2011; Zero Carbon Hub, 2010; Zero Carbon Hub, 2011). This type of approach makes use of a two tiered analysis process. The performance data is subject to a comparative analysis between the different fabric types and then a more introspective analysis that compares the measured data and the predicted design values.

Going beyond a straightforward direct comparison of statistics, the aim or this project is to apply the data from the study to determine which construction type results in a product that most closely resembles the original design intentions of the residence. This will be used as evidence alongside the more standardized direct comparison of results to establish the practical efficacy of TPC as an ecologically viable alternative to traditional masonry construction methods.

1.5 Key Objectives

The objectives of the study are based around answering the core research question, is modern timber prefabricated construction an ecologically viable alternative to established masonry construction methods in mainstream British housing? This is in turn based on the significant gap in knowledge surrounding the post occupancy performance of mainstream timber housing developments. The conclusions developed during this study are intended to inform the future and development of the housing industry and ongoing research in academia.

Research Objectives:

- Using standardised POE techniques and a mainstream housing case study, generate post occupancy performance measurements over a full heating and cooling season for both masonry and timber housing.
- Using the post occupancy performance data, evaluate the gap between design intentions and reality within the context of space heating energy performance.

- Using standardised POE techniques, gather qualitative information on occupant's attitude toward their respective houses and their experiences within the dwellings.
- Using standardised POE techniques (insofar as possible) conduct a series of interviews with the case study management and key players in timber housing construction to establish the perceived barriers to integration within both the private and public sectors.
- Conduct a life cycle analysis of the timber and masonry envelope in order to ascertain the cradle-to-construction environmental impact of the timber and masonry construction materials used.
- Disseminate conclusions on TPC performance directly into industry for maximum impact on future building projects. Disseminate standardised results within academia and research institutions for large scale analysis and can be for further research applications.

1.6 Thesis Structure

The thesis is divided into 8 chapters in total, each with a specific role in developing, and ultimately dealing with the research aim.

Chapter 1: The introduction chapter develops a brief context of the research and highlights the key gap in research within the field of timber prefabricated construction in the UK. It goes on to explain the conceptual framework designed to address this gap in research; specifically identifying the key aims, objectives and a rough outline of the methodology that will guide the progression of the project.

Chapters 2: A timber fabrication evaluation literature review is used to justify the project, its focus on timber and outline the current state of both the industry and timber fabrication research.

Chapter 3: Introduces both the case study site and the primary methodological protocol used throughout the thesis. It then applies this methodology to a variety of environmental performance tests in order to assess the ecological impact of the two different housing types.

Chapter 4: Focuses on a sequence of fabric tests designed provide evidence to support the environmental monitoring data from Chapter 3. The tests are designed to gauge the instantaneous functionality of the fabric allowing for a comparison between the case study housing and an industry benchmark or previous performance tests.

Chapter 5: Introduces the concept of a gap between design and performance and uses the Standard Assessment Procedure (a mandatory benchmarking process) to assess this gap for each of the case study houses.

Chapter 6: Life cycle analysis does not fall within the standard remit of post occupancy evaluation, nor is it included as part of the TSB BPE. It was therefore credited with its own chapter that works through the structure, and methodological approach chosen for this particular study.

Chapter 7: Presents a detailed breakdown of the qualitative portion of testing, inherently including some quite in-depth discussion and application of the data from Chapters 3-6.

Chapter 8: The discussion and conclusions chapter pulls together all the various conclusions from the results and places them within the context of the project aims and goals, looking for cross validation between the results and ultimatly trying to establish the performance of a mainstream timber prefabricated development in relation its traditional masonry counterpart.

2 Housing in the UK

Approximately 1.34 million households are currently waiting for social housing and roughly 146,000 homes in England fail to meet the Government's Decent Homes Standard (DCLG, 2014, p. 6). Figures issued by the Government show that the total number of homeless households in temporary accommodation stood at 60,940 at the end of September 2014, of which 45,620 of these households include dependent children and/or a pregnant woman (Wilson, 2015, p. 5). Considering current figures indicate only 112,000 homes were built in 2014 and government forecasts predict a need of over 232,000 per annum (DCLG, 2014, p. 1), the deficit results in hundreds of thousands of families on housing waiting lists, and pushes house prices even further out of the reach of those on ordinary incomes (Shelter, 2011). These are revealing statistics in a supposedly developed and relatively wealthy country such as the UK.

Change is no longer an aspiration, it is a stark and immediate necessity. There are fundamental flaws in an industry that generates figures like this, flaws which extend far beyond just the building materials and construction methods and include factors such as land shortage, a stringent planning system, less financial investment within the property market and fewer smaller house builders (De Castella, 2015). It is a fact however the inherent weaknesses associated with current construction methods (Energy Saving Trust, 2009; Barker K. , 2004; Ross, 2002) within the UK housing industry only serve to aggravate this situation.

In answer to the call for change and the overall aims of the research project, this chapter reviews the innovative characteristics of TPC as one component of the larger modern methods of construction movement. It explores the potential role it may play in advancing UK housing practice. It exposes the paradox of an entrenched ideology, namely the fixation on masonry construction methods, by establishing the need for innovation within the industry. It uses the plight of vulnerable levels of society to highlight the benefits of a flexible, cost effective, quickly erected and thermally efficient method of construction, finally delving into the cultural and industrial barriers which face TPC and its large scale integration into mainstream developments. The chapter concludes by looking at the extent of current research using performance statistics to push forward the legitimacy of TPC as a viable construction method.

2.1 Drivers for Innovation in the Housing Sector

With the recent slump in housing construction due to the global financial crisis (DCLG, 2011; Lambert, 2011) there is little room for speculation and if this project is seriously proposing the wide scale introduction of a radically different form of construction, it must be initiated by research that clearly highlights the inadequacy of existing practice.

2.1.1 A Shortage of Affordable Housing in the UK

A report by the Royal Institute of Chartered Surveyors (2010) reveals 2 key facts of the post-crisis market:

- Despite small fluctuations on a monthly basis, housing prices remain high – subsequently private rents have continued their upward trend as first time buyers look to alternatives.
- New housing starts remain well short of pre-credit crunch figures and significantly below the government's target figures of approximately 250,000 homes a year (resulting in 3 million new homes by 2020).

This evidence is backed up by figures from the Department of Communities and Local Governments (DCLG, 2010; DCLG, 2011) property developer Crest Nicholson (2010) and financial institutions, Nationwide, Halifax (King, 2011; Lambert, 2011).

"The measurement of housing need depends on a few key concepts; the definition of acceptable standards of accommodation, the total numbers of households, and the supply of housing of at least the required standard."

(Barnett and Stuart, 1990, p.184) In this case the acceptable standards are defined by the financial capacity of the nation and the findings reveal a substantial need for cheaper and more abundant housing (Pan, 2010).

Figures from 2003 (DCLG, p. 12) maintain that in spite of pressures on the housing stock, some 730,000 dwellings remained vacant – 3.4% of the stock. Some may argue that based on these figures the housing market is in fact saturated and simply needs time for prices to come down. However, when coupled with the fact that 80% of these vacant dwellings were privately owned it reveals the stark contrast within the public and private housing sector only exacerbated by local authorities selling off properties and the right to buy decimating government housing stocks (Dugan, 2014). Consequently, we see that the evidence exposed by the RICS report is compounded within the public/social and affordable housing sector (DCLG , 2014). The problem facing the UK housing Market is succinctly summarized by Barker (2004, p. 1) speaking in the Review of Housing Supply Final Report – Recommendations: "I do not believe that continuing at the current rate of house building is a realistic option, unless we are prepared to accept increasing problems of homelessness, affordability and social division, decline in standards of public service delivery and increasing the costs of doing business in the UK – hampering our economic success." The evidence of this section clearly illustrates a housing deficit in the UK, and considering that as a whole, brick and mortar dominates the industry accounting for as much as 85% of new build projects, (Lovell and Smith, 2010, p. 457) it is a fair conclusion that as the predominant construction method, the inherent characteristics of brick and mortar construction, play a significant contributing role in this deficit.

2.1.2 The State of Existing Practices

This dominating presence, even fixation, on the brick and mortar construction technique is deeply ingrained within the culture and history of UK housing construction.

Figure 2.1 Construction Type by Dwelling Age

(DCLG, 2012, p. 22)

Traditionally this predominant use of brick would have been due to the basic availability and abundance of materials such as clay and the overarching requirement for durability and longevity, however in the modern era of rapid innovation, automation and assembly logistics this fixation looks to be somewhat paradoxical and dated (Craig et al. 2000; Lovell & Smith, 2010). Traditional masonry construction methods have been found to be costly and inflexible (Barker K. , 2004; Ross, 2002; HLSTC, 2005) as well as slow in adjusting to rapidly changing demand across the housing cycle. Inefficiencies (Energy Saving Trust, 2009), labour intensiveness (Gibb K. , 1999) and a general inability to cater to the quality, and sustainability standards required of the modern-day industry (Schmuecker, 2011; Bell et al. 2010) all seem to point to a technique at odds with key goals of UK housing policy and its pursuit of a ready supply of affordable and environmentally sustainable accommodation (Lovell & Smith, 2010).

Given these intrinsic deficiencies, adaptation and radical innovation would seem to be the obvious conclusion and with so much evidence from other countries attesting to the merits of timber as a material and prefabrication as a process there is understandably some pressure to integrate TPC into the housing construction cycle on a much larger scale the existing volumes (HLSTC, 2005; Barlow, et al., 2003).

However industry uptake remains slow (Goodier and Gibb, 2007; Johnson, 2007) and there remain some significant practical barriers including a lack of permanent factories, inadequate logistics and supply chains, limited natural resources, and a shortage of design, manufacture and assembly skills; all of which are needed to take advantage of any new innovation (Etzkowitz & Leydesdorff, 2000). Yet it is not these aspects that hold the key to large scale integration – these practical aspects can all be solved relatively easily once there is a desire, a genuine drive within the industry to incorporate TPC, and this will not happen until the public and developers alike, overcome the historically based cultural stigma of prefabrication and timber housing (Pan et al. 2007). The key is education. Historically, large scale TPC has performed poorly in the UK (Craig et al. 2000), subject to poor durability, poor performance and poor design. Technological and logistical advancements made in the past 40 years, however, make this viewpoint obsolete and clients and developers must be taught the reality of modern processes, materials and performance. This market confusion and ambiguity is perfectly summarized in a paper by Goodier and Gibb (2005, p. 157) "The belief that using offsite is more expensive when compared with traditional construction is clearly the main barrier to the increased use of offsite in the UK, even though a large proportion of the respondents also thought that two of the advantages of using offsite were both a reduced initial cost and a reduced whole life cost." The same paper found that 33% of Clients and designers and 46% of contractors felt that there was a lack of guidance and information pertaining to prefabrication. This confusion and controversy is indicative of the dilemma faced by major housing developers and the public as they seek to embrace the 'innovation' of timber prefabrication during a period of market pressure. A significant amount of research portrays timber prefabrication as a financial and sustainable solution to the UK housing industry and yet practically there is little to no relevant research from mainstream developments to back this up. With little clear, coherent and relevant information the result is confusion amongst clients, architects, and developers and a lack of faith in a possibly revolutionary method of construction.

There is a consensus that the UK house building industry is inefficient and lacks innovation in comparison to elsewhere in Europe (Barker K. , 2003; Barlow et al. 2003; BRE, 2006; Lovell, 2007; Pan et al. 2008), "This is alleged to stem from its labour intensiveness, site management problems, poor skills levels, fragmentation of design and production activities, the sequential nature of the production process and caution borne from the cyclical nature of housing demand and land prices." (Gibb K. , 1999, p. 44) This stagnation has coupled with increasingly complicated and costly land acquisition and a volatile market, resulting in significant housing shortages in both the public and private sector (Maliene & Malys, 2009; DCLG (b) 2010). There are additional concerns about the ability of masonry construction methods achieving the ever stricter environmental regulations set out in Part L. "In effect, it would become less profitable to use masonry construction in comparison with using other techniques, such as steel and timber frame building, because of the extra cost and technical difficulty of installing additional thermal insulation within walls (Lovell, Exploring the role of materials in policy change: innovation in low-energy housing in the UK, 2007, p. 2505).

There is overwhelming pressure to increase both the quantity and quality of housing while simultaneously bringing down the costs. "The UK is committed to increasing the number of new houses; 3 million by 2020. This increase in construction will have significant implications for the UK's national carbon budget. However the magnitude of this impact will be dependent upon how these houses are constructed" (Monahan and Powell, 2011, p. 181). It is this pressure that will force large housing developers out of their industrial stagnation toward construction innovations such as timber prefabrication. "Innovation, again, has been promoted as a key "means" to meeting the challenge (of building additional, cheaper homes) and delivering sustainable construction" (Pan, 2010, p. 78).

2.2 Modern Methods of Construction

2.2.1 Timber Frame Prefabrication

Prefabrication can be defined as "a manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of a final installation" (Tatum, 1987; cited in Haas et al. 2000 , p. 1). In an effort to combat the stigma associated with the word prefabrication or pre-fab, the terms Modern Methods of Construction (MMC) (Kempton & Syms, 2009; Lovell, 2007) and Off-Site Manufacture/Production (OSM/P) (Venables et al. 2004), were created. It can be assumed for the purposes of this study that the words, prefabricated, MMC and OSP will be used interchangeably. In reality MMC encompasses a much broader spectrum of build processes and materials than simply timber frame and intended to reflect technical improvements in prefabrication, encompassing a range of on and off-site construction methods (POST, 2003). It is these processes that many believe are an essential tool in the industry's fight to achieve a significant step change in technology and costs (HLSTC, 2005).

MMC includes volumetric, panelised and hybrid (panelised with volumetric elements such as bathrooms and kitchens installed as modules) construction (National Audit Office, 2005) using anything from steel to precast concrete. It is defined by the Homes and Communities Agency (2008) as a range of technologies and processes involving various forms of supply chain specifications, prefabrication and off-site assembly used, in order to achieve:

- Reduced interference from weather
- Fewer materials deliveries and so reduced disruption and fuel consumption.
- High standards of design quality
- Reduced construction times.
- Fewer defects.
- Higher quality.
- Minimized wastage.
- Meeting demand during skills shortages.
- Reduced labour requirements.
- Improved safety.
- Use of better more environmentally aware materials.
- Improved manufacture times.

MMC incorporates even within its definition the word prefabrication, and is used within industry to describe technologies and processes which have the same inherent benefits afforded through the prefabrication process, but crucially, it is not the actual word prefabrication. Fundamentally all construction involves some element of prefabrication or MMC, be it pre-formed lintels, precast bricks, windows, doors and even kitchen suites. Given its abundance, versatility and cost, timber is generally the predominant material used with MMC processes with the exact proportion of factory to site work dependent on the type of construction detailed later in this section.

The concept of prefabrication within construction is far from new in the UK. As previously eluded to and dealt with in Section 2.2.2. Prefabrication has long been accepted as a fast and simple construction method (POST, 2003). After its wide spread use in post-war accommodation in the 1960’s/70’s then essential demise following the now infamous “World in Action” episode in 1983 (Ross, Non-traditional housing in the UK - A brief review, 2002), prefabrication and its attributes once again rose to prominence in 1998, with the publication of a report by Sir John Egan, Rethinking Construction (1998). Accompanied by other government reports including Constructing the Team (Latham 1994), and followed by Rethinking Construction Innovation and Research, (Fairclough 2002) and Accelerating Change (Egan 2002), the so called “Egan Report” played a huge role in shaping the government’s construction policy, encouraging the industry to address market demands for "improved efficiency, better quality, faster construction, and better cost control" (Gorgolewski, 2005, p. 122). It even went as far as to suggest that part of the solution might be a greater application of standardization and prefabrication process taken from Europe (Egan, 1998, p. 27).

In recent years the subjects of efficiency and speed, identified within the Egan report, have been coupled with a strict sustainability agenda put forward by the Government, (Communities and Local Government, 2006; Council of EU, 2009) developed in response to the advent of global warming.

Until recently the UK has viewed MMC as simply a technique that builders can employ to keep up with housing demand, while in Europe the focus has been primarily on the environmental benefits afforded by the factory based process and rigorous results (HLSTC, 2005). However, research has revealed considerable areas of commonality between the agenda of improved industry efficiency and the need for ecologically aware construction, including attributes such as reduced site waste, rapid fabrication and better airtightness (Berge, 2009; TRADA, 2008; Pan et al. 2008). The realization that prefabrication, coupled with the right materials, could essentially overlap and solve both issues, creates an even greater need for information on performance and financial viability within the UK (Craig et al. 2000).

MMC is actually quite a broad term which incorporates many levels of prefabrication ranging from individual components and sub-assemblies to volumetric pre-assembly and entire modular buildings. (Sparksman et al. 1999; cited in Craig et al. 2000, p. 3). MMC as a process also draws on a number of different materials, primarily timber, steel and concrete in the UK (POST, 2003). Irrespective of the level of prefabrication or the materials used, the overarching theme is the initial factory setting and the controlled environment that it represents. Greater control is greater quality, repeatability, lower costs and crucially in the UK, less chance of weather interruptions or damage. The build process, is what differentiates MMC from regular construction and it is succinctly visualized in this diagram from the NHBC (Ross et al. 2006, p. 14).

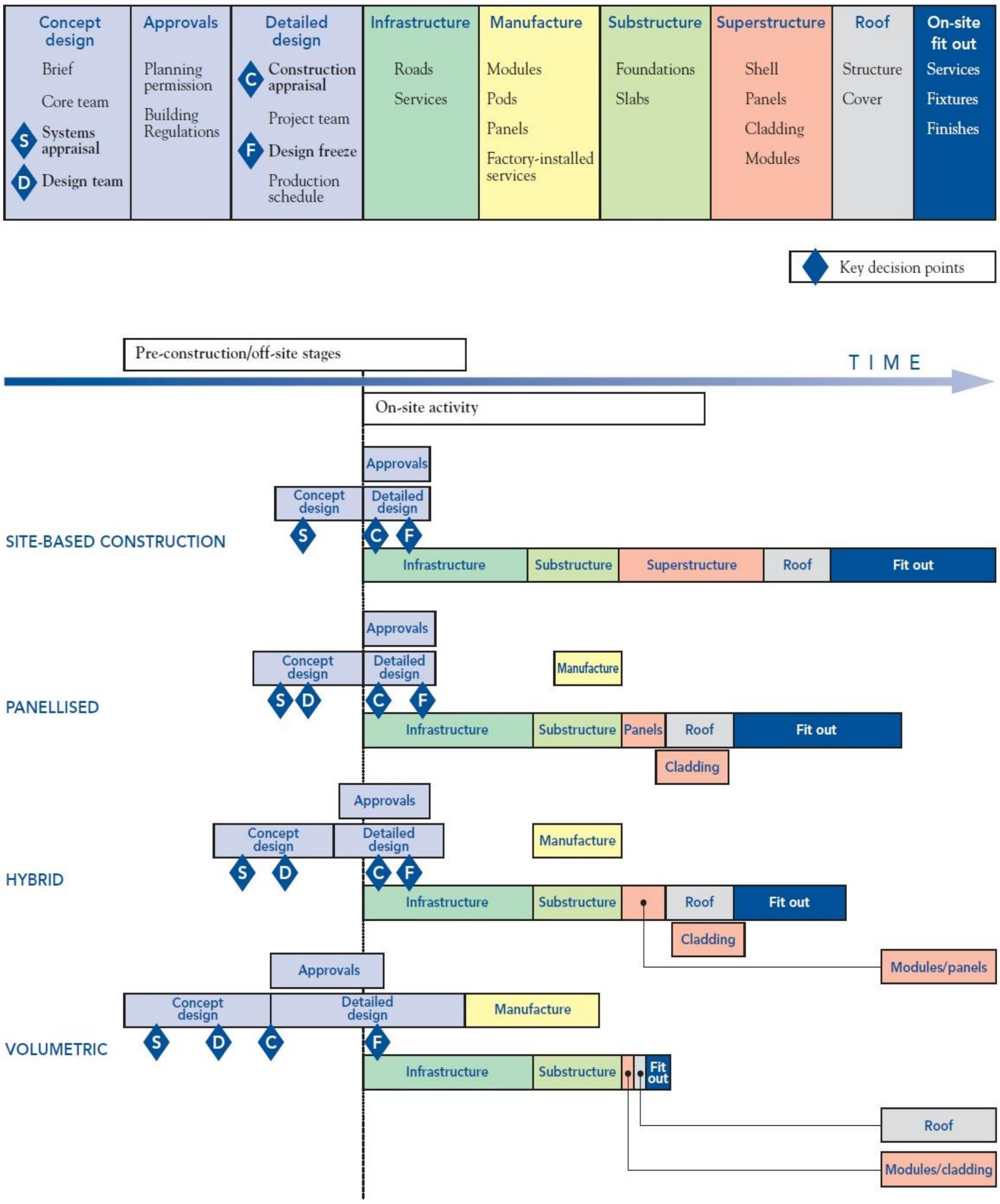


Figure 2.2 Mains Stages of the Construction Process

Ross et al. 2006, p. 14

The emphasis is in minimising on-site time and streamlining the actual build process. The result is a cheaper, more accurate method of construction with less waste and higher levels of productivity.

This research project is looking specifically at the application of timber frame prefabrication as a subset of MMC. The choice of timber (as opposed to steel or concrete slab) relates to the gap in knowledge specified in chapter 1 and correlates that with the fact that timber, on average, is the most commonly used material for single occupancy housing construction in the developed world, and the timber frame construction process is the most commonly used method of construction.

Timber Frame Market Share Worldwide

Country	Population (in millions)	Housing Stock (in millions)	Annual Housing Starts (000's)	Timber Frame Market Share (%)
Australia	17.84	6.09	135.6	90%+
Canada	29.25	9.91	110.4	90%+
Ireland	3.57	0.87	35.5	10%
Japan	124.96	40.54	1464	45%
Norway	4.34	1.82	19.2	90%+
Sweden	8.78	3.86	12	90%+
USA	260.71	97.31	1356	90%+
UK	58.39	21.39	169.2	8%+

Table 2.1 Timber Frame Market Share Worldwide

(Palmer S. , Sustainable Homes: Timber Frame Housing, 2000, p. 4)

While somewhat dated, Table 2.1 gives a clear indication of the extent of timber frame use, representing around 150million homes or roughly 70% of all housing stock in the countries displayed. There are currently 64 timber frame manufacturers in the UK registered with the Structural Timber Association, who represent the vast majority of the timber construction industry (STA , 2013, p. Web Page). They include companies such as Century Homes, Pace, Scotframe, Space4, Stewart Milne and Taylor Lane (WRAP, 2008, p. 5). These 64 manufacturers specifically supply the residential market and yet they represent under 25% of the overall number of houses being built, (Timbertrends, 2010, p. 4) far outweighed by predominantly brick and block companies such as Taylor Wimpey, Barratt, Persimmon, Bellway and Berkeley (The Construction Index, 2011). For a closer breakdown of timber frame market share in the UK and Northern Ireland Table 2.2 has figures ranging from the year 1997-2007.

Timber Frame Market Share

Year	England	Wales	Scotland	Great Britain	Northern Ireland
1997	2%	3%	40%	6%	1%
1998	2%	3%	43%	7%	1%
1999	3%	6%	44%	8%	3%
2000	5%	6%	51%	10%	2%
2001	6%	9%	46%	10%	2%
2002	5%	6%	52%	11%	4%
2003	7%	9%	59%	13%	5%
2004	9%	13%	62%	15%	6%
2005	11%	11%	63%	17%	6%
2006	10%	12%	60%	16%	12%
2007	12%	9%	75%	17%	12%

Table 2.2 Timber Frame Market Share Worldwide

(NHBC, 2007, p. 24)

Within the subset of MMC represented by timber prefabrication market in Table 2.3, there are actually a further 3 key subdivisions, representing various levels of prefabrication provided by the aforementioned manufacturers.

Timber Prefabrication Classification

Type	Description
Open Panel	Open panels comprising studs, rails, sheathing and an external breather membrane are fabricated in a factory and then erected onsite in a grid format. The thermal insulation, internal vapor control membrane (where needed) and lining are all installed on site along with internal walls, external cladding, floors and a roof.
Closed Panel	The most widely used method of house building in the U.S., Canada and Scandinavia. (Bergstrom & Stehn, 2005) (Kolb, 2008) In closed panel construction the walls are the same as the open panel design, but with insulation, protective membranes, linings, external joinery and sometimes even services already installed.
Complete modularization or volumetric construction.	Complete modularization is the ultimate evolution of panel construction in which an entire house is fabricated and constructed within the confines of a factory and then transported as a unit or several large units onto site.

Table 2.3 Timber Prefabrication Classification

(Twist & Lancashire, 2008, p. 18)

Figure 2.3 Typical timber frame procurement and construction process outlines a typical development cycle and the client benefits associated with implementing timber prefabrication.

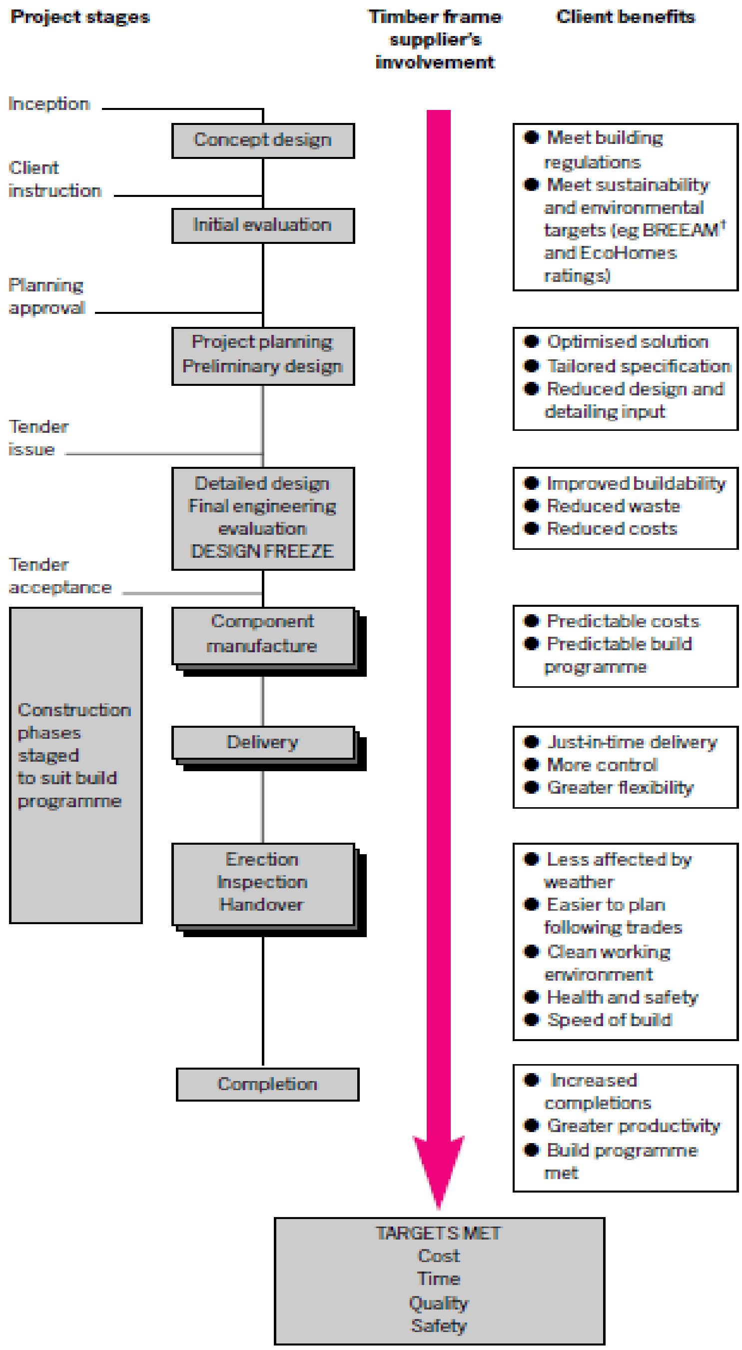


Figure 2.3 Typical timber frame procurement and construction process

(Reynolds & Enjily, 2005, p. 3)

Hybridized construction, not covered in Table 2.3, is simply a combination of panel and volumetric design, where often the bathroom or kitchen will be constructed as a volumetric, non-load bearing unit or "pod" and then slotted into the panel construction on site. Given the substantial repetition required to ensure financial viability, it is more common on large scale accommodation projects, such as University halls of residence or apartment blocks rather than single occupancy housing (Ross et al. 2006). This is why is omitted from the classification of timber based prefabrication in residential construction in Table 2.3. Ultimately, "the selection of an appropriate level of prefabrication and standardization will depend on the case to hand, and should be clearly driven by the stated 'value needs' of a given project" (Craig et al. 2000, p. 3).

The case study which forms the backbone of this research uses a timber frame, open panel construction, (see Section 3.1) which obviously somewhat limits the scope of the findings, but as the most prevalent system in the UK timber frame marketplace (approximately 80% of new builds) (Goodier & Gibb, Barriers and Opportunities for Offsite in the UK, 2005) the results theoretically cover the widest range of future developments and can be standardized within the larger framework of the TSB BPE study (Reynolds & Enjily, 2005).

Fundamentally all construction involves some element of prefabrication or MMC, be it pre-formed lintels, precast bricks, windows, doors and even kitchen suites. The level of prefabrication within timber housing construction is often what distinguishes it from other processes.

2.2.2 Timber Frame History in the UK

Section 2.1 on the subject of deficiencies within the housing sector, predicating the need for change in the industry. Sub-section 2.2.1put forward a response in the form of timber-prefabricated construction, as the key subset of MMC, citing the beneficial attributes associated with factory-based construction and the worldwide market penetration of timber housing.

Section 2.2.2 takes a step back and places this process within the historical context of UK housing construction in order to address the cultural acceptability of prefabrication as a process and timber as a material. Unlike most new technologies incorporated in modern sustainable construction, TPC comes with a long and turbulent history. This history represents as much of a barrier to the process as its actual practical viability (RGU, 2002; Goodier & Gibb, 2007). It is therefore important to establish briefly where it came from, and how it evolved.

The demands and rigours of WWI devastated the UK's construction industry resulting in major shortages of skilled labour and building materials - both having been diverted into the war effort. The obvious consequence of these shortages was a severe lack of housing. It was these circumstances that stimulated the first significant departure from traditional brick and mortar into new methods of construction as a strategy to provide the vast volume of housing required (Taylor, 2009). In England the result was a number of different systems based on steel or timber frames, pre-cast concrete and occasionally cast iron. Scotland based much of its construction purely on timber, due to its abundance and the lack of alternatives; an inclination they have carried on into modern generations. During the period between the end of WWI, 1918, and the beginning of WWII, 1939 there were over 4.5million houses built, and yet only 5% were constructed using these new methods (Taylor, 2009, p. 138). It was not until the end of WWII that the UK saw an actual wide scale implementation of prefabricated housing (Phillipson, 2003). The almost ubiquitous halt of planned builds during the wars, as well as rationing, lack of traditional materials or skilled personnel and reconstruction of damaged or destroyed buildings, once again led to a significant housing shortage. Following World War II, there was yet another organised and government-led push for the mass provision of (mainly social) housing. These "prefabs" were again constructed of concrete and aluminium, or wood, simple and practical in design and only ever intended to be temporary residences, often with a lifespan of approximately 15 years (Vale, 1995). However, the lack of experience with this type of housing, absence of quality materials and inadequate management of the scheme resulted in many poorly finished houses (POST, 2003; Gillilan, 2002; Ross, 2002). While a minority of residents cherished these developments, (Walker, 2011) the majority suffered from a serious lack of reliability (water penetration, shifting of the house on foundations, rot, mould and limited or no fire resistance). This coupled with adverse media attention (Jonsson, 2009; Ross, 2002; Taylor, 2009) and a perceived lower-class standing, resulted in the decline of the building method in the 1970s. In summary, the image of timber frame and the prefabrication process as a whole was severely tarnished by the UK's early exploits in the field. Questions regarding longevity and visual impact, thermal mass and acoustics, plague the industry resulting in a lack of consumer confidence and an averse attitude among mortgage lenders and insurers (HLSTC, 2005).

It is only in more recent years, with the shift towards more sustainable dwellings, that the industry has once again been forced to consider the prefabrication process and its partnership with timber (Gaze et al. 2007). This new drive towards prefabricated construction is tending towards mass-customisation and flexible production (Barlow, 1999). These differ from the standardised housing of past experiences in that they take into account market preferences, as well as the perceptions of potential occupants, while still maintaining the production levels and sustainability credentials associated with this style of production (Craig et al. 2000). Building practice has improved and standards are much higher than in post war Britain. People no longer have to choose between practicality and aesthetics, no more is there contention between prefabrication and architecture as voiced by Davies (2005, p. 8), "The strength of the prefabricated house lies in its popularity, its cheapness and the industrial base from which it operates. These are precisely the areas in which modern architecture is weakest." Rather, the two have now merged as this new style of prefabrication has worked itself into the UK's housing industry (Stacey, 2001). That being said, the UK prefabrication housing industry remains small, and the housing industry as a whole staunchly maintains its traditional practices, and resistance towards innovation (Barker and Naim, 2008).

2.3 The Role of Timber Frame in Affordable Housing

Over 70% of people in the developed world live in timber frame homes and in the US and Canada it accounts for 90% of low-rise buildings (Palmer S. , 2000, p. 2) In the UK this figure drops to just 25% with England accounting for only 17%. (UKTFA, 2009, p. Web Page) This comparatively low percentage is primarily the result of cultural propensities, historical precedence and sparse timber resources. The advent of global warming and threat of ever stricter environmental regulations has catalysed the housing industry into developing new and more sustainable methods of delivering housing. Timber frame construction and prefabrication has become a focal point of these innovations and yet many large developers still remain firmly dedicated to traditional masonry construction methods.

In practice there are a number of substantial barriers to TPC including client resistance, negative image and a significant skills gap. The overall structure and ideology of the UK housing market results in resistance toward innovation and particular animosity towards prefabrication (Lovell, Exploring the role of materials in policy change: innovation in low-energy housing in the UK, 2007) despite its dominating presence in the rest of the developed world (Kingspan Century, 2007). These barriers culminate in a simple lack of reliable, applicable, peer reviewed data on which industry players can base their decisions. (Section 2.6)

Given these significant barriers to innovation, the timber prefabrication technique is unlikely to develop a significant market share within the next 5-10 years, however, there are accelerated means by which it can gain legitimacy. "In 1998, the Egan report highlighted the role social housing should play in leading the way in quality enhancement for the housing sector and pointed to learning from innovative housing from overseas" (Palmer S. , Sustainable Homes: Timber Frame Housing, 2000, p. 2). Essentially what Egan was suggesting is to build houses where there is the greatest need, and play to the strengths of whatever innovative construction method is being used.

Cost savings are an inherent benefit of the prefabrication technique, this is an undisputable fact supported by research from countless other countries. What is missing in the UK are the economies of scale that serve as a prerequisite for these cost savings. What Egan is suggesting is the structure of the social housing sector renders it more predisposed to large scale developments, which in turn, are an ideal proving ground for the characteristics of prefabrication. Using current production methods the government will be facing a housing deficit of over 750,000 homes by the year 2025. (Schmuecker, 2011, p. 1). Innovations such as timber fabrication and its theoretical benefits are essential in dealing with these challenges, but in order to gain wide scale acceptance, they must first practically demonstrate their viability through rigorous performance and cost analysis. Government support targeting the shortage of affordable housing in the southeast of England is seen as an ideal opportunity to introduce innovations such as TPC. Movements such as the Sustainable Communities Plan offer an important opportunity for cost-effective housing innovation and experimentation, benefiting from both economies of scale and government support (Lovell, 2007). "As affordability often takes precedence over environmental standards, especially in the social housing sector, prefabrication and standardisation, with their inherent cost savings could allow housing providers to achieve better environmental standards at a given cost" (Craig et al. 2000, p. 6). These higher environmental standards equate to lower gas bills, lower electricity bills and reduced life cycle costs for occupiers for whom life in a "sustainable" home is associated with a higher quality of living.

Ultimately there must be a step change in the construction industry if the Government is to produce the quantity and quality of housing required by the population of the UK (POST, 2003). The fact that timber pre-fabrication flourishes in many areas of the USA, Canada, Europe, Asia and South America is proof that it is adaptable and can cater to a fluid and changeable market. Additional scientific research (Bergdoll & Christensen, 2008; UKTFA, 2009) has generally served to corroborate this flexibility from an academic stand-point. Research also shows that "Companies that have succeeded over the long haul punctuate ongoing incremental innovation with radical innovations that create new markets and business opportunities" (Leifer et al. 2001, p. 102). The opportunities and mutual benefits afforded through partnership in the social housing industry should not be overlooked.

2.4 Benefits of Timber Frame

Current studies and historical research have time and again identified the technical and economic advantages and disadvantages of timber as a material and prefabrication as a process. They predominantly conclude that, as a construction technique, its performance should surpass that of traditional masonry construction (Barlow et al. 2003; Hartman, 2010; Mullens and Arif, 2005; Pan et al. 2008; TRADA, 2008; Waern, 2008; cited in Smith, 2009, p. 1359). The nature of many of these theoretical advantages and disadvantages falls outside of the framework for this research project and as such, they are simply provided for comprehensive contextual purposes. The focus of this research is performance based post occupancy evaluation. This creates limitations in terms of data collection and project scope. The advantages listed in Section 2.4 and the disadvantages in section 2.5 affect a wide range of industrial factors, from technical benefits to societal gains.

TPC offers a number of advantages linked to the use of timber as a material, and prefabrication as a process. These benefits have been split into succinct categories within this section: Technical, Economic, Social and Environmental. Many of the benefits bring value to multiple factors, and it is important to identify where these overlaps are.

Technical benefits

Technical benefits afforded to TPC are generally divorced from material specifications, as they rely almost exclusively on the manufacturing process rather than material properties.

- The extensive use of CNC machines and digitally modelled templates during manufacturing provides greater accuracy and tolerances for cutting, aligning, screwing, nailing, painting and handling. The result is better control over quality, efficiency and rapid fabrication (TRADA, 2008; Barlow, et al., 2003).
- The indoor environment protects materials from weather and reduces the potential for damage and theft. Construction indoors is also not subject to

delay by the weather, thus reducing timescales and increasing productivity over the winter period. Rapid completion of structural or weatherproof shell means a typical housing envelope can be rendered weatherproof very rapidly (Phillipson, 2003; Reynolds & Enjily, 2005).

- "The controlled conditions within a factory mean better quality of finish and fewer defects can be achieved. Services can be tested within the factory prior to the units being despatched, leading to lower latent defects." (Ross, 2002, p. 20)
- For a given building volume, timber prefabrication generates a much lighter footprint than traditional masonry construction. The benefit is less costly foundations and the potential to construct larger buildings on sites with poor ground conditions, eg. brownfield sites (Mahapatra & Gustavsson, 2009).
- Buildings are often delivered to site in preformed sections, each component designated for a particular section of a particular house. Materials are then stored by house and construction stage allowing for quick and efficient access. This streamlining of the construction process minimalizes handling of the materials, which costs time and money (Reynolds & Enjily, 2005; MEP Solutions, 2007).

Economic benefits

- A factory based fabrication process is subject to assembly line rigour and greater productivity than predominantly site based work - reduces labour requirements and the associated costs (Taylor, 2009).
- Fewer raw materials are required due to the precision afforded by computer aided drawing and CNC machines (Barlow, et al., 2003).
- A streamlined supply chain and simplified logistics (Figure 2.2) emphasises a minimal on-site time. The result is a cheaper, more accurate method of construction with less waste and higher levels of productivity.
- Less waste equates to fewer skips and the bill for waste disposal comes down (Reynolds & Enjily, 2005).

Societal Gains

- As most of the construction takes place within a factory there is far less site activity than conventional masonry builds. Shorter build times result in a reduction in noise and sound pollution and less disruption in the surrounding areas, usually caused by tradesmen's vehicles and heavy machinery (Ross, 2002).
- The factory environment allows for more control over working conditions than on a traditional construction site leading to both health and safety benefits.
- The nature of a factory lends itself to a less transient workforce, as staff live nearby and are not forced to drive from site to site round the country. A steady workforce also acts as a greater incentive to employers to invest in their staff through training programs and benefit packages.

Environmental Benefits

- In an age of strict environmental regulation, all stages of the construction process are now under scrutiny, including the materials being used. TPC emphasises the fact that timber is viewed as a sustainable resource, and a carbon sink exhibiting lower levels of embodied energy than its traditional counterpart (Monahan & Powell, An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework, 2011). "Research has indicated that timber frame walls consume around 58% of the energy required to produce a lightweight block wall. In terms of intermediary floors the figure is just 35% when compared to concrete" (Palmer S. , Sustainable Homes: Timber Frame Housing, 2000, p. 12).
- Timber framed houses tend to have higher levels of insulation than masonry construction. This possible due to thinner structural elements, which allows for a greater proportion of insulation in walls of comparable thickness. The outcome is a structural envelope with exceptionally low U-values. Minimised heat loss means less burning of fossil fuels to heat the dwelling and subsequently less pollution.

- A recent report by the Waste Resources and Action Programme – WRAP (2008, p. 2008) estimated the waste reduction through substitution of traditional methods with timber prefabrication amounted to 20-40%, directly proportional to the level of prefabrication.
- The use of sustainably sourced wood to produce the timber frames for prefabricated housing can aid in reducing net CO2 emissions associated with embodied energy (Gustavsson & Sathre, 2006a; Gustavsson et al. 2006b; Mahapatra et al. 2012).

The following list is a summary of the widely accepted benefits associated with TPC, it essentially condenses the advantages introduced in this section. Compiled by Goodier and Gibb (2007, p. 586) through a rigorous literature review of existing surveys, a pilot study, a questionnaire and input from a steering committee of key construction organisations, these benefits are hypothetically true although as future sections and chapters will attest, there is little hard evidence from mainstream housing developments in the UK to support them:

- Rapid fabrication and greater productivity
- Rapid erection, with less site impact
- Greater precision and overall quality
- More consistent product with less waste, both in fabrication and on site
- Reduced environmental impact (both embodied and operating energy)
- Reduced Initial cost
- Reduced whole life cost
- Increased flexibility
- Increased value
- Increased flexibility
- Increased component life

2.5 Barriers to Timber Frame

Before introducing the drawbacks and disadvantages of timber prefabrication it is important to highlight the duplicitous nature of the construction industry when it comes to poor workmanship. There are numerous and pervasive problems that crop up during the construction of traditional masonry dwellings. These include things like sulphate attack of mortars and brickwork, problems with concrete blocks manufactured using low-grade aggregates, weak mortar mixes and wall tie corrosion (Ross, 2002). The fact is, that the industry has been around long enough that these problems should never realistically occur, and yet they do, and it is often simply a case of ignorance or poor quality workmanship. The controversy arises when these mistakes are repeatedly ignored or simply accepted as inevitable collateral within the construction industry. On the other hand when there is a similar issue associated with timber prefabrication, it is immediately labelled as a fault within the process rather than simply a mistake as with the masonry construction. This is the protective nature of an industry subject to an entrenched ideology. The problem is, if there is to be innovation within the residential construction industry this blanket rejection of non-traditional construction must stop. Mistakes will be made through whatever construction process is used, these mistakes must be identified, recorded and rectified, not vilified and blown out of proportion.

Having said this, there are a number of established weaknesses associated with timber as a material and prefabrication as a process. These can be divided into real and perceived weaknesses, however both forms negatively impact the industry.

2.5.1 Perceived Weaknesses

Perceived weaknesses are flaws that are generally unfounded in modern day construction and include things like:

Fire Safety: All forms of construction need to comply with the fire performance requirements laid down by national building regulations (HM Government, 2010a). "Timber frame dwellings have no difficulty in meeting the required levels, given correct design, standards of manufacture and workmanship" (TRADA, 2012, p. 1). Contrary to many people's perceptions, timber does not simply combust and then disintegrate, rather it burns steadily, forming a protective layer of charcoal, which serves to insulate and protect the core, thereby maintaining its structural integrity. Timber is often treated with fire retardant coating and further protected by fire retardant plasterboard, which covers the structural elements of the walls. Cavity barriers are designed into the structure of the wall, incorporating lines of fire-resistant materials fixed in the cavity between the external cladding and timber frame wall panel (UKTFA, 2011). If fire overcomes these protective measures and takes hold, timber reacts in the following manner:

- Uniform charring at a low rate (after the protective plasterboard has fallen away)
- Low heat conduction
- No deformation at high temperatures.

(TRADA, 2012)

Fundamentally TPC has to conform to the exact same health and safety standards of any other construction process (HM Government, 2010a), and in doing so, it creates timber dwellings that are no more dangerous than their masonry counterparts.

Durability: Given the organic nature of timber and the damning reports of the 1980's the public often expect British weather to have a significant impact on the structure, causing rot, degradation and even outright collapse. Modern construction techniques have been refined significantly in 30 years. Any rain that might penetrate exterior claddings, is removed via the special 'weep-holes,' with breather membranes adding an extra layer of control for both water ingress and air permeability. All exposed timber can be treated against water and insect permeation (Wood Solutions, 2013) as required by NHBC, Zurich and HAPM alike. In modern heated houses the moisture content of the timber should never reach the required minimum of 20% for rot to set in. There are of course ways to circumvent the linings and treatments such a nailing a hole through them or cutting service passageways, but unlike traditional construction, these alterations are usually completed under factory conditions, thereby reducing the potential for error. While a true lifespan is hard to judge, all new "cellulose" based homes much conform to a minimum 60 year design life stipulated by the NHBC Technical Requirement R3 (NHBC, 2011, p. 23). This is not a maximum lifespan, rather it is an indication of a hesitant but firm acceptance of timber as a viable, durable and sustainable construction material (TFHC, 2003).

Acoustics: In housing, sound travels through two mediums, the air and the structure. Heavy weight materials tend to transmit less sound, but the lightweight nature of timber walls can lead to a weakness in this area if not properly addressed. In modern housing this is addressed through a combination of dense wall linings such as plasterboard and absorbent quilts within the wall fabric. In addition to that, the structure borne sound is attenuated through the concept of structural discontinuity; essentially constructing adjoining walls with air gaps inside them, rendering the structural components independent of one another. Sound cannot then travel directly across solid objects from one building to another (Palmer S. , Sustainable Homes: Timber Frame Housing, 2000). Again, timber prefabricated structures must conform to Part E of building regulations, which requires that new homes are designed and constructed to provide reasonable resistance to the passage of sound and that a sample of dwellings on every new development is tested (HM Government, 2010b).

Materials Availability: A lack of materials is often quoted as one of the reasons TPC maintains such a low market share in the UK as a whole where historically a lack of timber and the abundance of clay for bricks in England impacted how housing was constructed. This is evidenced by the disparity between Scottish and English levels of timber housing. In 2008, the market share of timber frame in England with 200,000 hectares of woodland was was 17% vs. Scotland with nearly 450,000 hectares at approximately 76% cent. (Forestry Commission, 2009, p. Web Page) (Mahapatra et al. 2012, p. 1472) There are obviously other cotributing factors, but resource availability has undeniably played a significant historical role in the introduction of TPC to the UK. However the modern era of shipping and logistics, coupled with the existence of extensive timber reserves across the North Sea in Scandinavia, means that resource availability is no longer a significant factor. In fact, while much of the world's forests are in decline, Nordic and Scottish softwood forests are actually growing in size, specifically cultivated and farmed to provide for the increase in timber frame demand within Europe (TRADA, 2008).

2.5.2 Genuine Weaknesses

The following is a compilation of genuine, and unavoidable weaknesses often linked to the particular industry players that they impact the most.

Initial capital cost:

- The greatest barrier facing large scale integration of TPC is the initial capital costs associated with setting up the manufacturing, logistics and supply chain required (Goodier & Gibb, 2007). In addition to these setup costs, there is usually a minimum number of units required in one batch to achieve a viable economy of scale. This places pressure on the company to find large development sites willing to invest in a relatively untested (within the UK) technique. The cost of facilities, staff, and tooling logically represents too much of a gamble for companies to take without firm evidence that the technique is financially and practically sound.

Ongoing maintenance costs:

- For private sector developers, ongoing maintenance is not really a concern as their input and obligations often end with the handover of the dwelling. However Local Authorities, Housing Associations and Councils all have a vested interest in potential ongoing costs associated with weatherproofing, insect treatments and cosmetic degradation. This is of particular concern as social housing is viewed by some as the ideal proving ground for TPC and other prefabricated method of construction (Lovell, 2007).

Longer lead-in times:

- The very attribute that gives prefabrication so many of its benefits also requires much better organisation and planning than traditional construction. Factory construction requires the design work to be finished far in advance of the estimated construction date and to a much higher level of detail than traditional builds. This is imperative so that material and components can be ordered and stocked at the factory ready for construction. The knock on effect is a precarious dependency on the supply chain – a risk many housing developers would prefer to avoid (Ross, 2002).

Appearance:

- In recent years timber frame housing developments have predominantly used brick skins and stone cladding to disguise their outward appearance and mimic their more widely accepted masonry counterparts. The reasons for this are varied; planning consent was historically a problem, but with current pressure to explore more sustainable housing solutions there is less contention in this area. For many developers and manufacturers, the aim behind disguising the properties is to reassure clients that there is no difference between timber and brick housing. From the perspective of the TPC process itself this is a double edged sword – yes more people are likely to accept the results of TPC if it is rendered as a familiar, however if TPC housing must disguise itself, to be accepted then how will it ever gain legitimacy as a product in its own right within the wider market? In the modern era of housing construction the material which makes up the structure is almost entirely divorced from the external appearance anyway, thus the issue of appearance may simply become a moot point in the near future, neither a weakness nor a strength of the TPC process.

Supply Chain and Skills Shortage:

- In practice the UK lacks permanent factories, logistics and supply chains and a fundamental support structure of design, manufacture and assembly skills; all of which are needed to take advantage of any new innovation.

2.5.3 Stakeholder Specific Risks

Various stakeholders in the housing construction market face trade specific risks (real or perceived) when dealing with TPC, the following are a list of these stakeholders and some of the challenges that they face. This information has been compiled from a combination of two studies, the first being a timber frame housing consortium (TFHC) study on timber frame housing in Ireland for the Department of Environment, Heritage and Local Government, (TFHC, 2003) and the second a review of non-traditional housing in the UK, commissioned by the Council of Mortgage Lenders and written by Keith Ross of the BRE. (Ross, 2002)

Financial institutions:

- Given the relatively young age of the TPC industry within the UK, there has been no opportunity to exhibit a constant market value of dwellings in the medium to long term. For banks looking to provide mortgages, this lack of evidence raises questions as to the dwellings' ability to adequately offset the value of a loan in the future in the event of a foreclosure on the property.

Warranty providers:

- Timber prefabricated housing is built in large production runs in order to achieve the economies of scale that make this process profitable. In building so many identical homes, there are concerns that a systematic defect that appears during the warranty period could affect the entire batch of housing leading to a disproportionate and potentially ruinous number of claims.
- Once again a lack of historical data results in ambiguity over the cost of repair for untried and untested technologies and components. A warranty provider cannot simply rely on guess work to estimate the cost of maintaining potentially thousands of buildings.
- Timber frame dwellings have an indeterminate life expectancy directly linked to a periodic maintenance regime (which may not be carried out). This variable make it very difficult to estimate costs and the structure of warranty packages.

"The warranty normally covers a fixed period (e.g. ten years) and, given that most structures would last ten years even if they were prone to rapid decay, there ought not to be much of an issue. The problem with that approach is that implicit in the issuing of a ten year warranty is an expectation that the structure would last much longer than that. The whole process of issuing a warranty, with the associated quality inspections and use of standard details, gives lenders much more confidence in the structure than the warranty guarantees. If the structure were to fail before its design life (which would be long after the warranty had expired) then confidence in warranty organisations would be undermined, thus devaluing the warranty" (Ross, 2002, p. 22).

Registered Social Landlords (RSL):

- The historical and cultural bias behind TPC may result in tenants simply refusing to live in properties.
- The ongoing costs associated with maintenance are as yet an undefined figure, (again, due to a lack of historical data in the UK) but represent a significant expenditure for which the RSL will be accountable for. This uncertainty represents a substantial risk to the RSL.

House Builders:

- The life expectancy of a material is an incredibly hard thing to test; the most accurate estimations being based on historical evidence. In this case TPC house builders are utilising brand new materials in ways that they have never before been applied. The risk to them is a product that is not durable enough to give required life expectancy.
- As with RSL's, the historical and cultural bias behind TPC may result in potential customers refusing to purchase the properties.
- In utilising a new technique and new materials, they open themselves up to the risk of failure and few companies can afford the subsequent negative impact that the 'brand' will suffer.

Surveyors:

- While TPC has been around for many years in the UK, under its modern guise of sustainability, new materials and technology driven design, it is still a relatively untried and untested construction process. There may yet be problems (latent defects) that surveyors are unable to diagnose through traditional inspections. This may simply be due to an unfamiliarity with the materials and technology used to construct the dwelling or it could be cause by a lack of historical data indicating the life expectancy of key components. Either way, it represents a risk to surveyors who would potentially require additional training and an entirely new skill set in order to analyse the specific problems associated with timber prefabricated structures.

Insurance companies:

- Untried and untested construction techniques may make it difficult for insurers to assess the costs of repairing dwellings if they are damaged by flood, fire subsidence, etc.
- Unlike traditional construction where the house is built entirely on site, prefabrication necessitates much of the work being done in a factory setting. In fabricating and transporting housing components to site they may be damaged or destroyed. It may necessary therefore to instigate separate policies and conditions based on whether the housing components are in the factory or on site.

This is by no means an exhaustive list of disadvantages and risks associated with TPC. The nature of the industry and the process itself creates a very fluid environment where problems are solved and new ones are discovered. What this section does is highlight some of the key issues facing TPC in order to give the reader a context in which to place the performance review encompassed within this thesis. As with the benefits section, some of these the disadvantages and risks will be addressed directly or indirectly through the performance review, but overall the majority of these issues fall outside of the scope of this research, which is designed to validate TPC from an environmental performance perspective through a rigorous framework of POE.

2.6 Benefits and Barriers Discussion

In order to highlight the need and significance of this research project section 2.6 takes a brief look at one of the most prominent studies on barriers and opportunities to offsite fabrication in the UK by Goodier and Gibb (2007). An analysis of their findings displays significant confusion and contention within the construction industry regarding what exactly constitutes a benefit and a disadvantage. It is expected that different stakeholders will tend to gravitate towards different benefits and barriers, however the study by Goodier and Gibb structures their interview process around a fairly narrow cross section of the construction industry, focusing on Clients, Designers and Contractors for whom the benefits and advantages should, overlap considerably. A brief examination of the study immediately reveals differing levels of awareness and education pertaining to the benefits and pitfalls of timber prefabrication (Goodier & Gibb, 2007). The following tables demonstrate some of these inconsistencies and give a clear indication of perceived advantages and disadvantages within the housing industry.

Advantages	Contractors		Clients/designers	
	% of respondents	% as 1st choice	% of respondents	% as 1st choice
Decreased construction	87	38	92	69
Increased quality	79	28	7	15
More consistent product	77	18	54	0
Reduced snagging and	79	8	69	0
Increased value	51	5	2	0
Increased sustainability	43	3	31	0
Reduced initial cost	44	3	15	8
Reduced whole life cost	41	0	15	0
Increased flexibility	33	0	1	0
Greater customization	33	3	0	0
Increased component life	28	0	15	0
Other	18	15	8	8

Note: 'Other' includes improved health and safety and reduced requirement for skilled labour.

Figure 2.4 Advantages of offsite construction

(Goodier & Gibb, 2007, p. 26)

The conventional drivers of time, cost and quality Rasmus Waern (2008; cited in Smith, 2009, p. 1359) remain a significant deciding factor in the decision to use offsite production and are joined by the attributes of consistency, and reduced snagging and defects. The most important and revealing information, however, is the number of supposed benefits to which less than 50% of respondents actually attributed as a benefit of prefabrication. This very clearly displays contention and confusion amongst various industry players and even within similar subsectors of the industry such as contractors or designers. Ultimately this leads back to the overall gap in knowledge discussed in Section 1.2 and the theory that there is not enough relevant evidence for industry players to make informed decisions as to the viability and applicability of TPC.

When comparing Figure 2.4 and Figure 2.5 it is interesting to note the role of cost and how it is viewed as both an advantage and a disadvantage.

Barriers	Contractors		Clients/designers	
	% of respondents	% as 1st choice	% of respondents	% as 1st choice
More expensive	67	54	77	38
Longer lead-in times	46	8	6	8
Client resistance	38	13	31	23
Lack of guidance & info	33	5	46	0
Increased risk	36	0	1	0
Few codes/standards available	33	3	23	0
Other	31	18	15	8
Negative image	28	0	46	8
Not locally available	18	5	1	0
No personal experience of use	18	3	38	15
Obtaining finance	18	3	8	0
Insufficient worker skills	21	0	23	0
Reduced quality	13	0	15	0
Restrictive regulations	13	0	31	0

Figure 2.5 Barriers to increased use of offsite construction

(Goodier & Gibb, 2007, p. 26)

For many years, timber frame prefabrication has been portrayed as a more expensive method of construction due to the high initial capital investments, yet the build process as whole remains significantly shorter than masonry, thus theoretically reducing overhead and finance costs. There is little to no evidence to quantify the capital set up costs or whole life costs associated with erecting a timber frame dwelling. There is no pool of evidence from which to benchmark the value proposition offered through the use of TPC.

The conclusion, as supported by remarks from Goodier and Gibb, is that there is an atmosphere of confusion and conflict surrounding the use of prefabrication in the industry. While the majority of the study's respondents were aware of the possibilities and potential of off-site production, they were at odds over what the actual drivers were for the process. Opinions on the advantages and disadvantages varied widely signaling a lack of concrete evidence on the construction technique. In addition to this, and as a consequence of this lack of evidence, there remains a significant resistance to change and innovation within the housing construction industry. There remains a deep rooted pervasive negative image of prefabrication throughout the industry as evidenced by the vast majority of surveys concerning offsite production (RGU, 2002; Pan et al. 2007; Venables et al. 2004). Ultimately if TPC is to become a significant factor within the residential construction industry, there must be a concerted effort to study the process more and in greater depth, thereby generating abundant and transparent information for the consumption and analysis of decision makers in the construction process. Clear cost comparisons and timescale measurement are an imperative, while the research developed by this project and others like it, will help to validate the performance attributes of the construction technique.

2.7 Timber Frame Post Occupancy Evaluation Research

The advent of global warming and threat of ever stricter environmental regulations has catalysed the housing industry into developing new and more sustainable methods of delivering housing. Timber frame construction and prefabrication has become a focal point of these innovations and yet many large developers still remain firmly dedicated to traditional masonry construction methods. Speaking in reference to the timber housing development Elm Tree Mews, in Leeds, Wingfield et al. (2011) acknowledge the fact that there is a lack of published performance data supporting the sustainable innovations available to the industry. The Elm Tree Mews project itself sought to evaluate a timber frame development, eventually concluding that the gap between dwelling fabric performance design and reality was over 54% and almost entirely the fault of process and supply chain issues, not the materials themselves. It is evident that while techniques and practices may work in Europe or the US, the theoretical benefits exhibited in these foreign applications do not inherently translate into the British context. Research is therefore needed to bridge this gap in knowledge and better inform the industry as it explores TPC as a viable alternative to traditional masonry construction.

It would be wrong to claim that there is no UK based POE data pertaining to the performance of single family occupancy timber frame housing, however, the little that does exist is often fragmented (EST, 2008) and based on unique houses built for research or demonstration purposes eg. The BRE innovation Park. This gap in relevant and cohesive knowledge is even more apparent when the scope encompasses life cycle analysis (LCA) as a necessary part of the performance evaluation of a house. For any assessment of environmental performance to be meaningful, it must take into account the emissions expended throughout the life cycle of a material. (See Chapter 6) "Literature specific to the embodied carbon and energy of UK housing construction is sparse" (Monahan and Powell, 2011, p. 180). Initial research has revealed only four recorded case studies in the UK that incorporate an LCA into the performance analysis (Hacker et al. 2008; Asif et al. 2007; Hammond and Jones, 2008) including that by Monahan and Powell (2011).

Reports by the BRE and HCA (BRE, 2006; Homes & Communities Agency, 2010) are indicative examples of the existing research on sustainable timber prefabricated housing which so often focus on the design and construction phase of development and the potential for timber frame use in the UK, rather than examining the quantifiable reality of post occupancy performance. Current research places emphasis on the theoretical attributes and the perceived notions of the public and industry, and rarely carries that interrogation forward into the vitally important occupancy period. This is the stage at which the purported performance characteristics and process benefits are actually tested. Some research takes the subject of performance and breaks it down into separate elements such as air tightness, durability or embodied energy, only addressing one subject at a time. This lack of all encompassing, in-depth POE is predominantly due to its inherent invasive nature, the length of time required to physically acquire all the relevant data, the cost of monitoring equipment and small sample sizes, (data from one house is unlikely to be deemed representative of an entire sector thus making it impractical to do an in-depth study on just one house). What little POE information is available is usually qualitative questionnaire information and rarely taken from mainstream developments. Rather it is sourced from purpose-built research dwellings and unique show houses. Some examples of existing case study research can be found in:

- The Department for Communities and Local Government's (DLCG) The Code For Sustainable Homes - Case Studies (2009)
- The Code for Sustainable Homes: Case Studies Volume 2 (2010)
- A Case Study on Innovative Social Housing in Aberdeenshire, Scotland, by Stevenson (2004)
- The DLCG's Lessons Learnt 1and2: Designed For Manufacture - The Challenge to Build a Quality Home for £60k (2006, 2010)
- Prefabricated housing in the UK (BRE Parts 1-3) (Bågenholm et al. 2001)
- Timber-Frame Dwellings: Section 6 of the Domestic Technical Handbook (Scotland): Energy (Doran, 2008)
- Benefits of off-site manufacture (Park, 2009)
- Life cycle assessment: A case study of a dwelling home in Scotland (Asif et al. 2007)

While all these studies and reports provide excellent information regarding the costs, construction methods, lessons learned during the design and erection and even some LCA, very few contain any comprehensive POE. The scope of a comprehensive POE is variable (Meir et al. 2009), but for the purposes of this study it is defined as both a quantitative and qualitative analysis of the dwelling with ideally, an extensive LCA.

2.8 Housing in the UK Conclusions

Chapter 2 highlighted both the need for additional affordable and sustainable housing in the UK, and many of the current inadequacies with the current construction methods. It introduced the concept of innovation and the catalyst that could trigger that innovation – timber prefabrication. After a brief commentary on the method itself and the history of the construction technique in the UK, the discussion turned to the reasons why the UK has yet to adopt timber prefabrication on a large scale within the context of mainstream housing development. Despite a myriad of documented advantages, there remains little evidence to support the technique from within the UK itself, and barriers toward timber prefabrication, including, both perceived and genuine weaknesses of the technique are unlikely to be challenged without relevant evidence and case studies. A review of existing research reveals very little pertinent case studies and the little relevant research on timber prefabricated housing that does exist, is fragmented and often based on unique houses built for research or demonstration purposes rather than mainstream housing. Chapter 2 establishes, both the necessity and novelty of this research and its conclusions.

3 Environmental Monitoring

This research advocates a cautious and well informed approach to the integration of TPC into the British Housing industry as the construction technique can little afford a repeat of the post war prefab boom and its associated negative press. Therefore, the aim of this project is to provide evidence demonstrating the ecological performance of mainstream constructed timber frame housing in the UK through the use of post occupancy testing and evaluation methods. With the many established barriers facing the integration of timber frame construction in the UK (2.5.2) the focus on performance may initially seem a redundant factor, however it makes little sense to promote a technique or practice such as TPC, no matter what its other benefits might be, without first understanding how it performs in the environment for which it is intended (see Section 1.3).

Essentially, performance and cost seem to represent the baseline variables in the housing construction industry (RGU, 2002). These variables are influenced by countless factors, this study focuses exclusively on one of these factors, the ecological performance impact of using timber frame within the context of sustainable housing in the UK. The established performance viability then serves a foundation on which to build other projects looking to address the disadvantages and barriers associated with TPC. If POE reveals that there is a gap between what was expected from the TPC process and the reality of what happens on site, it remains a valuable outcome as it gives proponents of the process the opportunity to identify problem areas and rectify them before wide scale adoption of the process.

The study will use an extensive testing protocol developed by the UK's Technology Strategy Board (TSB) under the Building Performance Evaluation (BPE) scheme. The scheme funds a host of studies looking into the performance of case study buildings, covering post completion and early occupation and in-use and post occupancy stages with the eventual aim of helping builders and developers deliver more efficient and better performing buildings in the light of Government emissions targets within the building sector (DECC, 2011a). The simplified and standardized data acquired through this methodology is used to establish various performance benchmarks applicable to both industrial development and client education.

Post Occupancy Evaluation (POE) is defined as the structured process of evaluating the performance of a building after it has been built and occupied. This is achieved through systematic data collection, analysis and comparison with predetermined or specified performance criteria (Menezes et al. 2012). The process of POE is not actually new, dating back to the 1960's architectural practice research lead to the publication of Part M: Feedback, in the RIBA (Royal Institute of British Architects) Plan of Works (Turpin-Brooks & Viccars, 2006). Unfortunately concerns over fees, insurance and liability led to the exclusion of Part M and its accompanying Plan of Works in 1973 (Cooper, 2001). Until recently these barriers of "cost considerations, time constraints, perceived challenge to professional judgement (including risk of litigation) and the availability of researchers and practitioners possessing the broad range of skills required for undertaking a POE study" (Taylor et al., 2010, p. 8) have prevented industry-wide adoption in the UK (Bordass & Leaman, 2005). However, as the housing industry becomes ever more performance focused, there has emerged evidence, quantitatively showing a significant gap between in-service physical performance characteristics and design predictions of sustainable housing (Herring & Roy, 2007; Johnston, 2010; Taylor et al. 2010; Zero Carbon Hub, 2010) (Wingfield, 2011). In February of 2011 a report published by the Zero Carbon Hub (Zero Carbon Hub, 2011) formally recognised the existence of a performance gap between design and reality and stated that from 2016, ecological compliance should be based on as-built performance rather than design predictions. POE is the best methodology available as it provides an objective measure of quantitative and qualitative information ranging from fabric performance to user satisfaction surveys, which can be used for benchmarking and comparative evaluation.

It is for this reason that POE has been explicitly selected as the overarching process for the procurement of primary data in this project. Its very definition speaks to the goals and aspirations of the project as it endeavours to provide a comprehensive, in depth evaluation of energy performance in British mainstream timber frame developments. The first step to solving the performance gap is being able to quantify it through the use of environmental monitoring. There is little point in approaching policy makers, client and commissioning organisations, designers, builders, developers and product suppliers if there is no proof that a problem exists.

3.1 The Case Study Site

The importance of UK industry relevant data is detailed in Section 1.2, and supported by research into prefabrication, (masonry and timber) which found that the most common method of overcoming client resistance in offsite construction methods (of which timber forms a large percentage) was the provision of examples and case studies of previous successful developments (Goodier and Gibb, 2005; Pan et al. 2005). Based on research into contemporary timber construction in other countries, many academics predict that the performance of timber housing, in particular combination prefabricated housing, is likely to be similar or better than existing masonry methods (Berge, 2009; Hartman, 2010; DCLG, 2006). In order to confirm this within the context of a UK based development it is necessary is to gather quantitative performance proof via strict monitoring of a representative housing development. This use of case study evidence in POE studies such as this is supported by Yin (2009) and research by Turpin-Brooks and Viccars (2006, p. 178), which states: "Without case studies, POE would lack a robust or real context. Indeed, POE's chief purpose of progressing understanding and satisfaction of building users' needs is inevitably contextual to the environment the participants are using…" Their research goes on to outline the key merits of case study based research.

Case studies provide:

- Contextual information (or reality.)
- Greater depth of qualitative data.
- Opportunities for benchmarking performance; and learning opportunities from each project for all stakeholders involved (a key component of the research goals of this thesis).

Green Street is the representative housing development and case study central to this project. This newly constructed housing scheme is located in the

Nottingham, England and accredited to Code for Sustainable Homes Level 4. The somewhat unique feature of this site is the fact it was constructed in two phases, Phase 1 fabricated using timber frame construction methods and Phase 2 built using traditional masonry construction. Both phases were conceived by the same developer, designed by the same architect, and most importantly, built by the same contractor. The houses are all built to the same level of sustainability, incorporating identical technologies and sustainable design techniques, and are even constructed with similar layouts. These operating parameters represent an opportunity to directly compare the timber and masonry building methods through post-occupancy performance monitoring of the dwellings and their occupants. Usually the lack of standardisation among dwellings means that a direct comparison is considered too inaccurate to generate significant data. Performance results can also be compared to design specifications in order to determine a performance gap for each of the construction techniques.

Table 3.1 Green Street Development Details

Location	The Meadows, Nottingham
Total Number of Houses	38
Construction Materials	Phase 1 – Timber and Phase2/3 - Masonry
Architect	Marsh Grochowski
Developer	Blueprint
Main Contractor	Lovell
Completion Dates	Phase 1: 01/05/2011 Phase 2: 31/10/2011
Houses to be monitored	8 houses total – 4 in Phase 1 and 4 in Phase 2

The new development is located on the site of a former primary school demolished several years ago. Design was subject to competition and planning permission was granted in October 2009. Figure 3.1 shows Phase 1 (Timber) is highlighted in red, Phase 2 (Masonry) is highlighted in blue.

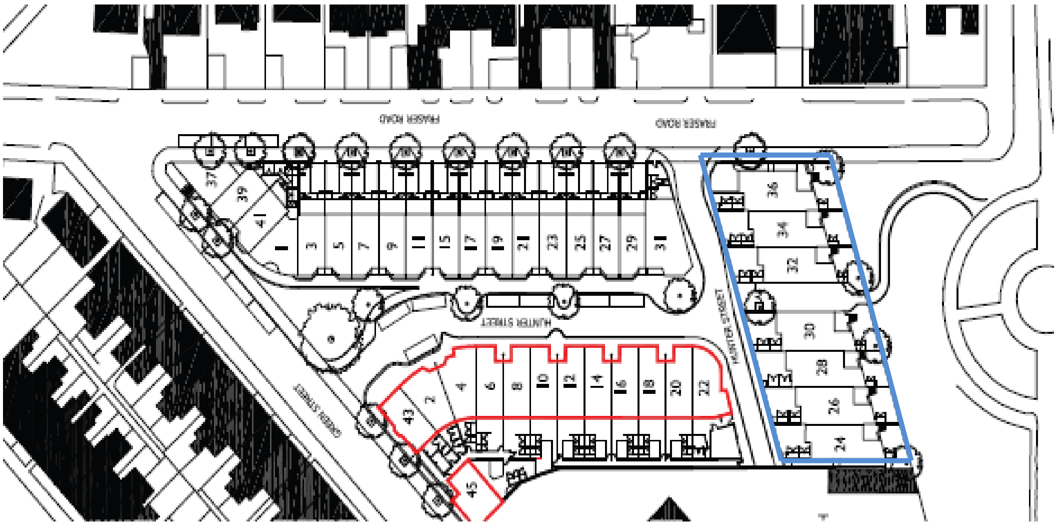


Figure 3.1 Green Street Site Plan

Table 3.2 and Table 3.3 display fabric performance information predominantly based on the initial architect's specification completed in October of 2009 and revised in December of 2009 supplemented by Standard Assessment Procedure (SAP) analysis data. These fabric performance specifications are the initial step in establishing baseline values for the "as designed performance," figures, which will be compared with results from the POE analysis. In this case there are 3 potential areas that can be analysed – the heat transfer coefficient of individual fabric elements, a whole house heat transfer value and the air permeability of the dwelling.

Table 3.2 Preliminary Outline Fabric Performance Specification - Phase 1 (Timber)

CSH Rating	Level 4
Walls	U-value 0.13 W/m^{2}K, 400mm Timber Frame with a mixture of brick skin (Ground Floor) and render (1st & 2nd Floor) facades
Floor*	U-value 0.15 W/m^{2}K
Roof	U-value 0.11 W/m^{2}K, Flat roof - Radmat warm roof flat roofing system. Roof mounted photovoltaics.
Terrace Roof	U-value 0.11 W/m^{2}K, Flat roof - Radmat inverted roofing system
Windows	U-value 1.2 W/m^{2}K, Triple Glazed timber frame.
Doors	U-value 1.1 W/m^{2}K
Ventilation	MVHR
Air Permeability	Designed: 3 m^3/h.m^2
Thermal Bridging**	14.73 W/mK

***The floor acts as a thermal mass and must provide a concrete topping in some form. **Values taken from SAP analysis. For more information please refer to ESE (2011).**

These Tables demonstrate that from the initial conception the two different phases were designed to be identical in performance, only separated by their build process.

Table 3.3 Preliminary Outline Fabric Performance Specification - Phase 2 (Masonry)

CSH Rating	Level 4
External Walls	U-value 0.13 W/m^{2}K,
Floor*	U-value 0.15 W/m^{2}K
Roof	U-value 0.11 W/m^{2}K, Flat roof - Radmat warm roof flat roofing system. Roof mounted photovoltaics.
Terrace Roof	U-value 0.11 W/m^{2}K, Flat roof - Radmat inverted roofing system
Windows	U-value 1.2 W/m^{2}K, Nordan double glazed and argon filled.
Doors	U-value 1.1 W/m^{2}K
Ventilation	MVHR
Air Permeability	Designed: 3 m^3/h.m^2
Thermal Bridging**	14.73 W/K

***The floor acts as a thermal mass and must provide a concrete topping in some form.**

****Values taken from SAP analysis. For more information please refer to ESE (2011).**

The following figures depict examples of the construction layout and section views for each phase of construction. These are included to help the reader visualise the context in which the research took place.

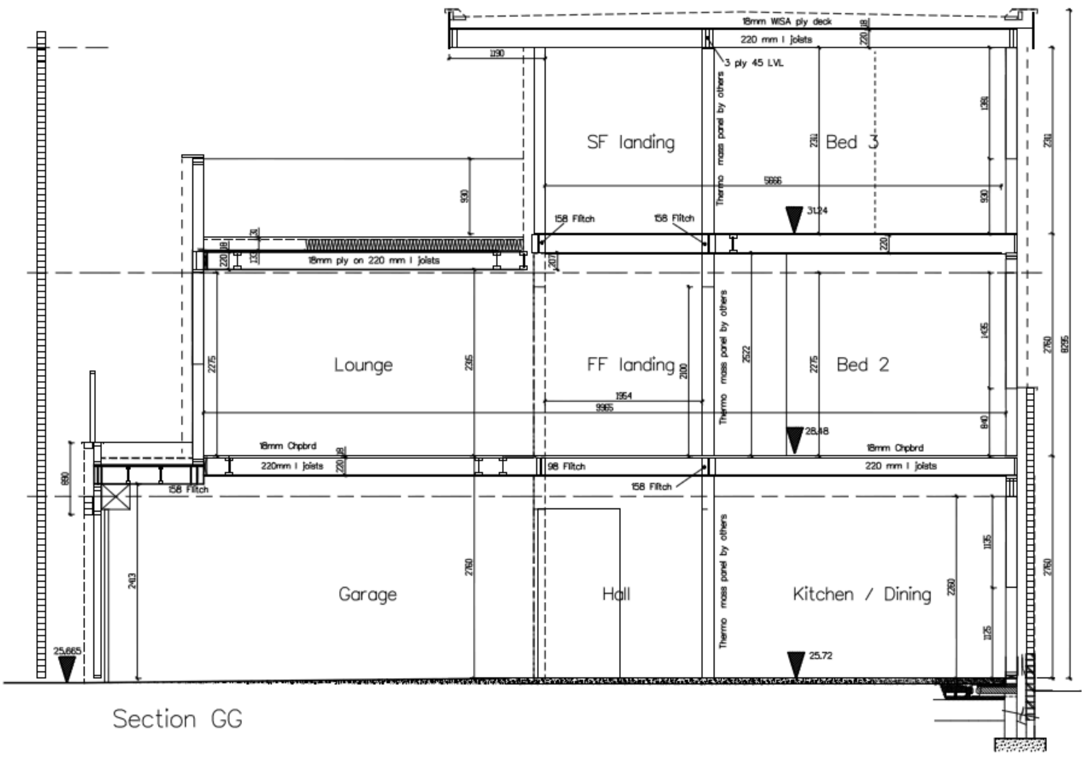


Figure 3.2 Phase 1 - House Section (Source: Marsh Grochowski, 2010)

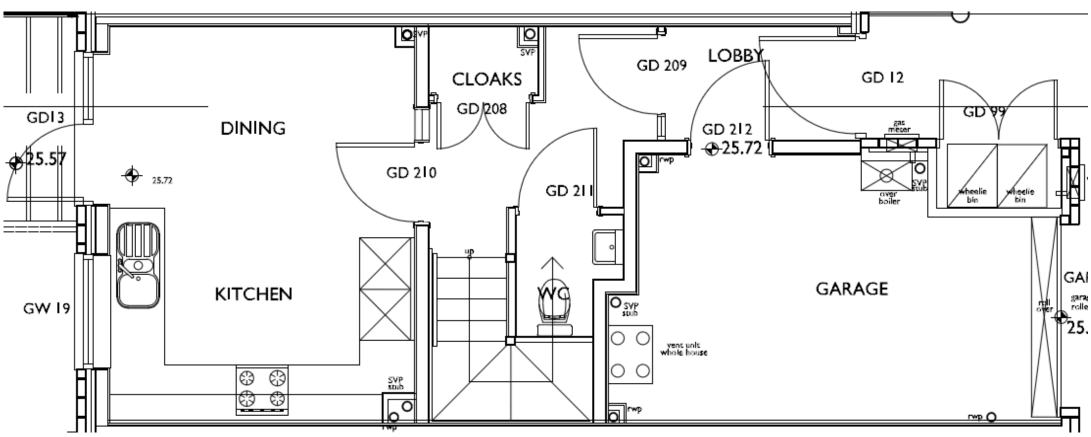


Figure 3.3 Phase 1 - Ground Floor Layout (Source: Marsh Grochowski, 2010)

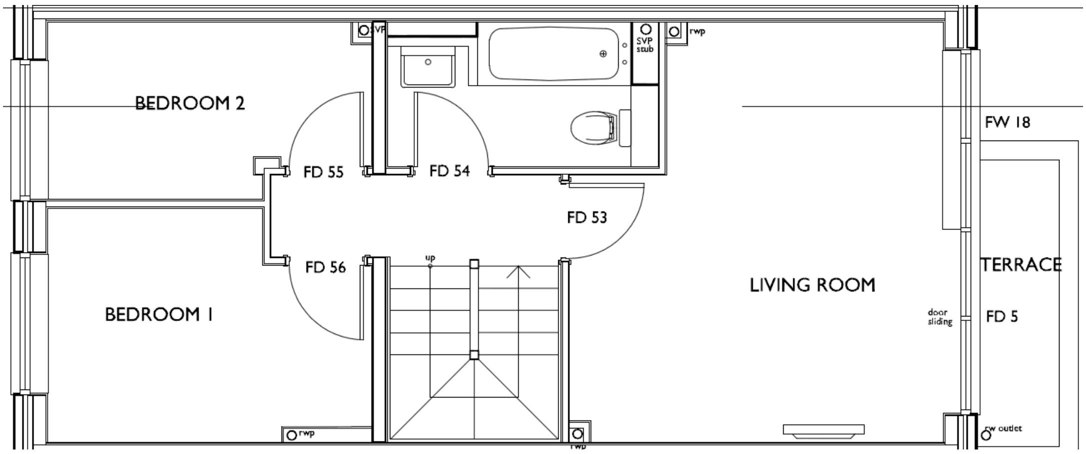


Figure 3.4 Phase 1 - 1st Floor Layout (Source: Marsh Grochowski, 2010)

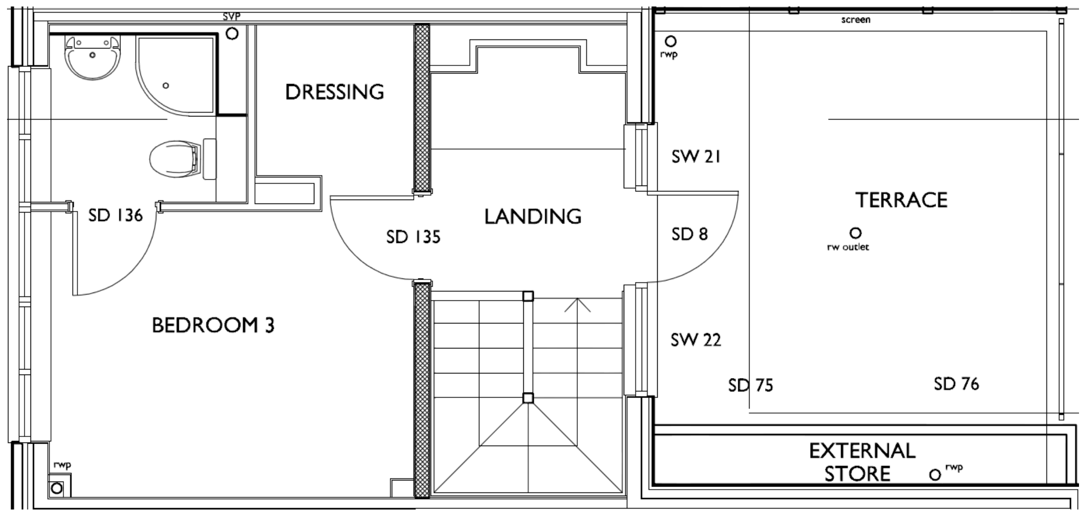


Figure 3.5 Phase 1 - 2nd Floor Layout (Source: Marsh Grochowski, 2010)

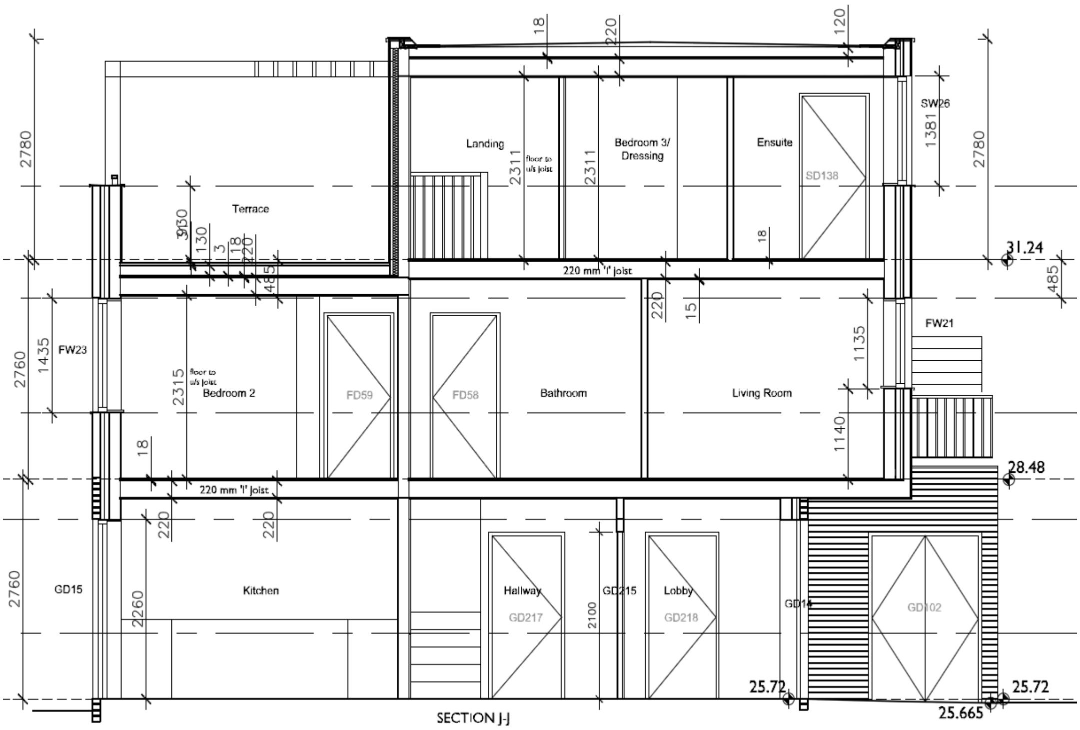


Figure 3.6 Phase 2 - House Section (Source: Marsh Grochowski, 2010)

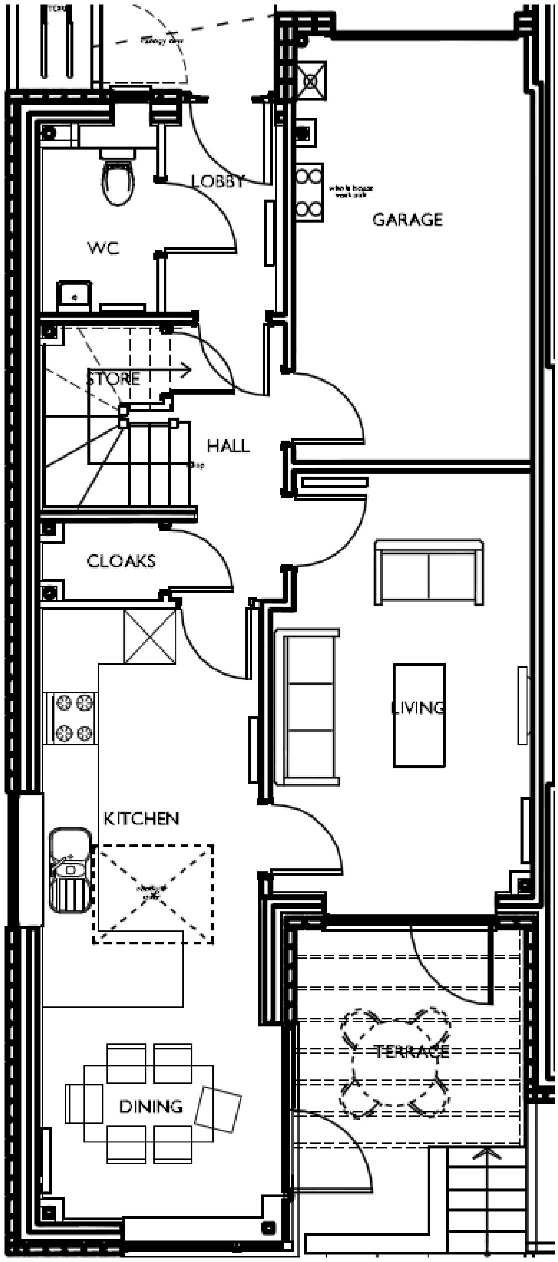


Figure 3.7 Phase 2 - Ground Floor Layout (Source: Marsh Grochowski, 2010)

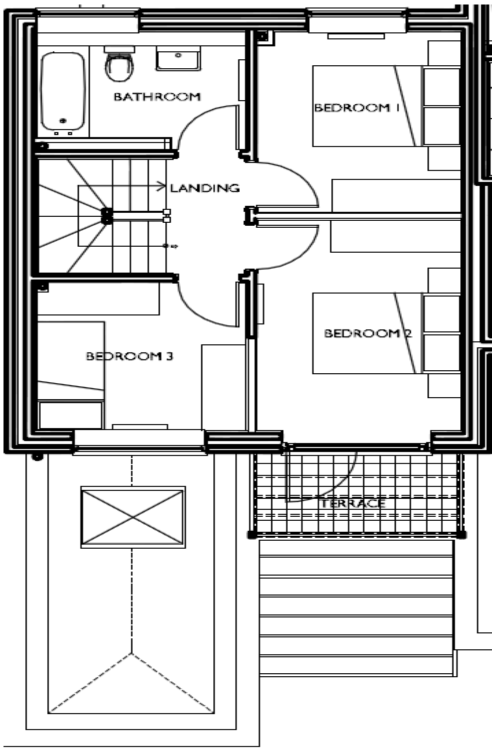


Figure 3.8 Phase 2 - 1st Floor Layout (Source: Marsh Grochowski, 2010)

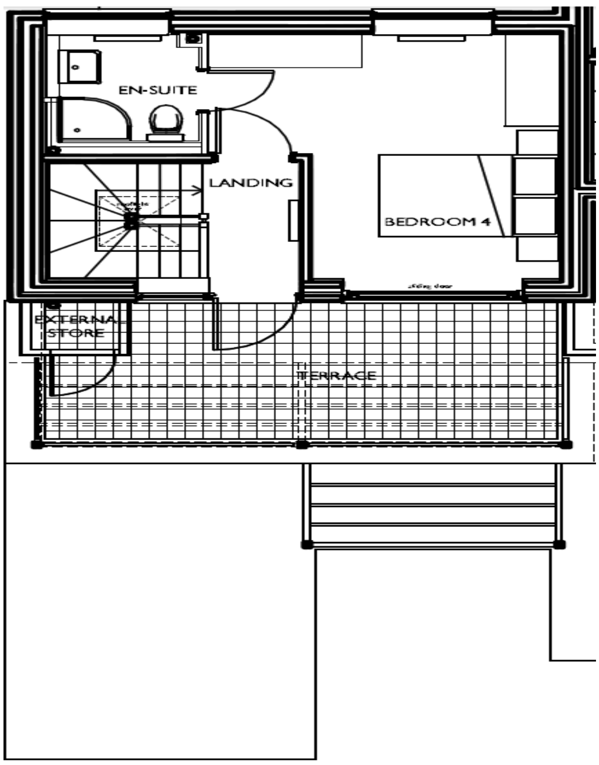


Figure 3.9 Phase 2 - 2nd Floor Layout (Source: Marsh Grochowski, 2010)

All units are designed to comply with:

- Code for Sustainable Homes Level 4
- National House-Building Council Standards
- Building for Life – Gold rating
- English Partnerships Quality Standards
- National Affordable Homes Agency – HQI standards
- Lifetime Homes – Units 13-21 inclusive.
- Environment Agency flood risk design

(Blueprint, n.d.)

Very few of these accrediting bodies incorporate any form of post occupancy evaluation to ensure that the homes do indeed fulfil their requirements, instead they rely purely on the design calculations and standards.

The visualization of the Green Street development in Figure 3.10 gives an idea of the layout of Phase 1 (on the right hand side) and Phase 2 (along the back) and Phase 3 (on the left). Phase 3 was not completed in time to be part of the study.

Figure 3.10 Graphic Visualization of Green Street

(Copyright BluePrint Regeneration)

Sustainability features include:

- All building materials are Green Building Guide A-C rated, with FSC certified timber.
- Air tightness $3m^3/h.m^2$
- High levels of insulation.
- 'A' rated Kitchen appliances
- Combination gas boiler (90% efficiency)
- MVHR (90% efficiency)
- Solar Photovoltaics
- External blinds (to prevent overheating)

(Blueprint, n.d.)

Facilities in each house include cycle and bin stores, washing lines, balconies, large roof terraces with timber louvers to provide shading and a small garden containing lawned area. All houses, from Phase 1, 2 and 3 have an Energy Performance Certificate (EPC) Grade B rating, and CSH Level 4 (with the building fabric rated as 6). (Blueprint, n.d.)

Despite the unique nature of the site and the vast similarities between the housing types there still remain some fundamental differences which can be taken from the relevant Standard Assessment Procedure (SAP) analysis for each dwelling and site specification documents. These include:

- Thermal shading on South Easterly facing windows of the timber housing to prevent overheating. This variation in orientation between the two phases and the subsequent shading of the Timber housing will have a significant impact on all overheating analysis, however without complex modelling and sensors on each window it is impossible to quantify that impact.
- Heat Loss Perimeter – directly related to dwelling volume/floor area which can differ very slightly from house to house
- Thermal Bridging – dependant on fabrication methods
- Shelter Factor – Timber houses (4 mid terrace), Masonry (3 end terrace and 1 mid)
- Useful Solar Gains – the houses are oriented differently and maintain different levels of glazing.

To give some context to the future SAP analysis in Chapter 5 the following is a breakdown of the as built SAP calculated performance factors for each house, including occupancy which was added post-construction.

Table 3.4 Individual House SAP Statistics

	House 1	House 2	House 3	House 4	House 5	House 6	House 7	House 8
Floor Area (m^2)	123	107	107	107	121	121	121	121
Dwelling Volume (m^3)	329	283	283	283	313	313	313	313
Sides which are sheltered	2	2	2	2	1	1	1	2
Shelter Factor	0.85	0.85	0.85	0.85	0.92	0.92	0.92	0.85
Total area of heat loss perimeter (m^2)	231	184	185	184	288	280	282	288
Fabric heat loss (W/K)	73.5	63.5	64.1	63.5	82.1	81.5	93.4	82.1
Thermal bridges (W/K)	18.5	14.7	14.8	14.7	23.1	22.4	22.6	23.1
Total fabric heat loss (W/K)	92	78	79	78	105	104	116	105
Ventilation heat loss (W/K)	23.3	20.1	19.9	20.1	23.5	23.7	23.3	22.9
Heat loss coefficient (W/K)	115	98	99	98	129	128	139	128
Heat loss parameter (HLP), (W/m^2K)	0.93	0.92	0.92	0.92	1.06	1.06	1.15	1.06
Useful Solar gains (W)	1042	931	937	931	1317	1312	1457	1314
Mean Internal Temp (°C)	18.9	18.9	18.9	18.9	18.6	18.9	18.6	18.9
Temperature rise from gains (°C)	9.04	9.47	9.48	9.47	10.24	10.28	10.46	10.26
Base Temp (°C)	9.47	9.05	9.03	9.04	8.34	8.31	8.13	8.32
Space Heating fuel requirement (kWh/year)	***2620***	***2048***	***2052***	***2046***	***2296***	***2260***	***2370***	***2277***
Main Space Heating (kg CO_2/year)	508	397	398	397	445	438	460	442
Occupancy	2	3	2	1	2	2	2	4

The final variable, as highlighted at the bottom of Table 3.4, is often one of the largest, the "human factor." Occupants and their unpredictable behaviour can represent the largest variable in any project such as this, where all testing is conducted under real world conditions (as opposed to purpose built research housing.) There is, and never will be a way of accounting for every action and reaction caused by occupants, however, qualitative testing in the form of Building Use Surveys and quantitative Personal Infrared (PIR) occupancy sensors give some indication of activities within the dwelling and can be taken into account where there is a specific investigation into an anomaly.

3.2 Environmental Monitoring Review

Menezes et al. (2012, p. 356) divides the scope of POE into three separate strands based on work by Cooper (2001):

- Feedback: A management aid mechanism aimed at measuring building performance mostly as an indicator of business productivity and organisational efficiency.
- Feed-forward: Aims at improving building procurement through the use of acquired data as feedback to the design team and future briefings.
- Benchmarking: Aims at measuring progress striving towards increasingly sustainable construction and stricter targets of energy consumption."

The objectives of this project suggest it most closely follows a benchmarking exercise, incorporating a combination of technological and socio-psychological testing under the umbrella of a standardized testing regime TSB (2011b). Research by Preiser (2001) and Langston & Ding (2001, p. 256) dictates a 3 tiered system of complexity that helps to gauge the finances, time, manpower and the final outcome of a POE project, this is summarized in a Table 3.5 by Turpin-Brooks and Viccars (2006, p. 180).

Table 3.5 POE Complexity Levels

Level of POE	Aims	Methods	Timescale	Comments
Indicative	Assessment by experienced personnel to highlight POE issues.	Walk through evaluation. Structured interviews. Group meetings with end-users. General inspection of building performance. Archival document evaluation	Short inspection period	**Quick, simple, not too intrusive/disruptive to daily operation of building. Judgmental - an overview only.**
Investigative	In-depth study of the building's performance and solutions to problems	Survey questionnaires and interviews. Results are compared with similar facilities. Report appropriate solutions to problems	From one week to several months.	**In-depth/useful results. Can be intrusive/time-consuming, depending on the number of personnel involved.**
Diagnostic	Show up any deficiencies (to rectify) and collect data for future design of similar facilities.	Sophisticated data gathering and analysis techniques. Questionnaires, surveys, interviews and physical measurements.	From several months to several years.	**Greater value in usability of results. More time consuming.**

(Turpin-Brooks & Viccars, 2006, p. 180)

By following the TSB BPE protocol (TSB (d), 2011) this study inherently validates its methodology and creates a set of data and conclusions comparable diagnostic level of POE. There are of course alternatives to the TSB protocol, such as the Energy Assessment and Reporting Methodology (EARM) published by the Chartered Institution of Building Services Engineers (CIBSE) as a technical memorandum (CIBSE TM22), which describes a method for assessing the energy performance of an occupied building based on metered energy use (Menezes et al. 2012). However the TSB protocol was developed specifically for a BPE of sustainable housing and was therefore an obvious choice when it came to deciding the structure of the testing regime for this project.

The specification for environmental and systems monitoring is based on this structure with 8 case study houses, 4 masonry and 4 timber, outfitted with a variety of environmental monitoring technology in order to establish operational performance benchmarks over the duration of the project. The measured parameters include:

- Metered gas
- Sub metering of the hot water and heating circuits leading from the boiler in order to separate energy use for each element.
- Monitoring of internal environmental conditions (temperature and humidity)
- PIR detectors to measure occupancy rates.

3.3 Environmental Monitoring Methodology

3.3.1 Technology Strategy Board Protocol

Year one of the research project established a historical perspective and developed the background position and rationale behind the study. It introduced the gap in research relating to the lack of post-occupancy performance data of timber based housing in the UK and the need for testing on mainstream housing developments in order to establish performance benchmarks for comparison of the building technique with more traditional methods. This introduced the search for a suitable suite of POE testing methods that could address this gap in knowledge in a simple and intuitive way – for immediate feedback into industry (Section 2.1).

However, the specification and validation of POE tools can be difficult within a narrow field of research, as they vary considerably in their scope and complexity, catering to different building conditions and research goals. It was only by chance that the University of Nottingham's Department of Architecture and Built Environment initiated a partnership (around same time as the beginning of this project) with a development company, Blueprint, and engaged upon a joint TSB BPE project (TSB (b), 2011) based on a case study – Green Street. A review of the TSB BPE protocol (TSB (b), 2011) associated with the Green Street TSB project immediately establishes its parallel intentions, mirroring those of this PhD thesis, namely the creation a post occupancy performance profile of timber and masonry housing. The collaboration with industry (Blueprint) and a research organization (TSB) is a fundamental component of the overall research process, allowing for direct dissemination of results and closing the research loop (Turpin-Brooks & Viccars, 2006).

In May 2010 the TSB introduced the BPE scheme with the aim of funding the costs of building performance evaluation studies on domestic and non-domestic buildings across the UK. The TSB studies focus on evaluating the performance of case study buildings, covering post completion, early occupation and in-use and post occupancy stages with the eventual aim of helping builders and developers deliver more efficient and better performing buildings in the light of Government emissions targets within the building sector (TSB (a), 2011).

As one of 46 competition participants within the domestic category (Colmer, 2012), the sustainable property developer Blueprint, entered the competition with the aim of better understanding of how a project actually delivers on its design and conceptual goals. A partnership with the University of Nottingham was formed around the funding available from the TSB BPE competition and the shared ambitions of obtaining a better understanding of post-occupancy performance in new housing. The case study development of mixed timber frame and traditional masonry housing provided by Blueprint forms the backbone of this research project and the TSB BPE scheme provides a clear and well-founded methodological framework for establishing the performance of housing through quantitative and qualitative testing.

By following the TSB BPE protocol (TSB (b), 2011) this study inherently validates its methodology and creates a set of data and conclusions which is easily comparable to the benchmark performance characteristics and context of other TSB based studies.

> *"Domestic building evaluation projects funded by the Technology Strategy Board's Building Performance Evaluation programme are required to undertake, as a minimum, common aspects of evaluation, according to prescribed protocols and approaches and to report their findings in standard formats. This is important to allow accurate benchmarking and to enable meaningful analysis across projects. It will also provide consistency with our Retrofit*

for the Future programme and other future programmes." (TSB (b), 2011, p. 2)

Obviously for the purposes of this research, which focuses on the direct ecological impact of the construction process and materials of the housing envelope, there are components of the TSB study which are either inappropriate or simply unfeasible due to the time and budget constraints associated with a research project such as this. These components include metering of water and electricity, neither of which should have a significant impact on the overall thermal performance of the housing. Electricity and the subsequent heat produced by the appliances it is powering may contribute to heat gains within the dwellings, but the nature of the study, with members of the public in their own homes, would seriously compromise the accuracy of calculating these heat gains. The occupants would have to keep track of their use of every single appliance, or alternatively each appliance would have to be installed with a data logger. Within a controlled academic setting, in specially designed research housing this may be feasible, however Green Street is simply too unpredictable for that level of analysis. In addition to the monitoring of electricity consumption, the TSB protocol also calls for the monitoring of microgeneration technologies, and while the Green Street housing does incorporate solar photovoltaic electricity generation, the efficiencies of that generation has no impact on the thermal performance of the dwellings and is therefore not included in the study. Monitoring of both the performance and energy use for the Mechanically Ventilated Heat Recovery units in each house was included in the original specification for the research, but had to be dropped due to budget constraints. While the use profile of the systems may impact the thermal performance of the dwellings, the units throughout Phase 1 & 2 are the same specification and should therefore perform the same as occupants were all given the same instructions on use and the systems should simply run in the background. Future research however should incorporate additional monitoring of these systems. Monitoring of CO_2 levels is deemed beyond the scope of the report is the energy and appliance audit. For the most part, the elements not incorporated from the TSB protocol should have little to no bearing on an ecological performance analysis of the buildings primary construction method and materials, however it is important that the results of the study be placed within the context of this understanding.

3.3.2 Quantitative Review Processes

Following a successful joint bid for TSB funding by the University of Nottingham and housing developer Blueprint, Microwatt was contracted to install the suite of monitoring equipment - under the supervision of this project manager David Bailey - specified by the TSB BPE protocol into 8 houses on the newly constructed Green Street housing development in Nottingham.

Phase 1 of the equipment installation on 4 TPC houses was completed in August of 2011, however the subcontractor responsible for the installation, Microwatt, never correctly commissioned the equipment and shortly after the installation, went bankrupt. The challenges arising from this bankruptcy and subsequent equipment failure included a complete lack of data, delaying the project by approximately 6 months and the obligation of an equipment refit for all 4 houses in Phase 1, with the project partners fronting the costs. Fundamentally, the author and project partners learned that within the relatively new industry of architectural environmental monitoring, the credibility and size of the monitoring company must be taken into account when looking for a partner to work with.

Installations of equipment in Phase 2 were completed by a new subcontractor by the name of Invisible Systems (IS), in April of 2012. These were completed in a professional and timely manner, with all equipment feeding back into an online "dashboard" where environmental conditions and utilities can be viewed in real-time. Based on the success of this installation, the same company was commissioned to refit the Phase 1 housing in September of 2012 with the aim of acquiring 1 full year of data from each housing type.

The 8 houses, 4 masonry and 4 timber, in the case study project are outfitted with a variety of environmental monitoring technology in order to establish performance benchmarks over the operational phase (Dixit, et al., 2013) of both masonry and timber housing in the Green Street case study (1 year for this project.) Again, this case study site and the monitoring equipment installed has a dual purpose, catering to both the need of the TSB BPE and within that, the more focused intentions of this research project. As such the full range of measured parameters include:

- Metered gas, incoming electricity and cold water.
- Sub metering of 4 major electrical circuits including kitchen appliances, cooker, lights and MVHR.
- Sub metering of the hot water and heating circuits leading from the boiler in order to separate energy use for each element.
- The performance of micro-generation technologies, in this case monitoring the generated power of a photovoltaic array located on the roof of each dwelling.
- Balance testing of the MVHR systems.
- Monitoring of internal environmental conditions (temperature and humidity in 5 different zones of each house including: entrance hallway, kitchen, livingroom, spare bedroom and master bedroom as well as external temperature and relative humidity on site.
- Personal Infrared (PIR) detectors to measure occupancy rates.
- Representative CO_2 measurements in a dwelling of each type of construction.

Obviously for the purposes of this research, which focuses on the direct ecological impact of the construction process and materials of the housing envelope, variables such a water use and electricity generation are not required. A revised list of pertinent sensors and their installation characteristics is presented in the following list of bullet points:

- Metered gas – 1 sensor per house, attached to the mains incoming gas meter. Incorporating a "Chatterbox," the metered gas sensor is a specialised piece of equipment that provides an intrinsically safe barrier for the gas meter, isolating the pulse generation equipment from the potentially hazardous environment in the immediate vicinity of the gas meter.

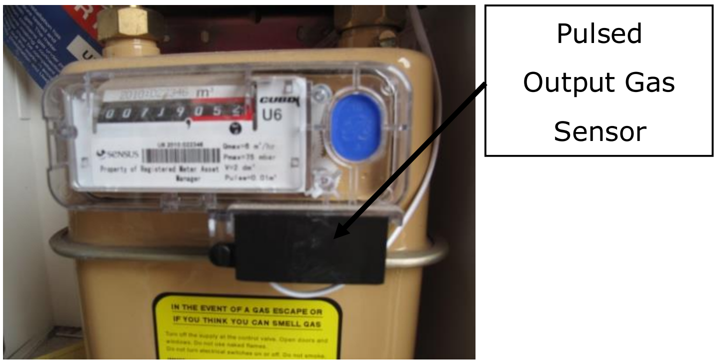


Figure 3.11 Gas Meter and Chatterbox

The chatterbox and pulse generator create a pulsed output per $0.01m^3$ of gas moving through the meter. This electronic pulse is picked up by an IS proprietary relay sensor which in turn conveys the information to the central Gateway – another piece of proprietary technology from IS. The Gateway contains a SIM card allowing it to transmit the data back to an online interface from which the data can be analysed and collated.

- Sub metering of the hot water and heating circuits leading from the boiler in order to separate energy use for each element. Phase 2 uses a 2 dedicated flow meters per house – the Supercal 539 – to simultaneously measure the flow rate and temperature difference between supply and return for each circuit. This gives an output for energy use in kWh for the hot water and heating in each house.

Figure 3.12 Heat Flow and Heat Meters

Budget constraints on the Phase 1 refit means that the flow meter and temperature sensors are separate and thus the calculation for kWh output is done manually through an excel algorithm based around the volumetric flow rate of a heating system:

$$q = \frac{h}{c_p * \rho * dt}$$

Equation 3.3.2 Volumetric Flow Rate

(The Engineering Toolbox, 2013)

q = volumetric flow rate (m^3/s)

h = heat flow rate (kW)

c_p = specific heat capacity of water (4.2 kJ/kg °C)

ρ = density of fluid (kg/m^3)

dt = temperature difference (°C)

Temperature difference is measured between the flow and return for heating and between the cold water feed and hot water flow for the hot water. Data from all the sensors, flow and temperature is sent once again to the Gateway and on towards the monitoring dashboard.

- Monitoring of internal environmental conditions (temperature and humidity) is achieved through the strategic placement of sensors (accurate to ±0.5°C over the range of -10°C to +85°C) throughout the property, generally 5-6 in total dependant on the number of rooms in the property.

Figure 3.13 Temperature and Humidity Sensor

Living rooms, kitchens, master bedrooms and spare rooms are all monitored to provide a clear temperature profile over the 3 levels in each house. Conditions data is collected in 5min intervals as dictated by the TSB protocol – this has proved to be somewhat of an issue as initially the sensors were set to 15min readings however this was rectified in January of 2013. Once again the retrofit of the 4 phase 1 houses necessitated a more cost effective approach than the IS proprietary temperature sensors installed in Phase 2. Tiny Tag temperature data loggers (accurate to ±0.9°C over the range of -40°C to +85°C) were chosen as their replacement based on their proven track record, rugged design and relatively large data storage capacity, necessitating a download every 56 days based on 5min reading intervals. 5 sensors were acquired per property and arranged in a similar fashion to the Phase 2 sensors. The mixture of sensors, the collection of data every 56 days and the generally more complicated data gathering approach in Phase 1 makes data analysis significantly more complicated than in Phase 2, where data is freely available and organised through the online platform.

- Monitoring of external environmental conditions (temperature) is reliant on the University of Nottingham's Architecture and Built Environment weather station located approximately 4km from the case study site – well within range for an accurate representation of the temperature and conditions on the Green Street site. This was deemed prudent for two key reasons. Initially there was an issue finding an appropriate position for the sensor itself – secure, protected, but at the same time exposed enough for accurate readings. Second, the importance of this information meant that there was no room for equipment failure or even interference by well-meaning but unfamiliar project participants on site. That being said, a tiny tag sensor was installed on site as a backup and periodically monitored in case of any loss of data from the main sensors at the University.

- Personal Infrared detectors to measure occupancy rates. Located on the ground and second floors of each property the sensors evaluate the number of people in the house, rather they are simply used to indicate if the house is occupied or not – an essential factor in the analysis of temperature and heating values

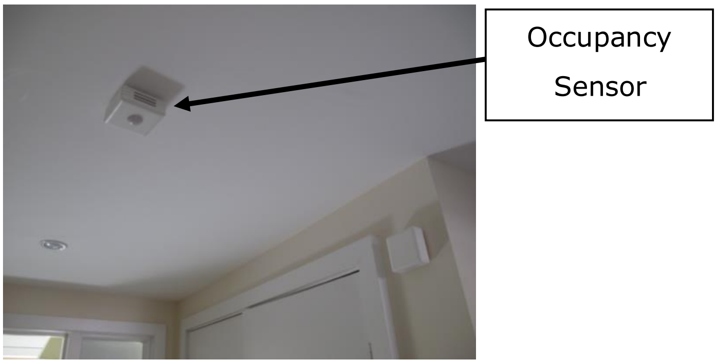


Figure 3.14 Occupancy Sensor

While the monitoring period for this study is limited to 1 year (due to the Microwatt bankruptcy and PhD timeframe) it is expected that information from the entire sensor suite will continue to accumulate for a further year as necessitated by the TSB protocol.

3.4 Environmental Monitoring Results and Discussions

3.4.1 Case Study Housing - Temperature Profiles

Monthly temperature profiles throughout the year provide a revealing context for the following sequence of graphs depicting the daily temperatures and monthly minimum/maximum temperature data over the study period.

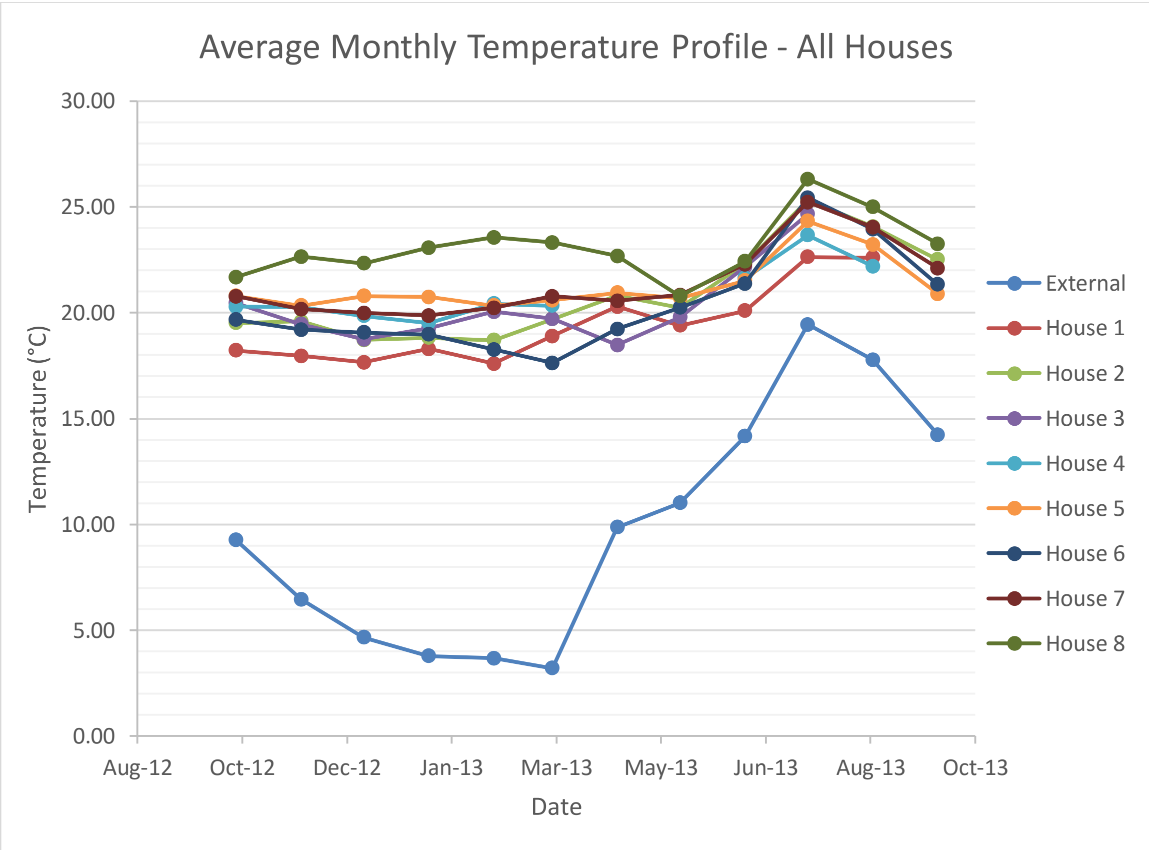


Figure 3.15 Average Monthly Temperature Profile – All Houses

Temperature profiles in isolation give very little practical information, and there are simply too many uncontrolled variables that can impact a direct comparison between the housing. Their purpose lies primarily in providing a context and basis on which to build a correlation framework with another measured variable. Given the nature of this research and the focus on the fabric performance, this alternate variable comes in the form of recorded energy data associated with space heating –by combining the two data sets it is possible to establish an in use heat loss coefficient for each house, proportionally comparable and directly indicative of which houses have a greater ecological footprint.

Section 3.4.5 examines the secondary motive for compiling temperature profiles; that is the visualization and highlighting of extreme or abnormal conditions recorded during the environmental monitoring phase. This is particularly pertinent during the summer months, when considering overheating.

It should be noted that the temperature profile of House 4, depicted in Figure 3.20 is missing a portion of data due to interference with the temperature sensors by the occupant – an unforeseeable accident which was deemed not to invalidate the entire data set, thus its inclusion in this series of analysis.

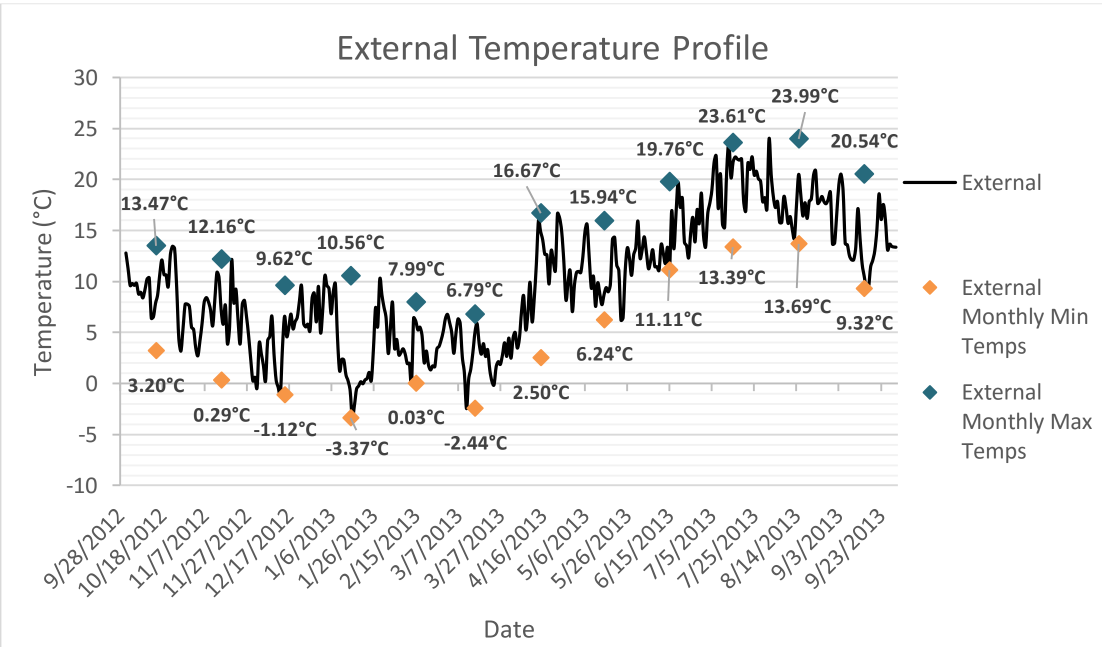


Figure 3.16 External Temperature Profile

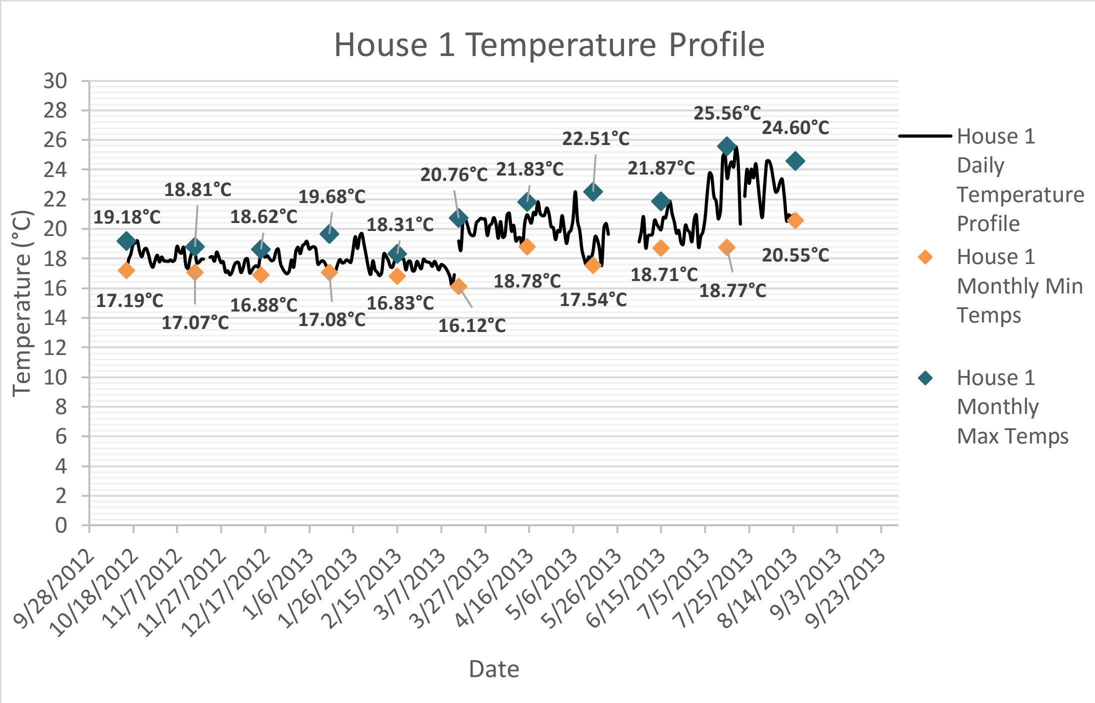


Figure 3.17 House 1 - Temperature Profile

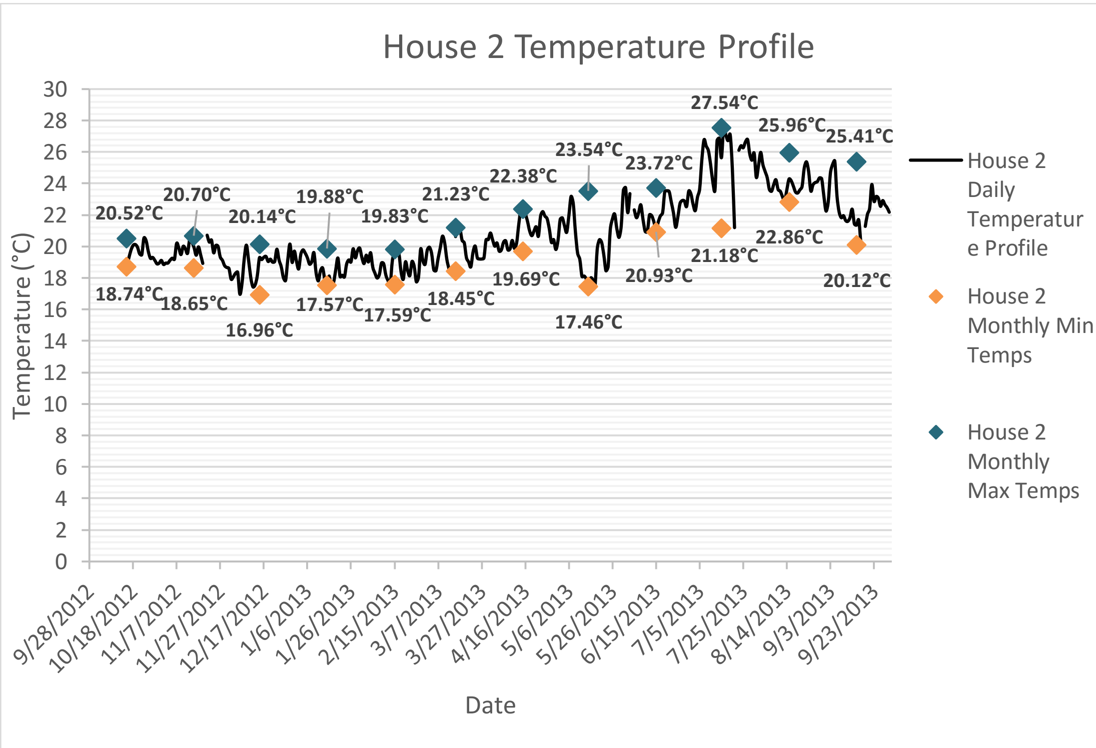


Figure 3.18 House 2 - Temperature Profile

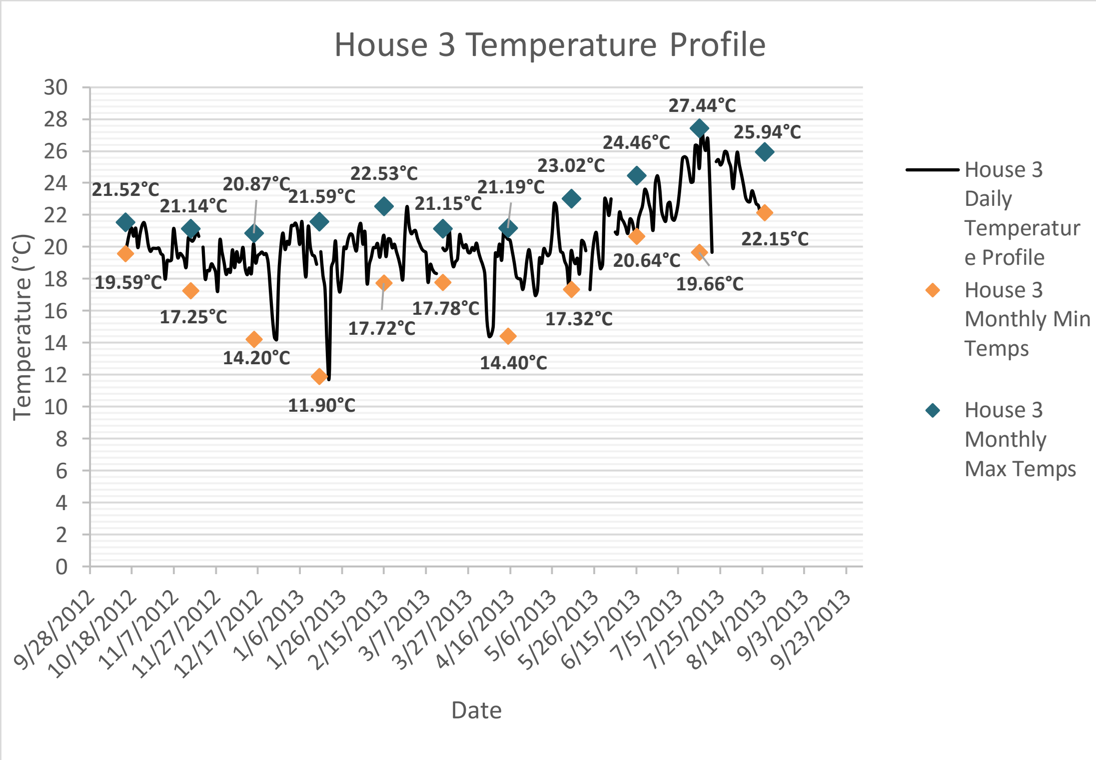


Figure 3.19 House 3 - Temperature Profile

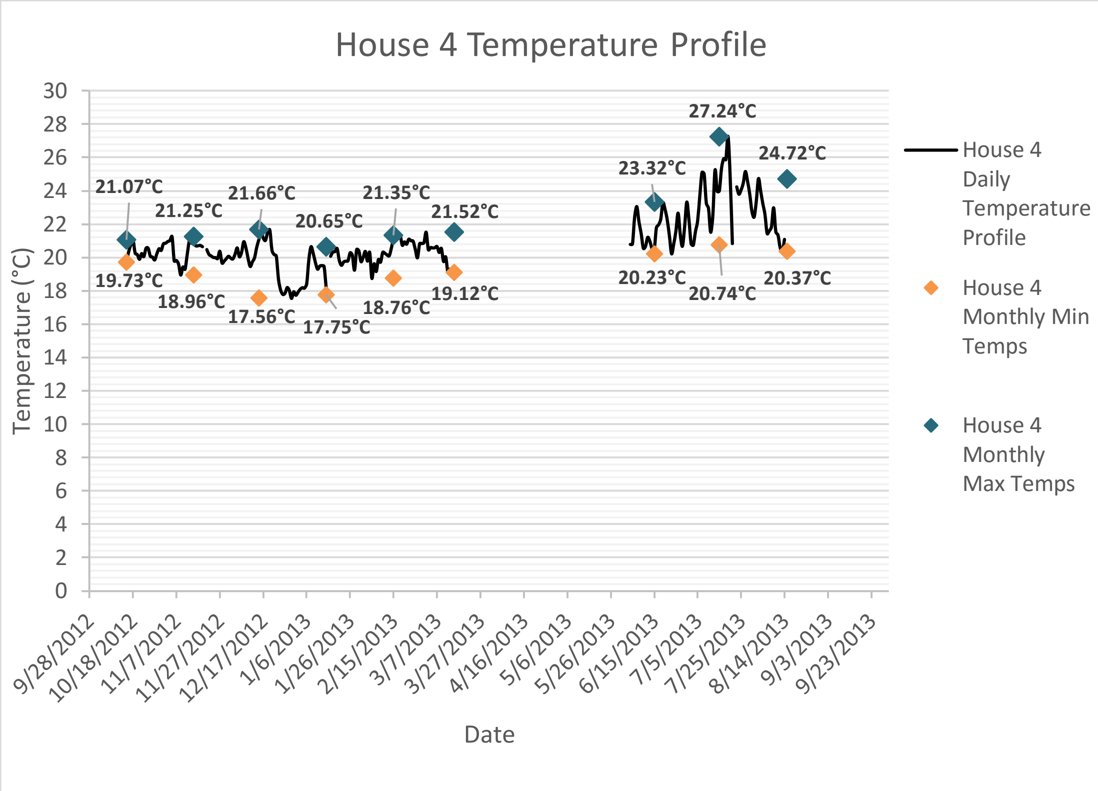


Figure 3.20 House 4 - Temperature Profile

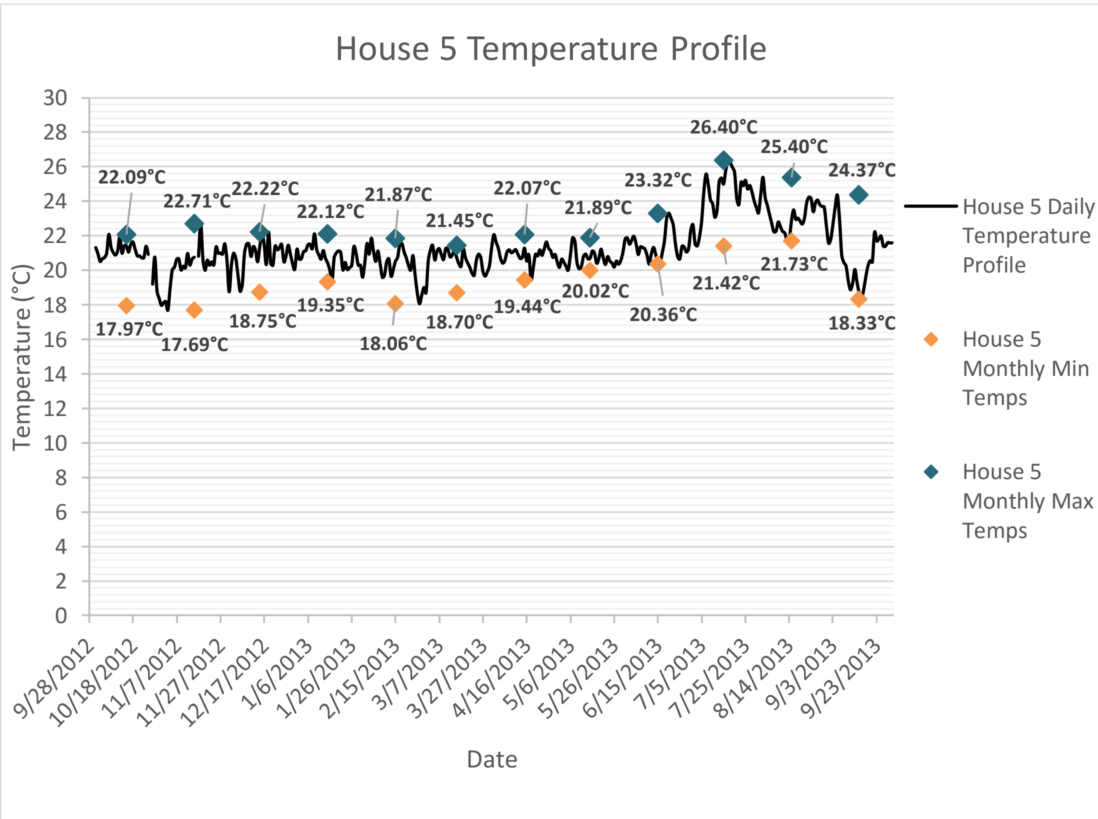


Figure 3.21 House 5 - Temperature Profile

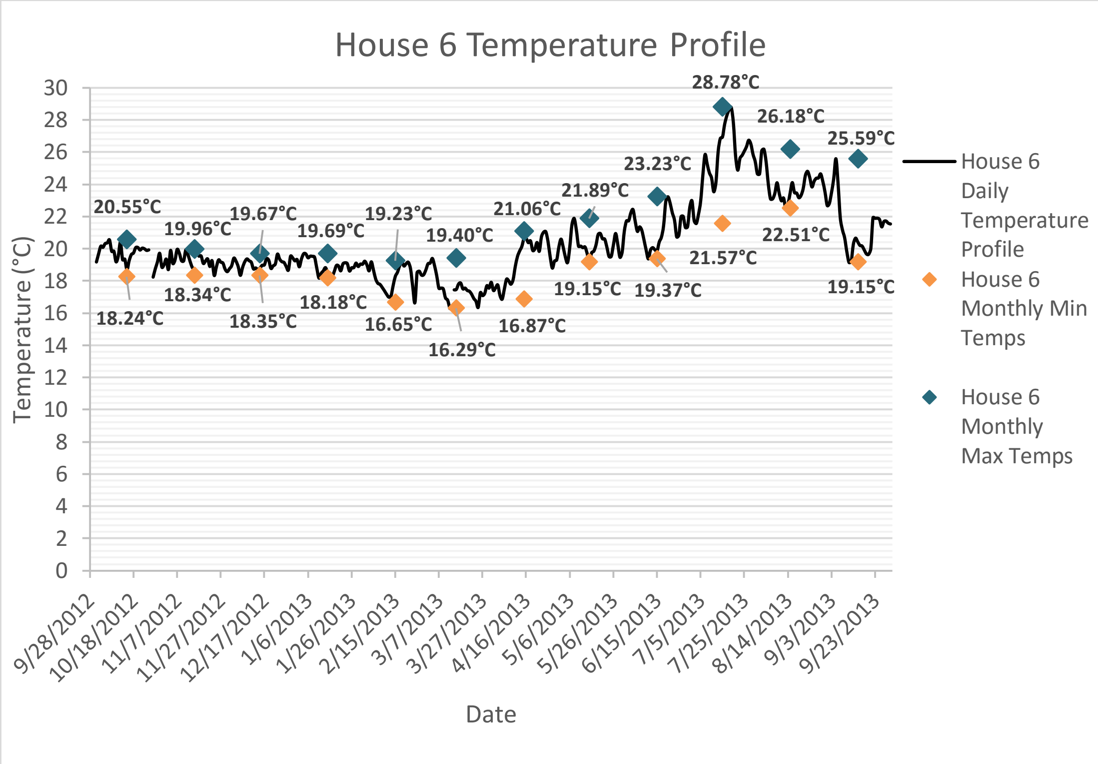


Figure 3.22 House 6 - Temperature Profile

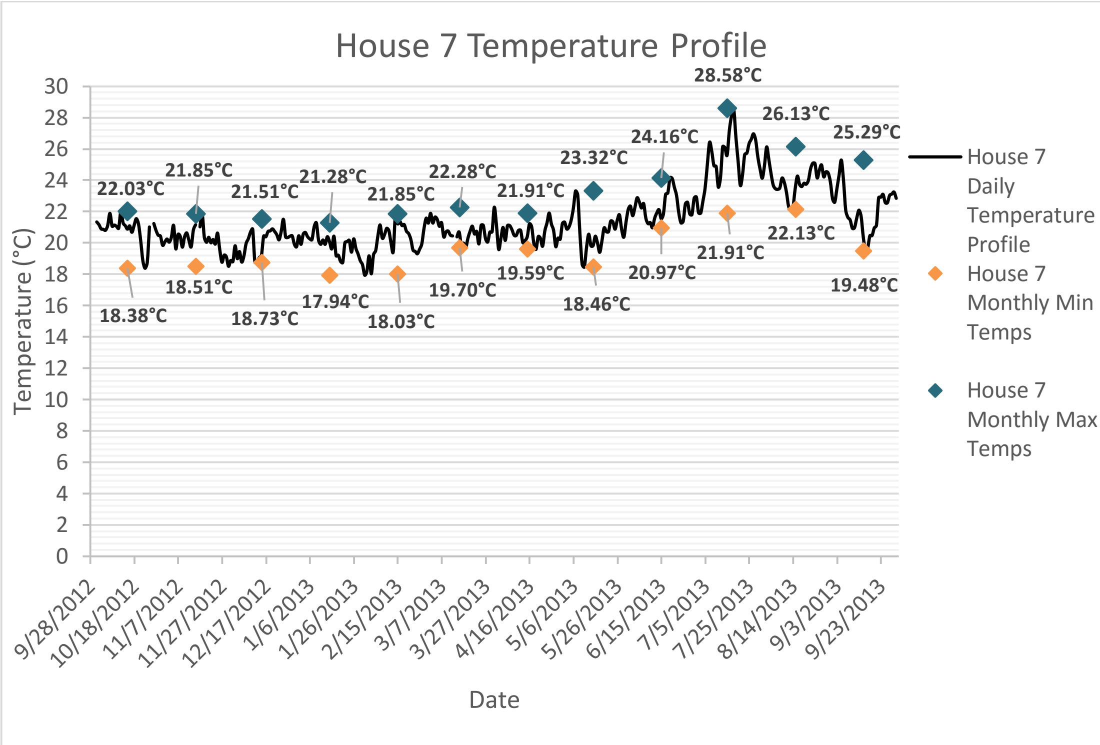


Figure 3.23 House 7 – Temperature Profile

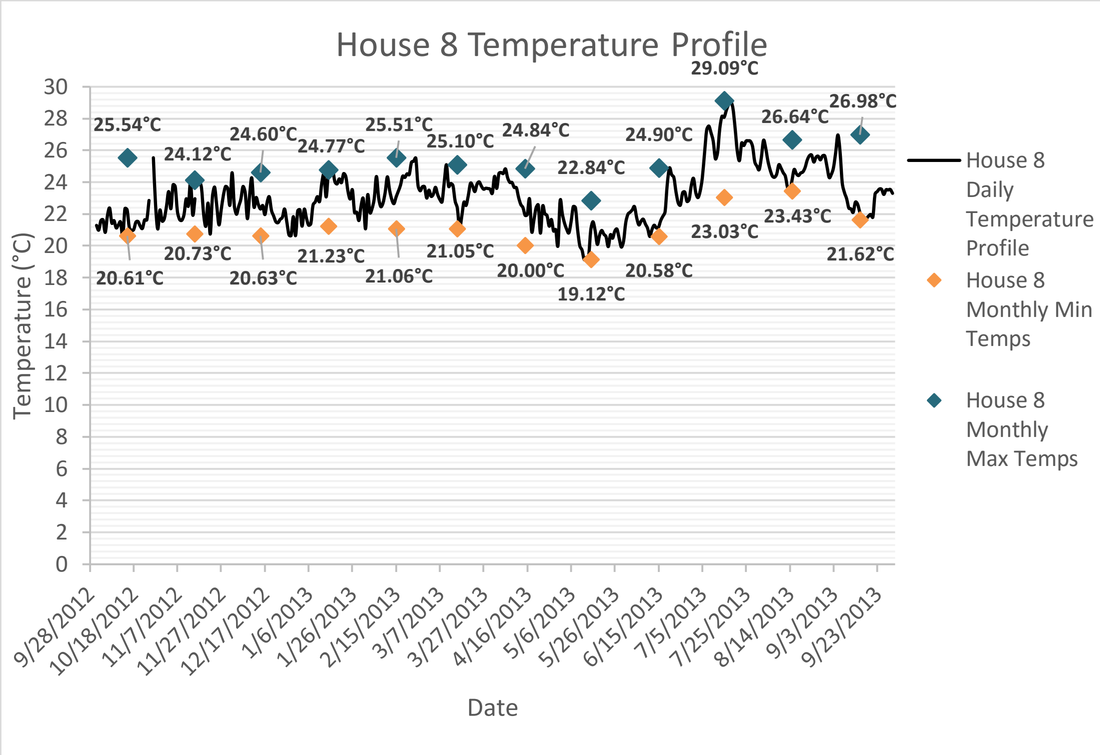


Figure 3.24 House 8 - Temperature Profile

3.4.2 Calculating Energy Use in the Case Study Housing

Ideally the research methodology calls for a disaggregation or sub-metering of the energy associated with hot water and heating – using heat meters plumbed directly into the relevant water circuits. The self-contained heat meters use the temperature difference between incoming and outgoing water volumes to calculate the amount of energy imparted to the liquid via the boiler and render a simple kWh value as their output. Unfortunately the complications associated with Microwatt completely removed one house outright from the sub-metering and forced a more complex and less accurate solution in the remainder of Phase 1, which subsequently failed as the following data tables will demonstrate.

Table 3.6 Heat Load Calculation Data

	House 4 Heating Energy (As measured)					House 24 Heating Energy (As measured)	
Date	Supply Temp (°C)	Return Temp (°C)	Mass Flow Rate (kg/s)	Heat Load (kWh)	Gas Use (m3)	Heat Load (kWh)	Gas Use (m3)
15/10/2012	32.04	24.39	0.005903	4.5561	1.51	21	3.26
16/10/2012	28.11	24.46	0.004977	1.8313	1.9	25	3.7
17/10/2012	26.35	24.04	0.005208	1.2130	1.82	21	3.2
18/10/2012	27.96	24.73	0.003241	1.0559	1.85	13	2.28
19/10/2012	34.92	25.57	0.004398	4.1452	2.41	12	1.98
20/10/2012	27.78	23.10	0.002199	1.0368	1.32	20	3.17
21/10/2012	26.92	21.83	0.003241	1.6629	1.33	24	3.7
22/10/2012	27.32	23.64	0.004282	1.5873	1.69	14	2.45
23/10/2012	25.98	22.18	0.002315	0.8857	1.42	24	3.56
24/10/2012	26.66	22.86	0.001620	0.6200	1.02	20	3.14
25/10/2012	23.20	19.79	0.002546	0.8759	1.29	24	3.58

The heat load for House 4 is calculated through Equation 4.1. The key values to look at in Table 3.6 are the heat load and corresponding gas use. Considering $1m^3$ of natural gas equates to about 10.8kWh of raw energy (Butler, et al., 2011) there is no way the figures for house 4 can be correct, and the values displayed for house 4 are indicative of the data collected throughout the phase 1 houses. One of the sensor types used in phase 1 must be malfunctioning and the hypothesis is that it is the mass flow rate water meter as this was installed by Microwatt (as most of their other equipment failed) and adapted for use with the Invisible Systems equipment retrofitted to the site. Whatever the case the kWh data from phase 1 is completely unreliable and the decision was made to revert back to the data taken from the gas meters. This process however is not without it complications. First there is the fact that where the heat meters separated energy into heating and hot water values, the overall gas use is recorded preboiler and the energy associated with the gas use is not separated. In order to isolate just the energy associated with space heating, a hot water gas profile was compiled for each house during the summer months, where gas usage is entirely dependent on hot water.

Average Daily Gas Use from Hot Water

Dwelling Designation	Average Daily Gas Use - Hot Water (m^3)
House 1	0.45
House 2	0.48
House 3	0.53
House 4	0.43
House 5	0.63
House 6	0.4
House 7	0.41
House 8	0.68

Table 3.7 Average Daily Gas Use - Hot Water

The temperature data was then separated into 3 sections –

- Heating season (heating on generally throughout): 01/10/2012 – 29/04/2013
- Transition period (heating is on sporadically): 30/04/2013 – 25/06/2013
- Cooling season (heating off): 26/06/2013 – 01/10/2013

This profile was then applied to the heating season and essentially subtracted in order to get just the gas usage for space heating. The adjusted gas use is then converted into kWh's, utilizing the calorific value of natural gas, 39MJ/m^3, (Butler, et al., 2011) and then the calculation 1kWh = 3.6MJ. The data is further manipulated to render it into Watts, simply by dividing it by 24 (hours in the day) and multiplying it by 1000 (to go from kW – W.) Efficiency of the condensingcombi GREENSTAR 42CDi boilers (90.2%) are then taken into account. The resulting daily energy figures for each house are depicted on scatterplot graphs, measured against the corresponding ΔT for each dwelling. ΔT simply calculated as the internal temperature subtracted from the external temperature.

These graphs, depicted in the following few pages, render a W/Kelvin value for each of the houses similar to that produced through co-heat testing.

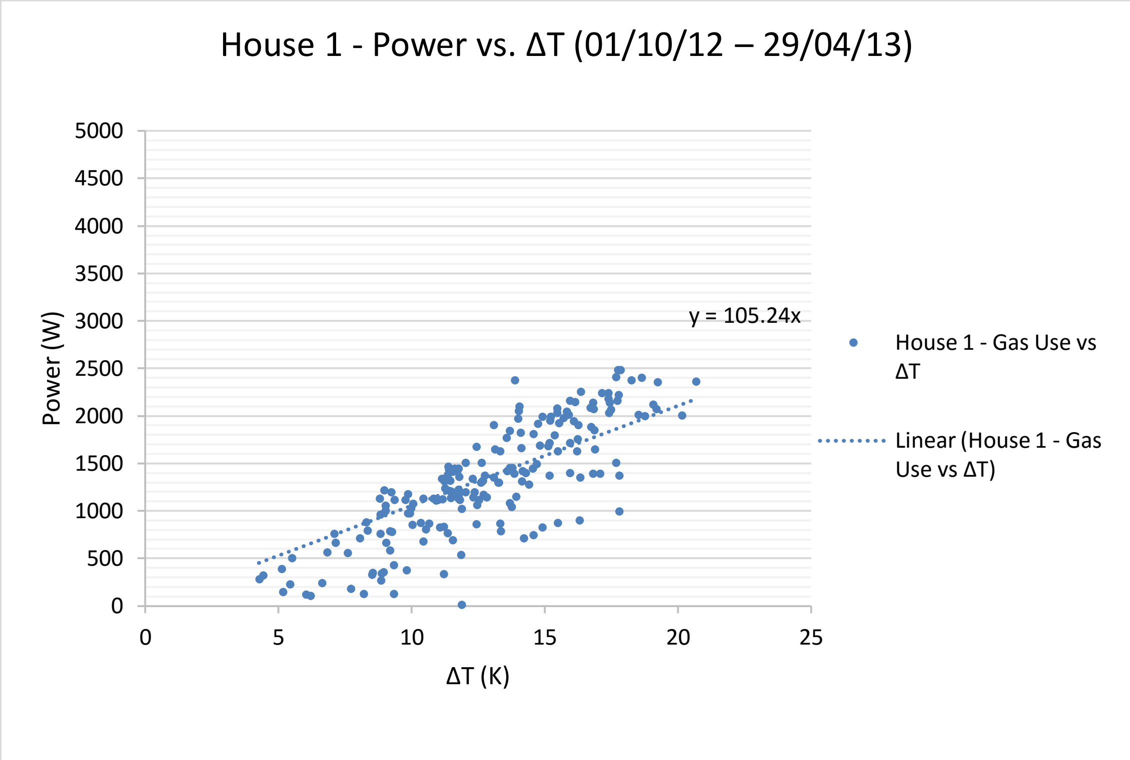


Figure 3.25 House 1 - Power vs. ΔT (01/10/12 – 29/04/13)

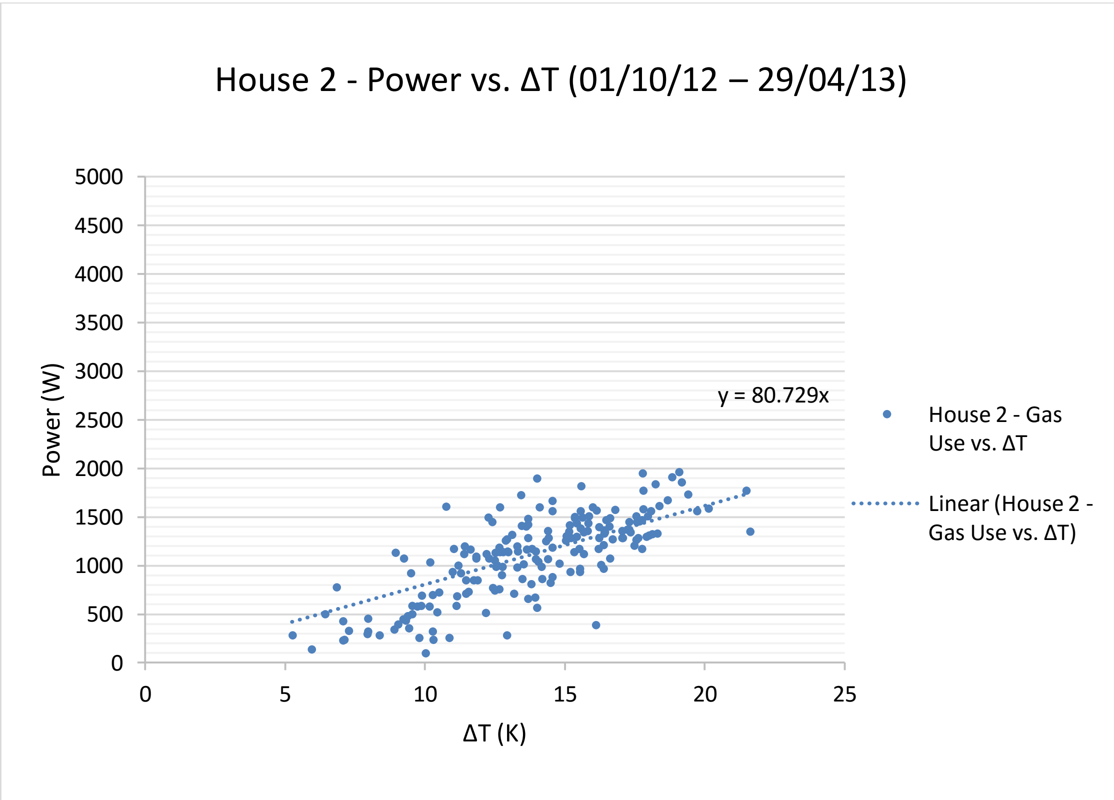


Figure 3.26 House 2 - Power vs. ΔT (01/10/12 – 29/04/13)

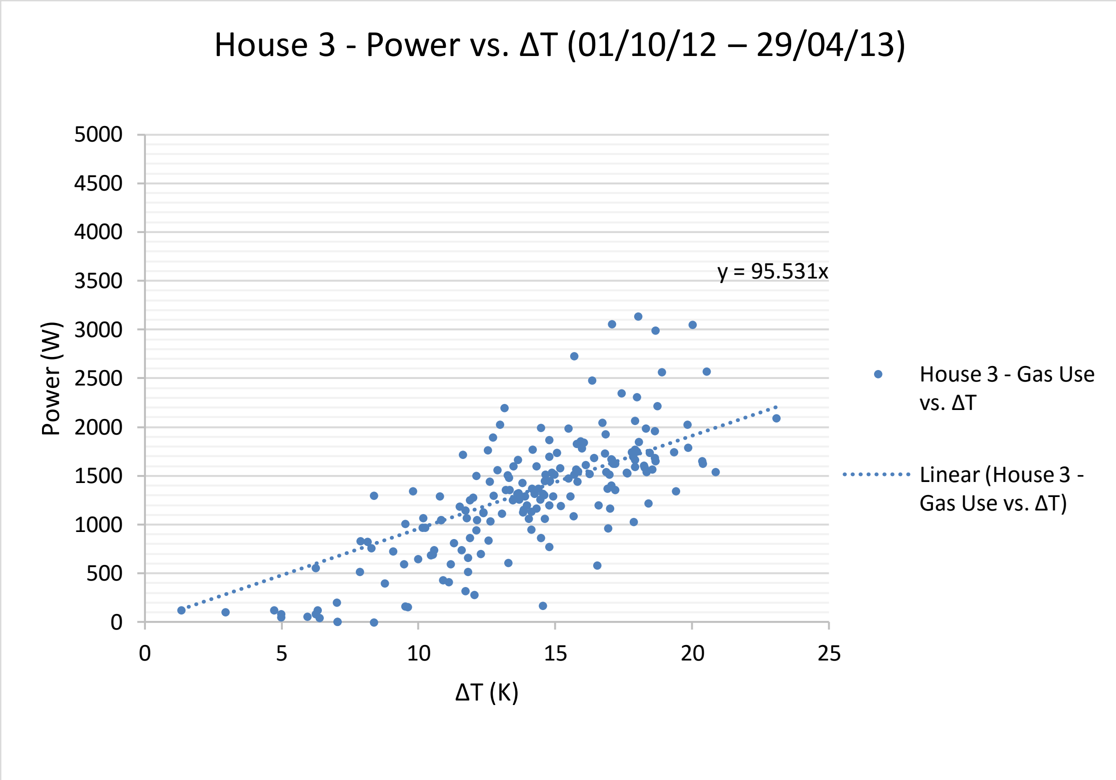


Figure 3.27 House 3 - Power vs. ΔT (01/10/12 – 29/04/13)

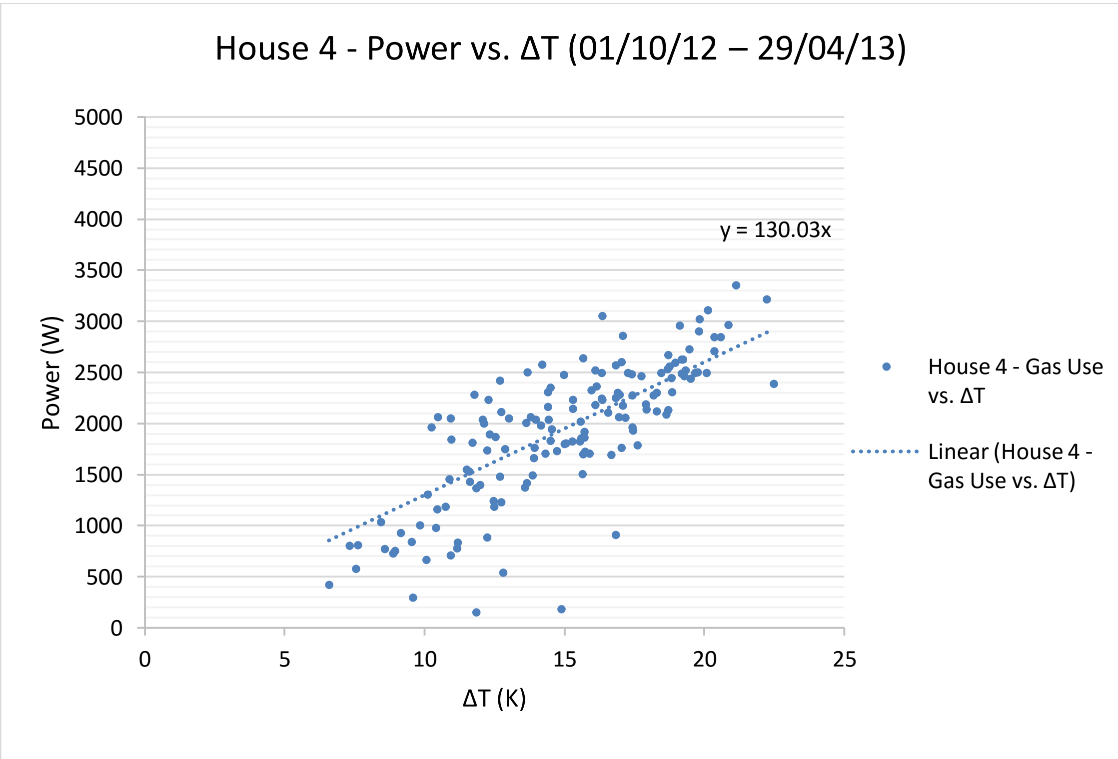


Figure 3.28 House 4 - Power vs. ΔT (01/10/12 – 29/04/13)

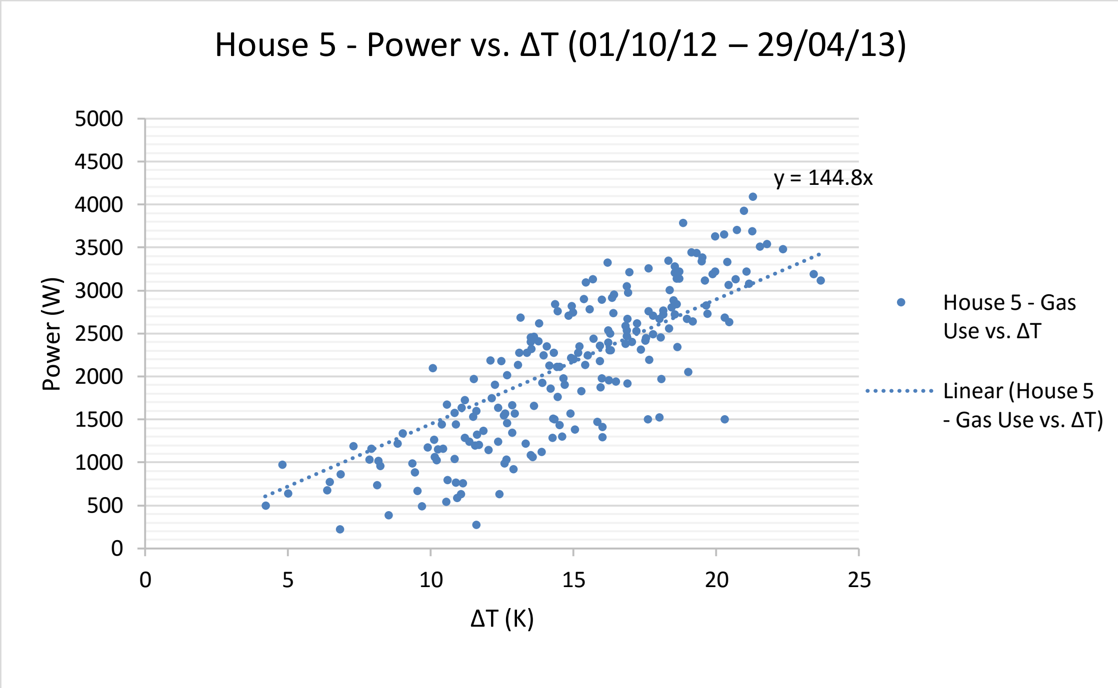


Figure 3.29 House 5 - Power vs. ΔT (01/10/12 – 29/04/13)

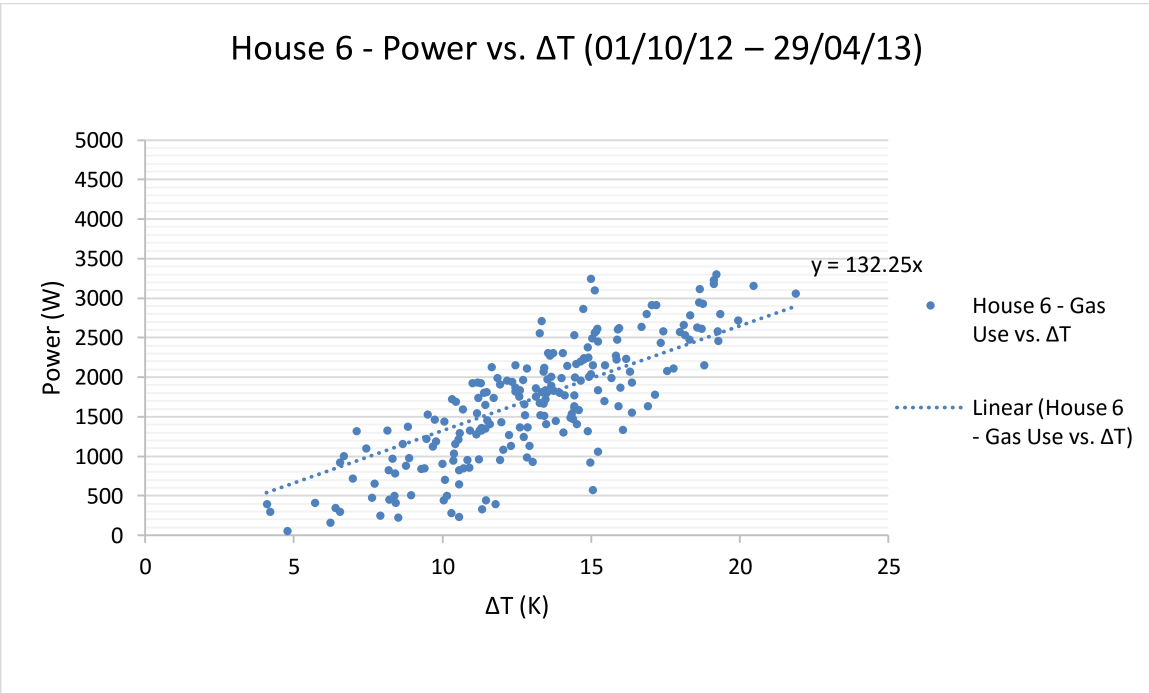


Figure 3.30 House 6 - Power vs. ΔT (01/10/12 – 29/04/13)

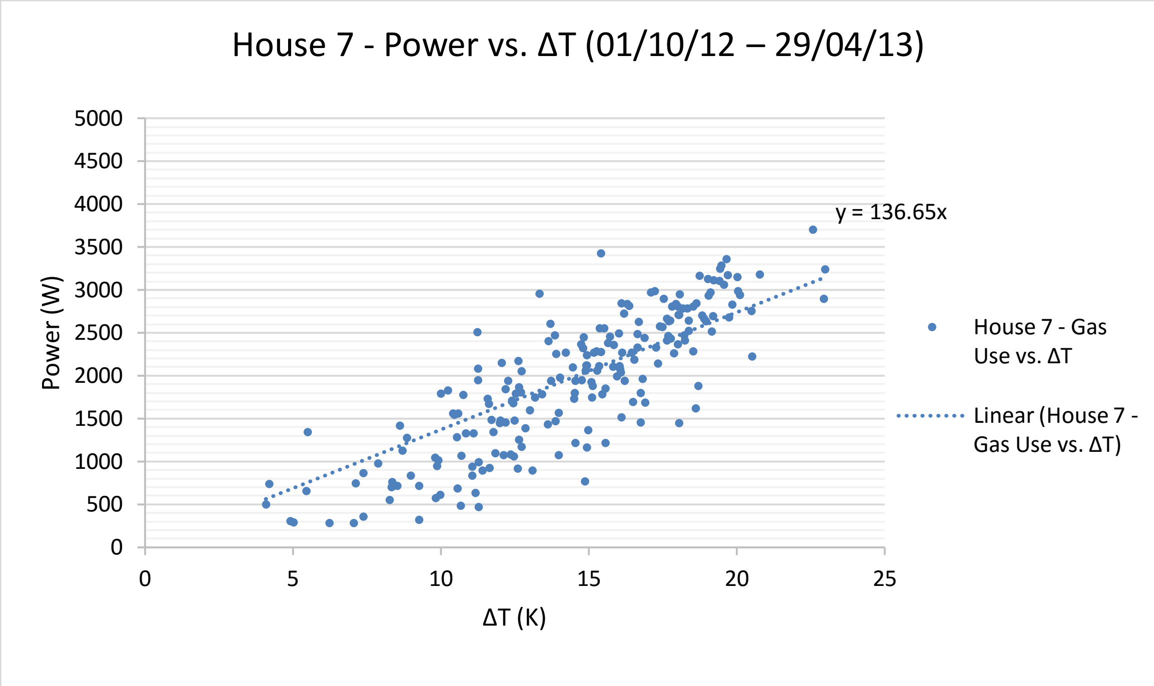


Figure 3.31 House 7 - Power vs. ΔT (01/10/12 – 29/04/13)

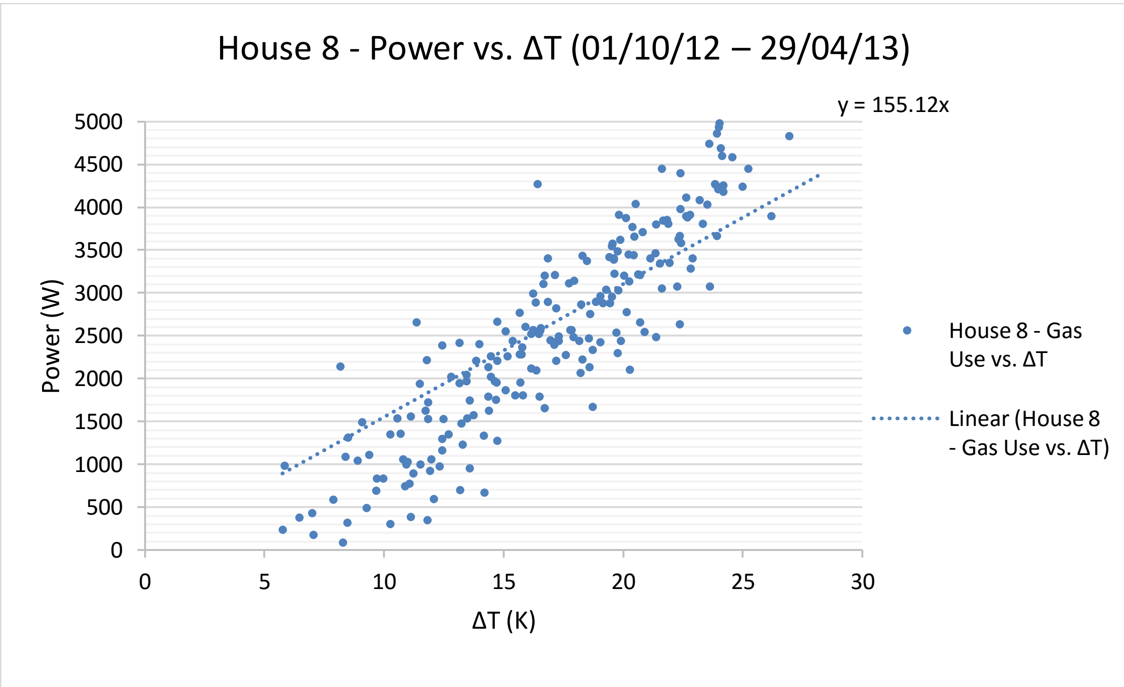


Figure 3.32 House 8 - Power vs. ΔT (01/10/12 – 29/04/13)

Compiled together, the power vs. ΔT values render an in use, or "working" HLC. The final step is to take into account the differing floor areas for each dwelling thereby producing a final "working heat loss parameter" (WHLP) value collated in Table 3.8.

Table 3.8 Final Corrected Working WHLP Value from Environmental Data

Dwelling Designation	WHLC (W/K)	Dwelling Floor Area (m²)	Working Heat Loss Parameter (W/m²K)	Average WHLP for Phase 1 and 2 (W/m²K)
House 1	105.24	231	0.46	0.53
House 2	80.73	184	0.44	
House 3	95.53	185	0.52	
House 4	130.03	184	0.70	
House 5	144.80	288	0.50	0.50
House 6	132.25	280	0.47	
House 7	136.65	282	0.48	
House 8	155.12	288	0.54	

3.4.3 Working Heat Loss Coefficient Analysis

Table 3.8 summarizes all the work from Sections 3.4.1-3.4.3, generating an energy performance profile for each house and quantifying the energy expenditure in relation to the temperature difference between inside an outside.

This designated “working heat loss parameter” (WHLP) differs from the standardised HLP in that it represents a more realistic picture of the overall housing performance. The standardised HLP is based purely on fabric elements and their insulative properties. The data is generated under a highly controlled conditions through a specified methodology. While this is perfect for developing a clear picture of the fabric properties it doesn’t really reveal how the house actually performs under normal, everyday use. Paradoxically, by stepping back and just letting the occupants and houses operate independently from any set methodology it is possible to create a more realistic profile of energy use throughout the dwelling (the WHLP) which incorporates the actions of the dwellings occupants which impact daily performance. The idea is that the industry should be building houses which conform to environmental standards even once they are occupied, so understanding the impact that occupants have on a dwellings performance is incredibly important. From a comparative standpoint the simple conclusion is that throughout the heating season the houses perform almost identically.

Another way to evaluate the data would be to compare the WHLC values to the standardized HLC test results from the co-heat testing. The co heat testing and resulting HLC is entirely fabric-centric removing as many outside influences as possible, the two largest being the solar gains and human interaction or human factor with the building. However if the solar gains are added back into the HLC equation and then the value compared to the WHLC it is possible to quantify the impact that the occupants have on the space heating energy profile. These impacts can even be linked to the dwellings occupant demographic to help build a picture of the impact a particular type of individual or family unit has on a dwelling. Unfortunately, given the fact that in this project the solar gains into the dwellings were unavailable and only representative houses of the type were actually tested for an HLC this type of analysis would be somewhat fruitless, however it does reveal the diverse research possibilities unlocked through POE and specifically this calculation of the WHLC.

The concept of a WHLP with units of W/m²K is completely transferable to other projects, and sheds valuable light on specifically the post occupancy evaluation stage of performance evaluation. The WHLP is potentially an incredibly important performance variable that is simply incalculable in dedicated research houses.

3.4.4 Night Time Temperature Degradation Profiles

One outcome of the environmental monitoring data is its potential to reveal how the houses react to no energy input through the heating system, essentially quantifying how well they maintain their internal temperature over a set period of time. This is an important characteristic which indicates the effectiveness of the insulation and will help establish the impact of greater thermal mass in the masonry construction. That being said, the exact proportions of heavyweight/lightweight materials used in each construction type is unknown as the timber housing incorporates an element of thermal mass in both the façade and an internal structure around the staircase areas (140mm solid blockwork), therefore the values calculated and conclusions drawn from this section will serve as an indication of how these particular houses are performing rather than conclusive evidence of industry practice as a whole.

The period under observation has been specifically identified through the temperature profiles in Section 3.4.1. The dates have been chosen as they exhibit both an extended period of very low temperatures and constant and reliable temperature data for all houses from both phases. The dates chosen for this investigation are the 11/12/2012 – 13/12/2013.

The temperature data is initially employed to illustrate a temperature degradation profile in Figure 3.33 - Figure 3.39. The right hand axis has been purposely left without a defined unit as the energy output, which it represents, is actually based on different variables in each house. These include gas consumption, water flow through the heating system and energy readings from heat meters embedded in the central heating system. In this case, the quantity of these variables is irrelevant, they are included simply to indicate when there is an energy input into the dwelling which might affect the internal temperature. The idea is to isolate night time intervals with no energy input and extract the temperature vs. time relationship as the house cools down. These intervals are represented in the graphs as a negative slope temperature line with a flat, zero rated energy input. House 4 was deemed unsuitable for this test when gas use data revealed that the heating is entirely controlled through a thermostat and constantly on throughout the day and night, making it impossible to determine an uninhibited time vs. heat loss figure.

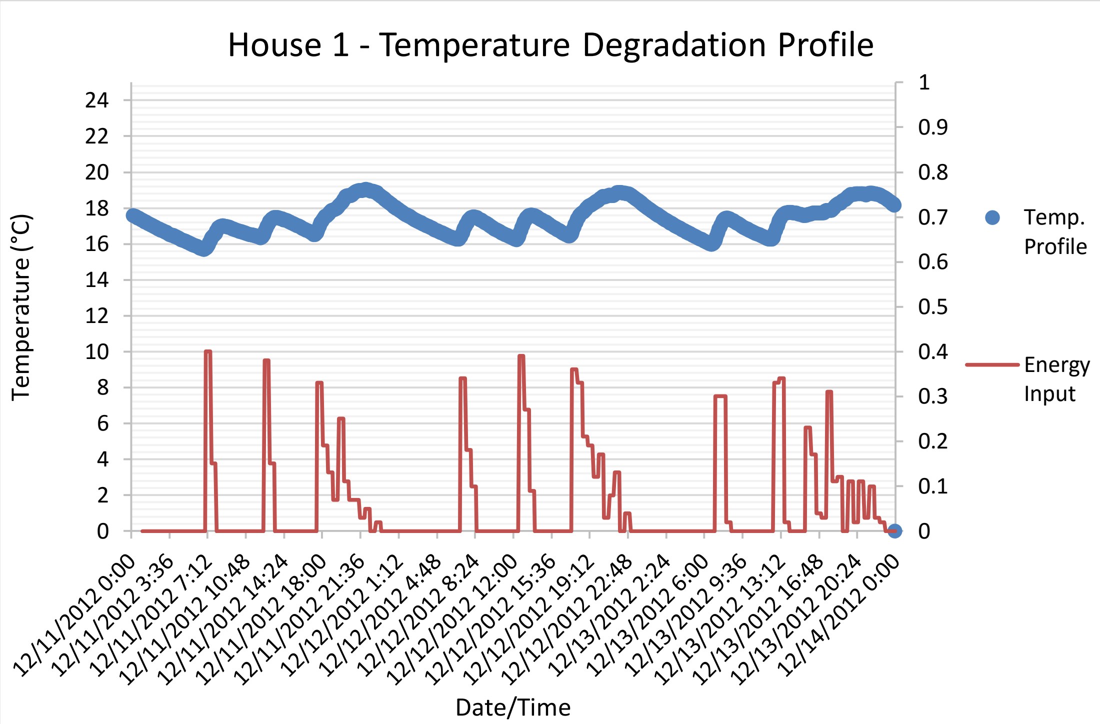


Figure 3.33 House 1 - Temperature Degradation Profile

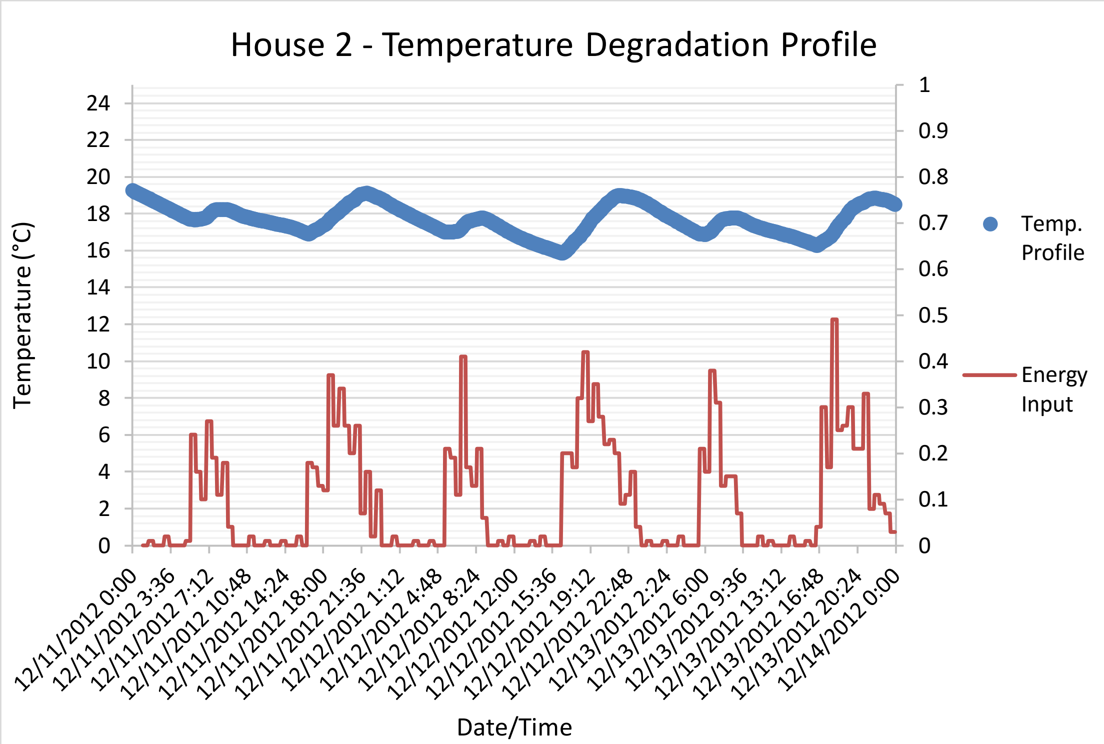


Figure 3.34 House 2 - Temperature Degradation Profile

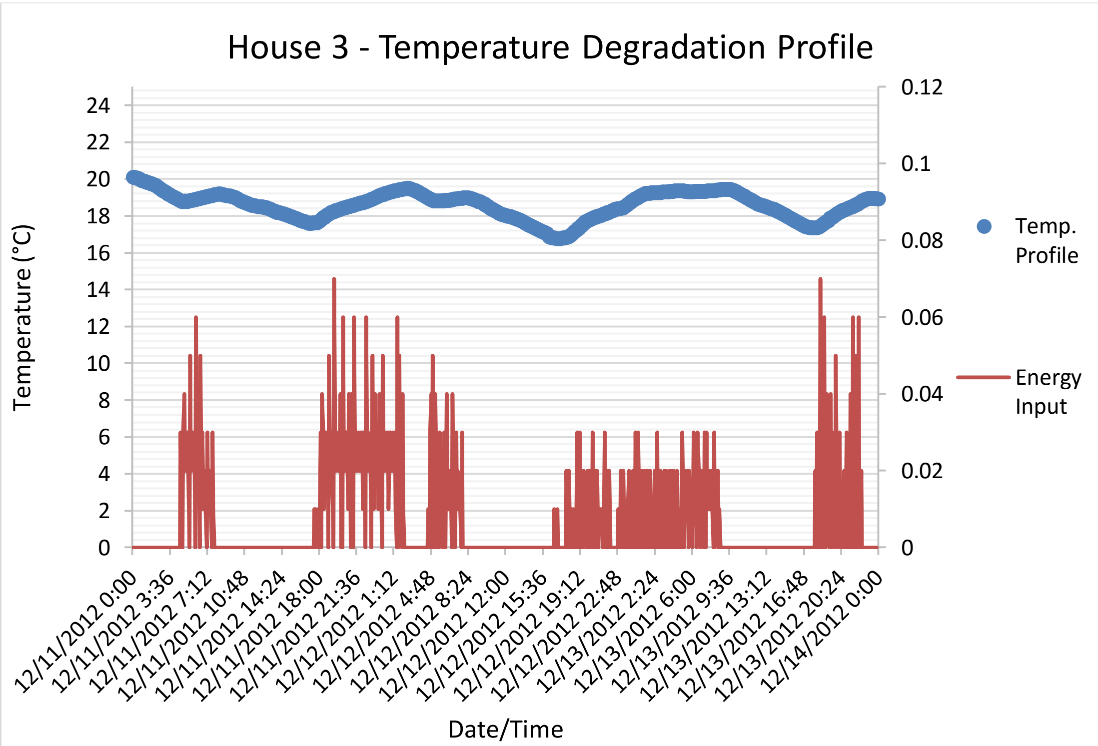


Figure 3.35 House 3 - Temperature Degradation Profile

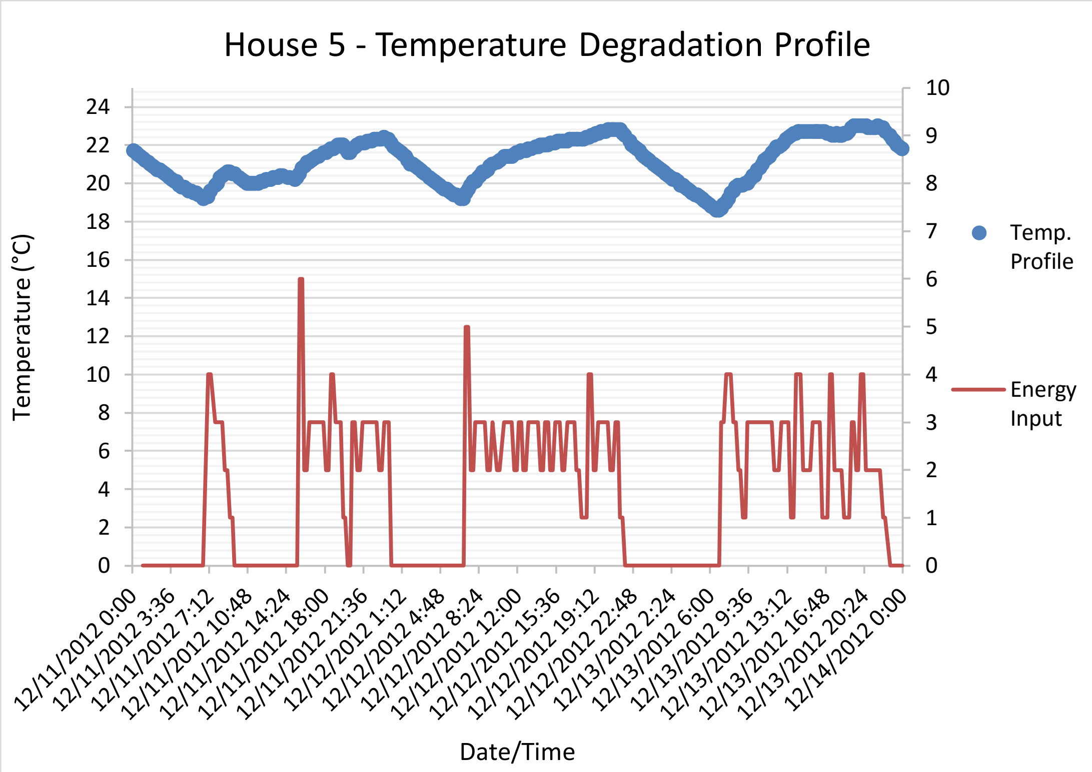


Figure 3.36 House 5 - Temperature Degradation Profile

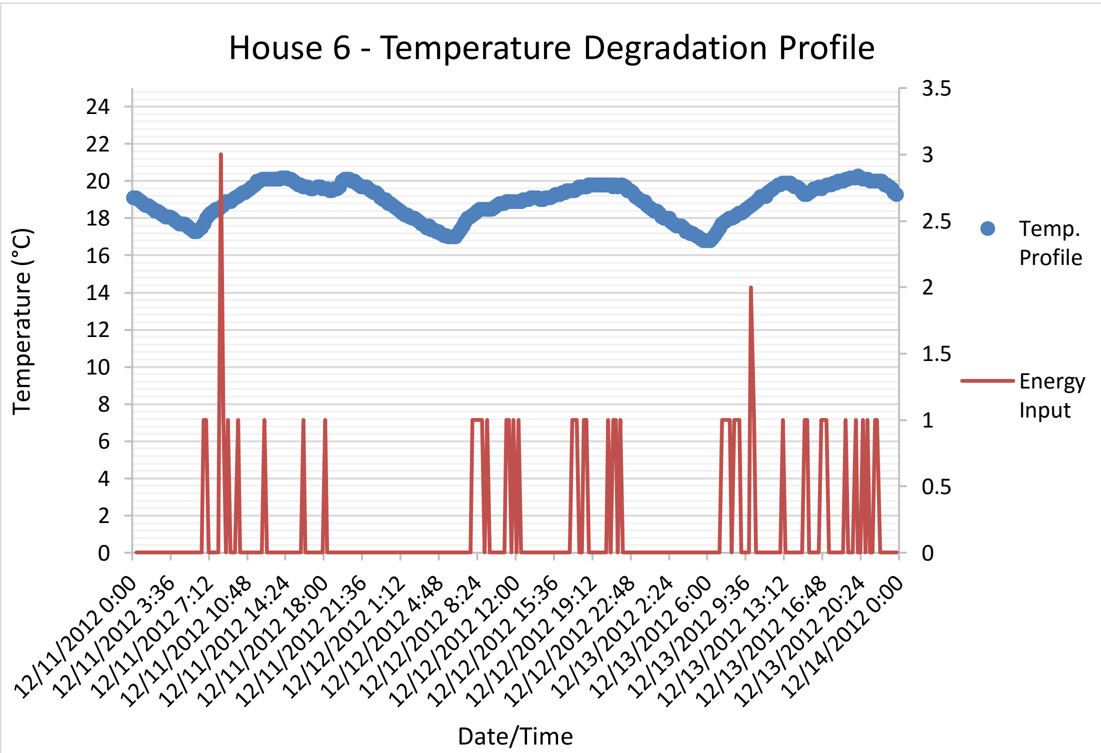


Figure 3.37 House 6 - Temperature Degradation Profile

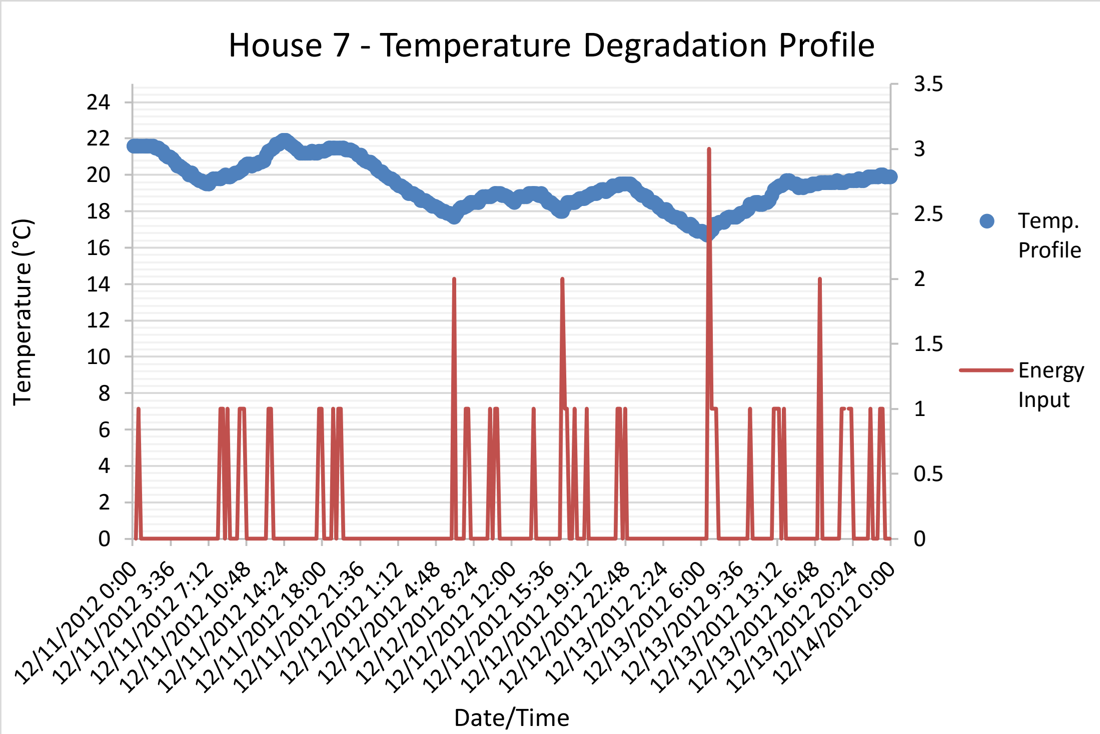


Figure 3.38 House 7 - Temperature Degradation Profile

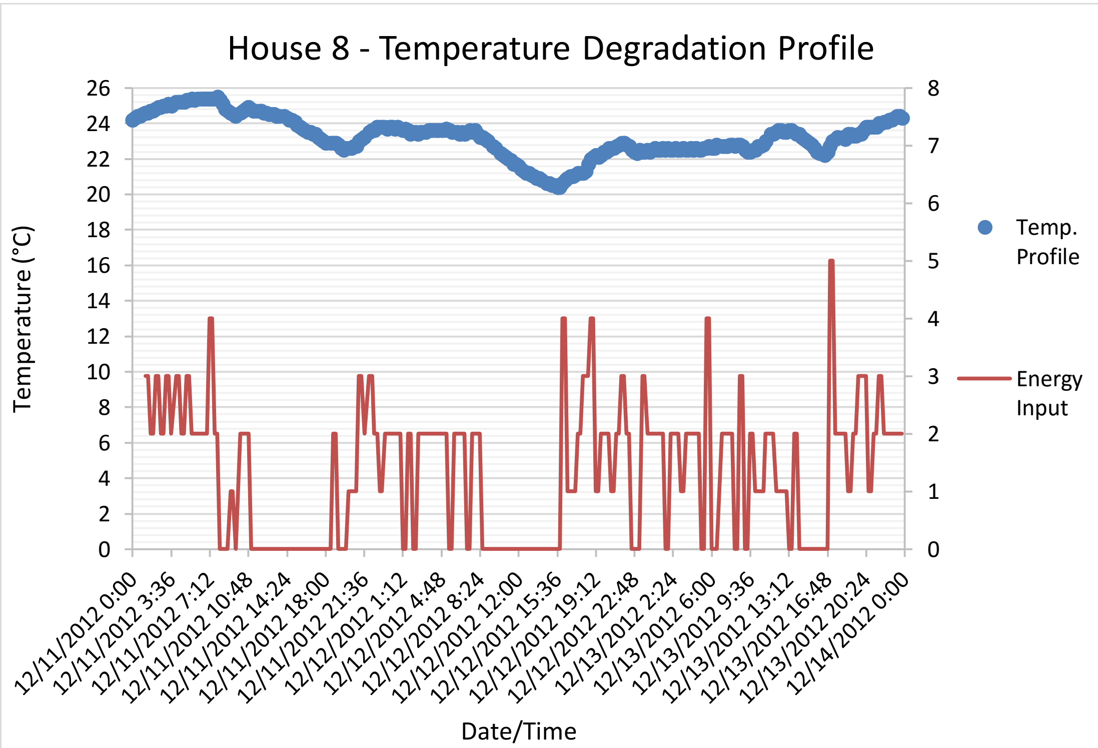


Figure 3.39 House 8 - Temperature Degradation Profile

The graphical representations of houses 3 and 8 clearly exhibit incompatibility with this testing process due to their heating pattern throughout the night-time periods. This profile means it is impossible to get a good period for the time vs. heat loss during the night without the interference of heating and narrows the data set to 5 houses, 2 from Phase 1 and 3 from Phase 2.

Table 3.9 compiles all the relevant intervals, as defined by the temperature degradation profiles and divides the temperature change during the zero energy input stage by the duration of the observation period in both minutes and hours. The resulting figures represent a characteristic expression of temperature loss over time where the implied impact of the fabric differences is under investigation.

Table 3.9 Night Time Temperature Degradation Data

House ID.	Observe Period	Time Period (Min)	Temp. Change (°C)	Temp. Degradation (°C /hr)	House Average (°C /hr)	Fabric Average (°C /hr)
House 1	Night 1	440	2.38	0.3245	0.3403	0.3251
	Night 2	460	2.73	0.3561		
House 2	Night 1	355	1.76	0.2968	0.3100	
	Night 2	355	1.91	0.3232		
House 5	Night 1	417	2.90	0.4173	0.4306	0.3623
	Night 2	527	3.90	0.4440		
House 6	Night 1	619	3.10	0.3005	0.2904	
	Night 2	642	3.00	0.2804		
House 7	Night 1	617	3.70	0.3598	0.3657	
	Night 2	452	2.80	0.3717		

The night time temperature degradation data is based around a simple need to quantify how well the dwellings maintain their internal temperature over a set period of time – a statistic directly proportional to the thermal efficacy of fabric and structure as a whole. The greater thermal mass of the masonry construction should in theory inhibit rapid temperature loss and provide a smoother diurnal temperature profile than a lighter weight construction such as timber frame (Yang & Li, 2008). The data in Table 3.9 seems to contradict this theory, however as previously mentioned this is a supposition based upon partially unknown quantities and qualities.

Three of the case study houses were omitted from the data analysis however the remaining houses, representative of phase 1 – TPC and phase 2 – masonry, clearly indicate that the timber houses are losing less heat per hour than their masonry counterparts. This could be the result of a significantly greater heat loss perimeter in the phase 2 housing and/or the greater amount of glazing.

Table 3.10 Housing Characteristics – SAP

	House 1	House 2	House 3	House 4	House 5	House 6	House 7	House 8
Window Area (m^2)	33.10	29.65	30.12	29.65	39.15	39.74	52.59	39.15
Total area of heat loss perimeter (m^2)	231	184	185	184	288	280	282	288
Heat loss coefficient (W/K)	115	98	99	98	129	128	139	128

While the expectation would be that dwellings with a larger glazing and exposed wall area should lose more heat more quickly, a comparison between glazing area and temperature degradation shows little to no correlation, however it is impossible to ignore the obvious impact that the combination of these variables would have on the heat degradation profile – as demonstrated in the heat loss coefficient data which varies widely between the housing. The extent of this impact is impossible to quantify under the current case study conditions, however the information in table is not completely useless as it shows that even if there is some extra heat loss through the greater perimeter and glazing, the heat degradation between the two fabric types is very similar. An additional factor to account for in any thermal mass discussion is the greater insulation in the TPC construction (an extra 55mm over the masonry walls) with would help to counteract the lack of thermal mass, helping to slow the heat degradation to a similar rate as the masonry construction.

While the evidence from this section is hardly conclusive, it should at the very least help to open up Green Street and timber construction as a whole to further research into the impact on thermal mass in similar sites.

3.4.5 Temperature Overheating Profiles

In addition to revealing the heating season performance profile, the temperature sensors throughout the dwellings can be used to monitor the peak temperatures exhibited during the cooling season or summer months. The following section contains a general overview of the temperature performance throughout the cooling season. Data specific to the month of July (the hottest month of the year) has been extracted, graphed and then further analysed through a peak temperature profile over 3 peak temperature days for each house. It must be made clear that this is far from a comprehensive investigation into thermal mass, as to truly do the subject justice would require many more years of focused study.

Table 3.11 Yearly Overheating Profiles

	House 1	House 2	House 3	House 4	House 5	House 6	House 7	House 8
Days Exceeding an Average of 25°C	2	26	18	7	12	23	23	41
Percentage of the year that exceeds 25°C	0.55%	7.12%	4.93%	1.92%	3.29%	6.30%	6.30%	11.23%

Table 3.11 portrays the results of the overheating analysis completed on the cooling period throughout the summer. Initially the temperature for each day was averaged and then these temperatures were separated, along with their corresponding days, to evaluate which days had an average temperature exceeding 25°C. The total days which exceed the comfort temperature level is then divided by the total days in the year to deliver a Passivhaus standardized benchmark for each house. (McLeod, et al., 2011)

The following graphs provide a focused and detailed view into the individual temperature profiles of the case study houses, measured over an identical month long period. Included within this data is a secondary more in-depth look at a specific 3 day timeframe in July, with a comprehensive breakdown of temperature variation.

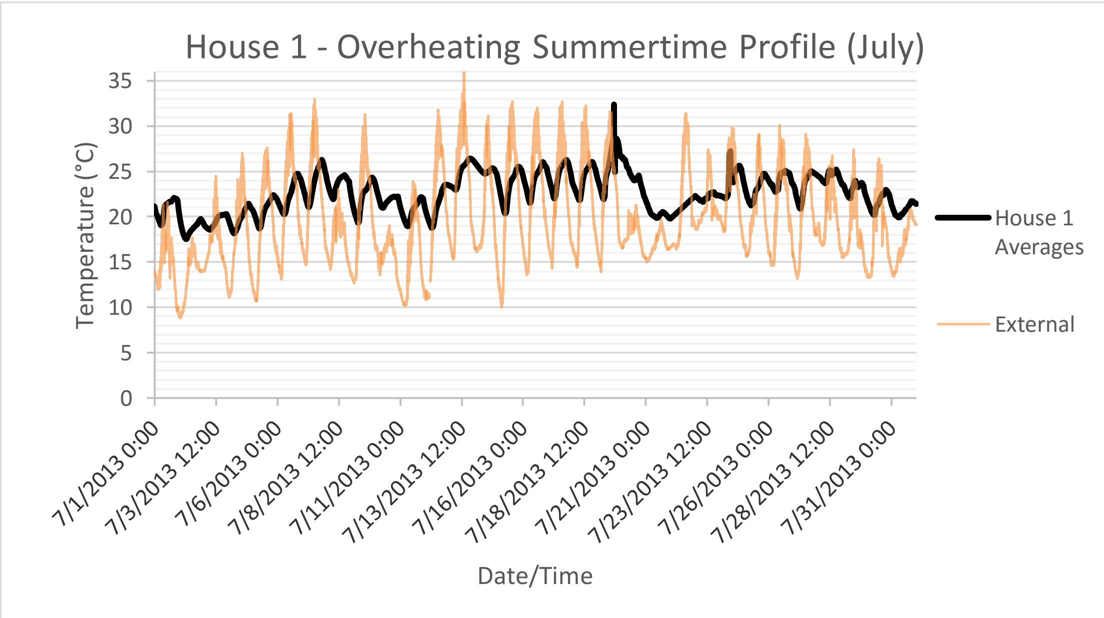


Figure 3.40 House 1 – Average Internal Temp. vs. External Temp.

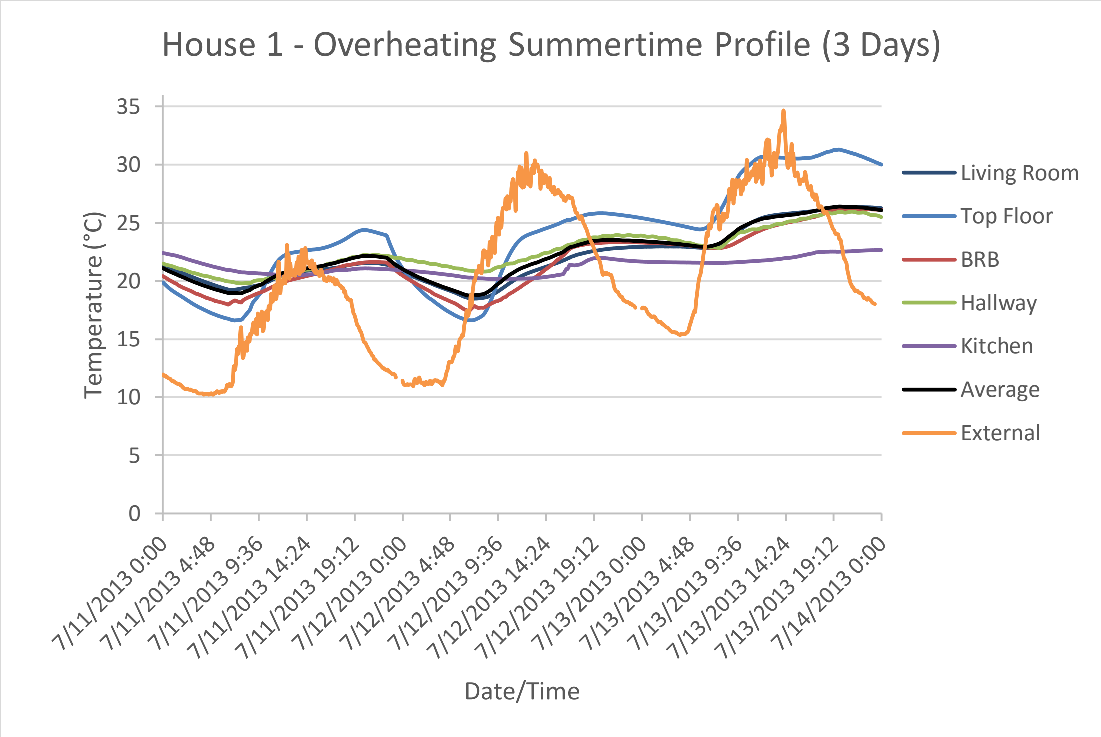


Figure 3.41 House 1 - Overheating Summertime Profile

BRB – Back Right Bedroom

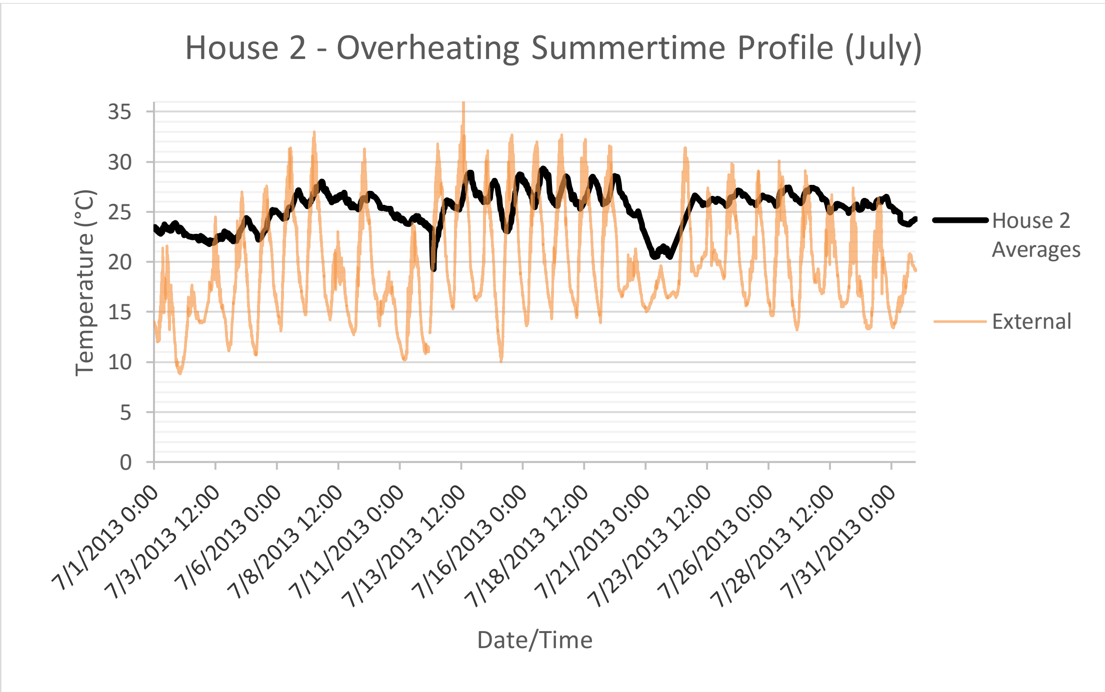


Figure 3.42 House 2 – Average Internal Temp. vs. External Temp.

The diurnal temperature variation is immediately visible in the broader overview, with more granular activities visible in the 3 day analysis.

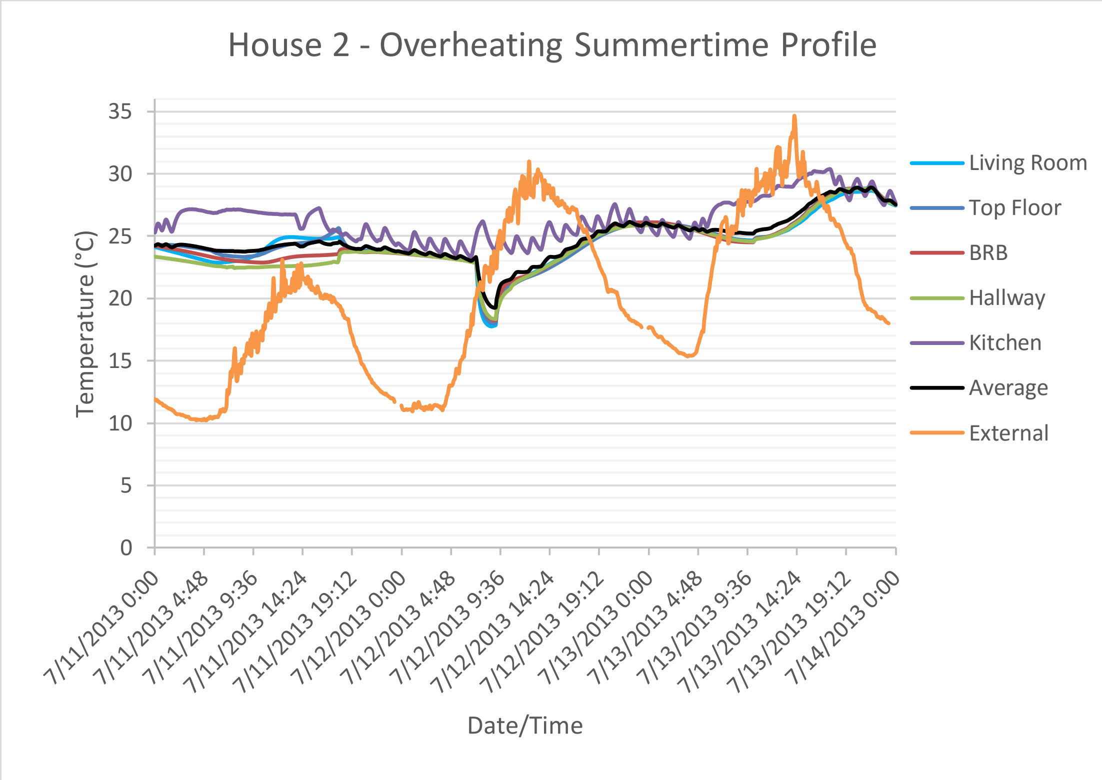


Figure 3.43 House 2 - Overheating Summertime Profile

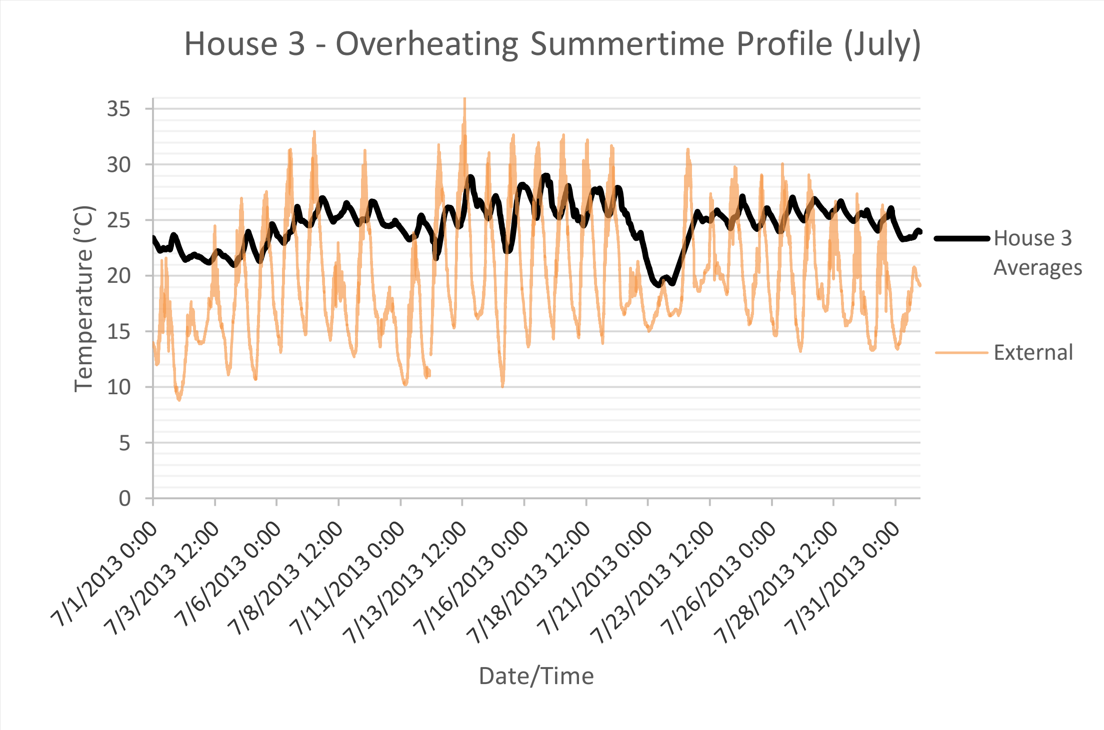


Figure 3.44 House 3 - Average Internal Temp. vs. External Temp.

House 3 displays a remarkably uniform temperature distribution throughout the house and a very tempered rise and fall of conditions.

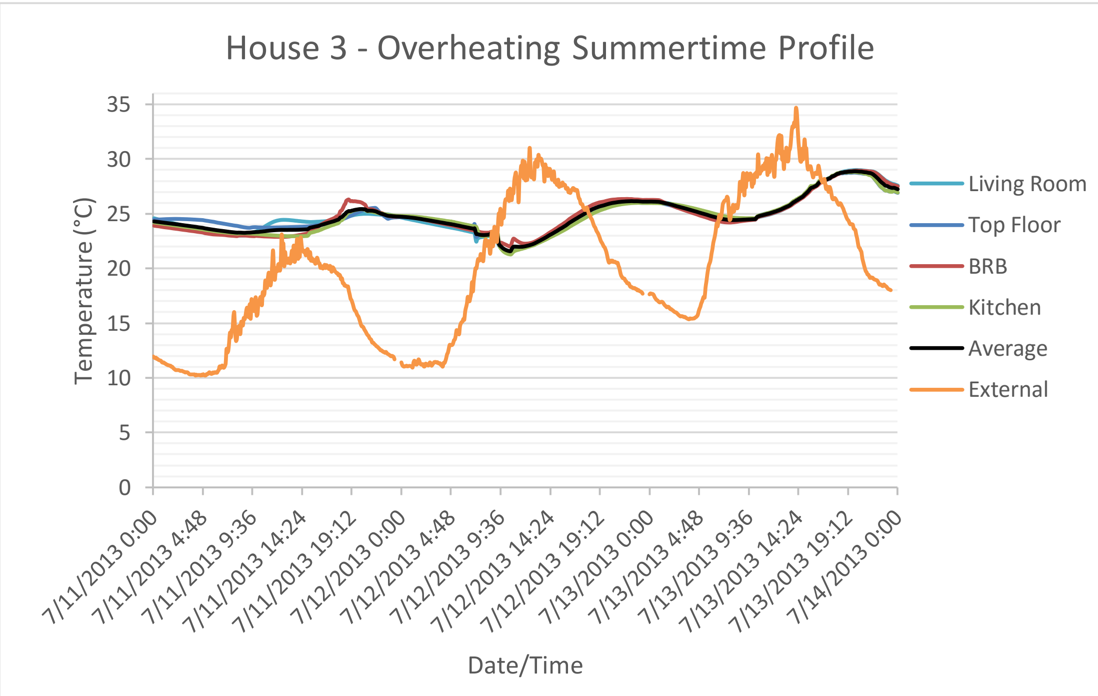


Figure 3.45 House 3 - Overheating Summertime Profile

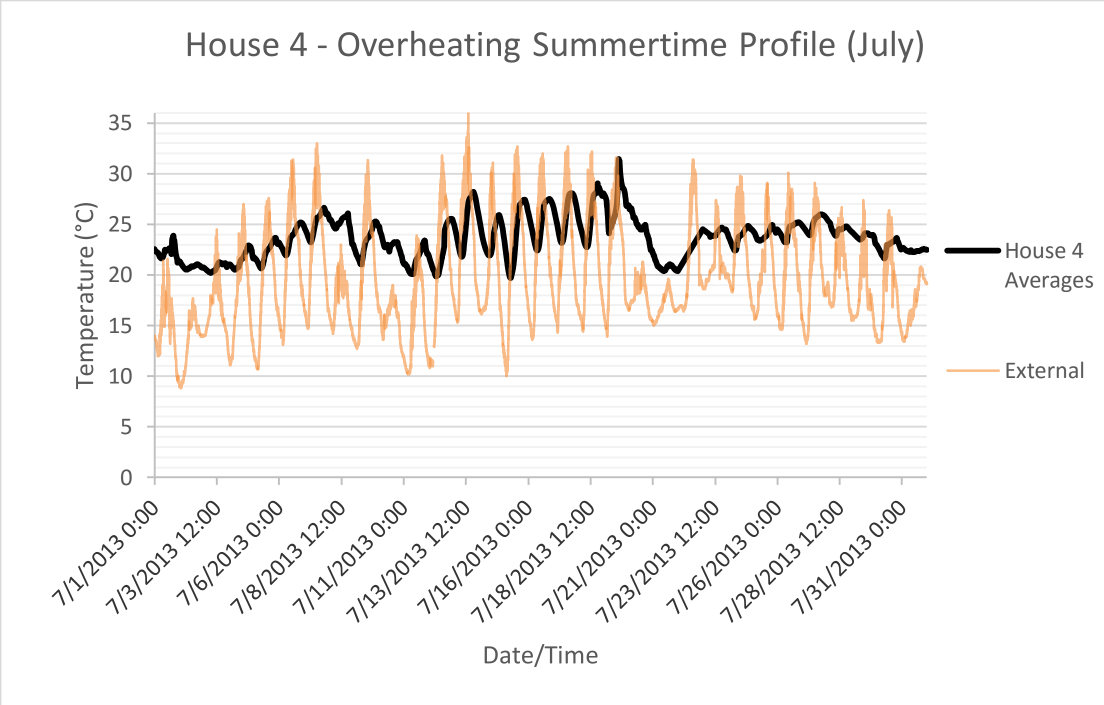


Figure 3.46 House 4 - Average Internal Temp. vs. External Temp.

The day/night temperature swing in house 4 is visibly larger than others in phase 1, particularly during the night, house 4 appears to get 1-2°C cooler.

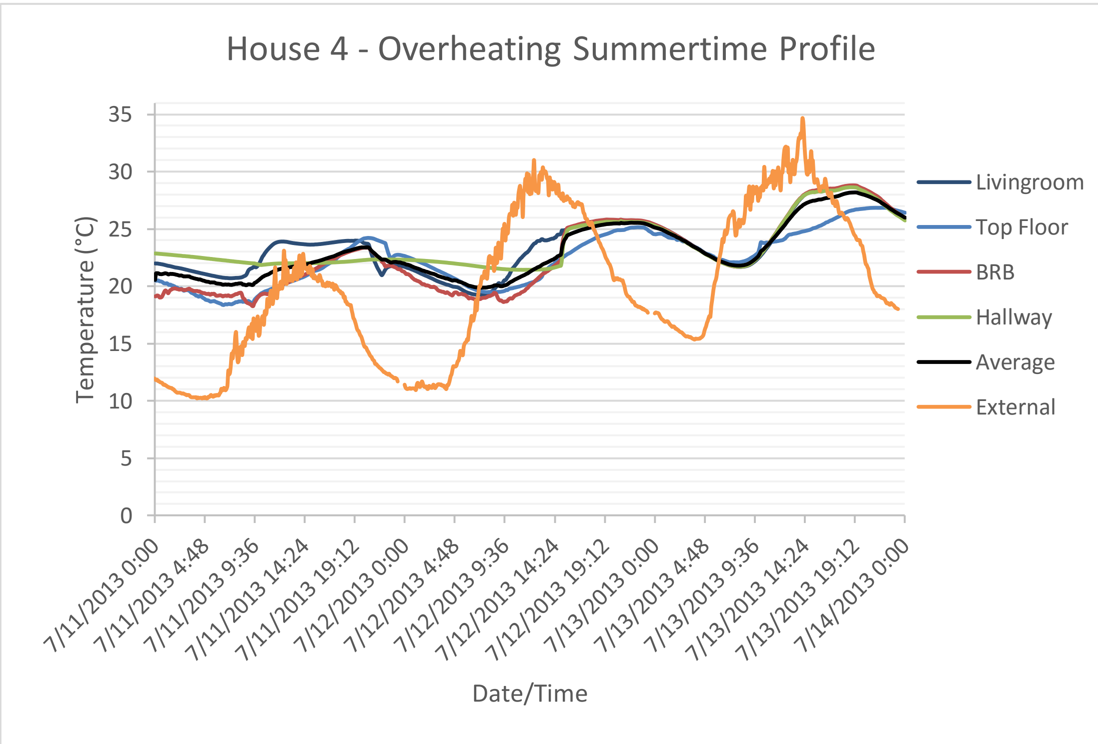


Figure 3.47 House 4 - Overheating Summertime Profile

With the masonry dwellings, the expectation is for there to be less of a swing between peak temperatures over a 24hr period. Ideally a house is looking to have no more than a 2°C variation throughout a 24hr period (McLeod, et al., 2011)

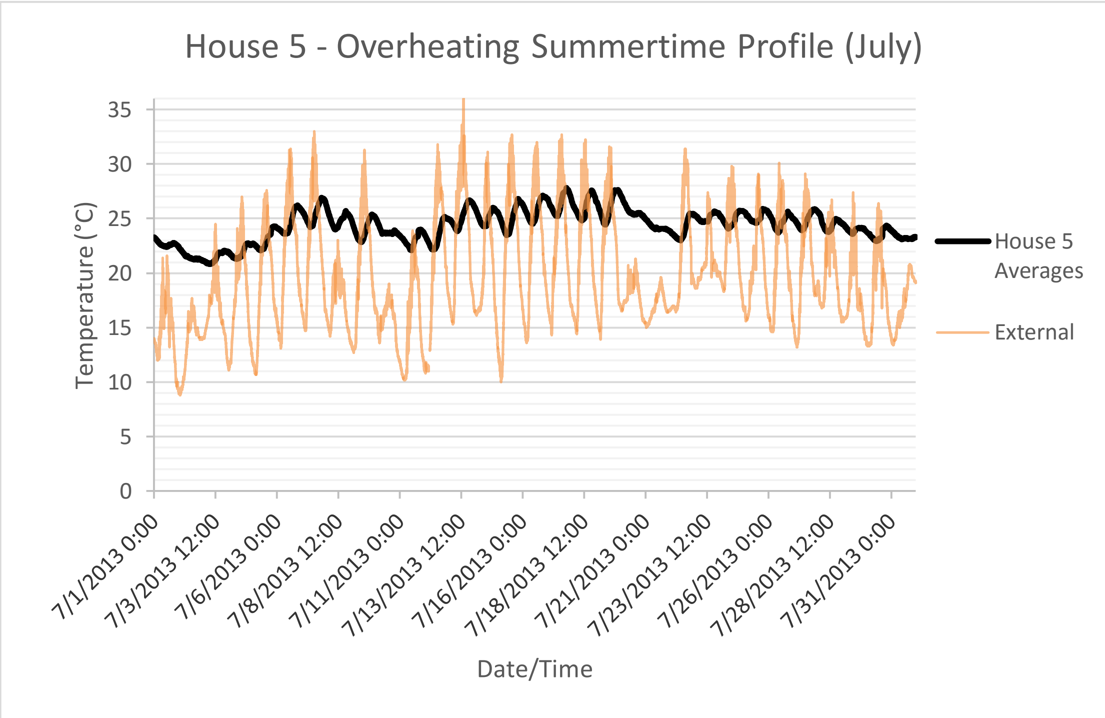


Figure 3.48 House 5 - Average Internal Temp. vs. External Temp.

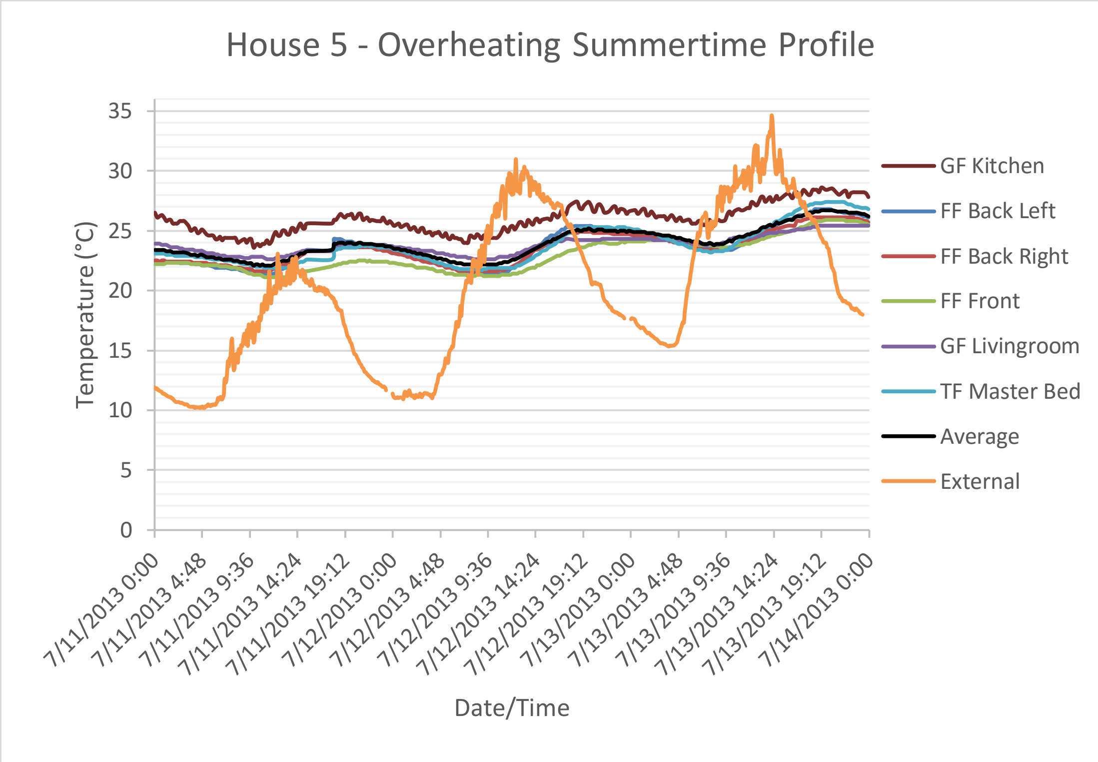


Figure 3.49 House 5 - Overheating Summertime Profile

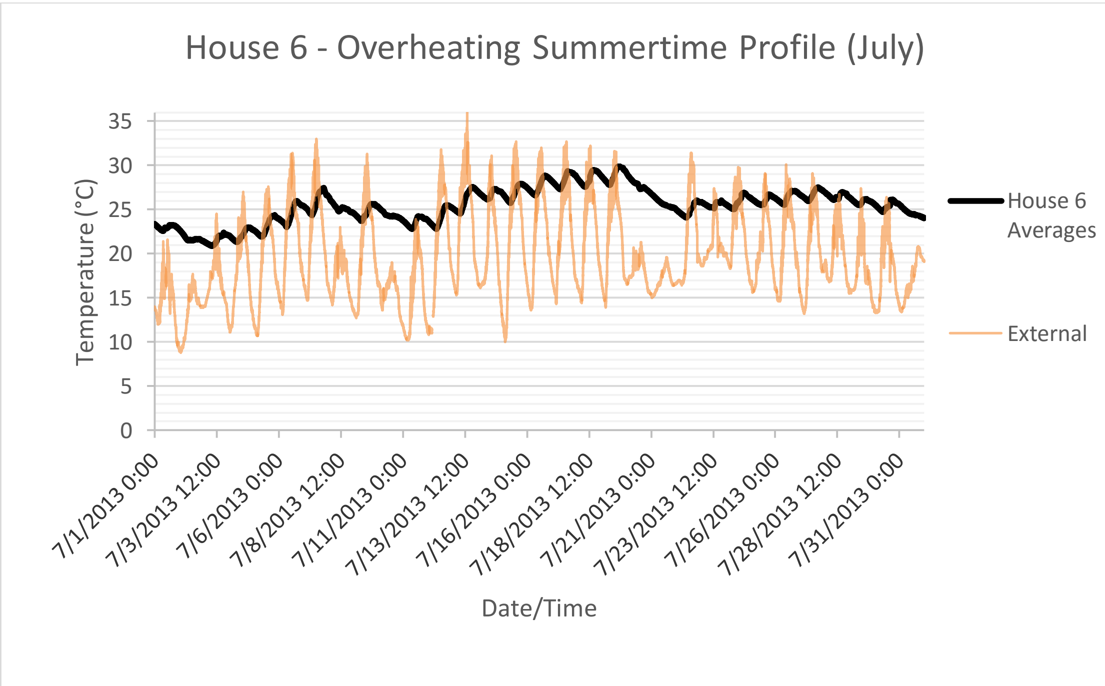


Figure 3.50 House 6 - Average Internal Temp. vs. External Temp.

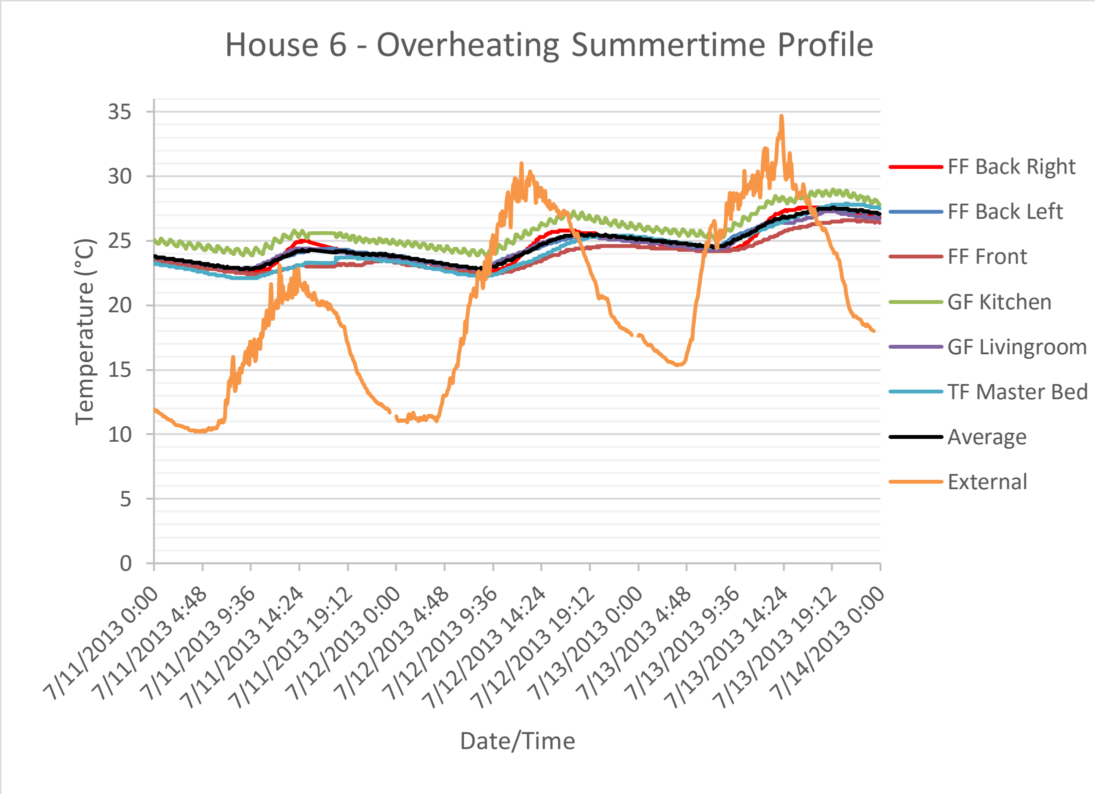


Figure 3.51 House 6 - Overheating Summertime Profile

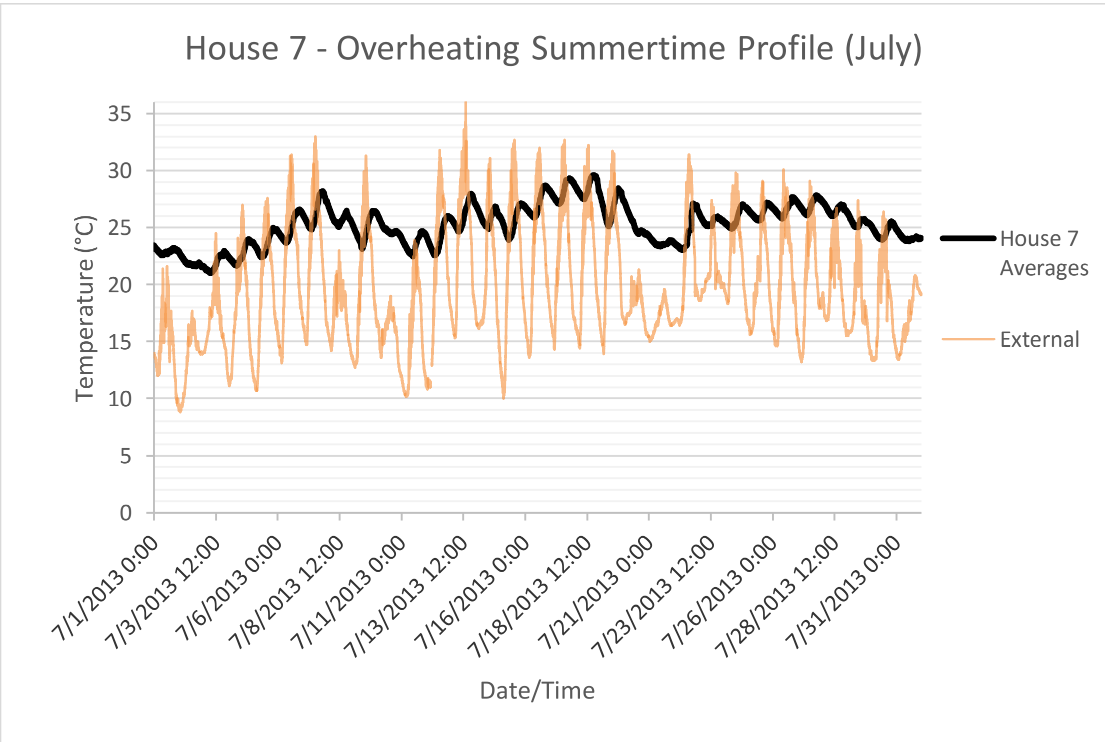


Figure 3.52 House 7 - Average Internal Temp. vs. External Temp.

Although the peak temperatures appear to be closer together, the overall temperatures exhibited by the masonry housing look to be consistently higher.

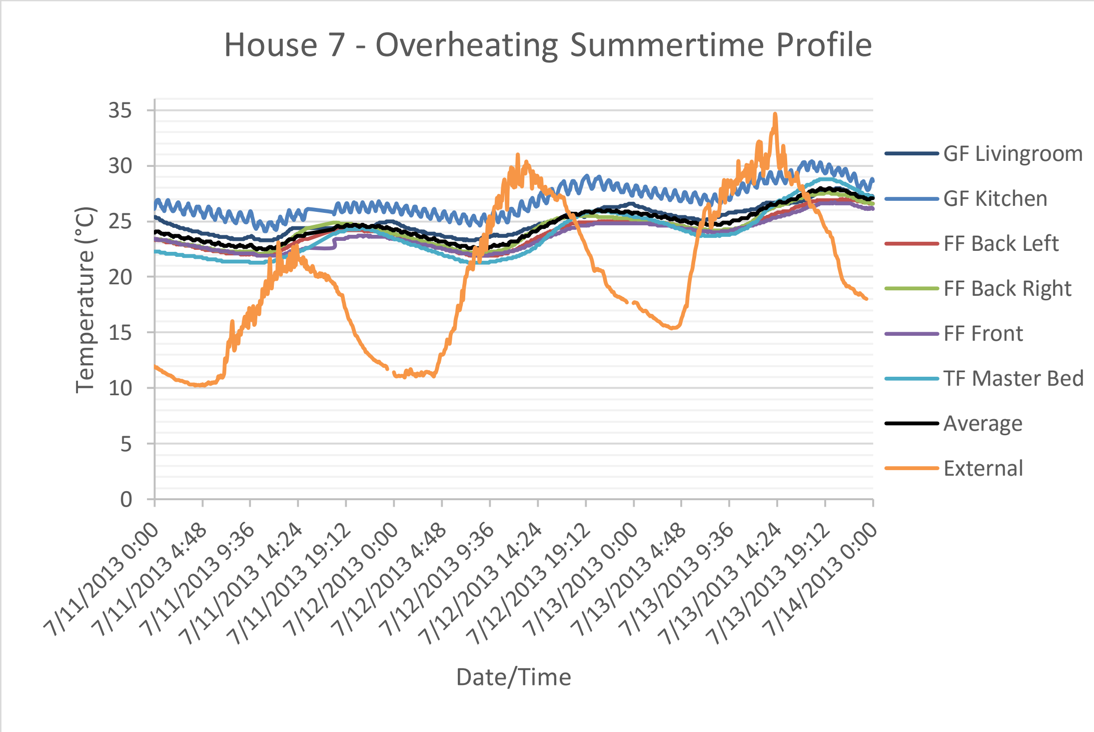


Figure 3.53 House 7 - Overheating Summertime Profile

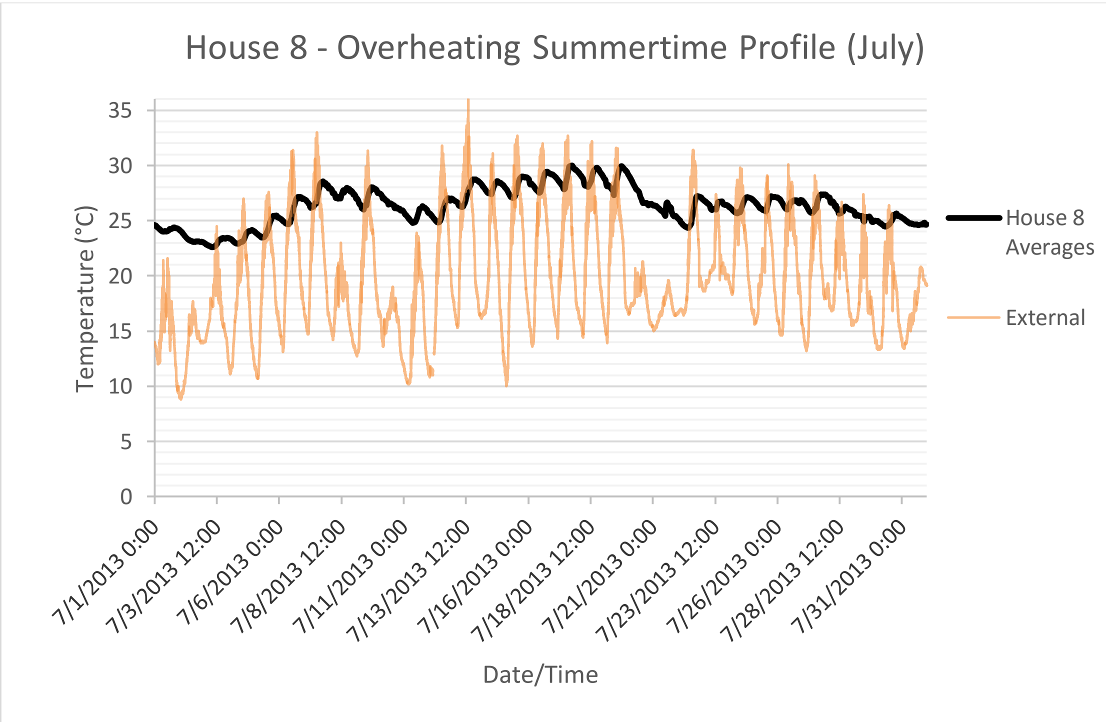


Figure 3.54 House 8 - Average Internal Temp. vs. External Temp.

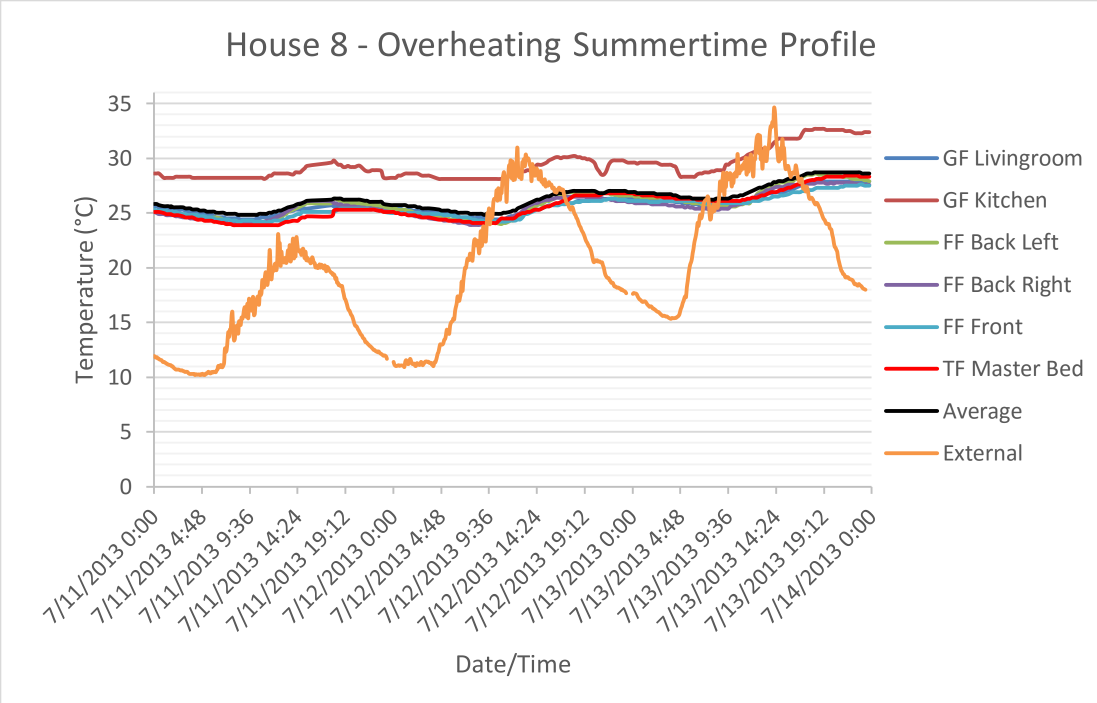


Figure 3.55 House 8 - Overheating Summertime Profile

Figure 3.40 - Figure 3.55 are organised and segregated into fabric specific groupings which are the displayed in

Figure 3.56 and Figure 3.57 with the solar gain.

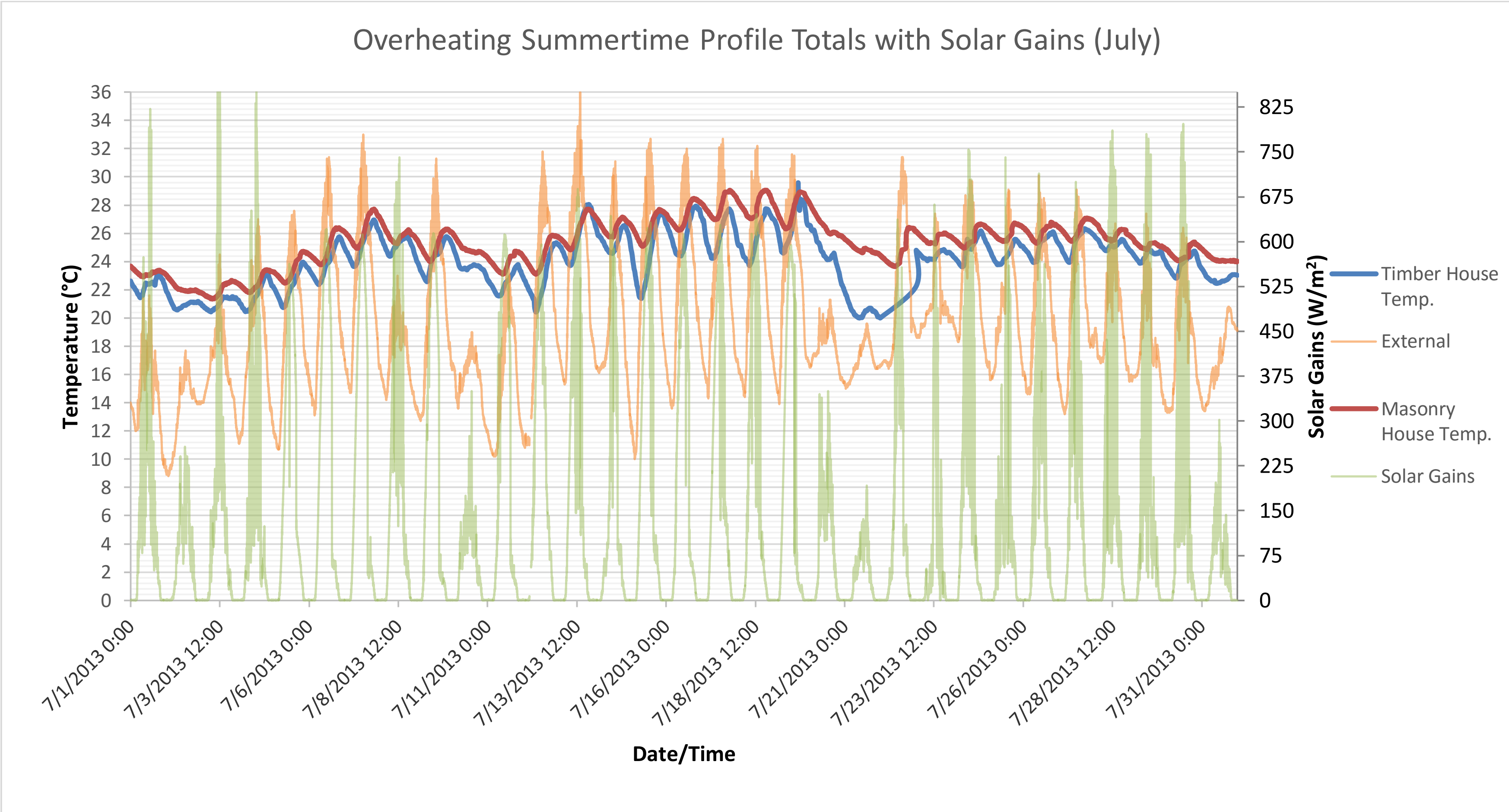


Figure 3.56 Overheating Summer Profiles – Masonry/Timber with Solar Gains (July)

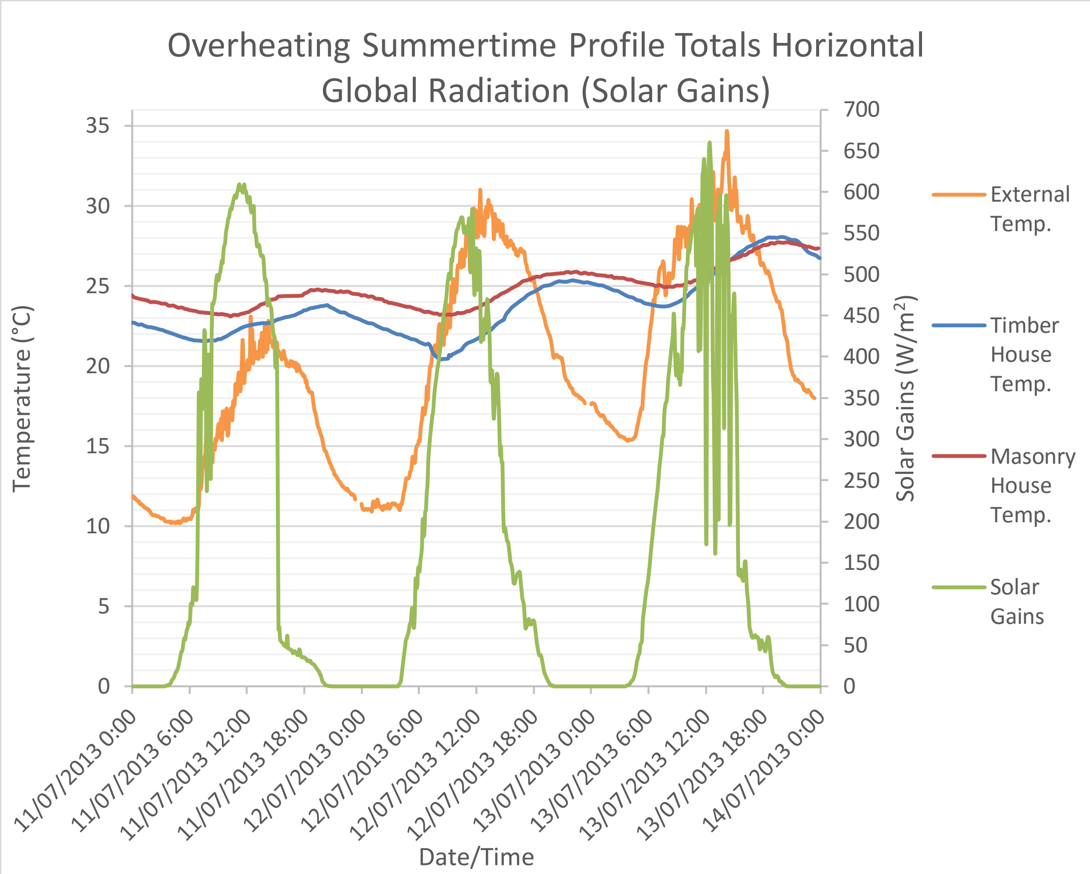


Figure 3.57 Overheating Summer Profiles – Masonry/Timber with Solar Gains (3 Day)

The information from Figure 3.57 is compressed even further within Table 3.12.

Table 3.12 Daily Averages - Cooling Season

Date	Timber (°C)	Masonry (°C)	External (°C)	Horizontal Global Radiation (W/m^2)
11/07/2013	22.59	23.90	15.41	187.85
12/07/2013	22.86	24.39	20.92	183.74
13/07/2013	25.78	26.17	23.76	177.83

3.4.6 Temperature Overheating Analysis

This section articulates a performance profile based on

Figure 3.56 and Figure 3.57 and the figures in Table 3.12, using them to compare and contrast the two methods of construction.

During the summer months the concept of performance shifts from the active environmental impact of the structure to the more passive idea of comfort and overheating. As UK housing stock generally does not integrate fossil fuel driven cooling solutions there is little to no quantifiable pollution directly attributable to overheating, rather performance is benchmarked against widely recognized temperature boundaries factored over a certain length of time. While these boundaries are generally defined by CIBSE Guide A (now moving to TM52) (Bergdoll & Christensen, 2008) in reality both the airtightness specifications and the inclusion of mechanical ventilation within the housing places the housing outside of the spectrum of the vast majority of UK housing for which CIBSE is responsible. Instead GreenStreet, at least in specification values, mirrors a far more stringent standard, that of Passivhause (McLeod, et al., 2011). Thus in establishing the boundaries of what constitutes a comfortable temperature, for the purposes of this project the most accurate choice of benchmark temperature values is accordingly based on construction guidance for Passivhaus, guidance specifically designed for domestic application. (McLeod, et al., 2011) The Passivhaus guides dictate that temperatures daily average temperatures exceeding 25°C are not allowed to occur within the dwelling for more than 10% of the occupied year, thus this is the standard to which the Green Street housing will be held to, with one caveat. Due to the difficulties and pitfalls associated with quantifying the "occupied year," within 8 dwellings, the assumption will be made that the house is occupied 24 hours a day, 7 days a week. While simplifying the calculation process, this also means the results will model a worst case scenario, being held to an extreme standard, even within the framework of the Passivhaus standards. Essentially if the houses pass at this level of testing then they should be well within the comfort levels by which the performance of overheating is measured.

Table 3.13 portrays the results of the overheating analysis completed on the cooling period throughout the summer. Only house 8 exceeds the strict parameters set by the Passivhaus regulations, but the “occupied year” definition coupled with the positive results from this house on the BUS methodology suggests that the occupants may simply enjoy a warmer ambient temperature.

Table 3.13 Yearly Overheating Profiles

	House 1	House 2	House 3	House 4	House 5	House 6	House 7	House 8
Days Exceeding an Average of 25°C	2	26	18	7	12	23	23	41
Percentage of the year that average dwelling temperature exceeds 25°C	0.55%	7.12%	4.93%	1.92%	3.29%	6.30%	6.30%	11.23%

The diurnal temperature profiles for each fabric type displayed in section 3.4.4 and summarised in

Figure 3.56 and Figure 3.57 reveal some interesting patterns. The visually depict the fabric specific temperature profile for the case study houses, measured over two time periods – a month and then a specifically targeted 3 days during cooling season’s peak temperature period and compiled from individual data from each house (See section 3.4.4). What is under scrutiny, in addition to the simple peak temperatures, are the diurnal shift patterns in temperature. The purpose behind thermal mass is to reduce the amplitude of the swing and smooth out the peak values, thereby reducing the potential for the house temperature to stray out of comfort levels. Comparing the amplitude of the swing for each house should give an indication as to the effect, if any, that the fabrication method has on the temperature profile.

The solar gains have been included in Figure 3.56 & Figure 3.57 in order to evaluate their impact on the overall temperature swing. Ideally a house is looking to have no more than a 2°C variation throughout a 24hr period (McLeod, et al., 2011) and while the masonry housing seems to conform to this stipulation for the most part, the timber housing displays up to a 5°C deviation on the 12/07/2013. The timber houses rise and fall in temperature on a steeper slope, indicating a quicker reaction to the evident appearance and disappearance of solar gains through the day/night cycle. The difference in external ambient temperature on days 1 and 3 in the abbreviated graph appears to have a far greater impact on the internal temperatures than the evident solar gains, with similar solar gains on days 1 and 3, but a peak temperature difference of 6°C between the two days.

The poor temperature swing profile is contrasted by the actual temperatures within the houses, the timber housing displaying a consistently lower temperature throughout the day and night. It is only as the ambient temperature approaches its maximum that this gap closes, and at an average temperature of approximately 30°C during the afternoon the internal temperature of the timber houses exceeds that of the masonry. However, these temperatures then fall more rapidly in line with the night time external temperatures. The information from Figure 3.57 in particular is compressed even further within Table 3.14 clearly showing the gap between the internal temperatures of the timber and masonry housing in relation to the average ambient temperature and solar gains throughout the daylight hours.

Table 3.14 Daily Averages - Cooling Season

Date	Timber (°C)	Masonry (°C)	External (°C)	Solar Gains (W/m^2)
11/07/2013	22.59	23.90	15.41	187.85
12/07/2013	22.86	24.39	20.92	183.74
13/07/2013	25.78	26.17	23.76	177.83

The analytical conclusion is that the temperature swing is greater in the timber, thermal mass does appear to temper the diurnal variations, but as the graphs demonstrate, the temperature in the timber housing remains consistently lower. With indeterminate factors of orientation and shading the only true conclusion to be made is that with the correct planning and foresight timber housing can be designed and built to perform as well and in some cases better than its more thermally massive counterparts a view supported by findings in Chapter 7.

3.5 Environmental Monitoring Conclusions

Chapter 3 establishes a context for the recorded energy data associated with space heating through the graphical representation of temperature profiles for the entire case study portfolio. These temperature profiles in conjunction with the space heating energy reading allow for the calculation of an in use heat loss coefficient for each house, proportionally comparable and directly indicative of which houses have a greater environmental impact.

The simple conclusion is that throughout the heating season the timber houses exhibited less heat loss, ultimately requiring less energy per degree difference between inside and outside temperatures to heat the respective dwellings. In addition the work develops the concept of a WHLC with units of W/m^2K which is transferable to other projects, and sheds valuable light on specifically the post occupancy evaluation stage of performance evaluation.

By graphing the night time, heating season temperature data at specific periods of time where there is actually no heating input into the house it is possible to discern how well the houses maintain their internal temperature over a set period of time. This characteristic is indicative of the effectiveness of the insulation and helps to establish the impact of greater thermal mass in the masonry construction, which in theory should provide a smoother diurnal temperature profile than a lighter weight construction such as timber frame. Unfortunately, due to the specific conditions of the data capture, 3 of the houses were ineligible for this portion of the research, however data from the remaining houses indicates that the heat degradation between the two fabric types is very similar, calling into question the overarching assumption that greater thermal mass equates to less thermal degradation over time. The primary theory behind these results suggests that the greater insulation in the TPC construction counteracts the lack of thermal mass, helping to slow the heat degradation to a similar rate as the masonry construction.

A final investigation into summertime overheating took place over the hottest month in the year – July. The study looks first at the monthly profile and then at a more in-depth snapshot of 3 of the hottest days within July. The conclusion is that there is a greater diurnal temperature swing in the timber housing, thermal mass does appear to temper the diurnal variations, but overall, the temperature in the timber housing remains consistently lower than the masonry housing. As mentioned earlier on in the Chapter, aspects like external shading louvres (which may or may not have been used) and the different orientation of Phase 1 & Phase 2 will have played a significant role in these findings thus the only inference to be made is that with the correct planning and foresight timber housing can be designed and built to perform as well and in some cases better than its more thermally massive masonry counterparts. Further testing in this area should focus on comparing completely identical housing with identical surface and roof areas in order to account for the impact of thermal lag in the heavier weight masonry housing.

4 Fabric Testing

As well as continuous environmental monitoring, the case study housing is subject to fabric monitoring tests. The sequence of fabric tests utilised in this study and sourced from the TSB BPE are designed provide evidence to support the environmental monitoring data as they gauge the instantaneous functionality of the fabric and then compare the results to an industry benchmark or previous performance tests, thereby revealing the performance gap between design and construction reality. For example, if the temperature probes detect one room significantly cooler than the rest of the house, the thermography can be used to test for thermal bridging, or air permeability testing can detect excessive leakage through the envelope. The following sections define the nature of the required tests and provide a brief breakdown of their origins and purpose within the POE context finally revealing the results and conclusions of each testing procedure.

4.1 Fabric Testing Review

4.1.1 Air Permeability Testing

Current evidence concludes that air-tightness (the terms air tightness and air permeability are used interchangeably throughout this study) contributes significantly to building energy performance, thermal comfort and the indoor air quality of dwellings (Energy Saving Trust, 2005; Badoo, 2008; Sinnott and Dyer, 2012). In 2002, after fomally recognizing the role of air-tightness as a fundamental component of building construction, an explicit air leakage target of 10 $m^3/(h.m^2)$ @ 50Pa was included in the Approved Document Part L1A (ADL1A). (DTLR, 2001) In 2006 these regulations were amended (the target of 10 $m^3/(h.m^2)$ @ 50Pa remained the same) and the concept of mandatory air tightness testing was introduced along with the requirement for retesting of houses that fail to meet design standards. Since then, there have been incremental revisions culminating in the most recent version – Part L 2013

(DCLG, 2013). The aim of the building regulations is to promote higher levels of air-tightness in domestic construction consequently resulting in reduced energy costs, less environmental impact and higher levels of comfort for occupants (Coxon, 2010). Air tightness testing for the purposes of meeting regulations is executed during the post construction phase, and arguably remains the only required thermal performance evaluation of a new dwelling during the post-construction phase of the dwelling life cycle (DCLG, 2013).

4.1.2 Co-heat Testing

Maintaining a high level of thermal performance, as close to design specifications as possible, is key in the domestic sector where space heating accounts for approximately 61% of energy use (Palmer & Cooper, 2012, p. 33). The heat loss coefficient (HLC) figure calculated by the co-heating test procedure relates directly to the thermal performance (U-values) of the materials used in the construction of the house. The co-heating test is used to estimate the HLC or steady state U-value of the dwelling as a whole, rather than the individual components. "In doing this it relates directly to the common understanding of 'design heat loss', 'whole house U-value', 'elemental design', and 'Building Regulations minimum design standards'. Therefore from this perspective it can be seen at this stage of understanding as the preferred way of estimating the thermal performance of the building envelope for the purpose of both quality control/assurance and regulatory compliance" (DCLG (a), 2011, p. 65).

Unlike air tightness testing, co-heating analysis is far from an established practice and there remains much controversy and debate as to the correct protocols to use and what assumptions can be made (Butler & Dengel, 2013). The co-heat test was originally developed in the 1970's, but with little information available from its early years the majority of research relies on work led at the time by a Senior Research Fellow at Leeds Metropolitan University, Jez Wingfield (Wingfield, 2011).

In its most basic form, current co-heating protocol dictates heating the inside of the building to a constant temperature at least 10°C higher than external conditions (equating to around 25°C internally) using electrical resistance heaters over a period of one to three weeks. All other internal heat gains are eliminated or accounted for. "By measuring the electrical energy required to maintain the constant temperature, the daily heat input to the building can be determined. The heat loss coefficient can then be determined by plotting the mean daily heat input (P, Watts) against the mean daily inside to outside temperature difference (dT,K). The resulting slope of the curve plot gives the heat loss coefficient (P/dT, W/K)" (Butler & Dengel, 2013, p. 9).

This HLC (W/K) details how much energy is required to heat the entire dwelling per degree of difference between the internal and external temperatures. In POE this thermal performance value can then be compared with design specifications found in the SAP documents for the property. Invariably dwellings perform below the pre-construction estimations (Johnston, 2010; Wingfield, 2011). The subsequent gap between design and actual performance is caused by a variety of sources ranging from the initial briefing process, design and modelling tools used, the build process and build quality, systems integration and commissioning, handover and operation through to the understanding, comfort and motivation of occupants. The 1-3 week window required for the co-heat test often allows the simultaneous assessment of the building fabric using various other diagnostic tests in order to pinpoint the areas of weakness in the building envelope and provide evidence to support the findings of the co-heat tests.

- Thermal imaging
- Pressurisation testing
- Leakage detection
- Tracer gas measurement
- Heat flux measurement
- Air flow measurements
- Cavity temperature measurement
- Partial deconstruction

The validity and future significance of the co-heating test is subject to intense scrutiny by a Building Research Establishment (BRE) led project with partners from academia (including the author of this thesis) and testing agencies exploring all facets of the co-heat testing process with the view to develop standardized and simplified test methods which could be employed on a national scale (NHBC, 2012).

4.1.3 Thermography

Thermographic analysis is an essential tool in diagnosing faults exposed in both the environmental monitoring and other fabric testing methods. Infrared thermography uses technology to visualize infrared or heat radiation images from the part of the electromagnetic spectrum just beyond the red end of the visible spectrum - simply defined as seeing heat (Hart, An introduction to infra-red thermography for building surveys, 1990). The surface temperature of an object dictates the amount and wavelength of infrared emanating from an object, which is depicted as different colours on the thermal image. The image is subject to the emissivity of the surface being analysed and the transmissivity of the atmosphere between source and the imaging equipment (Pearson, 2011). It can be used in the detection of voiding, thermal bridging, air leakage and position of hidden and possible faulty construction features such as wall ties in masonry building (Littlewood, et al., 2011). It is somewhat unique among POE testing methods, in that in its most basic form it is a non-invasive, non-destructive and rapid procedure that can highlight areas of complication meriting further investigation by other techniques (Institution of Structural Engineers, 2010). This is an essential theme throughout thermography research – it is primarily a qualitative diagnostics tool, intended to be used in conjunction with other testing methodologies. By itself cannot quantify the cause of any given anomaly (Gonçalves, et al., 2007).

Interpretation of thermographic results (image or video) must be within the context of a thorough understanding of the building in question and the various scientific and meteorological principles that impact the building envelope. The apparent simplicity of thermal image interpretation belies a strict and regimented process governing the internal/ external testing conditions, emissivity readings and camera settings (Hart, 1991)(see Section 4.1.3). Despite its established reputation as a diagnostics tool for buildings (BRECSU, 2000; Hart, 1990; Pearson, 2011; TRADA, 2004) as of yet, Building Regulations 2010 L1A – Conservation of Fuel and Power in New Dwellings makes no mention of thermography testing alongside the well-established air tightness testing regime (DCLG, 2013).

4.2 Fabric Testing Methodology

4.2.1 Air Permeability Testing

Air permeability testing for this project comprises of 5 distinct stages. Initially, upon completion in November of 2010, the housing in Phase 1 of the case study, the timber housing, was tested by a subcontractor, BSRIA, in order to meet with minimum building regulations. Three dwellings in Phase 1 of the Green Street case study were tested, of these three houses, two are part of the continuous monitoring phase.

The two remaining houses from phase 1 (not initially tested upon completion) were analysed by Dr. Edward Cooper of the University of Nottingham's Architecture and Built Environment in secondary study in November of 2011 with the results available in Section 7.2.

At this point Phase 2 (masonry) of the Green Street site was complete and underwent a similar testing regime to Phase 1, upon completion, once again through BSRIA. Air tightness testing procedure was observed following a somewhat unusual process. A house would be tested and subsequently fail the test, the contractor would then enter the house with a foam gun and plug any apparent gaps in the structural envelope and the house would be tested again. This was repeated in each dwelling until all three passed under the threshold 3 $m^3/h.m^2$@ 50 Pa. The neglect of the remaining houses, despite the obvious deficiencies experienced within the chosen test housing obviously raised some questions regarding the regulations of air tightness testing and the performance of the remaining houses not subjected to the remedial measures applied to the testing houses.

The unusually poor results from the Phase 1 housing and the continued neglect of untested housing in Phase 2 prompted stage 3 of the air permeability testing, a more in-depth study incorporating some independent testing of 9 houses in both Phase 1and2, by an approved and licensed air testing subcontractor, Aeratech Ltd. in May of 2012. The test houses were those originally untested by the house contractor upon the completion of the dwellings on the assumption that they should perform close to the completion tested housing in the case of Phase 1 and almost identical to the completion test results in Phase 2. The data from stage 3 of the testing showed a clear discrepancy between the theoretical results and the as-tested air permeability. These findings provoked stage 5, yet more testing in 3 Phase 2 houses, this time funded separately by the housing developer, BluePrint. Tests throughout all 4 stages were carried out using a positive pressure, blower door technique.

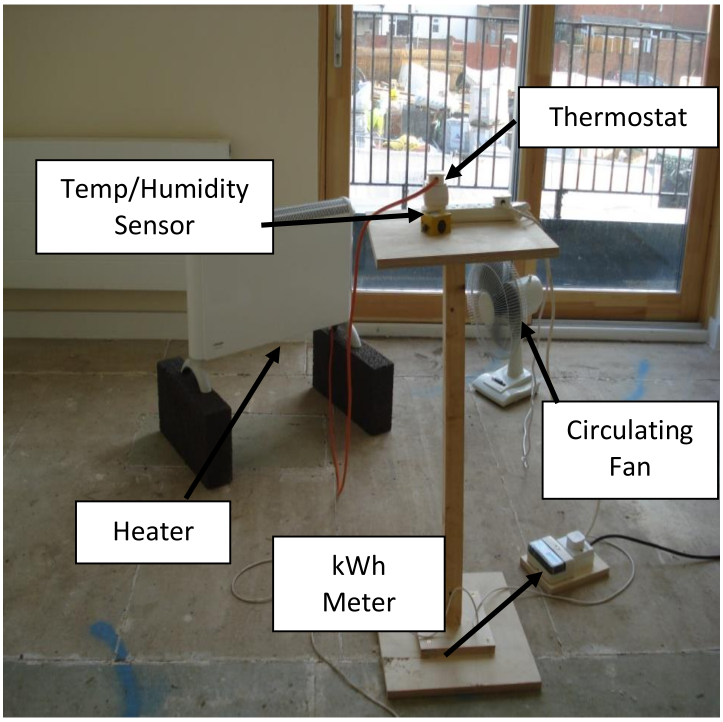
4.2.2 Co-heat Testing

There is no mandatory requirement to pursue whole house heat loss testing or "co-heat testing" (Wingfield, 2011), within the project briefing for In-Use Performance and Post Occupancy case studies (TSB (b), 2011). However this research project includes collaboration with other research projects in the University of Nottingham and involvement in a Building Research Establishment led project with partners from academia and testing agencies exploring the issue of co-heating testing in detail with the view to develop standard test methods, which measure a range of performance characteristics (NHBC, 2012). It is important therefore, to include some measure of co-heat analysis in the overall fabric testing of the case study.

Ideally the testing procedure should be completed in an unoccupied, just completed house, however, the practicality of commandeering a house for a minimum of 10 days during this stage of construction is almost impossible. The invasive and time consuming nature of this testing methodology restricts the sample size to 1 representative house from each typology. The representative Phase 1 house was tested in January 2011 and the Phase 2 house in November of 2011, both were tested post construction and commissioning, but before handover of the property to the new tenants.

The generally accepted framework found in work by Johnston, et al. (2012) details the following methodology.

- Testing Period: Heating season – generally stretching from October/November to March/April time thereby ensuring a ΔT (temperature difference) of at least 10°C between inside and outside the dwelling.
- Testing Duration: 2 weeks minimum, taking into account set up/take down time and the heat saturation phase at the beginning of the test when the structure is brought up to a steady state temperature.
- Dwelling Access: Access to the building should be kept at an absolute minimum, with allowances made for equipment checking and adjustments.
- Dwelling Control: All windows and external doors must be closed, all trickle vents, flues and mechanical ventilation systems sealed and switched off. All electrical appliances such as fridges, microwaves and ovens are to be turned off. Water traps and U-bends in kitchens, bathrooms, en-suites and toilets must be covered with water at all times. Internal drawers, cupboards and doors must be wedged open to allow the free movement of air round the dwelling
- Equipment and Procedure: The dwelling is heated to a constant 25°C (or to a minimum ΔT 10°C) using thermostat controlled electrical heaters and fans. The fans are used to circulate the heat throughout the house and maintain a constant temperature in all the rooms. The heaters and fans run through energy meters that record how much electricity they are using and then transmit the information to a centralised data logger for retrieval at the end of the test. Internal temperatures are recorded using temperature data loggers – in the case of this study this role is filled by the afore mentioned Tiny Tag Loggers (accurate to ±0.9°C over the range of -40°C to +85°C.)



Not included in this picture are the datalogger and the majority of the individual temperature and humidity sensors placed throughout the house and outside. Internal thermostats within the heaters have been bypassed and the set-up relies on the thermostat pictured. In addition there was a pyronometer placed on the roof.

Figure 4.1 Co-heat Test Equipment

External temperature is measured using the same equipment. A weather station should be mounted horizontally above ground level on a mast. It should be positioned to avoid any possible over shading or sheltering. A pyronometer is to be vertically mounted on the external south facing façade of the building, again free from any over shading. The daily electricity use is compiled and graphed relative to the average temperature difference between internal and external (ΔT) over the 24 hr period. The result is the HLC, a proportional value (W/K) which details how much energy is required to heat the entire dwelling per degree of difference between the internal and external temperatures. This value is adjusted to take into account the solar gains measured through the pyronometer. The final solar adjusted value is then compared to the design specified HLC where invariably dwellings perform below the pre-construction estimations. (Johnston D. , Fabric testing: Technical approaches and processes, 2010) (Wingfield, 2011) This gap between design and actual performance is caused by a variety of sources, ranging from the initial briefing process, design and modelling tools used, the build process and build quality, systems integration and commissioning, handover and operation through to the understanding, comfort and motivation of occupants. One of the objectives of this thesis is to understand the extent to which specifically the materials and construction process contribute towards this gap between design and performance.

- Combining Techniques: Ideally there should be an airtightness test immediately before and after the co-heat test, however, the limited access offered to this project did not allow for these additional tests within that timeframe. Combining the coheating test with other fabric analysis measures such as airtightness testing and thermography helps to gain a much better insight and understanding of the factors contributing to the heat loss identified though the coheating test, which by itself, has no way of identifying the contributing factors behind a design and as-built performance discrepancy. However, the practical logistics of organising so much equipment and the right expertise to converge in such a strict timeframe and under such a restrictive protocol is incredibly difficult – particularly if there are multiple properties involved.

A position paper entitled: "Designing Out Risk Using Post-Occupancy Evaluation Methods in Domestic Construction" (the abstract of which is available in Appendix B) was published by the author of this thesis detailing how the results of co-heat testing can be used as performance evaluation tool when comparing differing construction methods. Ultimately, this will form a fundamental building block in the case study evaluation, allowing for a direct comparison of the Phase 1 and 2 housing in this document. The position paper goes into more detail on the exact methodology of this process.

4.2.3 Thermography

The most important factor in qualitative thermography testing is an awareness of the environmental and material parameters that may affect the validity of the image. Requirements as set out by the TSB protocol (TSB (b), 2011, p. 10) seek to minimise the impact of these parameters by dictating a number of guidelines:

- There must be an internal to external temperature difference of approximately 10°C or more for at least four hours immediately preceding the survey.
- No sun should be incident on the facade for at least four hours immediately preceding the survey for low thermal mass structures and longer for high mass structures, ideally carried out before sunrise or late at night provided heating has been on to obtain a temperature difference.
- Dry building surfaces with no rain during the survey
- Wind speed less than 8 m/s (light to moderate breeze).

Phase 1 testing took place in March of 2011, shortly after the dwellings were handed over to occupants. At that stage access to the properties was prohibited, therefore the initial study excludes internal images, instead focusing on the facades and party walls of the TPC housing. A second round of imaging was recorded in Feb of 2014, with access to the internal structure of the Phase 1 dwellings. Phase 2 testing took place during the coheating analysis in November of 2011. Both internal and external images are available. "*The application and interpretation of thermal imaging requires a high level of expertise as factors such as direct solar radiation, surface dampness or surface emissivity can influence the image"* (TSB (b), 2011, p. 10).

For all thermographic tests incorporated in this study the following conditions are recorded to aid in the analysis of the final images:

- Sun Set
- Sky conditions
- Atmospheric Temperature
- Relative Humidity
- Emissivity
- Distance from target
- Internal Temperature of Dwellings
- Wind Speed

Ultimately the aim is to identify thermal anomalies in within the building envelope which may contribute to the gap between design and in-use performance. These anomalies may be caused by gaps in insulation layers, thermal bridging, and air movement within the structure or even a combination of contributing factors. This study is particularly interested in contributing factors that are material or construction process specific.

4.3 Fabric Testing Results and Discussion

4.3.1 Air Permeability Testing

This research project explores the role of air-tightness as an integral component in the development of housing performance and a key factor in the TSB BPE testing regime. Introduced in Section 4.1.1 the airtightness analysis takes two forms. Initially, there is the analysis of the data itself, a comparative breakdown of the timber and masonry readings and the design values of the housing development. The source data for this analysis is displayed in this section and subsequently analysed within the discussion chapter. However, questions were raised in the methodology regarding the air tightness testing procedure, testing methodology and the regulations governing airtightness testing. While not directly pertinent to the fabric analysis of the timber and masonry dwellings, a secondary analysis of the testing procedure is covered in a contextual fashion within this section.

4.3.1.1 Air Permeability Fabric Comparison and Design Gap

Airtightness, as defined by the Building Regulations Part L1A (DCLG, 2013), is measured within the workable envelope of a structure, generally comprising of the floor slab, perimeter wall and roof of the building. Airtightness, or air permeability as it is also known, is measured in m^3 of air, per m^2 of envelope, per hour, at 50 Pascals differential pressure between the inside and outside of the building [m3/(m2.hr)@50Pa]. The equipment used to achieve this measurement consists of a blower door, a micromanometer, barometer, thermometer and anemometer, all used to record the environmental conditions both inside and outside the house during the testing procedure. As previously mentioned, the Green Street case study site was subject to a number of different testing phases or stages.

Upon completion of Phase 1 in November of 2010, a representative percentage of the housing was airtightness tested by a subcontractor, BSRIA, in order to conform to standard building regulations practice. Three dwellings in Phase 1 of the Green Street case study were tested and of these three houses, two are part of the continuous monitoring phase. Houses that are part of the primary case study are labelled using their standard numbering system, 1-8. Houses which were airtightness tested, but are not part of the wider study, are categorized alphabetically, A,B,C,D etc. with a prefix identifying their primary construction material, timber or masonry. These have been included in order to add greater legitimacy to the findings through a larger dataset.

Table 4.1 Stage 1 - Phase 1 Completion Air Permeability Tests (10/2010)

Test House	Design Air Permeability ($m^3/(h.m^2)$)	Measured Air Permeability ($m^3/(h.m^2)$)
House 1	3.00	Not Tested
House 2	3.00	Not Tested
House 3	3.00	2.92
House 4	3.00	2.98
Timber A	3.00	2.98

The opportunity arose in November of 2011 to complete the testing of the phase 1 houses through the generosity of a colleague in the Nottingham University's Dept. Architecture and Built Environment. Utilizing the Department's equipment, House 1 and 2 were tested with some unusual results. Specifically House 2 was found to be outside of design parameters and even beyond Building Regulation boundaries. Upon querying this with Dr. Cooper he admitted that there may have been some unexplained variables affecting this result as it was very unusual. He suggested further testing (Table 4.2) to substantiate the evidence uncovered by his team.

Table 4.2 Stage 2 - Phase 1 Departmental Air Permeability Test (11/2011)

Test House	Design Air Permeability ($m^3/(h.m^2)$)	Measured Air Permeability ($m^3/(h.m^2)$)
House 1	3.00	6.02
House 2	3.00	12.40
House 3	3.00	Not Tested
House 4	3.00	Not Tested

At the same time as stage 2 was underway, Phase 2 of the development was completed and subjected to the mandatory airtightness testing procedure, once again through BSRIA. Some unusual testing practices were witnessed again at this stage, having initially been viewed in Phase 1 as simply a one off occurrence it was this secondary observance which set alarm bells ringing. The houses were tested and would subsequently fail the test, the contractor would then enter the house with a foam gun and plug any apparent gaps in the structural envelope and the house would be tested again. This was reiterated in each dwelling until all three passed under the threshold 3 $m^3/h.m^2$@ 50 Pa. A detailed analysis of this practice and its impact on the overall industry is outlined in the following section.

Table 4.3 Stage 3 - Phase 2 Completion Air Permeability Tests (10/2011)

Test House	Design Air Permeability ($m^3/(h.m^2)$)	Measured Air Permeability ($m^3/(h.m^2)$)
House 5	3.00	2.92
House 6	3.00	2.97
House 7	3.00	2.86
House 8	3.00	Not Tested
Masonry A	3.00	2.54

Having witnessed the unusual and seemingly incorrect practices of the contractor driven testing procedure, in conjunction with the discrepancies between the University's data and the Phase 1 completion tests it was deemed prudent to bring in an independent professional body to analyse the housing. A selection of 10 houses from both Phase 1 and 2, was tested by an approved and licensed air testing subcontractor, Aeratech Ltd. in May of 2012.

Table 4.4 Stage 4 – Aeratech Air Permeability Testing (Nottingham Funded)

Test House	Design Air Permeability ($m^3/(h.m^2)$)	Measured Air Permeability ($m^3/(h.m^2)$)
House 1	3.00	4.49
House 2	3.00	7.07
House 3	3.00	3.87
House 4	3.00	Not Tested
Timber A	3.00	3.6
Timber B	3.00	6.8
Timber C	3.00	7.23
Masonry A	3.00	3.64
Masonry B	3.00	4.01
Masonry C	3.00	4.37

Based on these results, and obviously concerned about the inconsistencies between the completion tests and this round of independent testing, the developer, BluePrint, commissioned yet another round of testing from Aeratech Ltd. a month later. This final round of testing included just 5 additional houses, focusing primarily on the phase 2 dwellings which were omitted from the Stage 4.

Table 4.5 Stage 5 – Aeratech Air Permeability Testing (BluePrint Funded)

Test House	Design Air Permeability ($m^3/(h.m^2)$)	Measured Air Permeability ($m^3/(h.m^2)$)
House 5	3.00	Not Tested
House 6	3.00	5.62
House 7	3.00	4.08
House 8	3.00	3.87
Masonry D	3.00	3.76

A comparison of the mandatory completion testing by BSRIA and the subsequent independent testing by Aeratech Ltd. immediately reveals worrying inconsistencies. Worrying for 2 reasons. There is the obvious gap between design and performance for Houses 1, 2, and 8 (Table 4.6) which were not originally tested upon completion and therefore were not subjected to the same remedial measures as the remaining housing. A value greater than the stipulated 3 $m^3/h.m^2$ is expected, but the extent of that gap is surprising, especially in House 2.

However, possibly just as worrying is the seemingly ineffectual modifications made to the houses that were tested upon completion and which, when independently checked showed a significant rise in permeability, well above and beyond what would generally be expected from factors such as settling and drying out of fabric elements (Proskiw & Parekh, 2004). The drastic changes suggest poor construction practices resulting in an unusual amount of egresses within the building envelope.

Table 4.6 Comparison of Mandatory Testing and Independently Verified Testing

Test House	Mandatory Completion Air Permeability ($m^3/(h.m^2)$)	Independently Tested Air Permeability ($m^3/(h.m^2)$)
House 1	Not Tested - Assumed: 3	4.49
House 2	Not Tested - Assumed: 3	7.07
House 3	2.92	3.87
House 4	2.98	Not Tested
House 5	2.92	Not Tested
House 6	2.97	5.62
House 7	2.86	4.08
House 8	Not Tested - Assumed: 3	3.87

Nevertheless, ultimately the research is interested in how the varying house fabrics compare with one another and the gap between the stipulated design specifications and the actual measured data. Given the unusual testing practices associated with the compulsory testing regime the relatively simple analysis of these relationships is based on the secondary round of testing completed by Aeratech Ltd. The Performance Gap - Design vs. Reality table reveals a clear leader in airtightness – the masonry, phase 2 dwellings. While both phases exhibit significant gaps between the design specifications and reality, the proportionally smaller gap, averaged across the test dwellings, represents a greater performance for the masonry housing. This is backed up by the Performance Gap - Design vs. Reality (Supplementary) table which is made up of additional Phase 1 and 2 housing, subject to the same design specifications and construction protocols as the case study housing, just not outfitted with the sensor array evident in the chosen 8 dwellings – Houses 1-8.

Table 4.7 Airtightness Performance Gap - Design vs. Reality

Test House	Design and Reality Gap ($m^3/(h.m^2)$)	Average Gap Fabric Specific ($m^3/(h.m^2)$)
House 1	1.49	2.14
House 2	4.07	
House 3	0.87	
House 4	Not Tested	
House 5	Not Tested	1.52
House 6	2.62	
House 7	1.08	
House 8	0.87	

Table 4.8 Airtightness Performance Gap - Design vs. Reality (Supplementary)

Test House	Design and Reality Gap ($m^3/(h.m^2)$)	Average Gap Fabric Specific ($m^3/(h.m^2)$)
Timber A	0.6	2.88
Timber B	3.8	
Timber C	4.23	
Masonry A	0.64	0.95
Masonry B	1.01	
Masonry C	1.37	
Masonry D	0.76	

Even at 4/5 $m^3/(h.m^2$ these houses are generally performing well in comparison to much of the existing housing stock in the UK, however, when put in the context of sustainable housing, and the strict performance thresholds associated with low energy, low carbon footprint living, the gap of up to 230% between design and reality is very significant. Air permeability is a crucial and interlinked component of sustainable building design, a factor on which many other decisions are based. MVHR for example, which is dependant on a consistently low air permeability. For the Green Street development the MVHR systems have essentially been rendered inefficient by this gap between design and performance as they were specified for housing rated at 3 $m^3/h.m^2$.

These findings beg the question, where do the irregularities stem from? On this particular site, the extent of the variation suggests poor translation of the design into reality; essentially poor construction practices, particularly in the case of the timber fabrications. This is supported by the evidence that the contractors were not particularly well versed in timber frame fabrication. However, if the discrepancies between the completion testing and the independent testing are purely related to time degradation (seals deteriorating, differential movement and shrinkage) then how can any housing claim to have a set air permeability, only to have that nearly double in some cases after as little as a year. Further investigations into air permeability degradation over time are required as air permeability becomes an ever increasingly important factor in sustainable housing construction.

4.3.1.2 Air Permeability Testing Procedure - Flaws and Weaknesses

The subject of this section and consequently the operating methodology is ultimately a derivative of observational research, associated with the standardized and ubiquitous airtightness testing methodology employed throughout the house building industry. Observational research protocol was employed alongside the quantification of the airtightness values for the case study, in order to better understand and record the airtightness testing regime in step by step detail.

In theory, the implementation of guidelines in 2006, (See section 2.3) later ratified in the 2010 regulations, and the financial risks associated with non-compliance should result in better standards of airtightness within the industry. However, in practice there remains little empirical quantitative analysis to substantiate this premise in the UK. (Pan, 2010) This is thought to be primarily the result of an overwhelming assumption that post construction performance accurately reflects design intentions; that is to say, the designed airtightness will automatically be translated to site. However, given the evidence presented in the previous section and observations of on-site practices, this assumption is being called into question. The notes from the observational research revealed some inconstancies between the in-practice procedure and the specified regulations found in ADL1A. Primarily these inconsistencies were associated with a vague testing process and the failure of pressure tests with the subsequent unofficial re-testing of the properties. In setting out the approved methods of air-tightness testing, Part L1A of the 2006 Building Regulations states that:

> *"Compliance with the requirements would be demonstrated if:*
>
> *a. The measured air permeability is not worse that the limit value set out in paragraph 37 [10 $m^3/h/m^2$ @ 50Pa]; and*
> *b. The DER (Dwelling Emission Rate - $kgCO_2/m^2/year$) calculated using the measured air permeability is not worse that the TER (Target Emission Rate - $kgCO_2/m^2/year$)*
>
> *This means that if a design adopted a low design air permeability in order to achieve a performance better than the TER it would not fail Part L if the pressure test achieved the limit value and the TER was achieved."*

The TER is the minimum energy performance requirement for a new dwellings and is calculated assessed using approved calculation tools such as SAP analysis. What this means in reality is qualified and licensed individuals test houses based on the design value air-permeability rating found in the "as designed" SAP analysis. If the house doesn't reach the design value the building does not in fact fail right then and there (as long as the tested value is below $10m^3/h.m^2$.) The tested numbers should be recorded and taken away to be actually inserted into the SAP software where the DER can be calculated and compared with the TER – if the subsequently calculated DER is greater than the TER THEN the house fails and is subject to the full extent of the Building Regulations remedial measures AND further re-testing. An example of this would be if a house is set a design specification of $3m^3/h/m^2$ @50Pa the regulations seem to suggest that the house can be tested to a higher rate of leakage as long as the overall energy performance of the house remains within the bounds of the TER. (This is only verifiable by actually consulting the SAP spreadsheets and inputting the tested data. However, there is obviously no provision to insert the as-tested figures, attained during the testing procedure, back into the SAP analysis while in-situ, on site. Consequently it is impossible to determine exactly whether the DER/TER ratio has been exceeded and the house subsequently failed.

Logic dictates that if a house is set a target of $3m^3/h/m^2$ @50Pa there is in fact no margin of error. The testing must show the house has an air-permeability matching or better than 3 $m^3/h/m^2$ @ 50Pa in order for the tester to be certain that the DER is lower than the TER. If the house fails to attain design specification values then it immediately fails and the house and the entire site is subject to the full extent of the Building Regulations remedial measures dictated in Part L1A of the Building Regulations. Unfortunately this is not the case.

Observational evidence gathered from this site unveiled a complete lack of SAP consultation and found a somewhat anomalous and frankly confusing sequence of events surrounding the airtightness testing procedure. A house would be tested and subsequently fail to achieve the design airtightness in all but 1 case of the mandatory post-construction air tightness testing. Once a house failed the contractor would then enter the house with a foam gun and plug any apparent gaps in the structural envelope and the house would be tested again until it passed. Given that only a small percentage of housing is required to be tested under regulations, only the houses being tested underwent these remedial measures. This, despite the obvious logic behind testing a representative percentage housing, logic which dictates that problems found within a representative few are most likely indicative of failings on a larger, site-wide scale.

Surprisingly this was actually discovered to be common practice, anecdotally confirmed by airtightness professionals who obviously want to remain anonymous. During the airtightness testing period a contractor is instructed to simply go into the failed houses while the tester "takes a break" – implement remedial measures and test again until the house reaches the design value target, thereby fulfilling their obligation to the Building Regulations and removing any risk of the DER coming in higher than the TER.

On the surface, this practice seems to fall within Regulations, even if it defies a logical train of thought. Theoretically because the house hasn't been proved to have failed – through the Building Regulations own protocol - it was never subject to the re-testing procedure (test this house and another like it) outlined in part L1A.

However, if testers are allowed to implement remedial measures and then retest – how do they know for sure that the original test values did not fail the DER/TER ratio and would therefore fall subject to the re-testing protocol. In addition if contractors follow this method of immediate re-testing there is nothing in the regulation that requires them to go into the other houses on the development and implement the remedial measures that they just put into the test houses to get them to pass.

The problem lies with both the Regulations and the manner in which the airtightness tests are actually conducted. There is obviously un-due pressure put onto the tester to remain and re-test because if they don't then they will get a reputation as not being lenient and costing more thereby putting them at an industrial disadvantage in a test that is meant to remain entirely impartial and governed purely by the measured data. The key is – NO remedial measures until after SAP analysis of the tested values, period. Or, simply amend the Regulations to clearly state that a house fails its airtightness test unless it meets its design standards, rather than rely on the ambiguity and complications associated with the DER/TER ratio. If a house fails then the entire development is subject to the re-testing regime outlined in the Building Regulations.

Fundamentally there needs to be greater emphasis on that first test – if it fails, this is significant and representative of the entire site and should therefore have ramifications for the entire site. If remedial measures are taken to get a house to the design level of air-tightness then these measures should be implemented across the entire development irrespective of the eventual DER that may be calculated weeks after the actual air tightness testing. Unfortunately, in reality most contractors do not have the time or money to risk letting the over-design-value numbers go back to the SAP analysis stage as failure at THAT stage would mean significant costs and delays associated with the remedial measures and testing just mentioned.

4.3.1.3 Air Permeability Analysis

Much has already been written regarding the air testing procedure and the inherent difficulties and problems associated with the Regulations. (Section 4.3.1) Table 4.6 summarizes the quantitative element of the arguments from both sections, highlighting the obvious fact that the mandatory testing does not reflect the reality of the housing performance throughout the development.

Despite the individual outcome varying from house to house, the average results across the fabric types reveal that the timber housing overall performs worse than its masonry counterpart. With the design benchmark the same across both phases, it follows on that the average performance gap is also greater for Phase 1.

Additional testing completed on the remainder of houses in Phase 1 and 2 corroborates this conclusion (Table 4.8). House 2 obviously exhibits the largest impact with the relatively high 7.07 $m^3/(h.m^2)$ air permeability contributing to over 100kg more of emissions per year than the design value. This reading was somewhat unusual though as the rest of the houses average around a 30kg CO_2/annum increase over the design value. The company that performed the secondary independent testing highlighted a number of factors that could contribute to this gap, including:

1. Floor/wall junctions into floor and wall cavities - this is often a problem in kitchens and bathrooms, where this junction is not made airtight before units are fitted. 90% of all problems are from this junction.
2. Pipework and boxing around pipework - holes around pipework are often not sealed. If the boxing is not sealed then this is a source of air leakage
3. Most window trickle vents are not airtight when closed.
4. Poor sealing around stairways and landings.
5. Integral garage doors are often not properly sealed.
6. Minor leakage is nearly always present through power sockets and light ceiling roses.

Many of these problem areas are confirmed through the thermography in both phases, however, the thermography did not reveal the extent of the infiltration revealed through the air testing procedures. Feedback paraphrased from the project management interview with architect Julian Marsh (Section 7.3.2.1) provides a clear and plausible suggestion as to origin of the air tightness discrepancies, and that is:

> *"It comes down to site skill most of all. Until we can get the same level detail and focus that you get in the factory, actually on site when the thing arrives, then the performance benefits theoretically associated with TPC will struggle to be realised. Completely modular construction is the best. Frames and panels are still too open to construction error. Half and half is where you get the problems." "It is easy to poorly install the vapour barrier and membranes – results in much higher risk of degradation than traditional masonry and the potential for poor airtightness. Only a problem on timber frame, built half in factory and half on site. Modular design leaves the factory much more complete mitigating the potential for poor practice."*

Fundamentally the construction phase of the Green Street development was completed by a contractor, Lovell, who builds using predominantly traditional masonry construction methods. It follows on that their lack of experience with timber fabrication, coupled with the only "part modular" nature of timber frame construction, left the timber housing particularly vulnerable to poor site practices – thus justifying the proportionally larger gap between design and reality for the air tightness testing in Phase 1 and potentially having a farther reaching impact on the housing performance as a whole.

4.3.2 Co-heating Tests

4.3.2.1 Co-heating Test Phase 1 (Timber)

A representative house from each phase was chosen to undergo a co-heating test post construction and just prior to occupation by the new owners. The first test took place between the 13th-24th of January 2011, on house 4 in phase 1. The external weather conditions (temperature, humidity, wind strength/direction and precipitation) were recorded throughout the testing period via a weather station located on the Nottingham University Campus approximately 4 miles away. The internal temperature was maintained at a constant 25°C in accordance with the Leeds Met protocol (Johnston, et al., 2012) using a combination of electric fan heaters and standalone fans with electricity meters attached.

Table 4.9 Co-Heating Test Equipment

Component	Equipment Used
Datalogger 1	Datataker DT500
Datalogger 2	Datataker DT85
Temperature and Humidity Sensor	Tiny Tag Plus 2 Loggers
kWh Meter	Elster A100C, 1 Wh pulse output
Thermostat	Timeguard ET05 Plug-In Thermostat Heating Control
Fan Heater	Stanley® Portable Electric Fan Heater 2kW
Circulation Fan	16” Free Standing Fan
Pyranometer Sensor	Skye, SKS 1110/S (±5%)

It was not possible to control the temperature of the adjacent properties, however, they were kept well above external temperatures thus interference from thermal flux between the properties should be at a minimum. The house was sealed for the entire duration of the test. While a lack of appropriate equipment precluded the simultaneous testing of airtightness or thermography this initial study did provide some valuable insight into the overall thermal performance of the building and provides some context for the thermal imaging and pressure tests which were completed at a later date. A plot of ΔT versus daily power usage during the co-heating test is available in Figure 4.2.

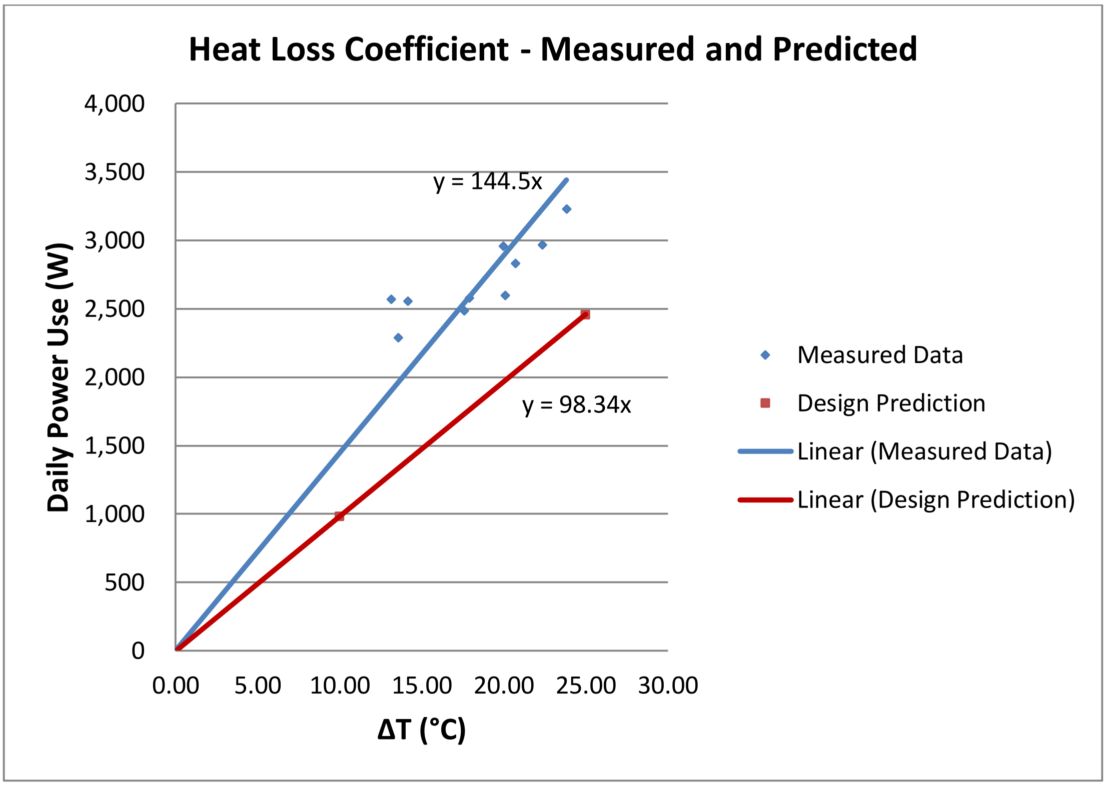


Figure 4.2 Heat Loss Coefficient Graph, Phase 1 Property – No Solar Gains

The equation of the line's slope represents the heat loss coefficient measured in W/K. As the equations demonstrate for every degree difference in internal and external temperature there is a corresponding energy consumption. The key issue here is the gap between the predicted design performance and the actual measured data. The predicted heat loss coefficient is found in the design SAP calculations for the property and takes into account nominal elemental U values for the wall, roof, floor and windows as well as the SAP bridging factor. (Declared in the SAP worksheet summary – Appendix E.) Figure 4.2 shows a significant 47% increase in energy that is yet to be accounted for through the remainder of the testing regime - thermal imaging, leakage tests and post-construction interviews with the developer, architects and various sub-contractors. There are no definitive answers as of yet, as to where all the heat is escaping however Section 4.3.3 lays out a significant construction flaw in the house-garage interface.

According to the Leeds Met methodology (Johnston, et al., 2012) the heat loss coefficient is not yet complete and must be corrected in order to take into account the solar gains on the house throughout the testing period. Unfortunately the pyronometer onsite failed thus an alternative yet lengthy solution was developed using a combination of solar data from a weather station at Nottingham University and a solar modelling software package – Ecotect. There are three key steps:

1. Develop model based on architects drawings and specifications.
2. Create weather file based on the data recorded on site.
3. Analyse sun-path and shading to determine heat gains (direct and indirect) over testing period.

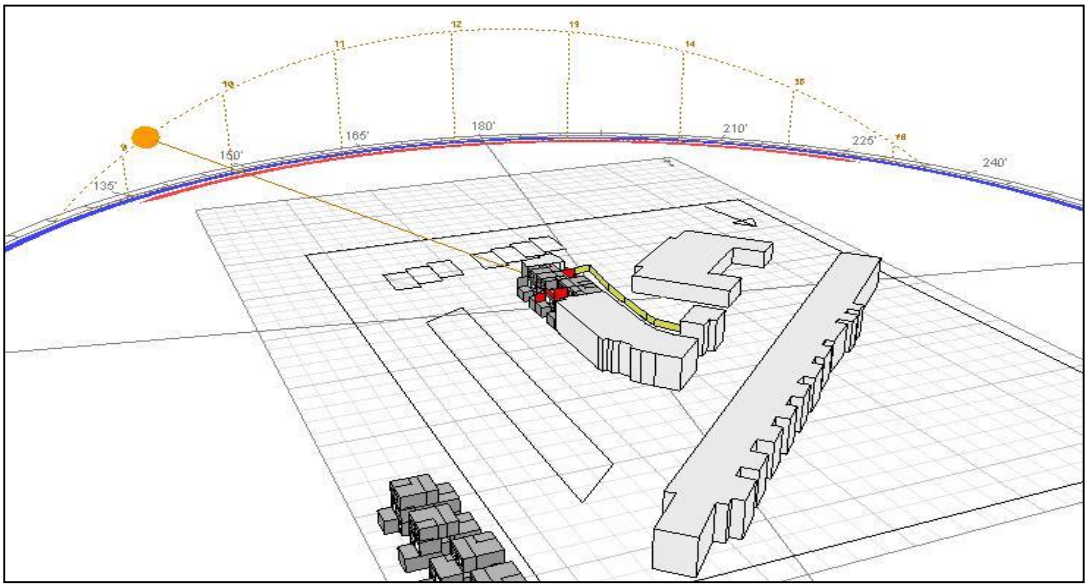


Figure 4.3 Ecotect Model of Phase 1 Sun Path

Table 4.10 Solar Heat Gains Over Co-heating Test Period

			Date in January								
			14th	15th	16th	17th	18th	19th	20th	21th	22th
Incident light ON window (W) (not transmitted)	Front of House	Living room	42	58	85	9	70	59	79	91	49
		Office Space	2	1	3	1	4	4	5	5	3
	Back of House	Kitchen window	68	84	81	120	78	127	68	83	132
		Kitchen door	97	117	116	168	112	178	99	119	187
		Bedroom left	66	80	78	114	76	121	66	80	126
		Bedroom right	66	80	78	114	76	121	66	80	126
		Master bedroom	110	138	132	195	126	206	109	134	215
		Ensuite	60	73	71	104	69	110	60	73	115
		TOTAL W/day	511	631	644	825	611	926	552	665	953
		Window Corrected	141	174	177	227	168	255	152	183	262

Given a solar heat gain coefficient (SHGC) of 0.55 and a transmittance value of 0.5 for the triple glazed windows the final results are:

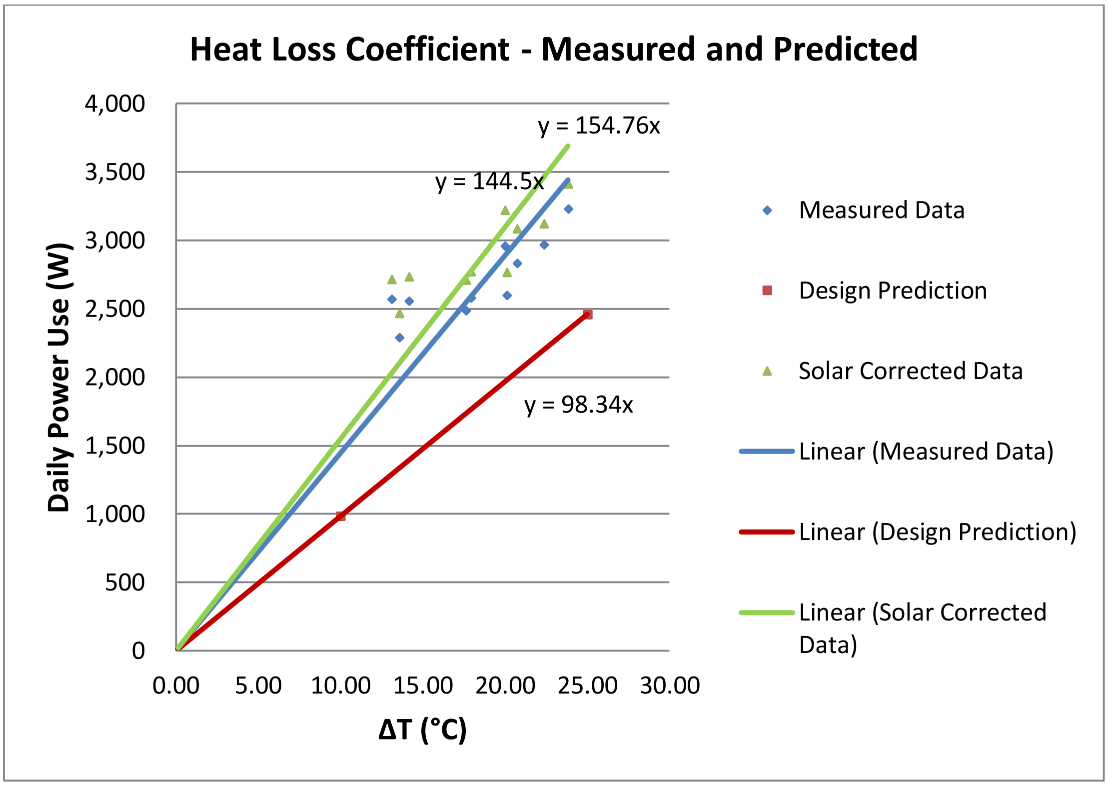


Figure 4.4 Phase 1 Co-heat Analysis

The heat gain coefficient is not substantially affected by the modelling results (57% difference in design and operation) as the test took place in January with a low sun angle and generally overcast days. The east-west orientation of the house also lends itself to solar shading with the southern wall actually forming the party wall between the properties.

4.3.2.2 Co-heating Test Phase 2 (Masonry)

House 8 was chosen from phase 2 to be monitored using the testing equipment and procedure detailed in Section 4.2.2. The house was chosen based on its mid-terrace construction, mirroring that of the Phase 1 house, in order to eliminate as many uncontrolled variables as possible. Once again the house was kept at a constant temperature of 25°C over an extended and uninterrupted period. Unfortunately once again the pyronometer failed during the test. As with the phase 1 test, accurate information regarding the direct and indirect solar radiation incident on the building is necessary in order to calculate the internal gains within the house. In an effort to avoid the time consuming process and complications outlined in section 4.3.2.1, a new hypothesis was suggested in line with research conducted for the BRE by the University of Nottingham. This methodological protocol is still in its infancy and currently being tested, thus the protracted validation process detailed in this section.

Its foundation represented a significant component of the university's contribution to the NHBC Foundation Co-Heating Test Research Project 2011-12. (Butler & Dengel, 2013) The following excerpt from the unpublished, but contributing report submitted by the Nottingham team summarises the project and its relevance:

> *The University of Nottingham was commissioned by the NHBC Foundation to undertake a co-heating test on House No.4 at the BRE site at Garston, Watford. This test formed part of a wider research programme involving other organisations and institutions, which aimed to evaluate the use of co-heating methodology to assess building fabric heat loss.*
>
> *The testing period extended from 23rd April – 8th May 2012 (16 days). The initial heat-up period of two days, and the final de-rig day were not included in the analysis, with data for the period 25th April-7th May being the relevant period for this study.*
>
> *This report comprises of a brief explanation of the methodology used, issues encountered, and a discussion of the resulting dataset. In addition, it includes a proposal for an adjustment to the data analysis protocol which aims to reduce the scope for experimental error, whilst also simplifying the testing and evaluation process.*
>
> *The data collected during the study resulted in a calculated measured heat loss coefficient of 73.89W/K, a difference of 12% from the specified design value of 65.92W/K.*
>
> (Bailey, et al., 2012 p. 2)

The theory introduced in this report is entitled the "Night Data Theory" and stems from a significant number of methodological inconsistencies revealed throughout the duration of the experiment concerning the analysis of solar gains. These include, but are not limited to, the following observations:

- No consideration is given to solar gains attributable to glazing on the North, West, or East facades.
- Calculations do not take into account the dwelling's specific glazing specifications (admittance, reflectance etc.)
- Consideration of the position of glazing and associated shading elements is not included in the analysis.
- There is no quantification of solar gains associated with the fabric of the dwelling.

The exclusion of such significant variables led the team at the University of Nottingham to question the current data evaluation process, which uses day time data, prompting the hypothesis that it may be more accurate to narrow the scope of the analysis to include data collected during the night time hours only. The utilisation of night time data to calculate the as-built heat loss coefficient would remove the potential errors that are involved in the assessment of solar gains and associated variables.

Even when modelling the site, (as with phase 1) the margin for error when calculating the solar gains is significant. Inadequate detail in the model, and error in the on-site solar data, can affect the result. Using solely night time data within the calculations presents a more accurate way of calculating the heat loss coefficient, by simply removing the whole issue of heat gain from the sun.

The definition of what constitutes a 'night time period' is somewhat subjective. Therefore, this initial iteration of the revised solar protocol bases this time period on thermographic methodology, which indicates that the dwelling fabric should not be subjected to direct solar radiation for approximately 2hrs preceding the assessment.

A significant disadvantage of using solely night time data is that it reduces the experimental timescale and subsequent data pool. The reasoning behind conducting the test over a period of 10 days is that it helps to negate weather variance and smoothes the effects of elements such as wind and rain. However, as Figure 4.5 and Figure 4.6 show, there is little correlation between these weather conditions and the power usage within the house.

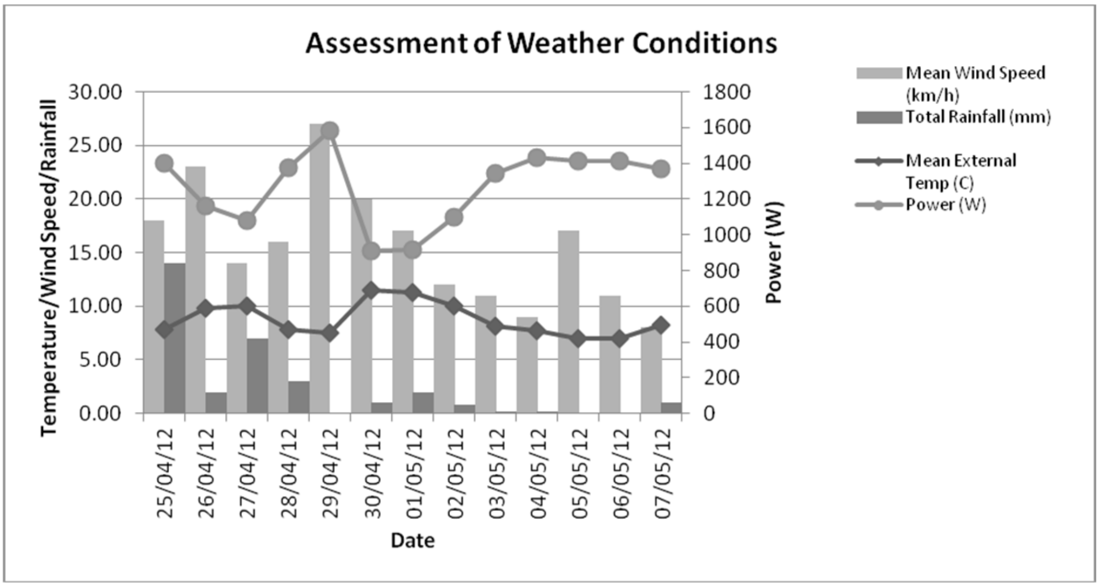


Figure 4.5 Assessment of Weather Conditions

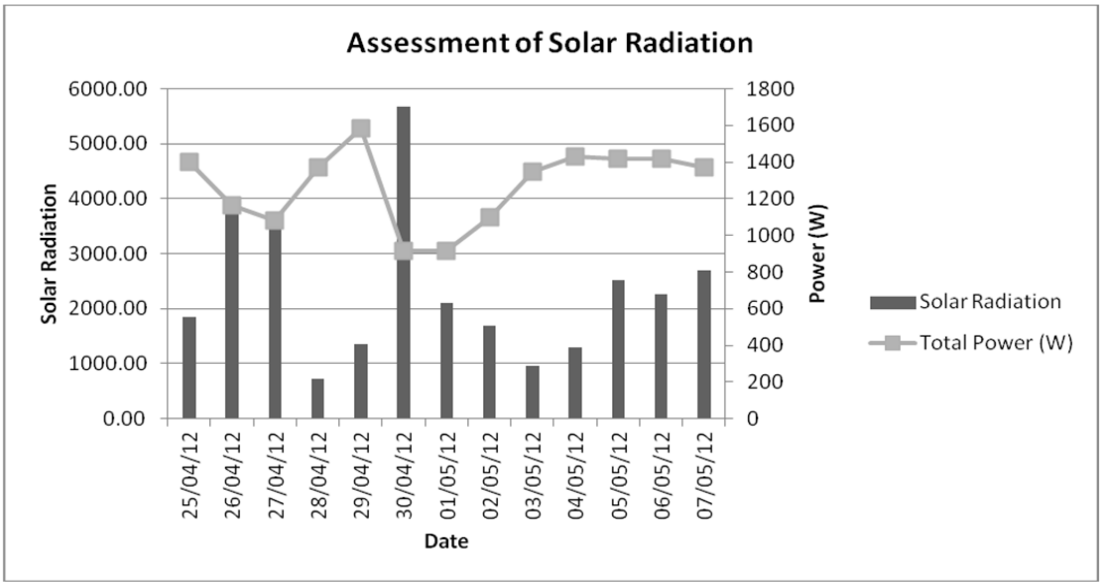


Figure 4.6 Assessment of Solar Radiation

It could be argued that homes are currently designed to take advantage of solar gains, and therefore by using only night time data the fabric performance variable could be marginalised. However, such a premise is potentially unfounded, as the design HLC, calculated through SAP analysis, only accounts for ventilation and fabric losses, with no regard to solar gains. With these issues in mind, a second analysis was undertaken based upon a period of 10pm-4am in order to test the hypothesis. The reasoning behind this evaluation was to test whether using solely night time data would result in a heat loss coefficient of similar magnitude to the original co-heat test value (solar corrected).

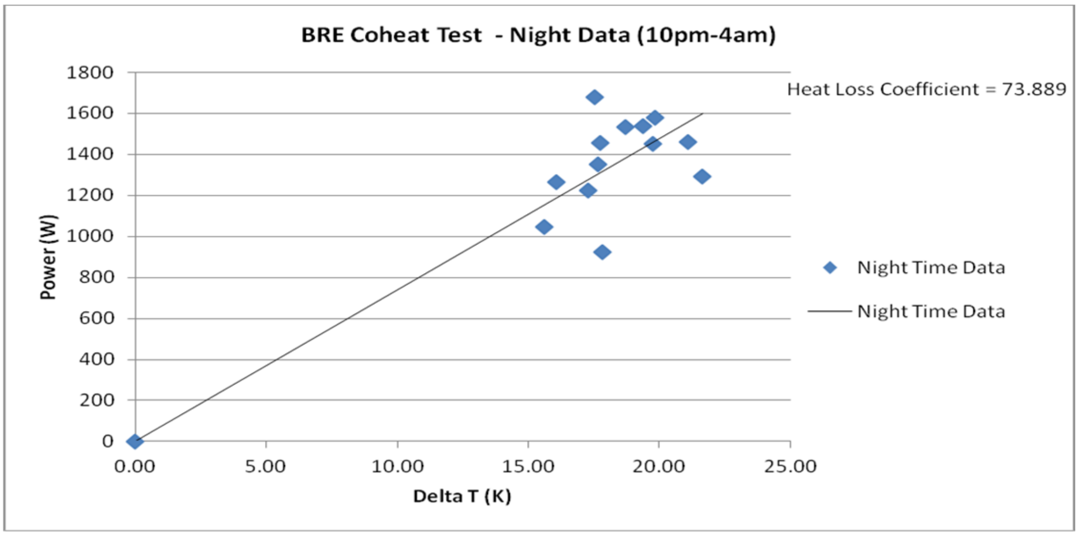


Figure 4.7 BRE Co-heat Test – Night Data

The results from the initial analysis compare favourably with the design stage heat loss coefficient value of 65.92W/K. The solar corrected data produced a coefficient of 78.02 W/K, whilst the night time only data resulted in a lower value of 73.889 W/K. The heat loss coefficient for raw data set, before any adjustments or correction, was 71.945 W/K. This initial comparison would suggest that there is some merit in utilising only night time data, however further questions were raised regarding the impact of solar radiation and the delayed heating impact throughout the night.

In answer to this the BRE was petitioned for additional co-heat data in order to create additional HLC profiles. Raw data from two houses on the BRE Watford site was provided and subsequently analysed to determine a more robust methodology accounting for solar gains in the thermal mass of the structure and the impacts of thermal lag on the heat energy expenditure during the night.

The data provided for the two test houses (House A and House B) includes power use throughout the dwellings, internal and external temperatures and solar irradiance in W/m^2 values. All the components required to structure and graph the standard co-heat analysis which acts as the benchmark for each house. These benchmark profiles are labelled as "Raw Data" and "Solar Corrected" in Figure 4.8 and Figure 4.9. A design value is not required in this case as the development of this methodology is dependent on the raw data or standard HLC, not the gap between design and performance. The concept is fairly simple, rather than set a time period for the night time data, based on somewhat arbitrary thermographic practices, it was considered far more appropriate to actually account for solar radiation incident on the dwelling and adjust the conditions of data collection appropriately. Some may say that if you have to have a record of solar data anyway, then how does this differ from the standard methodology? The difference is, the solar radiation in this case can be obtained from a nearby weather station or on-site simple pyronometer without the need to record both direct and indirect solar data or account for losses through windows or the angle of the sun into the dwelling. The goal of this validation project was to quantify a solar irradiance threshold above which the solar gains experienced on the house would have a significant impact on the end HLC values and invalidate the data. When the levels of irradiance remain below this threshold, in theory, the night time data becomes a valid alternative to the more standard, but significantly flawed, solar corrected values.

In order to calculate this threshold the data sent by the BRE was broken down into individual days. Each day split into day and night data and the temperature and power values for each night were graphed in a standard temperature vs. ΔT, HLC graph. The HLC value obtained from the slope of each of these graphs is compared to the solar corrected benchmark HLC value already formulated in another graph. The HLC values from the daily graphs which fall within 10% of the solar corrected HLC were immediately separated and highlighted. The solar irradiance values for each day were then isolated and analysed on an hourly basis to determine the differences between the profiles which produced accurate HLC values and those which fell outside of the 10% accuracy band. In order to take into account the profile and construction of individual houses the solar irradiance threshold was actually converted into two proportional unit-less values (global threshold) based on the area of a dwellings South facing façade (split into glazing and wall area.) This action standardises the results and makes them available for anyone to test, which is encouraged, as this methodology (and much of the co-heat test in general) is still yet to be formalized.

The conclusion is a fine balance between as little solar input during the day as possible, while still maintaining enough days of data to account for different weather patterns, rain and wind. The test houses provided relatively accurate HLC values up to a solar threshold of 175W/m^2 average in the 5 hours preceding sunset. When converted to the global threshold using the glazing area of 6.44m^2 and wall area of 29.42m^2 the final equations are as follows:

For the south façade of a house the:

$$Area\ of\ Glazing\ South\ Facade * Average\ Solar\ Irradiance \leq 1130$$
$$Area\ of\ Exposed\ Wall\ South\ Facade * Average\ Solar\ Irradiance \leq 5150$$

Equation 4.1 Solar Gains Threshold – Night Time Co-heat Testing

The area of glazing and exposed wall is measured in m^2 and the average solar irradiance (W/m^2) is calculated by averaging the values of solar irradiance for that location in the 5 hours directly prior to sunset. 1130 and 5150 are the unit-less global threshold values (GTV) to which the daytime data must conform. Obviously the equations are reorganised to account for the GTV and façade areas which are the constant variables and can be used to discern the irradiance threshold. If the average irradiance values remain below the calculated irradiance threshold, then, according to the testing procedure conducted on these two houses, the night time data for the corresponding days can be used to calculate an accurate HLC. Figure 4.8 and Figure 4.9 depict each stage of the HLC development. The linear night time uncorrected data is simply all the night time temperature and power readings profiled without any consideration for the solar gains. The linear night time corrected data takes into account the GTV and can immediately been seen to create a trend line more closely related to the traditionally calculated solar corrected HLC.

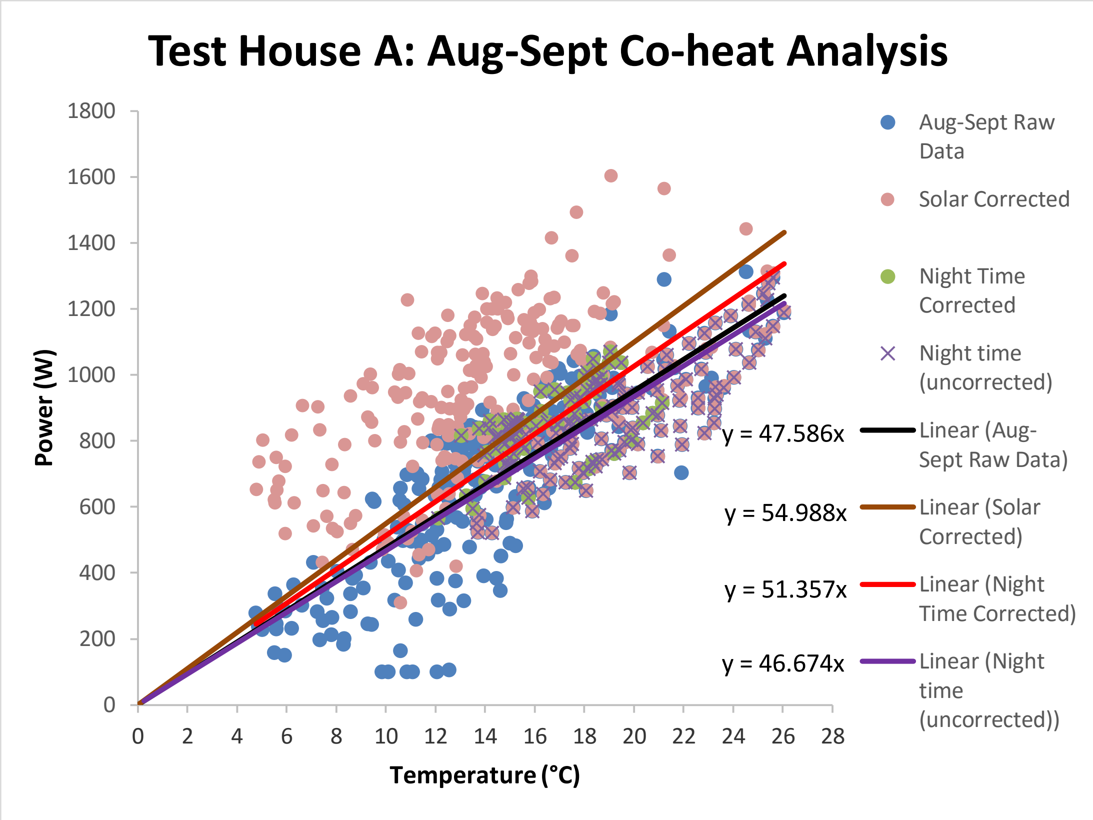


Figure 4.8 Test House A: Aug-Sept Co-heat Analysis

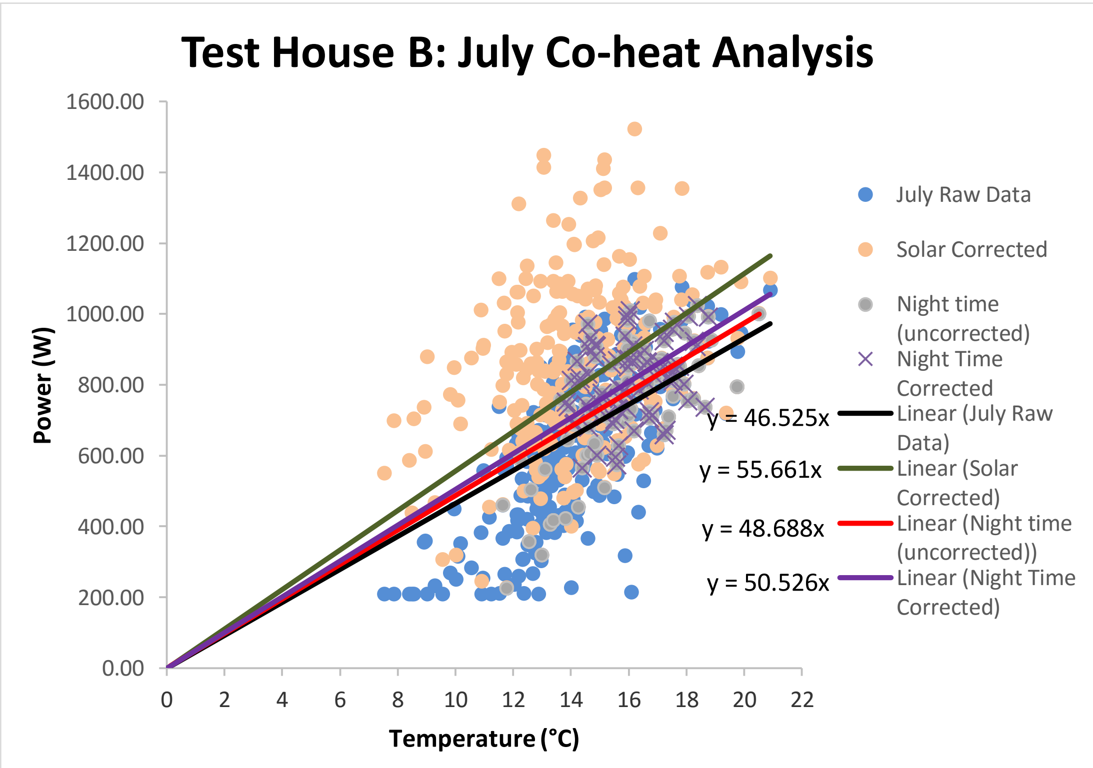


Figure 4.9 Test House B: July Co-heat Analysis

The HLC values summarised in Table 4.11, highlight the accuracy of the night time method in relation to one of the more standard solar correction protocols. The error percentage falls well within the boundaries exhibited by the various different methods employed within the NHBC Foundation Co-Heating Test Research Project 2011-12 (Butler & Dengel, 2013).

Table 4.11 Test Housing HLC Values

Test House	Analysis Category	HLC	Error
House A	Solar Corrected	54.99 W/K	7%
	GTV Corrected	51.36 W/K	
House B	Solar Corrected	55.66 W/K	9%
	GTV Corrected	50.53 W/K	

Having suitably justified and refined the night time data method for co-heating analysis the methodological protocol highlighted in this section was applied to the raw data collected from the representative phase 2 house. Out of the original 10 days set aside for the test, 8 were deemed viable for the co-heat analysis procedure (subtracting a couple of days to let the house settle" and of these 8, 6 qualified through the GTV calculations. Night time data from these 6 dates makes up the source material for Figure 4.10, which depicts both the design and measured HLC trend lines and equations. These final HLC values will be analysed in the context of a comparative performance analysis between Phase 1 and 2 of the case study, but also on a more relative scale, looking at the gap between design and performance.

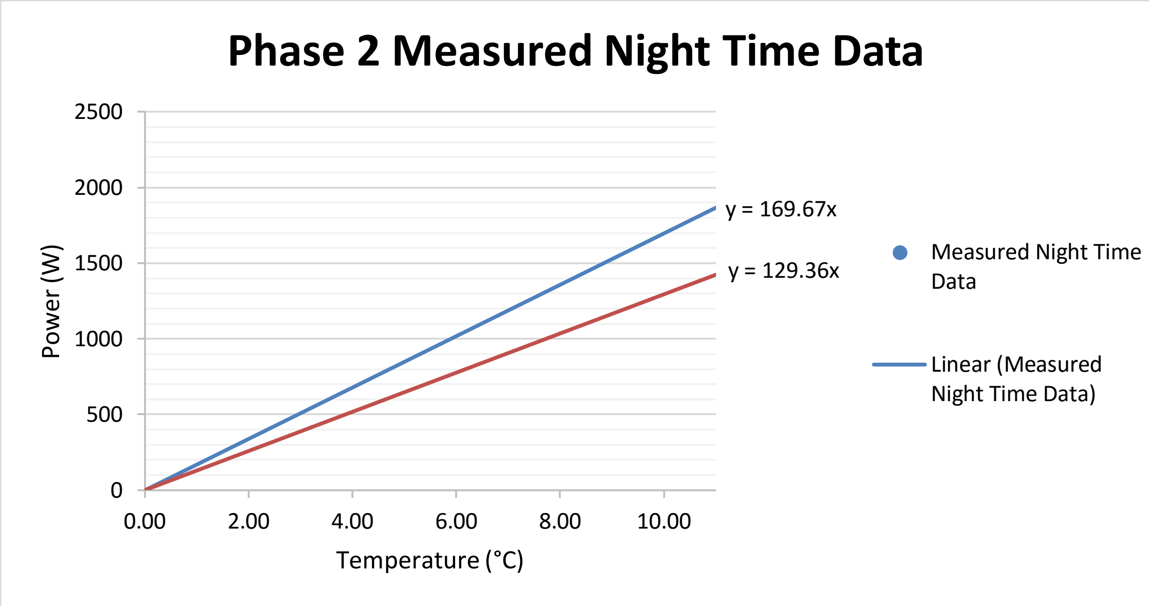


Figure 4.10 Phase 2 Co-heat Result - Measured Night Time Data

4.3.2.3 Co-heating Test - Heat Loss Coefficient Analysis

Due to the complicated and invasive nature of the co-heating test a representative house from each construction type was chosen to undergo the procedure. Unfortunately on both occasions the pyronometer, included to help calculate the heat gains due to solar irradiation, failed. At first this was viewed as a disaster, but through this failure evolved a testing procedure which ultimately could solve many of the inherent problems now associated with the co-heating test methodology. All of this is covered in detail in sections 4.3.2.1 and 4.3.2.2, however it is important to highlight that the HLC values used in Table 5.1 - Table 5.4 all come from these two representative houses. The Design HLC is taken from the design SAP specifications, the working HLC is calculated through analysis of the energy used to heat the house while occupied and the measured HLC was established through co-heat testing of the dwellings in question.

Table 4.12 HLC – Gap Between Design and Performance

Dwelling Designation	Design HLC (W/K)	Working HLC (W/K)	Measure HLC (W/K)	HLC Gap Between Design and Performance (W/K)
House 4 (Timber)	97.22	130.03	154.67	57.45
House 8 (Masonry)	128.68	155.12	169.67	40.99

A comparison between the two building fabrics clearly reveals that the masonry housing proportionally outperforms the timber frame construction with less than half the gap between design and performance - 59.1% (timber) and 31.85% (masonry). When the design values are replaced by the measured ones, there is a significant change in the outcome of the SAP analysis. Extra CO_2 emissions of up to 500kg a year in phase 1 obviously have a massive impact on how the house performs and is rated, the most significant being the reduction of the houses from CSH level 4 to CSH level 3 across the board. The exact nature and cause of this discrepancy is difficult to pinpoint. Generally, a study such as this would include a heat flux measurement to establish the U-value of each individual surface. Heat flux testing measures the heat transfer through a building element via an array of sensors over a given period of time. As such, it is possible to derive an in-situ u-value for the fabric in question. However, the nature of this study, with "real people" coupled with the generally destructive effects of the heat flux testing procedure proved one test too many. Evidence from Wingfield et al. (2011) suggests that when subjected to the heat flux testing the majority of building elements perform worse than their stipulated design value with external walls in the housing they tested recorded at twice their design benchmark. Ultimately their calculations attribute the difference between the measured and design values to this variability in the thermal performance of the individual building elements and junctions as-constructed. The Green Street site requires further testing in order quantify the exact causes of the heat loss, however thermal bridging and unexpectedly high U-values are likely to be the cause considering the potential for poor construction site practice, as previously discussed, particularly in the case of Phase 1. This supposition does not discount the various other potential variables which may contribute to performance gap:

1. Is the assessment model that was used to make the prediction accurate, and has it been correctly implemented in the software used by the designer?
2. Is the model's input data correct (and if not, is that due to the conventions or the user?)
3. Is the home's design overly complex, presenting unreasonable challenges to the construction team?
4. Do building materials and mechanical and electrical (MandE) systems perform as-well in practice as laboratory tests predict?
5. Do changes in specifications get properly communicated?
6. Are the post-construction tests and checks appropriate and adequate?

Some or all of these variables could potentially play a part in the gap between the design and performance HLC. Based on the limited evidence gathered throughout the duration of this project, it is impossible to confirm the relevance of these variables, to do so would require a separate study on the pre-construction phase of the project. This study started too late in the development process to gather enough relevant and accurate data to support these assumptions, the focus therefore falls on the construction phase of the development. What is known, is that the contractors had little experience in building with timber, the project was under strict time and budget constraints (Gleeds Research and Development, 2012) and other benchmark figures such as airtightness are significantly out of line with the design values – this would suggest issues with the construction phase certainly contributed, if not entirely caused this evident discrepancy between design and reality. The conclusions of the project therefore focus on enhancing the performance of the timber frame construction from this perspective.

As it stands, the co-heat test according to the Leeds Met protocol represents an indicative tool rather than an explicit quantitative representation of the actual housing performance. Thus, despite the extensive calculations, modelling and data collection the conclusions in this section are merely indicative of a problem or problems in the as-built performance of the housing. The co-heat testing procedure its validity and future significance are subject to intense scrutiny by a BRE-led project with partners from academia and testing agencies exploring all facets of the co-heat testing process with the view to develop standardized and simplified test methods that could be employed on a national scale (NHBC, 2012). It is hoped that the lessons learnt and the techniques employed in this study will help in this evolutionary process of simplification and standardisation.

4.3.3 Thermography testing

4.3.3.1 Thermography Testing Phase 1

As discussed within the methodology section, it is vital to record and account for the impact of environmental factors when taking thermal images. This can usually be accomplished by adjusting settings within the thermal imaging device employed in the study as in this case. The following is a compilation of thermal images taken on the 12/03/2011 at 21:30 in the Meadows, Nottingham. The environmental and material parameters are set as follows:

- Sun Set: 17:46
- Sky conditions: Slightly cloudy
- Atmospheric Temperature: 12°C
- Relative Humidity: 50%
- Emissivity: 0.81 – representative of the dry external brick facade covering the internal timber frame.
- Distance from target: 15m – This obviously varied and 15m was taken as an approximate average.
- Internal Temperature of Dwellings: 21°C – Assumed value as access to the houses was restricted, but properties were occupied.

The section begins with external photos and an initial set of 3 photos is taken using a sliding temperature scale in which the camera automatically adapts its colour variation to the maximum and minimum temperatures within the frame of reference. The maximum and minimum temperature values in each photo vary and correspondingly the colour spectrum in each photo represents a different set of temperatures. This information is indicated by a bar on the right of the photo.

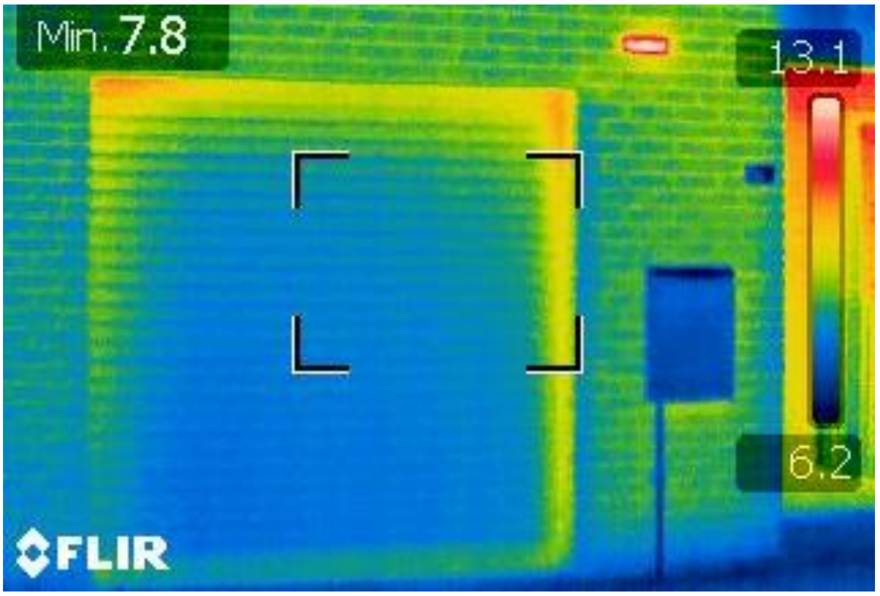


Figure 4.11 Closed Garage Door Phase 1 Heat Loss

Figure 4.11 shows some heat loss around the edges of the garage door. The overall profile shows the door it is fairly well insulating therefore heat loss is most likely due to gaps in the seal between the wall and the door. The fact that the garage is being heated at all raises some questions. The bright spot is a boiler flue pipe as the boiler itself is situated just on the other side of the wall. The wall temperature looks warm, but later images show there may be some interference due to the emissivity of facade. Further investigation is required, however the indicated heat loss is not too significant.

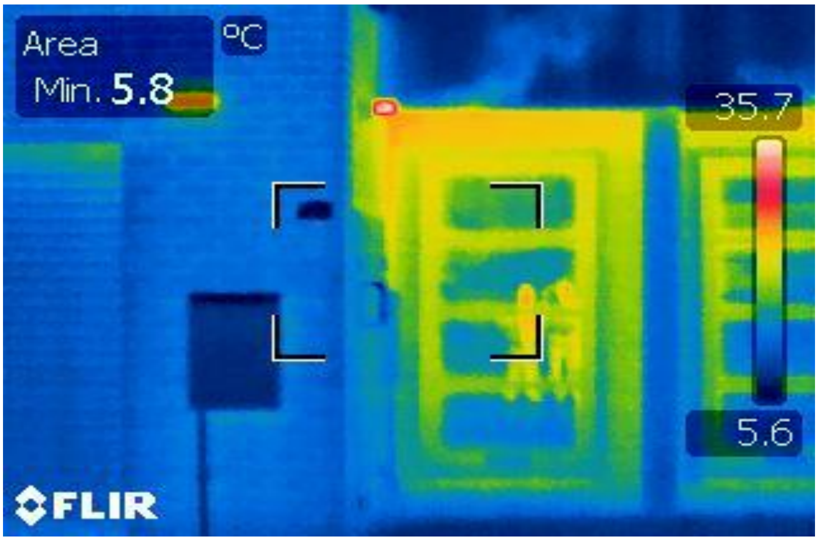


Figure 4.12 Front Door Phase 1 Heat Loss

The large amount of heat around the doorway is actually caused by exhaust gasses from the boiler flue which is trapped in the overhang. The profile of the door itself highlights the importance of material selection as heat loss is apparent in the framework of the door.

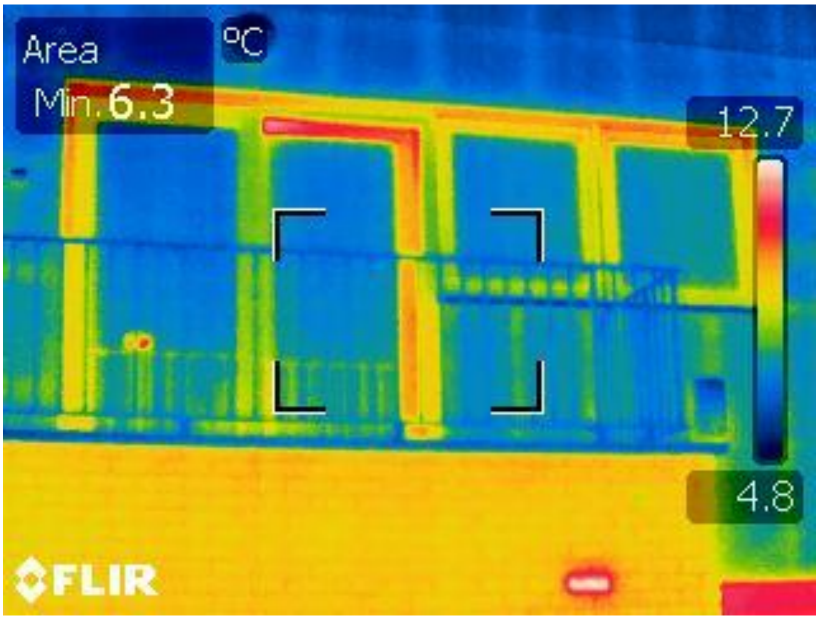


Figure 4.13 1st Floor Balcony and Windows Phase 1 Heat Loss

The heat loss around the window frames is not unusual, however the red spots indicate that there are gaps in either the framework or between the frame and the wall of the building. This is corroborated using internal images in section. The triple glazed glass of the window appears to be performing well, at its specified U-value of $1.2W/m^2K$.

The second set of 7 photos uses a single temperature scale set by an initial image and then applied to all subsequent images. This is useful as it allows quick and easy temperature comparisons, simply based on the colours of the image which indicate a specific temperature throughout the collection of photos. The 13°C max/5.5°C min variation was chosen as it clearly highlights all relevant information.

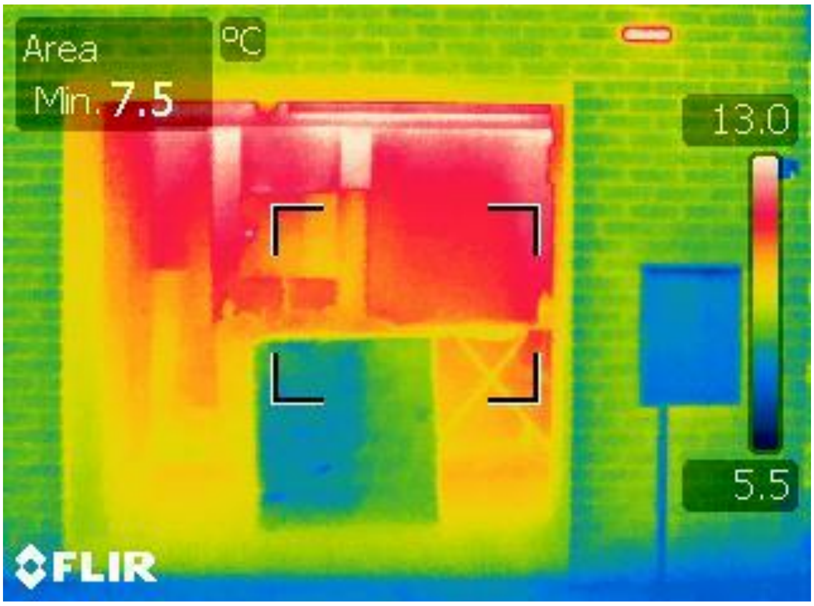


Figure 4.14 Open Garage Door Phase 1 Heat Loss

Figure 4.14 is particularly interesting as it shows considerable heat loss from an internal wall that backs directly onto the unheated garage. Further investigation finds indicate that despite the semi-exposed nature (between the house and the unheated integral garage) of the wall, the building regulation notes for Green Street specify only a 0.24 W/m^2K U-value, far greater than the U-value 0.13 W/m^2K for the external wall. While this would seem to be a serious error in design it was only in 2010 that changes to Building Regulations dictated that walls and floors formerly treated as semi-exposed must now meet the full U-value required for external walls and floors. Green Street was built to 2006 Building Regulations, thus despite the clear evidence of performance anomalies the houses actually do conform to regulations. While not visible on this picture, the roof of the garage/floor of the living room may have similar design flaws.

Figure 4.15 Front Façade of Houses Phase 1 Heat Loss

The stark contrast in temperature profile between the ground floor and first floor suggests more of a materials emissivity based error than a temperature differential.

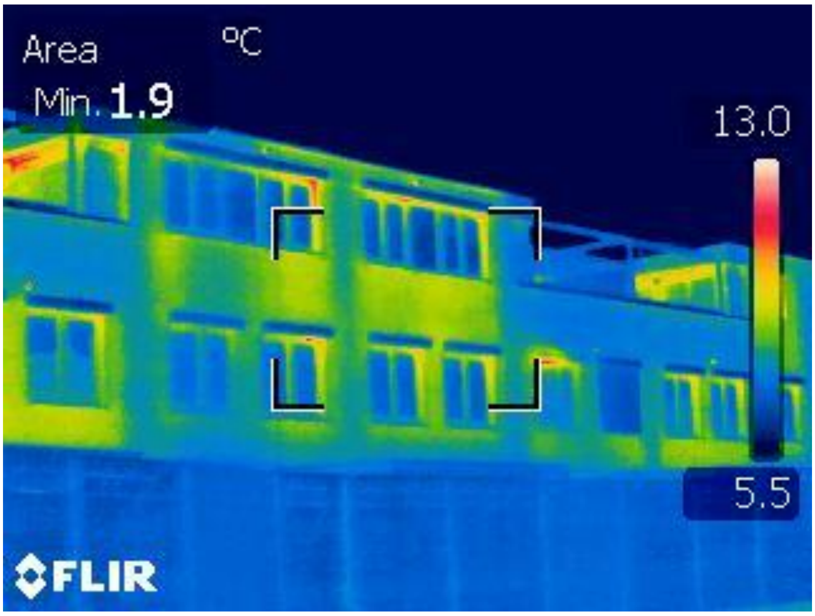


Figure 4.16 Rear view of 1st and 2nd floors, Phase 1 Heat Loss

Figure 4.16 shows warm walls on the western facade. Solar gains have been discounted here as the party wall is clearly visible between the two properties. If solar gains were the cause the temperature profile should be uniform across the facade. The walls on the 2nd floor balconies are blue as they are completely exposed on both sides. The heat loss through the walls is minimal and there are no obvious areas of thermal bridging, usually characterised by a distinct line of warmer temperature. One aspect to consider is the contrast in temperature between this western facade and the eastern facade visible in Figure 4.17 this facade appears to be uniformly warmer, but given the time of night and the location of the bedrooms this may simply suggest people are located in the bedrooms.

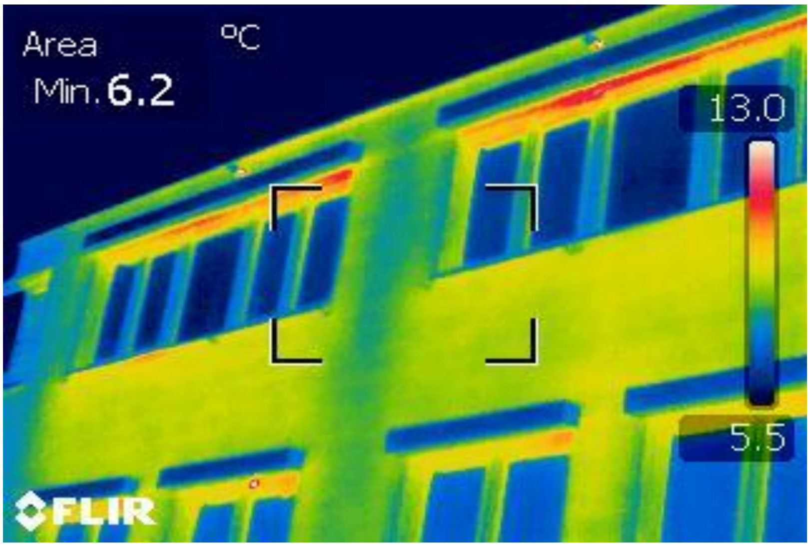


Figure 4.17 Rear view of 2nd floor, Phase 1 Heat Loss

The party wall is clearly visible here, however, no thermal bridging is evident and again the window panes are performing incredibly well. Significant heat loss is apparent in the joints at the top of the windows. This may be due to heat rising to the highest point in the frame or it may indicate gaps in the top of the frame itself.

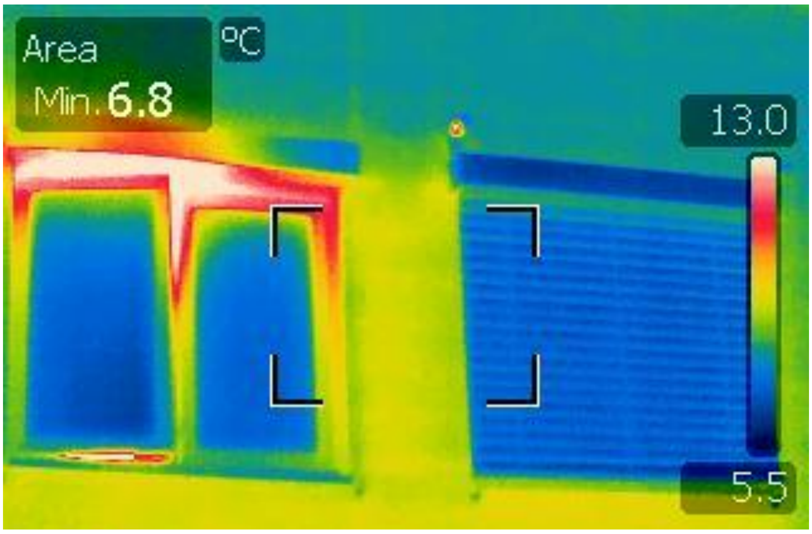


Figure 4.18 Rear view of 2nd floor, Phase 1 Heat Loss

The window on the left in Figure 4.18 has been opened by occupants. This could be due to a smell in the house, or just the desire for some fresh air, however it may infer that the occupants don't understand how the MVHR system works, as the MVHR relies on air-tightness and should provide as much fresh air as the occupants want. This could point to problems with the handover explored through a separate academic paper. (Appendix C) The solar blinds on the right hand window have an added benefit of creating an additional insulation barrier during the night.

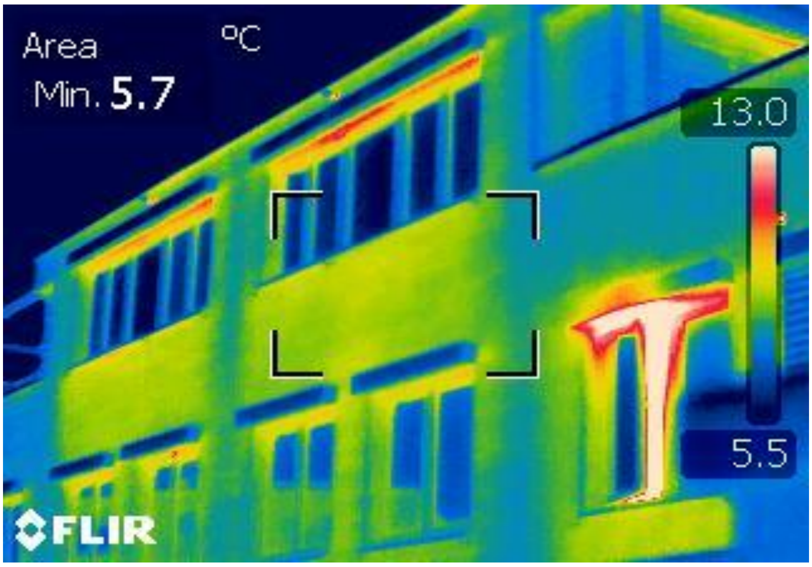


Figure 4.19 Rear view of 1st and 2nd floors, Phase 1 Heat Loss

Figure 4.19 is simply an overview of the past few images, to ensure continuity and confirm data.

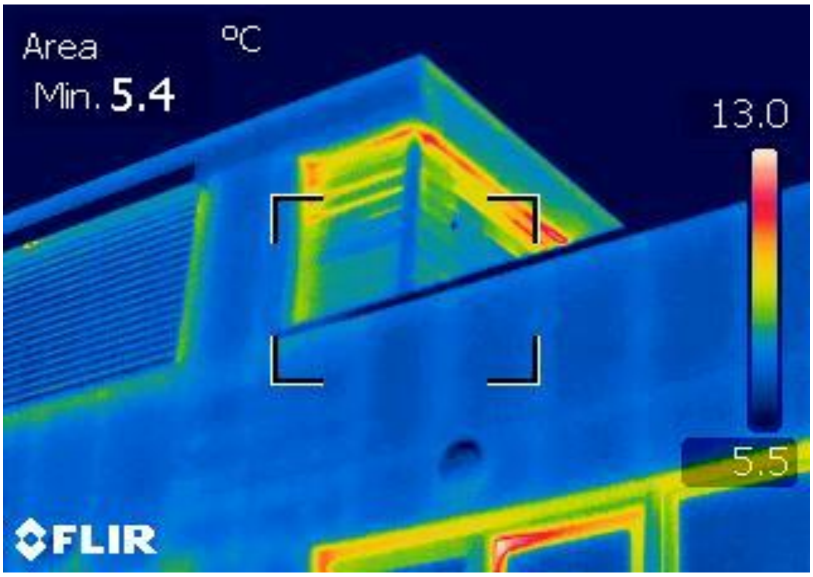


Figure 4.20 Front view of Balcony Shed Phase 1 Heat Loss

There is some unusual heat loss from a small shed located on the top floor of the dwelling. Further investigation indicates that this is most likely due to the presence of the solar PV inverter in the enclosed space.

The following is the culmination of internal thermal images from phase 1, taken on the 13/02/2014 at 19:15 in the Meadows, Nottingham. The internal images should reveal any gaps in insulation layers or thermal bridging. The environmental and material parameters are set as follows:

- Sun Set: 17:12
- Sky conditions: Clear
- Atmospheric Temperature: 5°C
- Relative Humidity: 50%
- Emissivity: 0.89 – representative of internal plasterboard used within the houses.
- Distance from target: 2-3m
- Internal Temperature of Dwellings: 23°C

The second set of internal photos from phase 1 were taken using the sliding temperature scale, identical to that used in the external phase 1 photos.

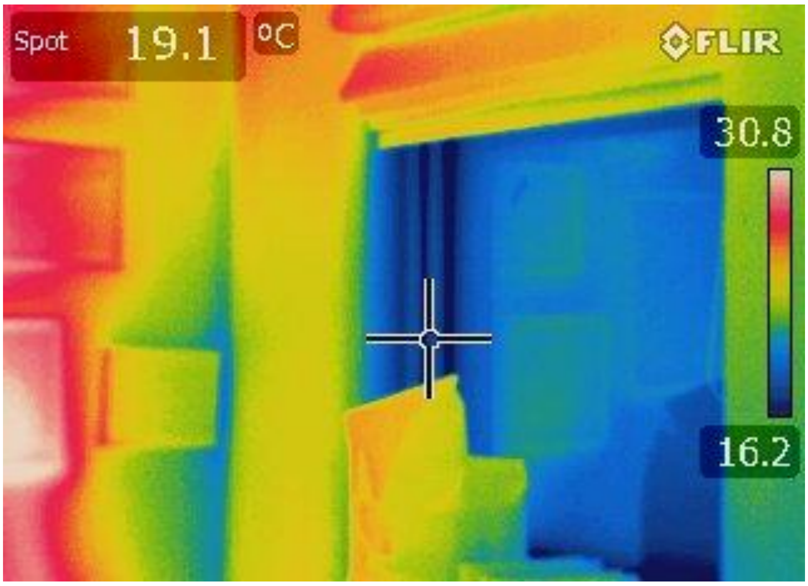


Figure 4.21 Benchmark Phase 1 Heat Loss (Window)

Upon entering the properties a number of owners remarked that the sliding doors leading to the balcony on the first floor of the properties did not fit very well and subsequently made the room very cold during the winter time. In order to test their assumptions two images were required. First Figure 4.21 depicts a standard window located adjacent to the sliding doors in the livingroom.

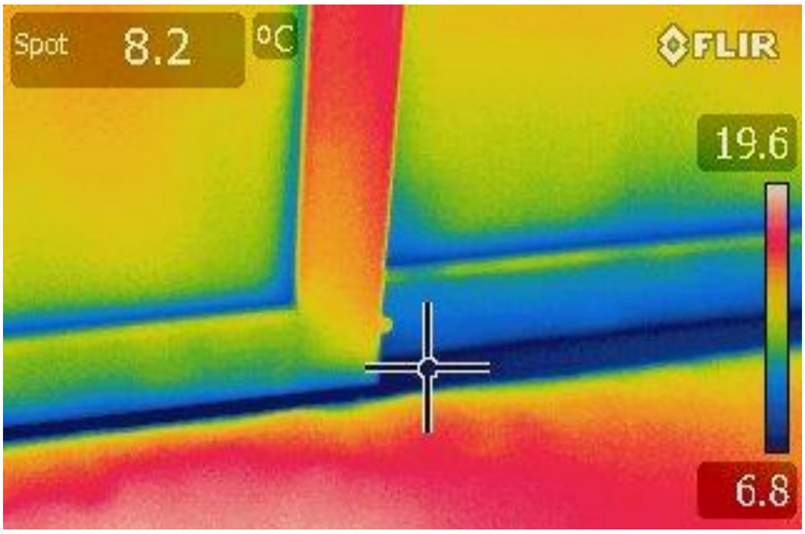


Figure 4.22 Alleged Ill-fitting Balcony Doors Phase 1 Heat Loss

The second image, Figure 4.23, highlights a dark blue area on the sliding doors, clearly depicting the seal between the doors and the house fabric. The important figures here are the spot temperatures located in the top left of the images. In the window frame image this registers at 19.1°C, whereas the door frame comes in at 8.2°C, almost a full 8°C lower. This discrepancy indicates a significant thermal bridge.

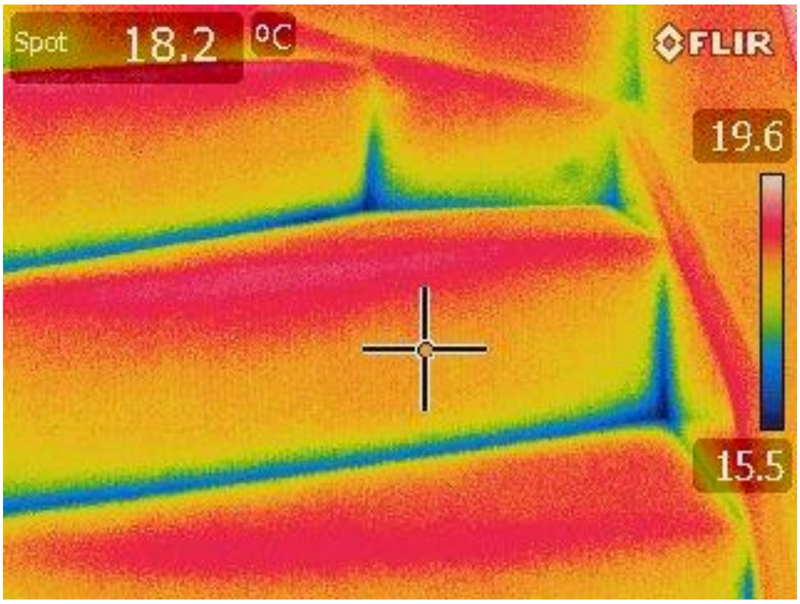


Figure 4.23 Stairs Adjacent to Unheated Garage Phase 1 Heat Loss

Already discussed from and external perspective within this section is the impact of a poorly insulated semi-exposed wall. Figure 4.23 shows how heat flows out of the dwelling more rapidly through this weak spot and the stairs adjacent to it.

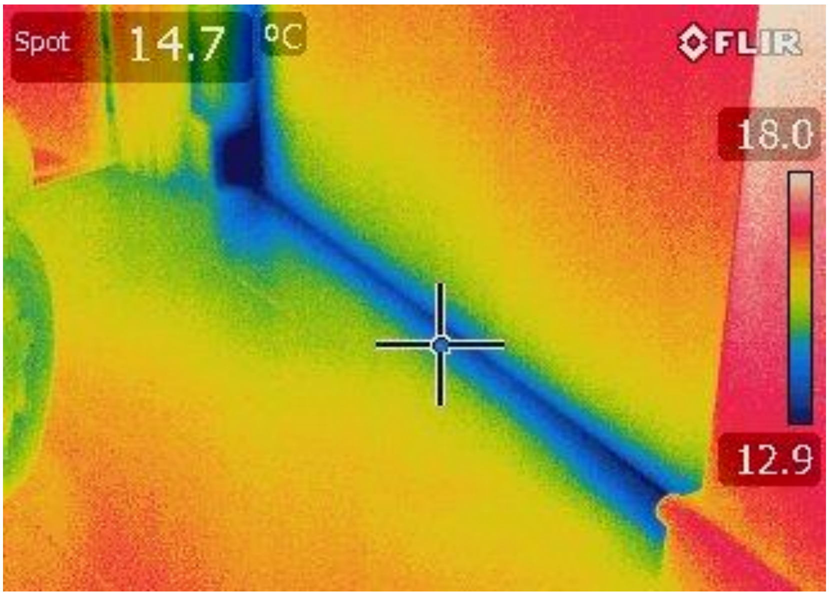


Figure 4.24 Door into Dwelling from Unheated Garage Phase 1 Heat Loss

While not directly fabric related any door leading off a semi-exposed unheated space should also conform to external U-value requirements. Failure to do so results in poorly sealed and poorly performing doors that present ideal thermal bridging potential.

Figure 4.25 Ceiling of Ground Floor Kitchen Phase 1 Heat Loss

Some of the most interesting images from the internal thermography of phase 1 come from the kitchen ceiling. The pattern of temperature differential is too irregular for it to be a single structural member. The pattern and shape of the anomaly suggest it is the result of water ingress through the external façade, and while this is supported by anecdotal comments from the occupants, no obvious source could be identified. Fundamentally if water can penetrate through the structure then significant thermal bridging will be evident, and in the case of timber construction this could also indicate a break in the water proof membrane protecting the structure or potentially and even more seriously, a lack of vapour barrier.

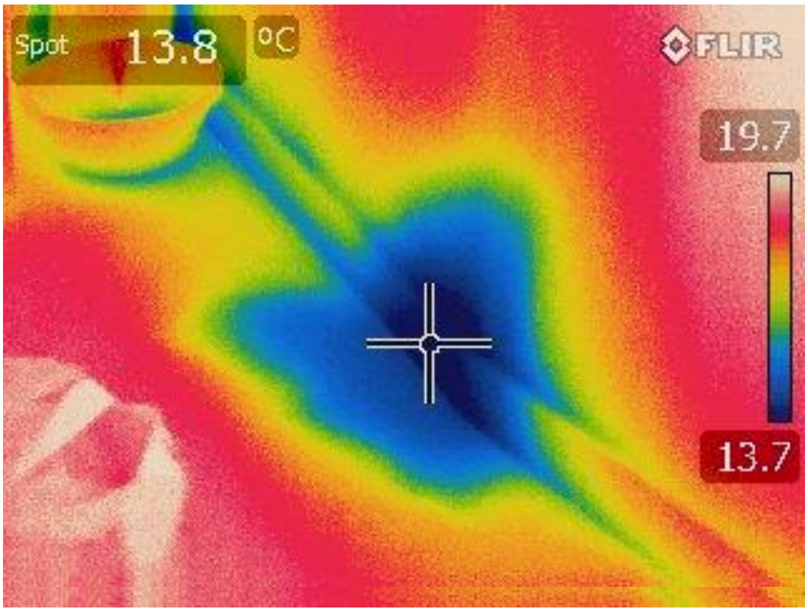


Figure 4.26 First Floor Bedroom above Kitchen Phase 1 Heat Loss

Images from the room above the kitchen corroborate the temperature differential.

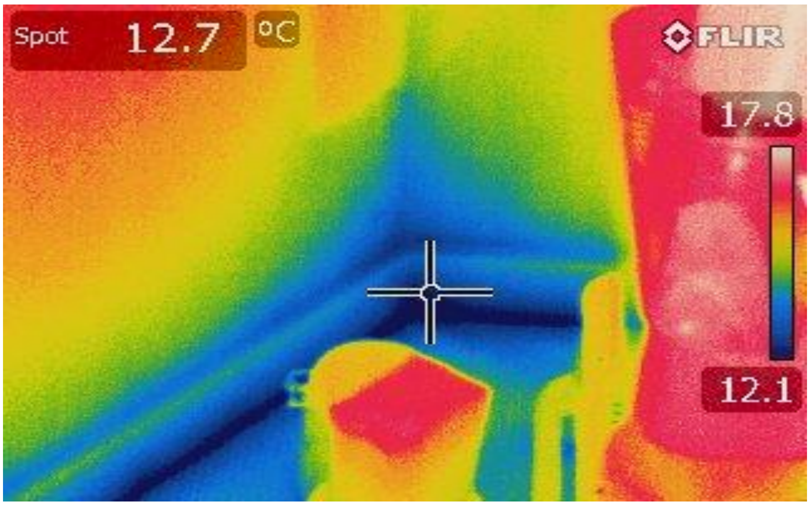


Figure 4.27 Skirting-board on Ground Floor Phase 1 Heat Loss

Common locations for thermal bridging include:

- Around low quality windows and doors
- Interior corners
- Behind furniture
- Where the building is in contact with the ground
- Rim joists
- Roof connections to the wall
- Concrete balcony penetrations through the wall
- Voids in the insulation layer

Figure 4.27 and Figure 4.28 show that despite the supposed precision advantages inherent within timber fabrication the timber frame houses of Phase 1 are not immune to the existance of thermal bridging which follows a similar pattern to its traditional masonry counterpart.

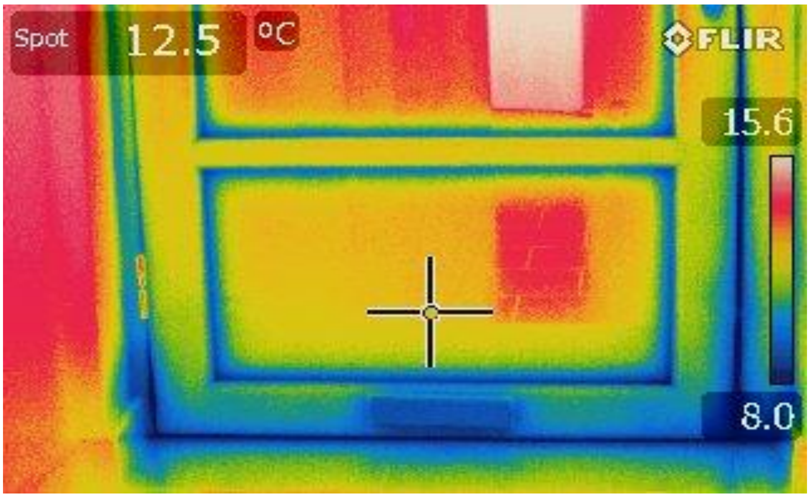


Figure 4.28 Front Door Phase 1 Heat Loss (Internal)

4.3.3.2 Thermography Testing Phase 2

The following is a compilation of regular photographs and thermal images taken on the 16/11/2011 at 22:00 in the Meadows, Nottingham depicting the external façade of Phase 2 of the case study. The photos are taken on a variable temperature scale.

The environmental and material parameters are set as follows:

- Sun Set: 16:10
- Sky conditions: Clear
- Atmospheric Temperature: 0°C
- Relative Humidity: 50%
- Emissivity: 0.81 – representative of the dry external brick facade covering the internal timber frame.
- Distance from target: 15m – This obviously varied and 15m was taken as an approximate average.
- Internal Temperature of Dwellings: 25°C

Once again windows and window frames are identified as key weaknesses in the thermal envelope of the dwellings with heat appearing to radiate predominantly from the tops of the window frames. More interesting is the evidence (highlighted by the black arrow in Figure 4.29) of a line of thermal bridging extending the height of the top floor, along the join between two dwellings.

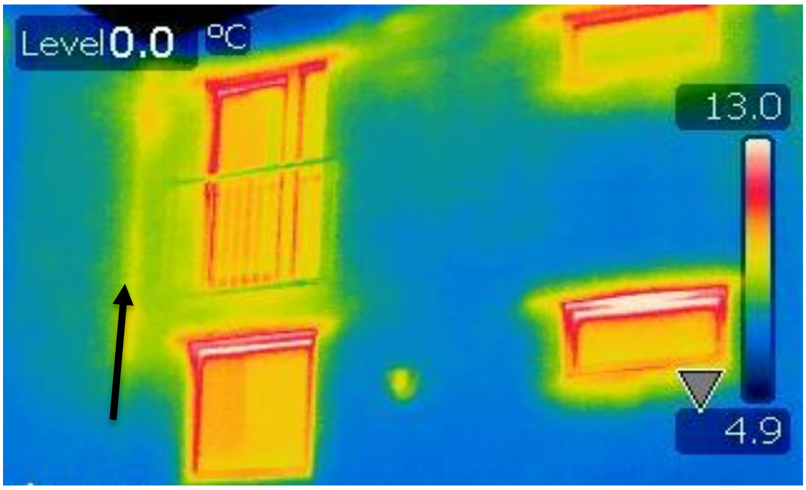


Figure 4.29 Front Façade of Phase 2 House Heat Loss

The yellow line delineates the boundary between the staggered facades of the two houses and may indicate a failure in the party wall on the top floor.

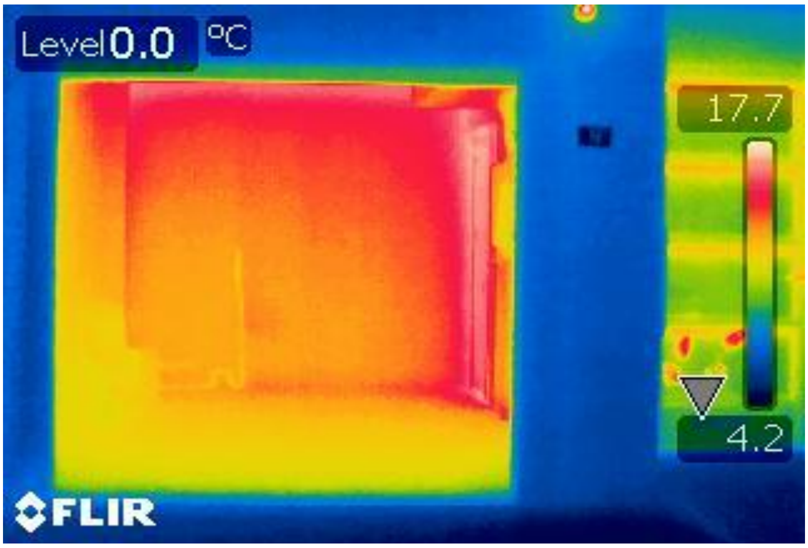


Figure 4.30 Open Garage Door Phase 2 Heat Loss

As with Phase 1, the Phase 2 houses incorporate an integral, unheated garage, and yet the semi-exposed walls within the garage are again shown to be leaking substantial amounts of heat into this space. All the heat from the living room on the other side of the wall is leaking into this semi-exposed area and subsequently through the garage door (when it is closed) and out into the night. While the garage door does act as an additional layer of insulation it is by no means the U-value standard of an external masonry wall.

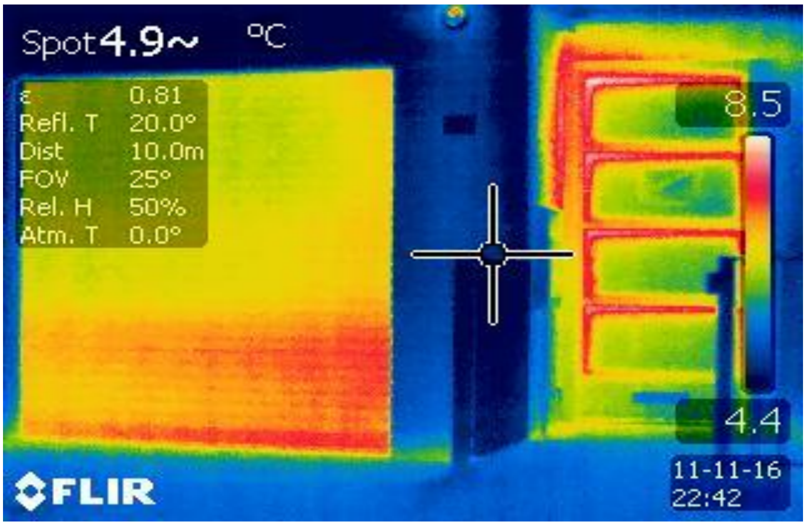


Figure 4.31 Closed Garage Door Phase 2 Heat Loss

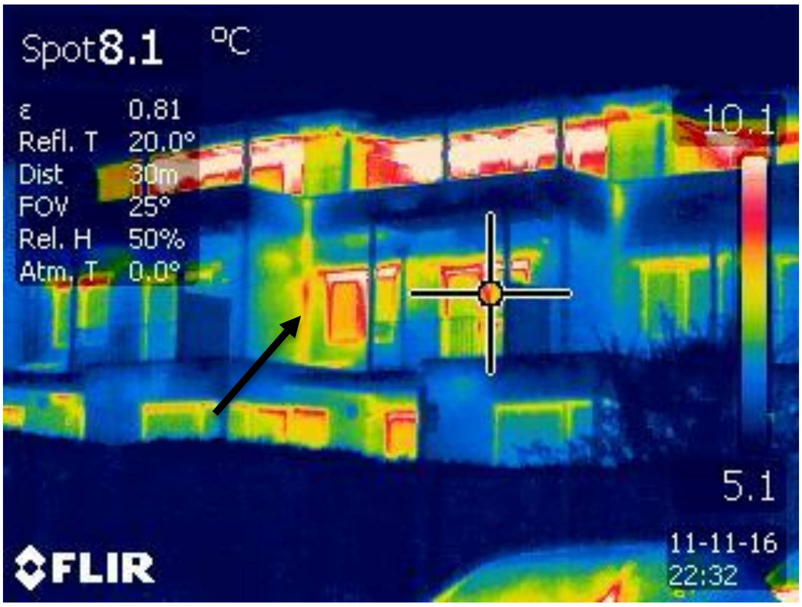


Figure 4.32 Rear Façade of Phase 2 Heat Loss

The location of the case study site and particularly Phase 2, situated directly next to a public park, means that clear thermal images of the rear of the properties were difficult to obtain. Figure 4.32, while somewhat distant, represents the best of the collection. There are obvious thermal bridging issues pictured around the windows and doors, however it is a line of warmer temperatures, highlighted by the black arrow, which confirms theories developed from Figure 4.29. This line once again falls on the border between two staggered houses and is clearly warmer than the surrounding external wall. This could represent an endemic problem with the party walls between the Phase 2 dwellings.

Moving to the internal envelope of the Phase 2 housing, thermal images were taken on the 16/11/2011 at 22:00. The photos are taken on a variable temperature scale. The environmental and material parameters are set as follows:

- Sun Set: 16:10
- Sky conditions: Clear
- Atmospheric Temperature: 0°C
- Relative Humidity: 50%
- Emissivity: 0.89 – representative of internal plasterboard used within the houses.
- Distance from target: 2-3m
- Internal Temperature of Dwellings: 25°C

The MVHR ducting in the Phase 2 houses is located within dropped-down sections of the ceiling depicted in Figure 4.33 and highlighted by the black lines. There is a temperature differential of approximately 7-8°C between the joints of this drop-down section and the rest of the internal structure of the house. Somewhere heat is leaking out of that space, unfortunately it is impossible to tell directly where without first removing the entire drop-down section, and this is understandably impossible given the occupied state of the dwellings.

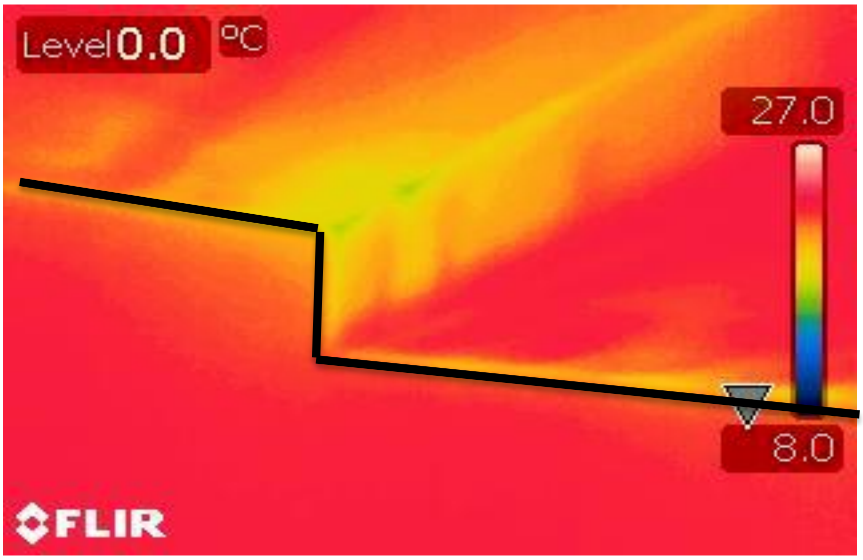


Figure 4.33 MVHR Duct Housing – Drop Down Section From Ceiling Phase 2 Heat Loss

Figure 4.34 Power Sockets Embedded in External Wall Phase 2 Heat Loss

As masonry housing is all constructed on site, fitting of electrical, gas and plumbing elements often involves cutting voids into the fabric of the house. These voids are often incorrectly sized and when coupled with an external wall, they can become significant thermal bridges and sources of air leakage. Figure 4.34 depicts a power socket installed in an external wall with clear areas of thermal leakage below the socket and extending into what appears to be a juncture in the wall.

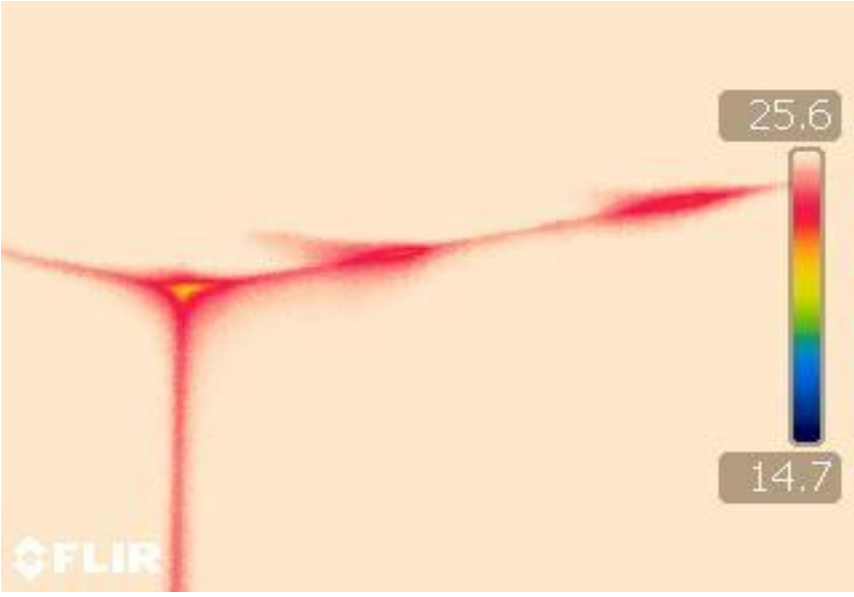


Figure 4.35 Top Floor Ceiling Joist Phase 2 Heat Loss

While thermal bridging at the juncture of the wall and ceiling is not too unusual, the regular pattern of the thermal inconsistency seems to suggest this has something to do with structural supports rather than a void through the insulation layer demonstrated by a clear and relatively uniform line between the floor to wall join in Figure 4.36.

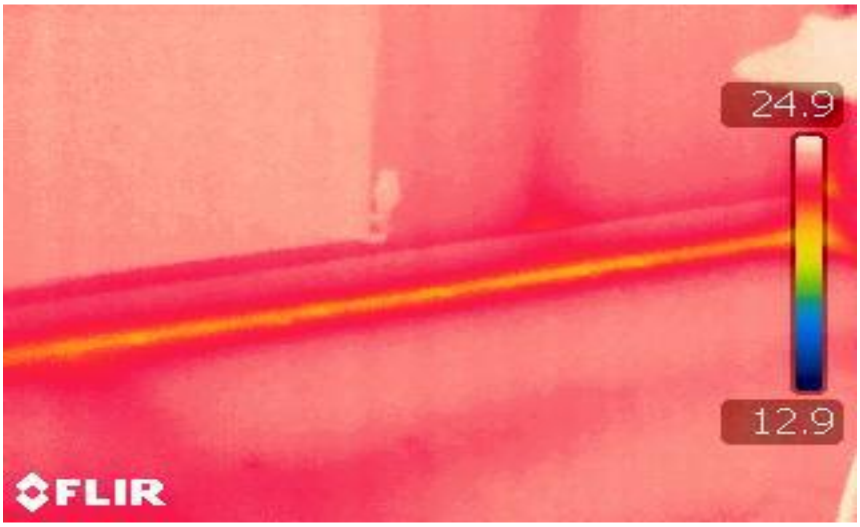


Figure 4.36 Floor to Wall Joint – Uniform Heat Loss Phase 2

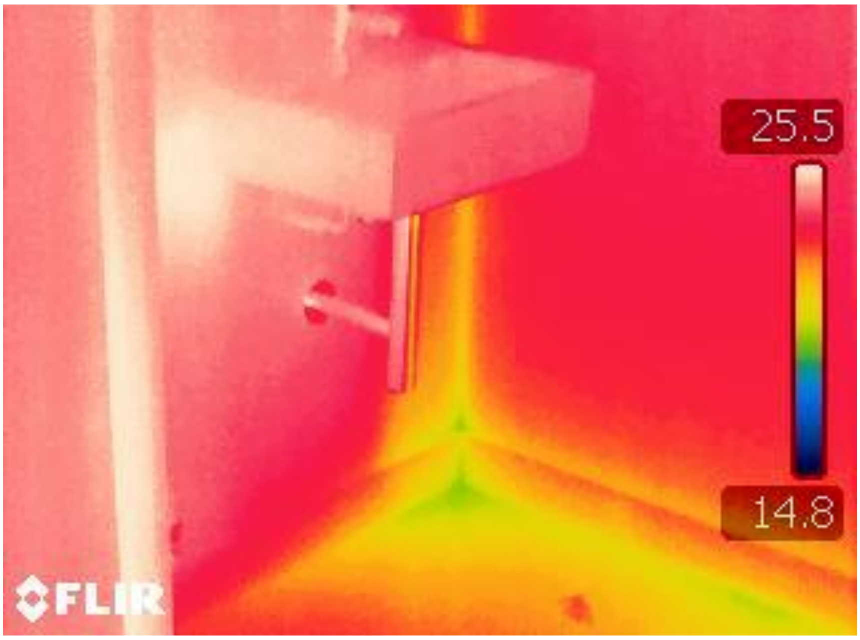


Figure 4.37 Floor to Wall Corner Phase 2 Heat Loss

The fabric monitoring tests are designed to help distinguish what flaws are inherent in the construction process and materials and what can be attributed to the other variables such as occupant interaction. One way to achieve this is through thermographic testing, which can help to identify systematic flaws in the construction process such as thermal bridging or infiltration. In this way the thermographic analysis was instrumental in diagnosing faults exposed through the air permeability testing and provided valuable evidence leading to a discussion on the Regulations surrounding internal garages.

Due to the semi qualitative nature of the thermography testing, a direct comparative analysis between the two construction types would be invalid, however the thermographic survey found no evidence to suggest significant thermal bridging. That being said, the key conclusion from the testing procedure is the ubiquitous existence of what would be seen in the industry as common areas of thermal ingress. This discovery adds credence to the theory that the construction phase of these houses was generally treated like any other development and in sustainable construction, where the tolerances and standards are so much higher than in the past, this is simply not an option.

4.4 Fabric Testing Conclusions

Chapter 4 defines both the nature of the quantitative testing and the results and conclusions drawn from the data collected through that testing procedure. Used in conjunction with the environmental monitoring data and SAP review, in the following the rest of the study they can reveal any irregularities concerning established industrial benchmarks and the gap in performance between design and reality.

The results and conclusions are broken down into 3 distinct sections, the chapter starts off with the results from a number of air permeability tests conducted on both phases. Quite unexpectedly the observational analysis of the air permeability testing procedures revealed some troubling practices on the part of the industry contractors completing the tests. Air testing contractors simply allowed site contractors to quickly patch gaps in the test houses over and over again until the house in question passed its design air permeability. But this brings up two points. First, how do the contractors know for sure that the original test values did not fail the DER/TER ratio if there was no consultation of the SAP documents (if it did fail, then the entire site would be subject to the re-testing protocol.) Furthermore if contractors follow this method of immediate re-testing there is nothing in the regulations that requires them to go into the other houses on the development and implement the remedial measures that they just put into the test houses to get them to pass. Ultimately these actions were deemed to be the result of poor regulations and the actual manner in which the airtightness procedures are conducted which puts un-due pressure on the tester to re-test because if they don't then they will get a reputation as not being lenient and costing more, thereby putting them at an industrial disadvantage. Fundamentally there needs to be greater emphasis on that first test – if it fails this is significant and representative of the entire site and should therefore have ramifications for the entire site.

Once the practicalities of the testing procedure were dealt with, the actual test results averaged across the fabric types reveal that the timber housing overall performs worse than its masonry counterpart – at odds with existing research. While many practical reasons for the discrepancies between design and reality in the timber frame housing were put forward, it was comments by Julian Marsh which seemed to encapsulate the core reason – a lack of relevant skills. "*Until we can get the same level detail and focus that you get in the factory, actually on site when the thing arrives then the performance benefits theoretically associated with TPC will struggle to be realised."*

In the co-heating phase of the study a representative house from each construction type was chosen to undergo the invasive testing procedure. Unfortunately equipment failure initially rendered the tests useless, but through this failure there evolved a testing procedure which ultimately could solve many of the inherent problems now associated with the co-heating test methodology – the night time methodology. Covered in detail within the main body of the chapter, the night time method uses only night time temperature and energy data to mitigate the need for complicated solar correction methods. It uses a calculation called the Solar Gains Threshold which takes into account the thermal time constant and endeavors to limit the data collection to as close to a thermally steady state period as possible. Using the adjusted night time method it is possible to conclude that the masonry housing proportionally outperforms the timber frame construction with less than half the gap between design and performance - 59.1% (timber) and 31.85% (masonry). Further study is required to determine the exact origins of such a large discrepancy in performance, however it is likely to be caused by the same poor site practice discussed in conjunction with the air permeability testing, although other variables are suggested.

Following on from the co-heating tests, the thermography study of Green Street was used to identify areas of thermal bridging or infiltration, thereby diagnosing faults exposed through the air permeability testing and prompting a discussion on the regulations surrounding internal garages. Ultimately, the thermographic survey found no evidence of excessive thermal bridging in either phase. That being said, the key conclusion from the testing procedure is the ubiquitous existence of what would be seen in the industry as "common areas of thermal ingress." This discovery adds credence to the theory that the construction phase of these houses was generally treated like any other development and in sustainable construction where the tolerances and standards are so much higher than in the past this is simply not an option.

5 Standard Assessment Procedure

Post occupancy evaluation is used in two distinct ways within this thesis. There is the comparison between two different building fabrics, and there is the comparison between the design intentions of the dwelling and its delivery or performance in reality – the gap in performance. For the second method there must be a baseline that defines the design intentions in a quantifiable manner. The baseline for this project is constructed through a combination of the architect's specification documents and a Government model for quantifying, assessing and comparing the theoretical energy performance of homes – SAP.

Despite the fact that SAP is fully incorporated into UK Building Regulations (Part L1A) there is evidence to suggest that it simply is not fit for purpose and represents an over simplistic tool in the modern era of sustainable construction. (Kelly, et al., 2012) This section also presents evidence that seems to support this position, however, the goals of this project and the requirements of housing research at large dictate its use, despite being conscious of its shortcomings. The following sections explain the reasoning behind this seemingly counterintuitive assumption.

5.1 SAP Review

The Standard Assessment Procedure (SAP) is a computational model used to assess the DER and TER of a planned dwelling and therefore demonstrate compliance with building regulations and sustainable legislation (BRE, 2005). Developed by the Building Research Establishment in 1992 and first published in 1995 it was founded on the BRE's Domestic Energy Model (BREDEM) – "a method for estimating the energy consumption in dwellings, providing an energy calculation that is substantially better than simple procedures such as design heat loss, but is considerably simpler to use than detailed simulation models." (Anderson, et al., 2001, p. 1)

The SAP calculations take into account a number of building characteristics, which are then used to generate figures for energy usage and associated CO_2 emissions. These characteristics include (DECC, 2013):

- Thermal insulation of built fabric
- Thermal mass
- Ventilation characteristics of the building and the ventilation equipment
- Efficiency and control of heating systems
- Solar gains through glazed areas
- Fuels used to provide space and water heating, ventilation and lighting
- Internal heat gains through lighting, cooking and occupation
- Renewable energy technologies

Once the energy performance of a dwelling is established SAP incorporates the figures into Building Regulations Part L to assess energy performance and carbon emissions resulting in solutions for the Dwelling Emission Rate (DER*)* and Target Emission Rate (TER) (DTLR, 2001). As well as playing an integral part of building regulations, SAP is also an important component of many other government policies, including modelling emissions of new build homes for carbon budgets (DCLG 2007; Monahan, 2013) and "providing accurate and reliable assessments of dwelling energy performance that are needed to underpin energy and environmental policy initiatives" (DECC, 2013).

SAP reviews ultimately produce a value between 0-100, this represents an overall level of energy efficiency associated with the dwelling; the higher the SAP number the better the performance. "These SAP values are calculated in order to not be affected by differences in the number of people in the building, the floor area, the ownership of domestic appliances or the geographical location of the building" (Spataru et al. 2010 p.150). Specifically important in this project are the fabric related calculations as they are directly attributable to the timber frame and masonry structures. In this respect SAP provides a number of outputs such as a whole house heating value, air permeability rating and the U-value of individual components which make up the housing envelope (BRE, 2005).

SAP was designed as a building performance modelling tool, with greater substance and scope than a simple heat loss model, but still based on a framework which could be replicated on a spreadsheet or even printed in hardcopy. Modern versions of the SAP software are varied (NHER, EES Design, Sapper and Stroma) and numerous but still based around the fundamental SAP structure. It is this varied nature that represents one of the criticisms of SAP as a ubiquitous benchmarking tool in that the subtle differences of each software (assumptions and defined values etc.) can affect and influence the final output values. Thus we find SAP is by no means an infallible method of benchmarking the design stage performance levels of a dwelling, however it is the most widely used and widely recognized performance modelling tool in the UK housing industry. As early as 1995 Oreszczyn and Gillott (Oreszczyn & Gillott, 1995) reported on the inadequacies of the SAP methodology, and whilst SAP has been incrementally modified over the last 20 years, research by Monahan (2013) elaborates on some of the continuing criticisms levelled against the process:

- Many of the assumptions and calculations that drive the SAP data sheet are based on data collected in the 1980's from houses built to 1980's standards. Modern housing is far more thermally efficient, with advanced heating systems, intelligent controls and complex boilers potentially rendering some of the supporting data inaccurate.
- The sustainable trend of modern dwellings is led by a fabric first approach incorporating super insulated, airtight design that consequently increases the impact of incidental gains such as lights and appliances. SAP in representing these gains assumes a historical energy value that often exceeds the energy load associated with modern lighting and machines. In addition to these overestimations, the simplistic nature of the SAP calculations does not allow for detailed analysis of solar gains and the effects of thermal mass.
- Assumptions made for the outputs of renewable energy technologies such as PV and solar hot water tend to be optimistic when compared with the default values used for efficiency measures such as low energy pumps, or light emitting diodes (LED) lighting, super insulated pipe work. This has led to accusations of the method favouring technology over efficiency encouraging the installation of "bolt on solutions" as opposed to sustainable measures contained within the structure itself – which tend to have a longer lasting impact.

While 2005 and 2009 saw incremental revisions of the SAP model, the existence of these anomalies, however small, are cause for concern as the majority of post occupancy evaluation projects, this one included, use SAP as the foundation for their gap-in-performance calculations, based on the fact that it is purported as giving accurate and reliable assessments of dwelling energy performance.

Beyond the general faults and failings of SAP as a performance analysis tool there are actual problems with the SAP analysis conducted on this particular site.

Phase 1:

- No accounting for integral garage and heat lost into that space.
- No scope to omit heat gains from water heating even though the boiler is located in unheated space.
- Internal gains from lights, appliances, water heating etc. remains the same across all the housing despite various configurations and sizes.
- Ventilation contributes a proportionally tiny amount towards heating losses. This may be a broader failing of SAP as opposed to a site specific problem.

Phase 2:

- The SAP calculations for House 6 incorporated solar gains from the west – the western facing wall is a party wall (similar findings in the rest of phase 2.)
- Heat loss perimeter and HLC is exactly the same for house 6 as house 8 despite one being a semi-detached house and one being a mid-terrace.
- The as-built water estimates to take no account of the number of occupants or their demographic. This may be a broader failing of SAP as opposed to a site specific problem.
- Despite the houses having varying amounts of solar panels and therefore electricity generating potential (installed before the "as built" final SAP assessment) the energy produced or saved by PV is exactly the same across the houses.

Individually these issues may not have much of an impact on the overall performance of the house, but it is hard to suggest that together they still remain innocuous. Furthermore, in principle, it is simply wrong. The development of an environmentally conscious dwelling must take on board and ethos of precision and responsibility throughout all stages of the program. The simplicity of some of the mistakes highlighted at Green Street shows a simple disregard for the importance of design stage predictions, a disregard that cannot be afforded in a modern era of performance driven construction. These are just a few of the immediately visible faults with the original SAP analysis, given access to the raw data sheets used by the NHER assessor would no doubt uncover further discrepancies.

Despite discovering that there are faults within the SAP process the thesis will still utilize the design values as a benchmark for the gap in performance analysis. There are two reasons for this somewhat controversial decision.

1. There has to be a design value benchmark. It is impossible to analyse the environmental gap in performance when there are two independent variables – the design value and the built data. One of the variables must be static and without SAP it is impossible to calculate a gap in performance because the design value is missing.

2. SAP represents by far the largest and most standardized form of design performance benchmarking (Kelly, et al., 2012). The majority of others doing similar research will use SAP data from the case study dwellings as their design value benchmarks because this is the only standardized, government supported methodology for such a task. The alternative is everyone models their research case study houses in different software under varying degrees of accuracy. Any cross project comparisons are then subject to yet another level of de-standardisation, one of the greatest hurdles facing housing research.

5.2 SAP Re-work Methodology

The methodological approach for the SAP analysis is taken directly from Domestic Guidance for Project Execution (TSB (b), 2011) with the exception of the actual analysis of results which is tailored to the goals of this project

Step 1

Initiate a review of the SAP calculations to ensure these accurately reflect the design of the dwelling and to identify any aspects of the design that one would expect to affect performance but are not captured adequately in the SAP calculations. This should confirm the 'as designed' performance profile of the dwelling.

Step 2

Once measured data is available, create working SAP files into which the data (such as airtightness) can be fed, thus developing an 'as built' performance profile. This is done though the NHER Plan Assessor software chosen through a rigorous analysis of approved software providers including EES Design SAP, Stroma FSAP and SAPPER (BRE, 2013).

Once completed, a comparison of the data from each step returns values for the actual against designed performance gap relating to key relevant variables impacted by the construction type or material. The performance gap information will be used to establish which construction type is better at turning design into reality.

Having established the position of this research paper in terms of the SAP design values, step 2 of the SAP review calls for the creation of working SAP files into which the data from the environmental monitoring portion of the research project can be fed. The purpose of this is not to calculate the gap between design and performance. This is already evident through a simple comparison between the SAP design data and the environmental performance data. The purpose in developing working SAP files is to take this established gap in performance one step further by calculating the impact of the reality based values on the overall performance, pollution and environmental credentials of the dwelling.

Unfortunately, the original raw data used to construct the SAP sheets was unavailable thus the SAP profile for each individual house had to be reverse engineered to uncover the correct input values for the NHER software (which was matched to the original NHER version used for the site.) Once a modifiable SAP profile was completed, three variables recorded through the data analysis were substituted one at a time into the NHER program to establish the individual and eventually the collective impact of the actual vs. design characteristics. These three variables include:

Measured data insertion – Airtightness SAP Re-work

				Air changes per hour	
Infiltration due to chimneys, flues and fans	(7) + (8) + (9) + (9a) =	0	÷ (6) =	0.00	(10)
If a pressurisation test has been carried out, proceed to box (19)					
Number of storeys in the dwelling		N/A	(11)		
Additional infiltration			[(11) - 1] x 0.1 =	N/A	(12)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction				N/A	(13)
If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0				N/A	(14)
If no draught lobby, enter 0.05, else enter 0				N/A	(15)
Percentage of windows and doors draught stripped		N/A	(16)		
Window infiltration			0.25 - [0.2 x (16) ÷ 100] =	N/A	(17)
Infiltration rate			(10) + (12) + (13) + (14) + (15) + (17) =	N/A	(18)
If based on air permeability value, then [q50 ÷ 20] + (10) in (19), otherwise (19) = (18)				0.15	(19)
Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used					

Figure 5.1 Measured data insertion – Airtightness SAP Re-work

Measured data insertion – HLC SAP Re-work

3. Heat losses and heat loss perimeter	Net area (m²)		U-value		AxU (W/K)	
Windows*	29.64	x	1.10	=	32.58	(27)
Doors	2.10	x	3.00	=	6.31	(26)
Ground floor	31.60	x	0.15	=	4.74	(28)
Upper floor	15.30	x	0.25	=	3.83	(28)
Walls	43.22	x	0.13	=	5.62	(29)
Walls	15.45	x	0.25	=	3.86	(29)
Roof	46.90	x	0.11	=	5.16	(30)
Total area of elements	184.21	(32)				
**for windows and rooflights, use effective window U-value calculated as given in paragraph 3.2*						
Fabric heat loss			(26) + (27) + (28) + (29) + (30) =		62.10	(33)
Thermal bridges - calculated using Appendix K					14.74	(34)
if details of thermal bridging are not known calculate y x (32) [see Appendix K] and enter in (34)						
Total fabric heat loss			(33) + (34) =		76.83	(35)
Ventilation heat loss			(25) x 0.33 x (6) =		20.39	(36)
Heat loss coefficient			(35) + (36) =		97.22	(37)
Heat loss parameter (HLP), W/m²K			(37) ÷ (5) =		0.91	(38)

Figure 5.2 Measured data insertion – HLC SAP Re-work

Measured data insertion – Annual Main Fuel Requirement SAP Re-work

9. Space heating requirement		kWh/year	
Space heating requirement (useful)	0.024 x (80) x (37) =	1753.49	(81)
9a. Energy requirements - individual heating systems			
Space heating			
Fraction of heat from secondary/supplementary system using value from Table 11, Appendix F or Appendix N		0.00	(82)
Efficiency of main heating system, %		90.20	(83)
SEDBUK or from Table 4a or 4b, adjusted where appropriate by the amount shown in the 'efficiency adjustment' column of Table 4c			
Efficiency of secondary/supplementary system, %		0.00	(84)
use value from Table 4a or Appendix E			
Main fuel requirement, kWh/year	[(1 - (82)] - (81) x 100 ÷ (83) =	1944.00	(85)
Secondary fuel requirement, kWh/year	(82) x (81) x 100 ÷ (84) =	0.00	(85a)

Figure 5.3 Measured data insertion – Annual Main Fuel Requirement SAP Re-work

Once completed, a comparison of the data from each step returns values for the actual vs. designed performance gap relating to key relevant variables impacted by the construction type or material. The performance gap information can then be used to establish which construction type in reality more closely follows its designed performance intentions.

5.3 SAP Re-work Results and Discussion

The somewhat complex structure of Table 5.1 – Table 5.4 warrants the following explanation.

For each house, the SAP values for each of the performance benchmarks has been taken from the design documents and places in the column – SAP Benchmark; these include the air permeability, heat loss coefficient and space heating energy requirement. The SAP Benchmark column represents the values that each house should achieve if it were built perfectly, as designed.

The three other columns – measured ventilation, measured HLC and measured fuel – represent the substitution of actual post-occupancy data into a recreation of the original SAP sheets. The numbers highlighted in yellow represent the reality of how the house is performing for each of the variables. For example, in the column "Measured Ventilation" for House 1, testing of the house after it was constructed revealed that actually the air permeability was rated at 4.49 ($m^3/(h.m^2)$)@50Pa rather than the 3 ($m^3/(h.m^2)$)@50Pa from the design SAP documents.

The second portion of the table, below the dark black line, portrays what happens to the performance statistics of the house when the as constructed performance data, highlighted in yellow, is substituted back into the SAP documents. This is done on a variable by variable basis to better understand the extent that each one impacts the overall performance of the house. For example, in house 3 it is clear that the increase in air permeability from 3 ($m^3/(h.m^2)$)@50Pa to 3.87 ($m^3/(h.m^2)$)@50Pa has little effect on the SAP rating. However the difference between the design fuel requirement and the as constructed fuel requirement results in a difference in 6 points for the SAP rating and over double the design rated CO_2 Emissions.

	House 1 Model				House 2 Model			
SAP 2005 Assessment	**SAP Benchmark**	**Measured Ventilation**	**Measured HLC**	**Measured Fuel**	**SAP Benchmark**	**Measured Ventilation**	**Measured HLC**	**Measured Fuel**
Ventilation ($m^3/(h.m^2)$)@50Pa	3	4.49	3	3	3	7.07	3	3
HLC (W/K)	109.73	109.73	154.76	109.73	97.22	97.22	154.67	97.22
Main Fuel Requirement (kWh/yr)	2322.3	2322.3	2322.3	6661.44	1944	1944	1944	5572.58
SAP Rating	90	90	87	84	90	90	87	85
Environmental Impact Rating	92	92	89	85	93	92	88	86
CO_2 Emissions (kg CO_2/yr)	1032	1071	1424	1874	852	964	1345	1557
DER (kg CO_2/m^2/yr)	10.21	10.58	13.8	16.65	9.82	11.03	15.05	16.07
TER (kg CO_2/m^2/yr)	20.1	20.1	20.21	20.1	20.19	20.19	20.34	20.19
CSH Level	4	4	3	1	4	4	3	2

Table 5.1 SAP Re-work Results Phase 1 – House 1 and 2

	House 3 Model				House 4 Model			
SAP 2005 Assessment	**SAP Benchmark**	**Measured Ventilation**	**Measured HLC**	**Measured Fuel**	**SAP Benchmark**	**Measured Ventilation**	**Measured HLC**	**Measured Fuel**
Ventilation (m³/(h.m²))@50Pa	3	3.87	3	3	3	N/A	3	N/A
HLC (W/K)	97.22	97.22	154.67	97.22	97.22	N/A	154.67	N/A
Main Fuel Requirement (kWh/yr)	1944	1944	1944	6406.88	1944	N/A	1944	N/A
SAP Rating	90	90	87	84	90	N/A	87	N/A
Environmental Impact Rating	93	92	88	85	93	N/A	88	N/A
CO_2 Emissions (kg CO_2/yr)	852	865	1345	1719	852	N/A	1345	N/A
DER (kg CO_2/m²/yr)	9.82	9.97	15.05	17.51	9.82	N/A	15.05	N/A
TER (kg CO_2/m²/yr)	20.19	20.19	20.34	20.19	20.19	N/A	20.34	N/A
CSH Level	4	4	3	1	4	N/A	3	N/A

Table 5.2 SAP Re-work Results Phase 1 – House 3 and 4

	House 5 Model				House 6 Model			
SAP 2005 Assessment	**SAP Benchmark**	**Measured Ventilation**	**Measured HLC**	**Measured Fuel**	**SAP Benchmark**	**Measured Ventilation**	**Measured HLC**	**Measured Fuel**
Ventilation ($m^3/(h.m^2)$)@50Pa	3	N/A	3	3	3	5.62	3	3
HLC (W/K)	129.47	N/A	169.67	129.47	128.2	128.2	169.67	128.2
Main Fuel Requirement (kWh/yr)	2155.16	N/A	2155.16	11319.48	2115.29	2115.29	2115.29	9023.4
SAP Rating	89	N/A	87	77	89	89	87	80
Environmental Impact Rating	91	N/A	89	77	91	91	89	80
CO_2 Emissions (kg CO_2/yr)	1101	N/A	1373	2890	1093	1164	1373	2433
DER (kg CO_2/m^2/yr)	11.15	N/A	13.83	25.81	11.07	11.78	13.83	22.06
TER (kg CO_2/m^2/yr)	22.82	N/A	22.91	22.82	22.53	22.53	22.63	22.53
CSH Level	4	N/A	3	0	4	4	3	0

Table 5.3 SAP Re-work Results Phase 2 – House 5 and 6

	House 7 Model				House 8 Model			
SAP 2005 Assessment	**SAP Benchmark**	**Measured Ventilation**	**Measured HLC**	**Measured Fuel**	**SAP Benchmark**	**Measured Ventilation**	**Measured HLC**	**Measured Fuel**
Ventilation ($m^3/(h.m^2)$)@50Pa	3	4.08	3	3	3	3.87	3	3
HLC (W/K)	140.85	140.85	169.67	140.85	128.68	128.68	169.67	188.68
Main Fuel Requirement (kWh/yr)	2287.94	2287.94	2287.94	10383.12	2235.26	2235.26	2235.26	13754.02
SAP Rating	89	89	88	79	89	89	87	74
Environmental Impact Rating	91	91	89	78	91	91	89	73
CO_2 Emissions (kg CO_2/yr)	1127	1151	1310	2697	1122	1132	1411	3356
DER (kg CO_2/m^2/yr)	11.37	11.61	13.17	24.14	11.27	11.38	14.07	29.24
TER (kg CO_2/m^2/yr)	22.53	22.53	22.6	22.53	22.88	22.88	22.98	22.88
CSH Level	4	4	3	0	4	4	3	0

Table 5.4 SAP Re-work Results Phase 2 – House 7 and 8

Table 5.1 - Table 5.4 build on the research of the previous sections in order to give a clear view of the gap between predicted design performance and the reality of performance characteristics recorded from the final product. Not all the data can be analyzed in this way as not all the variables explored in this research report are benchmarked through the SAP analysis stage, however the following attributes are:

- Air Permeability
- Heat Loss Coefficient
- Total Space Heating Energy

The nature of most dedicated research houses, built and operated under often heavily controlled and academic conditions, makes calculating a gap in performance inherently flawed as the performance is often intentionally manipulated or unintentionally controlled. The Green Street housing project on the other hand was built as a mainstream development, subject to the same financial constraints, requirements and deadlines as many other housing developments. Thus, not only is this data rare, but the measured gap between design and performance is a much clearer reflection of the reality faced by other mainstream developments.

The tables also reveal how the actual performance values would impact the original design ratings, calculated through SAP. In some cases the impact is huge and results in a significant and dramatic divergence from the original design intentions. The main fuel requirement and corresponding measured fuel value represent the collective impact of air permeability, insulation and unquantifiable variables such as human impact on the total energy required for space heating and the associated CO_2 emissions.

Government figures suggest the average domestic gas consumption for UK dwellings in 2012 was around 15,257 kWh/annum. (DECC, 2013, p. 5) Thus despite the massive difference between design and reality, particularly in the case of the phase 2 houses, all dwellings in the case study fall well below the national ratings.

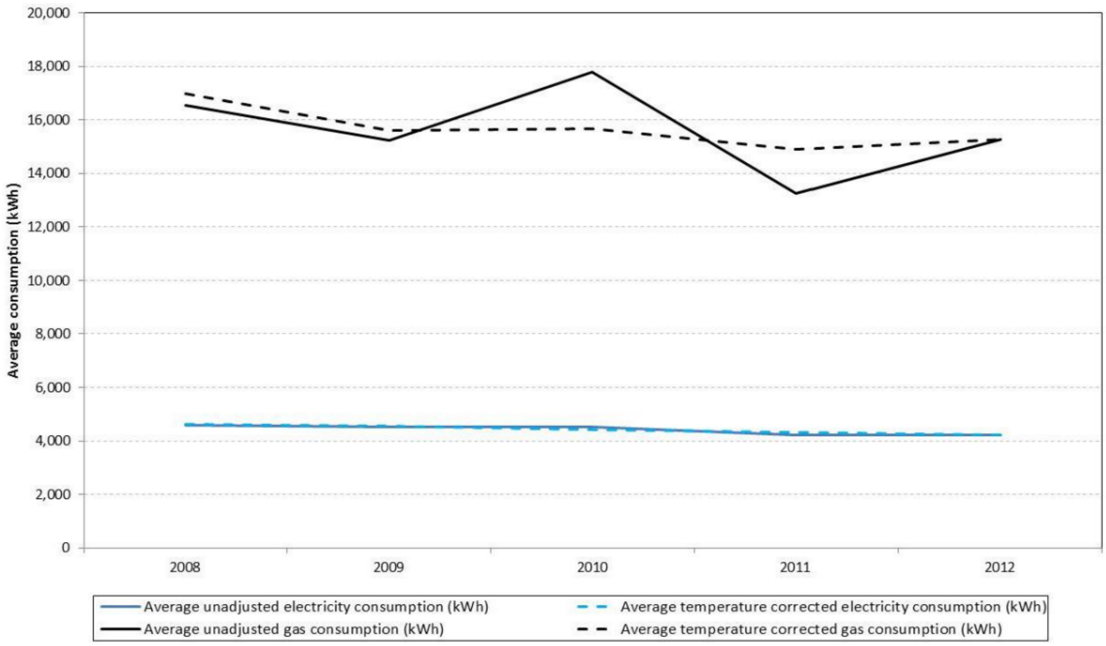


Figure 5.4 Average Annual Gas Consumption - UK

(DECC, 2013, p. 5)

Error! Reference source not found. Table 5.5 shows a direct contrast between both the two building types and the subsequently the contrast of the design vs. reality in each of the material performance figures cannot be ignored.

These variations would generally be attributable to a change in the fabric insulation characteristics (HLC) and a significant deviation in air permeability from the modelled dwelling; and while there is certainly a gap between design and reality in both these factors, by breaking down the performance into its constituent parts within the model and the model analysis it is plain to see that neither the ventilation or the HLC discrepancies seem to have a significant impact on the calculated CO_2 emissions. (Table 5.1 – Table 5.4) The space heating data is in a sense the purest reflection of the housing fabric performance as it inherently accounts for all the faults and deficiencies of the structure, equating them to a final energy performance figure. In this respect there is no doubt that the energy/m^2 for the masonry construction far exceeds that of the timber. However, there remains one key unaccounted variable which could have such a dramatic effect on the housing performance, and that is the occupant's interactions with the building which are obviously quantified through the space heating data and would directly impact the results tabulated in this section.

This prompts the question, could the occupants really have such a detrimental and unaccountable impact on the housing performance? Are houses of all fabric types being designed and built with enough consideration of the occupant effect and interactions with the fabric? If the effects of occupant interaction are potentially so influential on the space heating performance (Table 5.1 - Table 5.4) are the occupants themselves even aware of their actions? Are occupants being trained sufficiently to operate and work with the complex housing design and active systems? Bailey, et al. (2013) suggests that many occupants of new sustainable housing projects do not in fact undergo sufficient training to prepare them for the operation and maintenance of the sustainable dwellings in which they reside. His study of the handover process conducted on the Green Street dwellings found that occupants are were not receiving adequate training and guidance with regard to the sustainable measures employed in their housing. In addition the survey found that that residents struggled to absorb the information provided in the current format.

5.4 SAP Re-work Conclusions

Despite acknowledging the general faults and failings of SAP, the SAP analysis section makes use of SAP as a benchmark, primarily due to the fact it is the industry standard testing procedure to calculate the ecological impact of modern housing. Its ubiquitous use throughout industry predicates its use as a standard in the industry – a standard by which housing across the nation can be measured, and this study is no different. With this in mind the review reveals that at odds with the prior fabric tests, the energy expenditure per m^2 for space heating in the masonry housing far exceeds that of its timber counterparts. This value is of course subject to occupant interactions with the houses, which prompts a discussion on the impact of human interaction with sustainable housing and a review of the handover procedures. Ultimately, a study by Bailey, et al. (2013) proposes a complete reform of the handover process, based on existing commercial precedence and focusing on both the accessibility and content of the handover procedure. It seems as though this conclusion is supported by the quantitative evidence in this section that highlights such a large gap between the design and measured energy use, a gap which has been shown to far exceed the potential influence of HLC and airtightness anomalies. More research is required to better understand the way in which people use and interact with sustainable housing – this section concludes that no matter what the fabric type, or the supposed level of environmental performance the "human factor" is the single greatest factor that dictates if a dwelling is operationally sustainable.

6 Life Cycle Analysis

The goal of this study is to provide evidence illustrating the performance of TPC in a mainstream housing development in the UK. Chapter 6 introduces a key component of this performance breakdown - Life Cycle Analysis. (LCA) An LCA is defined as the compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system throughout its life cycle as shown in Figure 6.1.

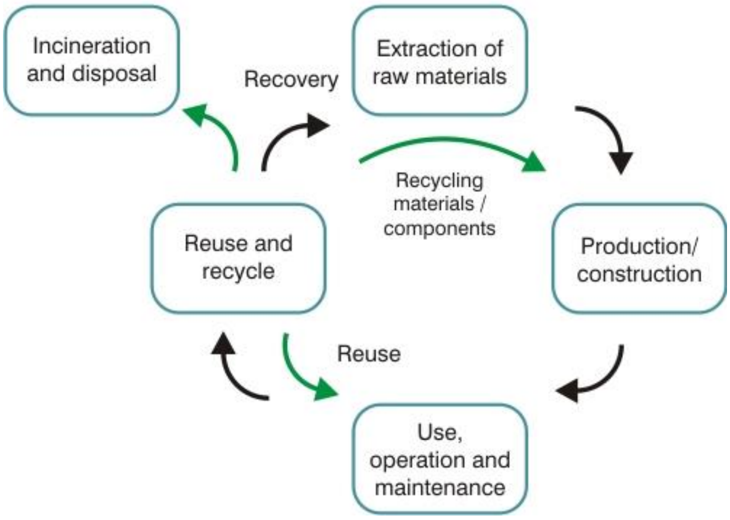


Figure 6.1 Life Cycle Diagram

(TTC, 2014, p. Web Page)

A well supported and justified life cycle analysis can assist in:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle;
- Informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign);
- The selection of relevant indicators of environmental performance, including measurement techniques, and marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration). (ISO, 14040, 2006)

6.1 Life Cycle Analysis Review

Reports by the UK's Department of Energy and Climate Change (DECC) identify the housing sector as one of the greatest single contributors of greenhouse gasses in the UK, responsible for nearly 26% of total GHG emissions (DECC, 2011). It is widely recognised that the majority of these emissions are generated during the use and operational phase of the housing lifecycle through the operation of space heating, hot water, lighting and appliances. Research concludes that the energy expended during the construction phase of the house, including the sourcing and transportation of materials, accounts for approximately 10% of the total consumption over the 60-100 year lifespan of a house (Iddon & Firth, 2013; Upton et al. 2007).

This energy use profile is changing. With the introduction of new practices in sustainable construction, new housing developments are experiencing a significant decrease in the operational energy required to maintain the house. Better insulation, new methods of ventilation and a better understanding of solar gains are just a few of the techniques employed to reduce energy usage in modern sustainable housing. (Palmer & Cooper, 2012) A report by Crest Nicholson (2010) estimates that by the year 2016:

- Emissions from heating, hot water, lighting and ventilation from new homes will reduce as a proportion of the household carbon footprint (from circa 55% to about one third).
- Emissions from the build phase will form a greater part of the total footprint, moving from circa 22% under 2006 building regulations to about one third in 2016.

This reduction in operational energy means the absolute value of energy used in an average house has come down, while embodied energy has remained the same or in some cases gone up (Sartori & Hestnes, 2007), resulting in a proportional increase in the percentage share of embodied energy. The simultaneous expansion of green energy production through wind farms and solar ventures and hydroelectricity further reduces the environmental impact of energy use during the operational stage as the GHG emissions associated with fossil fuel electricity production are eliminated. Thus, "In order to achieve a better understanding of the interplay between embodied and operating energy and its repercussions on the total energy needs, different versions of the same building have to be analysed at parity of all other conditions" (Sartori & Hestnes, 2007, p. 254). The inclusion of a basic LCA is particularly pertinent in this field of study as "Literature specific to the embodied carbon and energy of UK housing construction is sparse" (Monahan and Powell, 2011, p. 180). Research has revealed only four recorded case studies in the UK that incorporate an LCA into their performance analysis of housing (Hacker et al. 2008; Asif et al. 2007; Hammond and Jones, 2008) including that by Monahan and Powell (2011). This rarity is corroborated by research by Cabeza et al. (2014), which only records 2 building related LCA studies in the UK – those by Asif and Monahan. While the research acknowledges the advances and technological gains achieved through the use of prototype housing, it also recognizes that the houses are prototypes and that however practical the design and intentions, they are very rarely completed under the same conditions (time, budget, location, quantity) as mainstream developments. The Green Street case study provides the rare opportunity to conduct an environmental life cycle analysis on two different materials sourced and employed in very similar housing developments and subject to realistic industry pressures and principles.

6.1.1 Development of a Standardised Life Cycle Analysis

The structure of a formalized Life Cycle Analysis varies widely depending on the subject or object in question. For the purposes of this study on the use of timber as a construction material the methodology is governed by the International Standard Organisation's (ISO) ISO 14000 series of international standards on environmental management and life cycle assessment specifically: ISO 14040 - Principles and Framework and ISO 14044 - Requirements and Guidelines.

These provide a framework for the development of environmental management systems and supporting audit programs (British Standards Institution, 2008). The regulated structure of the ISO framework helps to avoid the risk of this project becoming yet another fragmented bit of data, relevant only to a specific housing case study. Adhering to the strict regulations of ISO 14044 (2006) this LCA study encompasses 4 distinct phases:

Phase	Description
The goal and scope definition phase	**Defines:** • purpose of study • intended use • product(s) defined • functional basis for comparison chosen • level of detail and quality
The inventory analysis phase	**Involves:** • Mapping processes that produce functional unit • Gathering data on amounts of energy and raw materials used, plus emissions to air, land and water for each of the processes • Converting data into environmental effects in an inventory table summed over the whole life cycle.
The impact assessment phase	**3 Steps:** • *classification* - effects of resource use and emission generation are allocated to the relevant impact categories • *characterisation* - contributions of different substances to each impact category are referenced to that of a specific substance ('*normalisation*' is an extension of this step and relates the level of impact recorded for the product in each category, for example, to the total amount of each problem occurring in the UK in one year) • *valuation* - results for each impact category are weighted to indicate their relative importance
The interpretation phase	**Results:** • A readily understandable, complete and consistent presentation of the results of an LCA, in accordance with the goal and scope definition of the study. • The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected in a way which is consistent with the defined goal.

Table 6.1 Life Cycle Analysis Phases

(Mundy, 2003, p. 2)

The final product of a successful LCA is generally a quantifiable impact for the material in question over a wide range of environmental factors (Carmody & Trusty, 2005):

- Fossil fuel depletion
- Other non-renewable resource use
- Water use
- Stratospheric ozone depletion
- Ground level ozone (smog) creation
- Nutrification (excess nutrients) and eutrophication (oxygen deficiency) of water bodies
- Acidification and acid deposition (dry and wet)
- Toxic releases to air, water, and land

However, many of these elements are very hard to accurately quantify and go beyond the scope and understanding of architects, contractors and developers. In order to further simplify results some LCA's choose to incorporate a PAS 2050 evaluation of the material. Prepared by BSI British Standards and co-sponsored by the Carbon Trust and the Department for Environment, Food and Rural Affairs, PAS 2050 builds on existing life cycle assessment methods established through ISO 14040 and ISO 14044 by giving requirements specifically for the assessment of greenhouse gas (GHG) emissions within the life cycle of goods and services (BSI, 2011). GHG's are simply the gaseous components of the atmosphere that regulate the amount of radiation incident on the earth's surface. PAS 2050, which relies heavily on the various ISO 14000 specifications, converts the diverse environmental impacts of a material and its associated processes into a single greenhouse gas or CO_2 equivalent (CO_2e) variable. By narrowing the scale of the material's impact to its effect on the atmosphere, it is possible to provide an appraisal of the environmental impact (Dutil et al. 2011), but just as importantly is allows for a quantitative standardisation of different building materials (TRADA Technology, 2009) and a simplified conveyance of this impact to a non-specialist audience. Unfortunately, while the PAS 2050 protocol may produce easily comparable results the methodology, and more specifically the source information used to attain those results, can still vary widely from project to project. The theory of simplification and standardisation is valid, it is simply the process through which this is achieved that must be adapted and updated.

Source information is the key to achieving an accurate, justified and comparable LCA (Frischknecht, et al., 2005). Source information is defined as the environmental impact of a basic component or process that makes up the whole of the product in question. In the past this would have been calculated on a project by project basis with different values for elements as simple as the CO_2 emissions for a HGV traveling a distance of 1km. Historically this variation is what made LCA such an incredibly subjective test, it is for this reason that practical, real world, case study based analysis is even more scarce than the post occupancy evaluations eluded to in Wingfield's (2011) research. It is only the recent development of large standardized databases that has legitimized the use of LCA in academic building studies, decreased its complexity and narrowed the scope of research projects. These databases provide peer reviewed and correlated data on the environmental impact of various base materials and processes that form a more complex product or component. They come in a variety of formats including: "CML, DEAM TM, Ecoinvent Data, GaBi 4 Professional, IO-database for Denmark 1999, Simapro, the Boustead Model 5.0 and US Life cycle inventory database" (Ortiz, et al., 2009, p. 30). Various proprietary LCA software packages from different organizations incorporate one or more of these databases into the structure of their programs. Information compiled from the database is then combined with dimensions, quantities and layouts provided by a third party from the material in question. This provides the parameters required to construct the process framework within the specialised computer modelling software, which then simulates the cradle to grave impact of an element.

Research by Hischier et al. (2005) and Lewandowska et al. (2008) voices concerns regarding the arbitrary use of a single LCA database such as the Ecoinvent LCI database, therefore a brief literature based comparison of different LCA databases and their attached software is in order, to determine the simplest and most widely used version for application in this project.

6.1.2 Choosing an Life Cycle Analysis Software

Unfortunately it is beyond the time frame and financial scope of this research project to test each individual LCA software and database available, however a study by Ren and Su (2013) gives a clear indication as to which programs stand out among the rest in terms of usability and database support

Considerations	CES	Solidworks	Sustainable Minds	SimaPro	Gabi
Product definition based on LCA	★★	★	★★	★★★	★★★★
LCIA Method	★	★★★	★★	★★★★	★★★
Database	★★★	★★★	★★	★★★★	★★★
Database Modification	★	★	★	★★★★	★★★
Presentation	★★	★★	★★★	★★★★	★★
Details	★	★★	★★	★★★★	★★★★

Table 6.2 Life Cycle Analysis Software

(Ren & Su, 2013, p. 48)

Further literature review uncovered the fact that Gabi - Pe International, Germany and SimaPro - Pré Consultants, Netherlands, appear in quite a number of studies covering a variety of topics (Monahan & Powell, 2011; Ortiz et al., 2009; Boureima, et al., 2007; Gong, et al., 2012; Selke, et al., 2012; Ramesh, et al., 2010) with a project by Lapinskiene and Martinaitis (2013, p. 671) outright claiming that the SimaPro LCA software is "the most widely used LCA software" a claim that the company itself backs. The research would therefore suggest that of the multiple options available, SimaPro is acknowledged as one of the best and most popular products (Hernandez & Kenny, 2010).

A detailed breakdown of functionality and attributes for the SimaPro software is provided by Loijos (2012) in a comparison of best life cycle assessment software report:

SimaPro 7 - Attributes	
Pros	Being a highly used piece of life cycle assessment software, SimaPro is thoroughly tested and robust. As well, its popularity makes SimaPro's findings and reports easy to share with colleagues. The hardware and software requirements for running this program are also fairly light.
Cons	To run this life cycle assessment software, you have to use Windows. If you use SimaPro through an emulator on any other native operating system, the stability is potentially an issue and there is no support for any operating system other than Windows. Having 5 GB of hard drive space is also necessary for every device running SimaPro on a server. A wide monitor is strongly recommended for effective high resolution modelling.
Notable Features	SimaPro life cycle analysis software can calculate a carbon footprint of many kinds of products and systems. Using its customizable parameters and Monte Carlo analytical capabilities, SimaPro can even determine the potential environmental impact that a system or service produces with statistical accuracy. With its ability to determine key performance indicators and issue full Environmental Product Declarations and GRI Environmental Reports, SimaPro presents a full view of the potential impact any design will have under realistic conditions.
Data	SimaPro comes with several databases, including US LCI, ELCD, ecoinvent v.2 and LCA food. You can also purchase an IVAM database.
Price Breakdown	SimaPro is 4,320 GBP (approximately $6,990) for the first year, and its licensing and service contracts can be renewed with a potential discount for a single user. The Analyst single user indefinite license is 8,640 GBP, while the developer single user indefinite license is 11,760 GBP. For a multiple user license, the analyst price is 15,120GBP (approximately $25,530) and the developer price is 20520 GBP (approximately $34,640).
The Verdict	While it is a significant investment with reasonably steep hardware requirements and no direct support for any operating system besides Windows, SimaPro's robust suite of features makes it a valuable piece of software for modelling a large number of variables for determining life cycle impacts and environmental performance. SimaPro also makes sharing the findings easy with your colleagues and other interested parties because of its widespread use.

Table 6.3 SimaPro Attributes

For further information on the program and its functionality Simapro provides excellent training manuals and general life cycle analysis guidance. (Goedkoop, et al., 2008) (Goedkoop, et al., 2010) These were used alongside the ISO 14044 protocol in the construction of the LCA framework for the materials used on the Green Street site.

6.2 Life Cycle Analysis Methodology - Green Street

Section 6.2 works through each phase of the ISO 14044 framework (see Table 6.3) with respect to this research project and the use of SimaPro as the source information/database provider.

The goal and scope definition phase:

The purpose of the LCA within this study is to determine which type of construction (timber or brick) has the least impact on the environment from an embodied energy perspective. The project scope ignores the end of life stage depicted in Figure 6.2 as it is far too inconstant to predict, particularly looking 60-100 years into the future; it is limited therefore to sourcing, manufacture, transportation and construction associated with the materials – a cradle to construction scope covered by the databases of SimaPro.

Figure 6.2 Stages in the Life Cycle of a Product

(TGH , 2015)

The information garnered in this stage of the project will be used to substantiate, or refute claims that timber construction has a lower embodied energy than its traditional masonry counterpart. In addition the data can be used to visualize the impact of other materials within the wall construction, not just the primary materials of brick and timber. Given the topic of this research project and the vast range of components that make up an average dwelling it was deemed prudent to once again narrow the scope of this LCA to a more manageable and pertinent set of materials, prompting a focus on the primary components unique to each style of construction – the walls of the dwelling. As the study ignores the foundations, roofing, windows and internal structure of the housing it unfortunately cannot be defined as an entirely comprehensive LCA of TPC, however, it gives a good indication of the environmental impact discrepancy between the two styles of construction.

The external walls of each type of dwelling are pictured in Figure 6.3 and Figure 6.4.

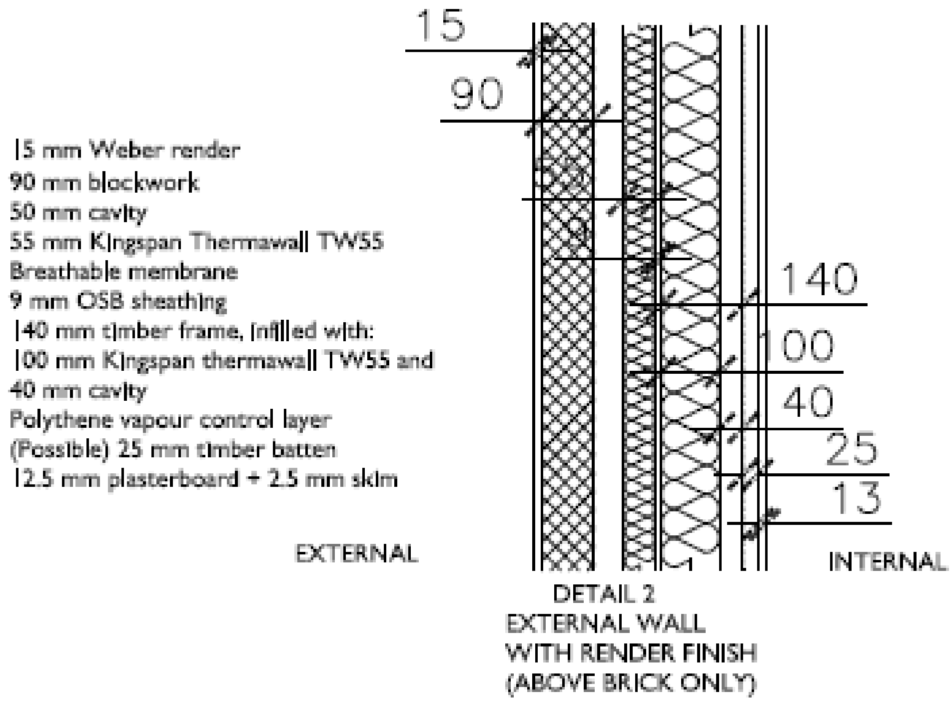


Figure 6.3 Phase 1 – First Floor Cross Section of Timber Frame Wall (Render Finish)

(Source: Marsh Grochowski, 2010)

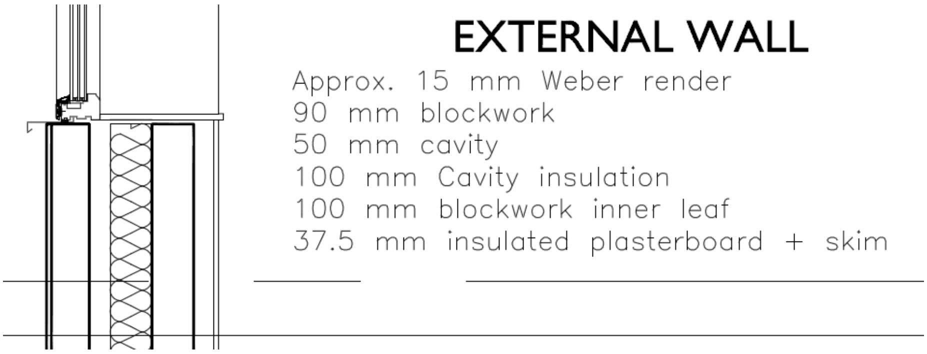


Figure 6.4 Phase 2 – First Floor Cross Section of Masonry Wall

(Source: Marsh Grochowski, 2010)

The individual materials that make up the walls are all factored into the LCA and the impact figures are calculated relative to 1m^2 of each construction type.

In order to compare the different materials that make up the walls, and in turn define a standardized and comparable environmental impact for the materials, it is necessary to have a functional basis for comparison. This functional unit was discussed in section 6.1.1 under the umbrella of the PAS2050 protocol in which all environmental impact variables (acidification, eutrophication, ozone layer depletion etc.) are converted to one unit of measurement – the CO_2e. The SimaPro software does not contain a framework for PAS 2050 however it does incorporate a number of other impact assessment methods designed to do the same thing. These include, but aren't limited to:

- BEES
- CML 2001
- Cumulative Energy Demand
- Eco-Indicator 99
- Ecological Footprint
- Ecopoints 97
- EDIP 2003
- EDP 2007
- Impact 2002+
- IPCC 2007

Each one of these assessment methods is governed by the SimaPro structure defined in the database manual (Goedkoop, et al., 2008) as:

- Characterisation – "The substances that contribute to an impact category are multiplied with a characterisation factor that expresses the relative contribution of the substance." For example if climate change is expressed in kg CO2 and the element in question is methane then methane would be expressed as 21 as it has 21x the impact on climate change that CO2 does.
- Damage assessment – "The purpose of damage assessment is to combine a number of impact category indicators into a common damage category such as DALY's (disability adjusted life years)."
- Normalisation – An extension of characterisation, "the impact category is divided by a reference such as 100km of transport by car, this can be useful to communicate the results of the LCA to non-experts."
- Weighting/Valuation – "The impact (or damage) category indicator results are multiplied by weighting factors, and are added to create a total or single score."

In defining the functional unit this study is primarily interested in characterisation and damage assessment with respect to a well-recognized and standardized unit of environmental impact. Choosing the right assessment method is on an entirely case by case basis. (Lehtinen, et al., 2011) Blengini and Di Carlo (2008; cited in Dutil et al. 2011, p.445) remarked that there is neither consensus on weighting nor on the best weighting method, such as the BRE's Ecopoint system, (Mundy, 2003) to integrate all the environmental impacts in a global indicator. For that reason this study will employ an assessment method that gives the most straightforward and standardized unit of damage assessment.

A comparison of the different assessment methods such as Eco-indicator 99 and Impact 2002+ immediately identifies differences in how the results are portrayed. Eco-indicator 99 relies on the less recognized disability adjusted life years (DALY) which is then normalized and weighted depending on the project. DALYs caused by carcinogenic substances can be added to DALYs caused by climate change.

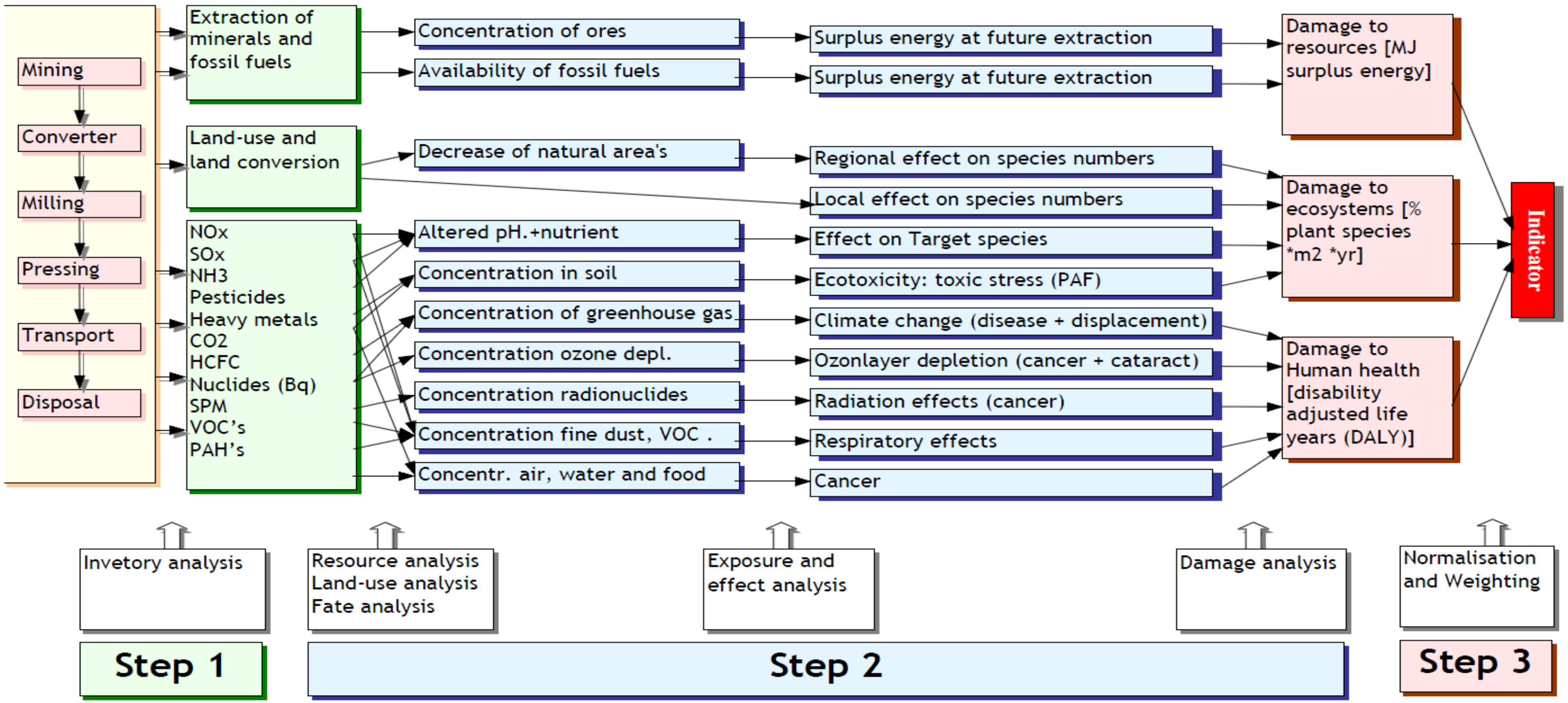


Figure 6.5 Damage model for Eco-indicator 99 (Goedkoop, et al., 2008, p. 22)

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However Impact 2002+ as the most appropriate method due to its characterisation factor - CO2e under the heading "Climate Change" (see

Figure 6.5) automatically providing a standardized and well recognized unit of measurement.

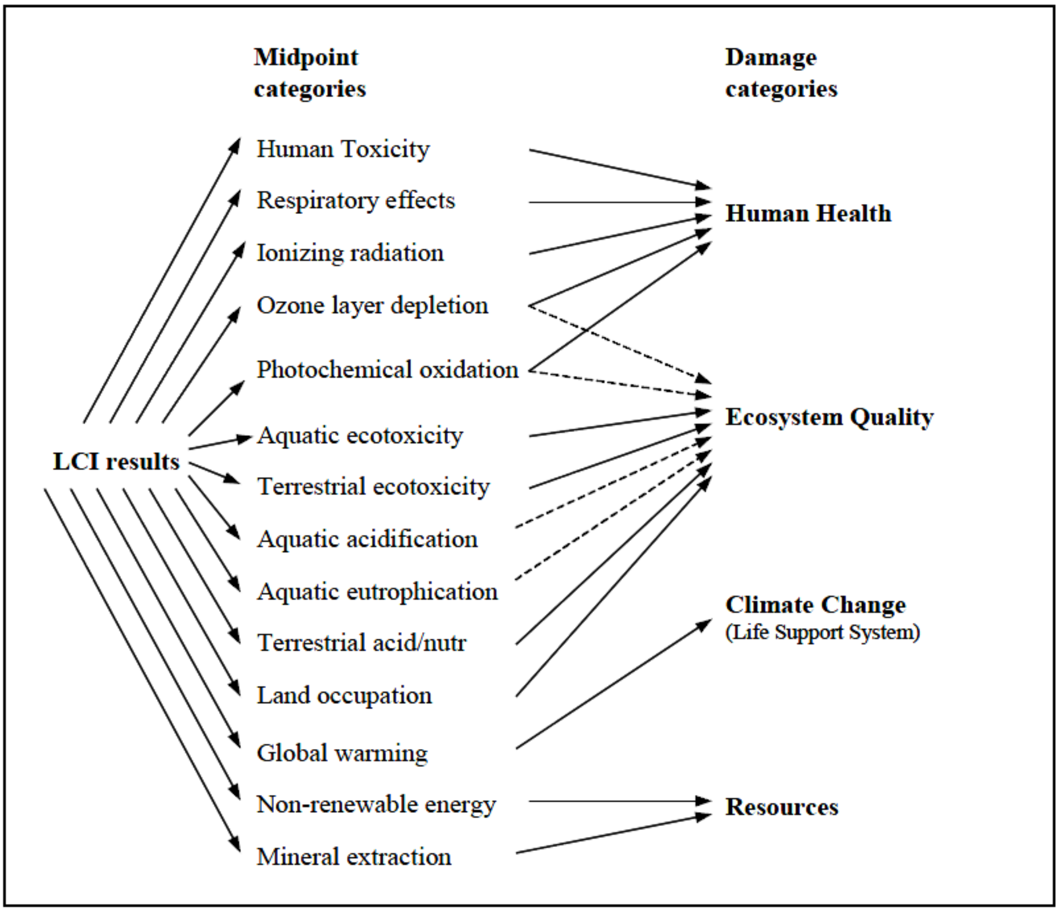

Figure 6.6 Damage model for Impact 2002+

(EC, 2010, p. 32)

"The IMPACT 2002+ Life Cycle Impact Assessment methodology proposes a feasible implementation of a combined midpoint/damage approach, linking all types of Life Cycle Inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories." (EC, 2010, p. 29)

In order to actually implement the chosen assessment method there must be a framework of materials, quantities and energy emissions. The Ecoinvent database built into SimaPro takes care of this traditionally difficult and time consuming step of LCA by providing peer reviewed and tested impact information about the materials that make up the object in question. Instead, the challenge has shifted (at least in the case of the Green Street site) to obtaining first hand data on the quantities and origins of the materials used on a building site, particularly when the contractor uses multiple subcontractors on site. Theoretically this information should be readily available, particularly on a sustainable building site, however, the reality of working with many different parties through a diverse and eclectic supply chain (usually based on the lowest bidder) can have a detrimental effect on the materials "paper trail." Fortunately the scope and depth of this LCA is relatively basic and the majority of information was available on the internet and through contacting the material providers directly. It should be noted that future developments must maintain a rigorous and easily accessible bill of materials for each dwelling in order to maintain environmental accountability.

6.3 Life Cycle Analysis Results and Discussion

6.3.1 Life Cycle Analysis – Timber and Masonry Wall Types

Each wall type is broken down into its constituent components which in turn are assigned levels of ecological impact through the inbuilt data-base within SimaPro. Elements of the life cycle process such as transportation vary from material to material and are dependent on the quantity of material being examined, in this case the amount of material used to create a unit area ($1m^2$) of brick or timber frame wall. These values are calculated separately to be included in the individual material impact. The materials are then compiled as a single entity corresponding to either the brick or timber wall details available in Section 6.2.

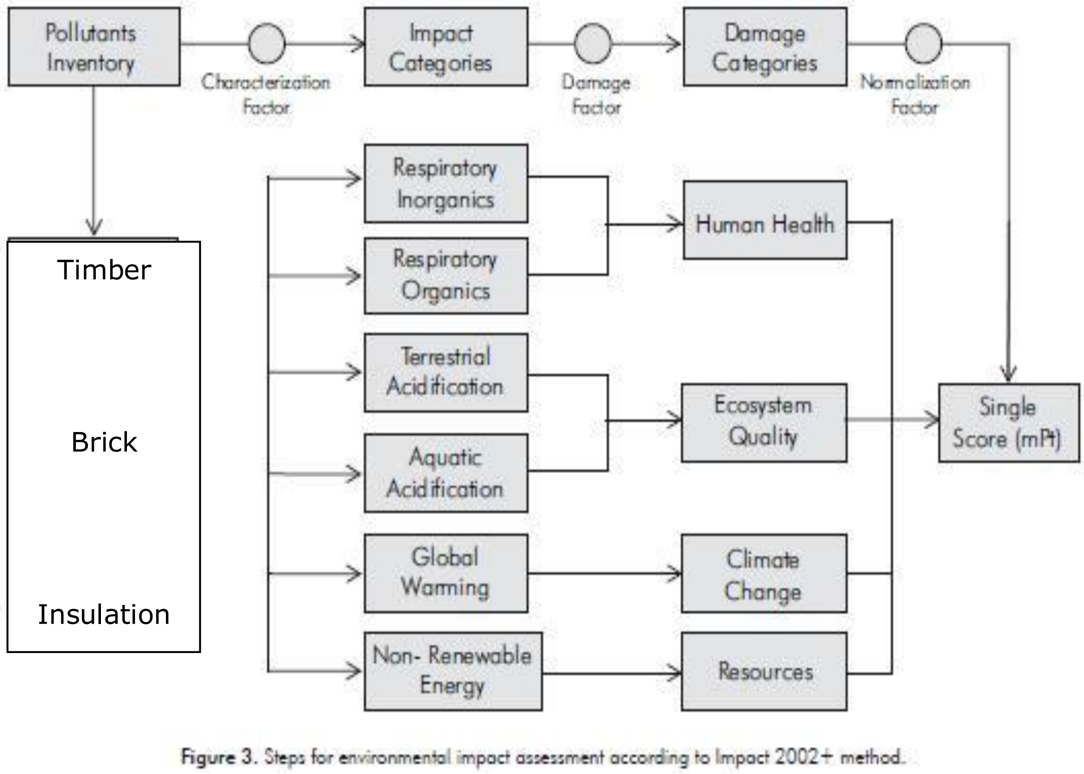

Figure 6.7 LCA Flow Chart

Martinez-Gonzalez, et al. (2011, p. 127) – edited for relevance

Figure 6.7 shows the stages used to assess the environmental impact of the construction materials through the Impact 2002+ software selected for this project.

Table 6.4 Brick Impact Assessment - Damage Assessment

Damage category	Unit	Total	Render	Kingspan Thermawall TW55 (100mm)	Plaster-board	Mortar	Internal Block	External Block	Kingspan Thermawall TW55 (22.5mm)
Human health	DALY	2.69E-05	1.39E-07	8.05E-06	2.16E-06	4.21E-06	4.17E-06	5.92E-06	2.21E-06
Ecosystem quality	PDF*m2*yr	3.2014	0.0399	0.4273	0.9263	1.0254	0.2742	0.3907	0.1175
Climate change	kg CO2 eq	70.766	0.484	11.236	3.454	6.754	20.361	25.388	3.089
Resources	MJ	988.66	3.35	298.29	57.79	149.89	168.95	228.38	82.01

Table 6.4 breaks down a typical damage assessment produced through the SimaPro analysis process. As previously mentioned, environmental impact can be quantified through a variety of mediums dictated by the analysis process. Impact 2002+ yields 4 primary categories:

- Human Heath: Disability Adjusted Life Year (DALY) – a single DALY unit is defined as "one lost year of "healthy" life or a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability." (WHO, 2014) It takes into account respiratory and carcinogenic effects, ozone layer depletion, greenhouse gas and ionizing radiation. The DALY is expressed as a number between 0 and 1, 0 for being perfectly healthy and 1 for being fatal.
- Ecosystem Quality: Evaluated as the Potentially Disappeared Fraction x m^2 x year, the ecosystem quality accounts for the probability of the plants species to disappear from the area as a result of acidification and eutrophication. Land use is also characterised by PDF and incorporates a wider impact on all species from the occupied land and surrounding area (Jolliet, et al., 2003).
- Climate Change: By far the most popularized and recognized measurement of environmental impact, is quantified through kg CO_2 eq (kilograms of CO_2 equivalent.) To further the goals of simplicity and standardisation this project uses Climate Change as the comparison benchmark between the two fabric types. Ultimately Human health and ecosystem quality are complex metrics of measurement necessitating a further stage of normalization in order to create a universal unit. CO_2 is immediately recognizable to most individuals as a damaging factor in the environment and by incorporating this as the defining performance statistic for the LCA it creates a much wider potential audience and dissemination pool.
- Resources are also a damage category defined through the IMPACT 2002+ analysis and based on mineral extraction and non-renewable energy consumption, (Jolliet, et al., 2003) however this too has been rejected (along with Ecosystem Quality and Human Health) on the basis of standardisation and simplicity.

Figure 6.8 shows the climate change process tree for the representative brick wall. This particular representation of the climate change values from Table 6.4 helps to visualise the proportional impact of specific elements within the wall construction through the varying width of the network arrows.

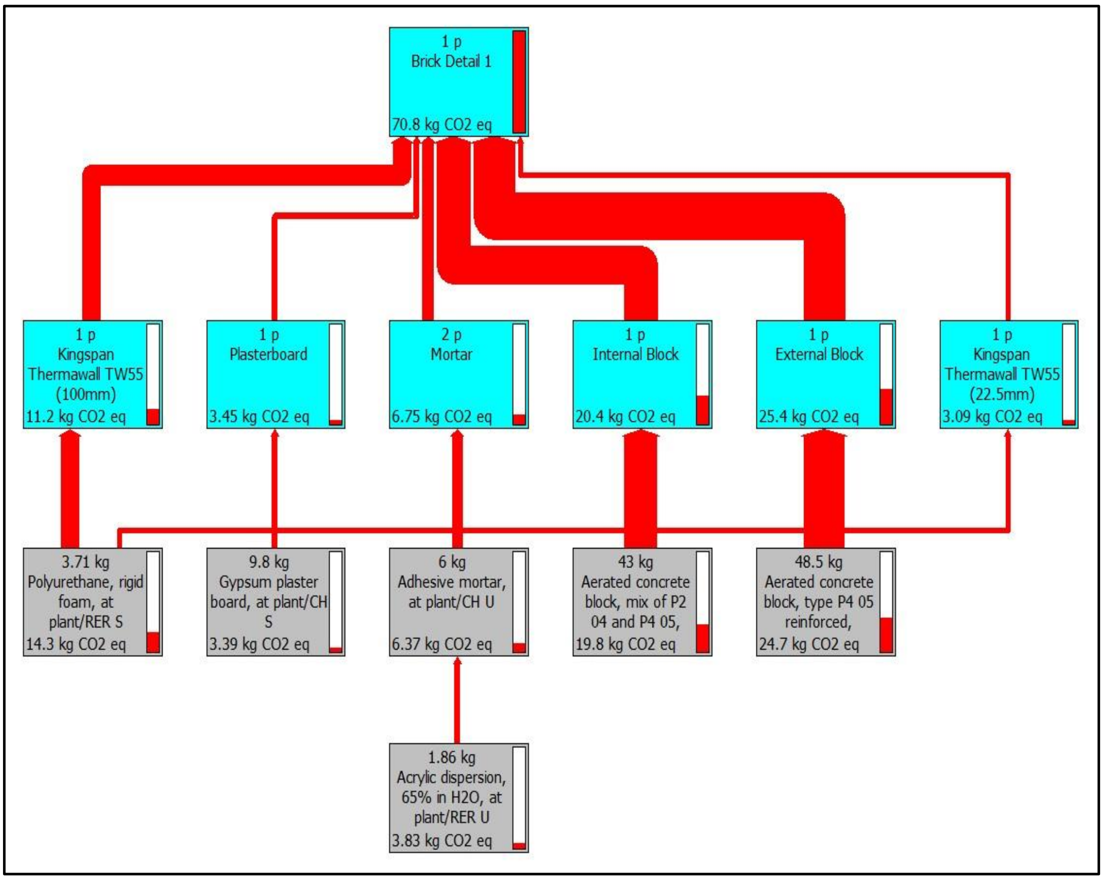

Figure 6.8 Brick Detail Process Tree

Identical to the process employed for the masonry walls, the timber fabrication was also divided into individual construction materials and quantified under the IMPACT 2002+ process with the following results.

Table 6.5 Timber Impact Assessment - Damage Assessment

Damage category	Unit	Total	Render	External Block	Kingspan Thermawall TW55 (155mm)	Mortar	OSB	Plaster-	Timber Frame
Human health	DALY	2.70E-05	1.39E-07	5.92E-06	1.25E-05	2.10E-06	1.72E-06	2.16E-06	2.51E-06
Ecosystem quality	PDF*m2*yr	2.796	0.0399	0.3907	6.62E-01	0.5127	0.1124	0.9263	0.1517
Climate change	kg CO2 eq	57.77	0.484	25.388	1.74E+01	3.377	4.892	3.454	2.761
Resources	MJ primary	922.83	3.35	228.38	4.62E+02	74.9	55.5	57.8	40.6

Each of the individual materials was tracked to its company of origin and from there back to its primary source. Unsurprising, but nonetheless important, was the sourcing of timber from Scandinavia and the associated pollution involved with transporting the materials to their point of manufacture and then erection. Much of the masonry wall was sourced relatively locally.

6.3.2 Life Cycle Analysis – Characteristics

The operational energy required to run modern housing has dropped significantly with the advent of low energy appliances, lighting and the integration of active technologies such as PV electricity generation generating. Consequently the absolute value of energy used in an average house has come down, while embodied energy, associated with the materials and construction processes has remained the same or in some cases gone up (Sartori & Hestnes, 2007), resulting in a proportional increase in the percentage share of embodied energy.

The ecological significance of construction materials is consequently changing as the amount of energy and associated GHG emissions incorporated in the extraction, transportation, and recycling, of materials comes under scrutiny. The increasing importance of material selection means LCA of representative case studies within the UK is an integral part of the performance evaluation of materials within a dwelling and as "Literature specific to the embodied carbon and energy of UK housing construction is sparse" (Monahan and Powell, 2011, p. 180), it makes information garnered in studies like this even more vital. The Green Street case study provides the rare opportunity to conduct an environmental life cycle analysis on two different materials sourced and employed in very similar housing developments and subject to realistic industry pressures and principles.

The limited research that actually deals with the life cycle analysis of building materials in dwellings unanimously finds that the materials associated with heavyweight construction, concrete and bricks, to have the greatest embodied energy (Hacker et al. 2008; Asif et al. 2007; Hammond and Jones, 2008). This corroborates a general consensus among industry, and the public that timber based construction is has inherently less impact on the environment. Thus the LCA procedure was seen initially seen as simply an exercise in quantifying this gap, with the predetermined conclusion that timber would produce significantly less pollution than the masonry construction. However, the results in Section 6.3 proved that this conclusion was not necessarily so inevitable.

In order to be able to compare the different materials that make up the walls, and in turn define a standardized and comparable environmental impact for the materials, it was necessary to have a functional basis for comparison. This was defined as the global warming potential (CO_2e) in Chapter 6.

TablesTable 6.4Table 6.5 reveal the damage assessment for the timber and masonry walls to be 57.77kgCO_2e and 70.77kgCO_2e respectively. This is in line with popular opinion, which generally considers timber to be the more environmentally responsible material.

That being said, the addition of a complete external layer of masonry blocks, predominantly for aesthetic purposes, is a uniquely British affectation, with the majority of foreign TPC employing cladding or brick skin solutions. The breakdown of environmental impact by material type immediately identifies the brick layer as the greatest single contributor to the CO_2e levels, with nearly half of the total 57.77kgCO_2e traceable to this seemingly unnecessary addition to the core fabric of phase 1.

These results demonstrate the importance of case study research, which in this instance, revealed that while the timber in isolation may indeed be a more sustainable material, the characteristics of a typical timber wall as a whole (in modern British construction) can add a significant level of polution.

One of the key debates in LCA is the relationship between operational and embodied energy and their associated CO_2 emissions. The following table provides a rudimentary summary of this relationship with data compiled from the SAP analysis and LCA results. The operational energy is of course limited to the space heating values and the LCA analysis is purely the emissions associated with the external wall fabrics.

Table 6.6 Environmental Impact - Operational vs. Embodied Energy

Dwelling Designation	Environmental Impact of Embodied Energy in External Walls ($kgCO_2e$)	Annual Environmental Impact of Space Heating (kg CO_2/yr)
House 1	5139.46	1874
House 2	3597.93	1557
House 3	3639.71	1719
House 4	3597.93	N/A
House 5	7810.87	2890
House 6	7256.68	2433
House 7	6608.49	2697
House 8	7810.87	3356

From the figures in Table 6.6 alone it is possible to discern that the embodied energy associated with the collection, manufacture, transportation and erection of the building fabric will ultimately form a fairly small part (roughly 4-5% throughout both fabric types) of the overall environmental impact of the dwellings guaranteed 60 year life spans. Of course, the longer the building lasts these number will grow even smaller. Given these numbers, the embodied energy associated with the materials would probably only start to make a significant difference when the housing's operational energy levels are brought down to around Passivhaus standards.

The conclusions follow that timber in isolation is characteristically a more sustainable material than brick and mortar and that is why timber construction is usually viewed as a more sustainable construction process. However timber housing does not make use of timber in isolation, it incorporates timber as one of the many materials that ultimately come together to create a wall and eventually a structure and dwelling fabric. The results from the LCA highlight the importance of this process and suggest that if timber construction is to actually fulfil its sustainable ambitions then this process must be more closely monitored and better planned. Crucially the materials must be sourced correctly, unadulterated and correctly balanced with the other components.

6.4 Life Cycle Analysis Conclusion

This section of the research serves to not only demonstrate the environmental credentials of timber and brick, but also to establish the growing impact that materials choice has on sustainable construction. Chapter 6 elaborates on this crucial component of the research and a factor that is often overlooked in both the construction industry and academia. After establishing a clear need for life cycle analysis within the framework of this research, there is a need to validate the methodology of the procedure (which falls outside of the TSB BPE framework.) This is done through a rigorous analysis of the software available and the development of a case specific LCA framework tailored to the objectives and limitations of the study.

Ultimately, the historical significance of operational energy has produced an ecological testing framework that revolves primarily around the operational phase of the house. The CSH for example attributes only 7.2% (after weighting) of its overall evaluation to the materials actually used for the structure of the building. (BRE, 2010) This research calls into question the stagnant nature of this legislation and suggests that as the proportional relationship between embodied and in-use energy changes, legislation should adapt to place more emphasis on the materials choice and origin. The analysis also reveals that in line with popular belief, the materials used to construct the timber walls have a lesser overall impact on the environment. Nevertheless, the findings highlighted the need for more studies such as this and more importantly, better sourcing of materials.

7 Qualitative Analysis

The following section introduces three key themes within the qualitative data gathering portion of the research.

1. Occupant Feedback – Building Use Survey (BUS) Methodology
2. Design Team Review and Retrospective
3. Industry Overview

The investigation utilizes a variety of interview and questionnaire techniques in order to create a more comprehensive picture of the housing performance and the state of the industry in general. Where possible, the theme of this research project is the utilization of standardized and well established/well founded research protocol – the simple reason for this is that the results are much more valuable and the conclusions can be scrutinized by others, thus adding to the validity of the research; this theme is carried throughout the majority of the qualitative data gathering methodology conducted in this study.

7.1 Qualitative Analysis Review

7.1.1 Occupant Feedback – Building Use Survey Methodology

In 2007 the UK Government introduced a new housing policy objective aimed at reducing the residential sector's estimated 26% share in greenhouse gas emissions (DECC, 2011). This widely debated legislation charges the housing industry with the goal of producing fully zero carbon homes by the year 2016 (DCLG, 2007). While subject to much controversy the policy is supported by the overarching mandate of the Climate Change act that commits the UK to legally-binding targets for emissions reductions of 80% by 2050 and at least 34% by 2020, against a 1990 baseline (DECC, 2014) In response to the Government policies, research organizations and housing developers have focused on developing technologies that both reduce overall energy consumption and produce renewable energy to supplement and replace that drawn from the national grid (Marsh, 2010). This focus and emphasis on technology and good building practice is prevalent throughout the industry but often comes at the expense of social considerations. "There is growing recognition that building performance studies should take more account of occupant behaviour and needs. In the past there has been over reliance on, for example, predictions from design models and estimations" (HCA, 2010, p. 3). Understanding how occupants interact with a building and the subsequent variations that may cause in the building performance is vital as occupant behaviours vary widely and can impact energy consumption by as much as 100% for a given dwelling (Dutil et al. 2011). Note that here occupant interaction and participation refers to activities that have a direct or indirect impact upon building energy consumption. With the advent of sustainable construction and the associated user participation, it is important to understand the interaction between occupant and building. The findings of a report by the NHBC Foundation (2011, p. 6) indicate further research is required to examine both occupant behaviour and the "best ways to inform users how to make the most efficient use of their homes and the systems in them. Understanding what information should be provided in user guides and what level of detail and in what format should this information be provided." For the purposes of this research, and with regard to the aforementioned gap in knowledge, a standardized POE questionnaire entitled the BUS methodology (Leaman, 2009) will represent the forum for the occupant feedback.

The standardised survey created by Adrian Leaman and Bill Bordass will form the majority of the survey with some additions and adaptations tailored toward gaining insight into the occupant's awareness and acceptance of timber construction. The reasoning behind using this particular questionnaire is while the answers are predominantly qualitative, they can actually be quantified through the way that the questionnaire is designed. This is a useful and efficient way of gaining an understanding into the activities and mind-set of the occupants. The questionnaire has already passed examination by various Ethical Standards Committees and is "statistically rigorous and yet easy to understand for non-specialists" (Leaman, 2009). It incorporates empirically sound benchmarks based on results from real buildings, not simulations, theories or guesswork and provides cross-disciplinary results that are equally useful for designers, managers, researchers, developers and occupiers. This allows for standardisation and benchmarking of the data with the results from the Green Street case study forming part of a nationwide database set up by BUS. The questionnaire is conducted at least one year post-occupancy to allow residence experience with at least 1 heating and 1 cooling season.

7.1.2 Design Team Review

The design team review is actually comprised of two mini studies focused around the design and construction team involved in developing Green Street. The studies' objective within the thesis is twofold:

1. The project management interviews seek to draw on the experience of the project leadership in providing a context to the qualitative data gathered through the monitoring in Phases 1 and 2 of the development. The primary purpose of the interview is to establish their views in relation to their direct involvement with the project, with an emphasis on their impressions of TPC.
2. The design team retrospective is more focused on the gap in performance and was developed by the TSB (TSB (d), 2011) to better understand the original aspirations for the project and then work through the process of design, construction and occupancy to better understand how those aspirations were realized and where they differ from the delivered building.

Both studies are interview based, but were developed in very different manners. Section 7.2.2.1 explains more about the chosen interview procedures and their role in the thesis.

7.1.2.1 Project Management Interview

"Anybody can write down a list of questions and photocopy it, but producing worthwhile and generalizable data from questionnaires needs careful planning and imaginative design" (Boynton & Greenhalgh, 2004, p. 1312).

The demands and intentions of innumerable research sectors vary significantly and thus there is no perfect model on which to base a qualitative study. In addition there is a vast and diverse school of thought dealing with subject of qualitative research design and the associated review and analysis of qualitative data (Denzin & Lincoln, 2005; Silverman, 2000). However, while the scope of this thesis does not include an in depth look into the psychological and sociological intricacies of qualitative research, there is none the less a need to develop and critique the rationale used in the formation of the Project Management Interview questionnaire, the Industry overview questionnaire and the analysis of the resulting data.

The following sections encompass a basic analysis of work from leading figures in the field of qualitative analysis and seeks to draw out practical and applicable conclusions that will drive the framework and scope of this questionnaire and theoretically and academically validate their design.

Much of contemporary qualitative research is developed through the use of small groups of individuals or focus groups who are brought together to ask a specific set of contextual questions (Silverman D. , 2007). This is in contrast to the more traditional ethnography approach, predominantly based on observational material. In reality the contemporary format lends itself to a type of pseudo-qualitative analysis, wherein the researcher sets boundaries and a structure that aims to answer specific questions and objectives. This qualitative "manufacturing" of data is particularly pertinent within the sphere of academic engineering research where even the basic structure provided by a targeted questionnaire allows for the creation of a comparative data set. For clarification, "manufactured data" is in no way implying that the data procured through these methods is made up or acquired in a leading manner, rather it is a reflection on the fact that qualitative data relevant to particular research goals is rarely openly available, and instead must be procured through a process; as eluded to earlier, the modern qualitative data gathering process usually takes the form of an interview - structured, semi structured or unstructured.

Drawing from research on case study methodology, principles and practice (Yin, 2009; Gerring, 2007) and practice-orientated theory-testing (Dul & Hak, 2008) this mini study utilizes a combination of research methods in the development of the research objective, which in its simplest form seeks to answer the question -

what are the key drivers for TPC, particularly in relation to its application on the Green Street site? The literature review and exploration of theory suggests a number of specific drivers and barriers to integration associated with TPC (see Section 2.5) – it is important to establish how, or even if, these factors play a role in the development of a real building project.

The framework for the type of practice-oriented research, is such that it engages a combination of research approaches including a literature review, case study analysis and an interview process. The "unit analysis" definition is fundamental in maintaining continuity amongst the methods of evaluation employed (Yin, 2009, p. 29). In this case, that unit of analysis is the traditional building method. The comparison of TPC with a traditionally built residence provides a common unit of measure that encompasses aspects of both technology and economy. This common unit of measure also aids in the development of a comparative data-set. The motive for using a case study/survey based methodology was based primarily on access to first hand data and subjects. The case study/survey methodology is ideal in this style of broad scale research, inclusive of an entire industry and its myriad variables, in that it can be tailored to address specific goals (Gerring, 2007).

The structure of the research is based on a clear set of propositions or hypotheses also known as the practice domain (Dul & Hak, 2008); which are supported by theory, and then further validated using the case study/survey methods. This study maintains legitimacy through the use of specified methods of research validation such as construct validity, external validity and reliability through the use of case study protocol as dictated by Yin (2009, p. 41).

This protocol calls for the use of pilot studies as they help to reduce the scope of questioning to a manageable capacity and allow for a greater understanding of the target audience in respect to the interview or questionnaire, thereby reducing the possibility for ambiguity and misunderstanding in answers (Davies and Mosdell, 2006; Yin, 2009). Essentially it is a time saving strategy that increases the accuracy, validity and relevance of the research conducted.

"Research using interviews involves a deceptive simplicity; it is easy to start interviewing without any advance preparation or reflection. This kind of theoretical naïveté and methodological spontaneity may in part be counteractions to the abstract theories and formalized methodology taught in some social science departments” (Kvale, 1996, p. 12). It is for this reason that a brief, but well informed pilot study was employed as an integral part of the initial theory research. As indicated by Davies and Mosdell (2006) and Yin (2009), a key function of the pilot testing for research design, is the development of a conceptual framework as preparation for the study’s primary focused interviews, thereby optimising the whole interview process. (Rubin and Rubin, 1995)

In the case of this research, the pilot study was primarily a review of data surrounding the case study. The purpose of the pilot study is to inform the next stage of information gathering – the project management interview. The actual results and feedback drawn from the pilot study resources do not in-fact address the key objectives of the thesis, rather they inform the evaluation methods used.

7.1.2.2 Project Management Interview – Pilot Study and Questionnaire Design

The design of the Project Management Interview involved an amalgamation of the theory and methodology discovered throughout the literature review on research and qualitative data gathering, with the obviously tried and tested questionnaire presented by Wingfield et al. (2011). As the product of this amalgamation is unproven it was considered necessary to conduct a pilot study, drawing on the resources and contacts developed during the first year of the thesis.

Pilot studies, provide no novel data, rather they are a tool used to increase the efficiency of qualitative data gathering. This pilot study consisted of a simple procedure involving one of the leading figures in building analysis questionnaires - Adrian Leaman, the developer of the widely established Building Use Surveys Methodology. (see Section 7.2.1) After completing initial drafts of the proposed questionnaire drawing on inspiration from the afore mentioned sources it was released to Adrian Leaman with the understanding that his extensive experience within the field of qualitative questionnaire design would help to refine the rough product. Upon receiving feedback from Leaman via a lengthy telephone call, the questionnaire was revised and finalized, ready for use.

The primary purpose of the project management interview is to gather qualitative information developed over years of professional experience dealing with TPC. The interview structure allows the interviewee to expound on the basic question and therefore develop an answer that encompasses personal feelings and impressions (Kvale, 1996). The focused interview questions (Appendix A) are designed to enhance the depth, accuracy and reproducibility of the research and conclusions of the thesis. The questions are designed to be interchangeable in order to maintain a fluid conversational execution (Rubin and Rubin, 1995); this was a key contribution made possible by the background information from the pilot case study.

7.1.2.3 Design team retrospective

The relationship between client, designer, developer, architect and contractor is essentially what drives a project forward and ensuring their opinions and views on how the project has developed over time is seen as an important component in closing the research feedback loop. The timeline of this thesis and nature of the Green Street case study, mean it was impossible to directly observe many of the interactions between project management and the subsequent practical implications these had on the construction of Phase 1 and 2. Instead, to better understand the dynamics of the project and collate this background information this study incorporates a series of semi-structured interviews with key members of the project team, on location at the housing development. The interview process is designed to uncover gaps and hopefully explain some of the shortcomings in the project in order to ultimately avoid such complications in future projects. The interview protocol focuses on 5 key areas:

- Dwelling operation and usage patterns
- Maintenance
- Energy and water management
- Other points

- What would be done differently next time

As there is no real set structure for a design team retrospective analysis to be found in literature, the study makes use of the format set out by the TSB protocol (DECC, 2011a) in view of its widespread use on a significant number of research projects.

7.1.3 Industry Overview

Fundamental to the development process was a pilot study based on a workshop held on the 1st of February 2012. This workshop was entitled "Green Street – Lessons Learnt" and was attended by the key stakeholders associated with the design and construction of the Green Street Project including

- Igloo - Investors
- Blueprint - Developers
- Gleeds – Building Surveyors
- Lovell - Contractors
- Marsh Grochowski – Architects

Considering these stakeholders double as the target consultants for the interview process, the workshop, as a design and construction retrospective tool, provided a unique opportunity to refine the scope of questioning in the interview structure to a manageable capacity and allowed for a greater understanding of the target audience. As a pilot study the workshop and the subsequent report acted as essentially a time saving strategy that increased the accuracy, validity and relevance of the interview as a research tool. Thus, derived from the overall research objectives, and informed by the pilot study, a set of questions was generated. However in order to add further validity to the interview process, the questions were individually analysed and reviewed by the renowned researcher Adrian Leaman, creator of the BUS methodology (Leaman, 2009) widely accepted as one of the best qualitative building analysis tools throughout industry. It is based on his recommendations that the final product, available in section 7.3.3, was instigated and tested.

7.2 Qualitative Analysis Methodology

This section of the research utilizes 4 separate qualitative studies in consultation with three groups of individuals who directly and indirectly impact the goals of this project, namely to provide a comprehensive ecological performance analysis of a mainstream TPC housing development. The studies are a mixture of structured and semi structured interviews with questionnaires developed specifically for this study (Project Management Interview and Industry Overview) and those based on existing and established practice (BUS methodology and Design team retrospective.)

7.2.1 Occupant Feedback – Building Use SurveyMethodology

While not strictly speaking a qualitative study, BUS methodology nonetheless speaks to the aims of qualitative research, which at its core is characterised by a focus on human behaviour and a capacity to ask how and why decisions are made. The quantification of these factors within BUS does not in any way detract from the purpose of this methodology, rather it serves to aid in the dissemination and validation of the results by creating a standardised data set – a key objective of this study.

In order to get the most out of the survey the TSB released a report - How to carry out a BUS occupant survey - Domestic Buildings, (TSB (c), 2011, p. 3) which contained the following advice:

- The study sample should be as large and possible – in this case all of the case study houses are surveyed.
- Hand delivery a paper version of the BUS questionnaire ensures a higher response rate – given the close relationship between the author of this project and the occupants of the case study dwellings, this was the method of delivery.

- If possible the BUS questionnaire should be left with occupants for a few days – again this will result in a higher rate of return.
- Timing is critical when delivering the forms. Allow for at least two visits to deliver the forms in order to maximize your chance of making contact with the occupants. Allow the same time for retrieving forms. For the purposes of this study occupants of the 8 houses were pre-warned about the questionnaire, which was posted through the letterbox with an accompanying information sheet to explain the reasons behind the questionnaire and the expectations placed upon them. Pick-up dates were again arranged by e-mail.

After the surveys have been filled in by the occupants they were collected and the data is transferred into a spreadsheet file template provided with the BUS methodology package. Once all data is digitally recorded within the template it is sent off to be analysed and benchmarked by ARUP on behalf of the TSB. The result is a set of graphs and tables summarising the attitudes and impressions of the respondents.

For the purposes of this thesis this whole process is supplemented by an additional questionnaire attached to the BUS methodology, but developed specifically for this study. It was constructed with the specific aim of evaluating the occupant's attitude towards TPC – a subject not covered in the BUS methodology yet obviously central to this research programme. The author of the BUS methodology questionnaire, Adrian Leaman, was consulted regarding this addendum and it was decided that under the circumstances an additional TPC focused mini questionnaire was appropriate.

7.2.2 Design Team Review

7.2.2.1 Project Management Interviews

Created and conducted by the author of this research project, this semi structured interview protocol (found in Appendix A) is designed to establish the project management's views of TPC in relation to their direct involvement with the project on Green Street. The finalised version broken down in this section was subject to scrutiny by one of the leading figures in building related questionnaires – Adrian Leaman (TSB (c), 2011).

The semi structured interview starts off by asking the interviewees name and profession. These simple questions serve two purposes – the name helps in tracking the information source and the profession indicates the individual's capacity to answer the questions professionally. Moving on from the introductions, the next question tries to establish if the theoretical attributes of timber construction, as displayed by the motivations of the client and architects, are substantiated in the reality of the construction environment. Then looking retrospectively at the Phase 2 change in building methods, the interview probes what the thought processes were behind the move, seeking to identify who was behind this decision and at what stage of construction was it made? Questions 5 and 6 relate to the perceived barriers and advantages associated with TPC in an effort to discern theory from practical reality. These are followed by questions 8-10 that focus on the historical, current and future market profiles of TPC from the perspective of the project management. The interview comes to a close with a performance based question placing the construction processes of masonry and TPC within the context of the Code for Sustainable Homes. (Section 7.3.1.2)

Throughout the interview there is a strong theme relating to the barriers and advantages associated with wide scale integration of TPC. The reasoning behind this is to establish if these industry professionals have actually seen or experienced any of these attributes for themselves, or if they are simply relying on what they have heard. The targets of this interview protocol are the project management team, an experienced and diverse group that includes representatives from architecture, M&E engineering, developers and contractors, all in some way or another connected to the Green Street site.

7.2.2.2 Design Team Retrospective

A clear framework for the design team retrospective is set out in the guidelines of the BPE Domestic Guidance for Project Execution document. (TSB (b), 2011) The aim of the exercise is to "explore the degree to which the design intent had been followed through in terms of delivery and subsequent adoption by the occupant(s)." (TSB (c), 2011, p. 17)

First of all the procedural material dictates two separate walkthroughs of the dwelling in question, one with the design and delivery team and one with the occupants. Each walkthrough incorporates a semi structured framework of questions based around the following subject areas:

- Dwelling operation and usage patterns
- Maintenance
- Energy and water management
- What would be done differently should there be opportunity to work on a similar project in the future?

The evaluator, in this case a member of the housing development team, leads the discussion and prompts the design team and users alike with questions such as: Are there any issues relating to the dwellings operation? Questioning and answers are audio recorded, however, photographs, while recommended, were deemed too much of an invasion of privacy. Typically the walkthrough and associated interview lasts approximately 45 minutes.

The comments and feedback from the design team and occupant walk through should be compared to ascertain whether the design intent was delivered, valued or even wanted by the occupant. "If action was taken to remedy misunderstandings, improve support or feed occupant preferences into future design cycles this should be explained" (TSB (d), 2011, p. 4).

7.2.3 Industry Overview

There is incredible value in the experience and collective knowledge inherent within industry, the difficulty is harnessing these resources in a productive and standardised manner. The aim of this, the final qualitative data gathering procedure was to try and glean some of this understanding, and specifically focus on key problem areas and barriers within the TPC industry, hopefully addressing some of the theoretical benefits and obstacles that research has uncovered.

The industry overview approaches the subject of TPC performance with the knowledge and hindsight gained specifically from the Green Street – Lessons Learnt workshop and the vast amount of theoretical data accrued throughout this research project. Fundamentally research has shown timber fabrication (timber frame, volumetric and panel) potentially has substantial benefits over traditional masonry construction within the housing sector.

Based on the literature review findings, timber housing should theoretically perform better than traditional masonry because of the very characteristics that make it cheaper and quicker to build; namely that factory conditions allow for stricter implementation of design and higher quality fabrication with respect to joints, air tightness, and thermal bridging. Inherent modular design and delivery allows for reduced site activity and as the majority of work can be completed under factory conditions the result is fewer sub-contractors and a more transparent build process with respect to service installation and commissioning. These benefits relate to time savings, quality, sustainability, and overall costs.

Despite these overwhelming features and characteristics, despite a substantial precedence in countries round the world, masonry construction still dominates the UK market. This questionnaire is designed to reveal some of the underlying motives behind this domination. The questionnaire is broken down question by question within the results section, as such there is no reason to go into great detail regarding its composition within this section. That being said, the complexity and structure of the questionnaire has been intricately thought out to cater to the requirements of the research and character of the target audience.

The questionnaire is purposefully designed to be answered by professionals, and people who understand the business. If an individual doesn't understand the question then they should not answer it and the overall industrial picture is not muddied by uninformed random decision making. The structure of the questionnaire has also been designed to try and remove any bias (which given the target audience is a difficult, but not impossible thing.) Questions regarding the performance of traditional masonry housing are situated before the similar question for timber housing so the respondent doesn't know that there is a comparison being done until they are finished with the masonry question.

7.3 Qualitative Analysis Results and Discussion

This section of the research utilizes the four separate qualitative studies in consultation by gathering data from three individual groups who directly and indirectly impact the goals of this project. The structured Building Use Surveys (BUS) gather qualitative information on 'occupant's' attitude toward their respective houses and their experiences within the dwellings. The 'design team' review and retrospective in conjunction with the 'industry' survey provide feedback in the form of qualitative performance analysis, perceived barriers to integration for timber prefabricated construction (TPC) and the general context and state of the industry.

7.3.1 Building Use Survey

The aim of utilizing the qualitative BUS methodology is to better understand the attitudes and perceptions of housing occupants in order to better interpret performance attributes displayed in the quantitative data gathering portion of the research. The results of the individual questionnaires are incorporated into a larger benchmarking database.

This benchmarking process unfortunately diminishes the resolution of the questionnaires, organising the data by question type rather than house number. This means that results between the two construction types are not differentiated. Fortunately the original hardcopies of the BUS methodology questionnaire were also retained allowing for a further analysis of the results in respect to the housing types – timber and masonry. Crucial to this process was the addition of the supplementary questionnaire, designed to highlight the construction elements of the housing development and obtain specific feedback regarding the attitudes towards the brick or timber fabrication.

7.3.1.1 Building Use Survey Questionnaire

Despite the consolidation of brick and timber construction results through the benchmarking process, there are still important lessons to be learned through the Building Use Survey. The subsequent graphs and tables have been included in this section as they provide some valuable feedback on the overall performance of the case study site and where possible the results are divided in to fabric type for comparison purposes. Figure 7.1 provides an overview of the slider graphic employed in the BUS analysis phase and is subsequently followed by Figure 7.2 depicting a summary of the variables examined throughout the questionnaire.

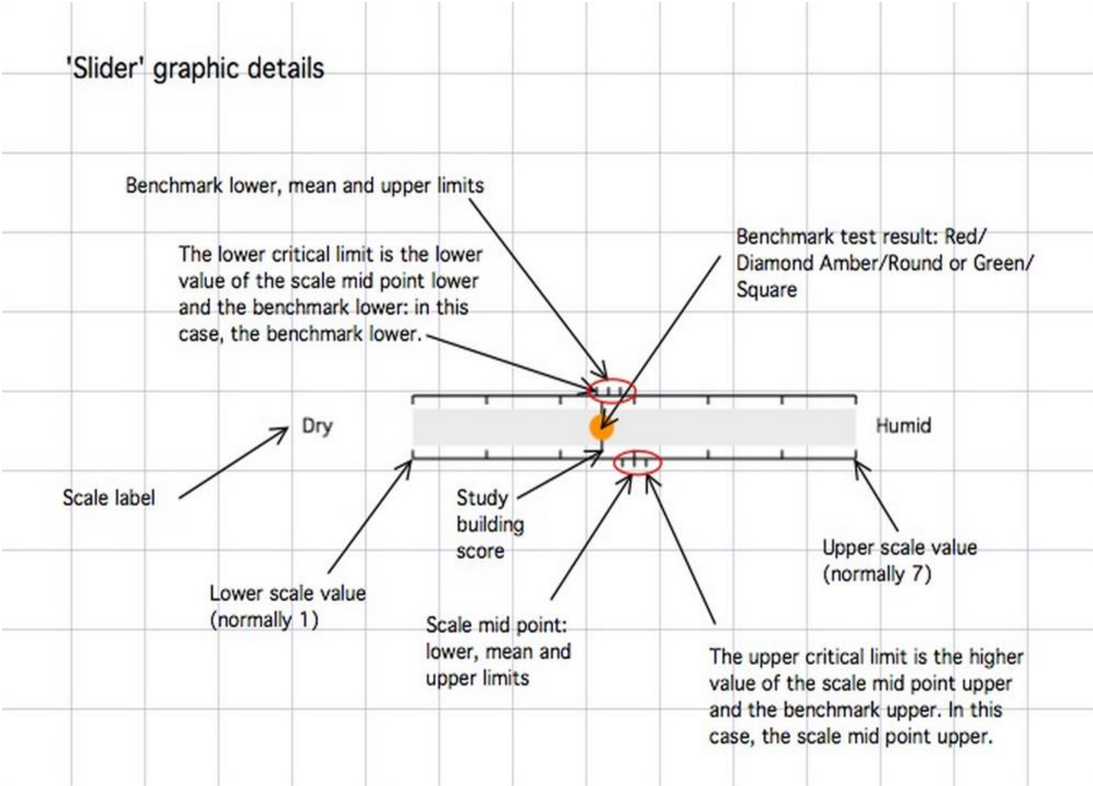

Figure 7.1 Slider Graphic Details

A green square denotes a variable with an average score better than both the scale mid-point and the corresponding benchmark. An amber circle indicates an average score which is typically better than the mid-point of the scale, but not significantly different from the benchmark for that variable. A red diamond represents an average score that is lower than both the mid-point of the scale and the corresponding benchmark.

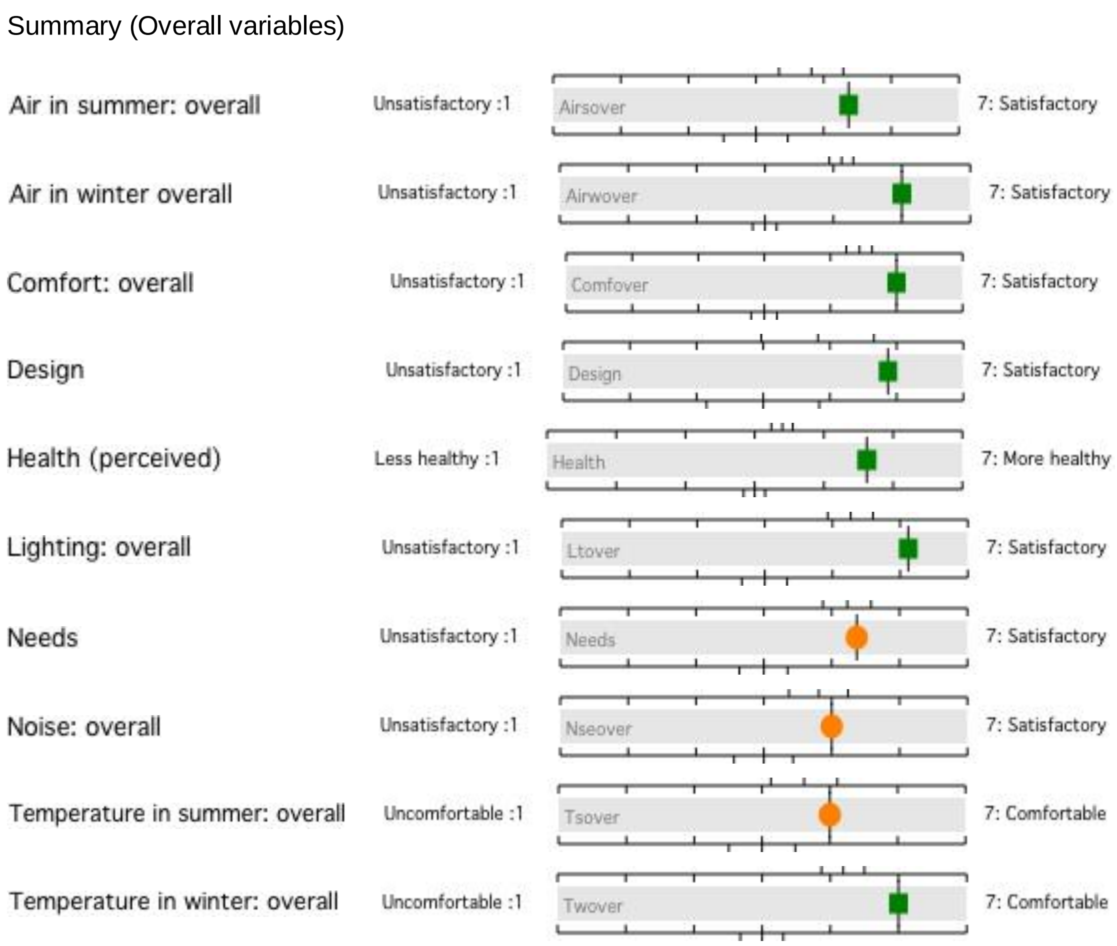

Figure 7.2 Summary of BUS variables in Slider Graphic Format

Figure 7.3 was constructed by going back to the original hardcopy questionnaires and extracting the relevant data to match the same scales (on the x-axis) and labels as Figure 7.2. The key difference being that the feedback from the timber and masonry housing is now split and the correlation between the two can be clearly analysed.

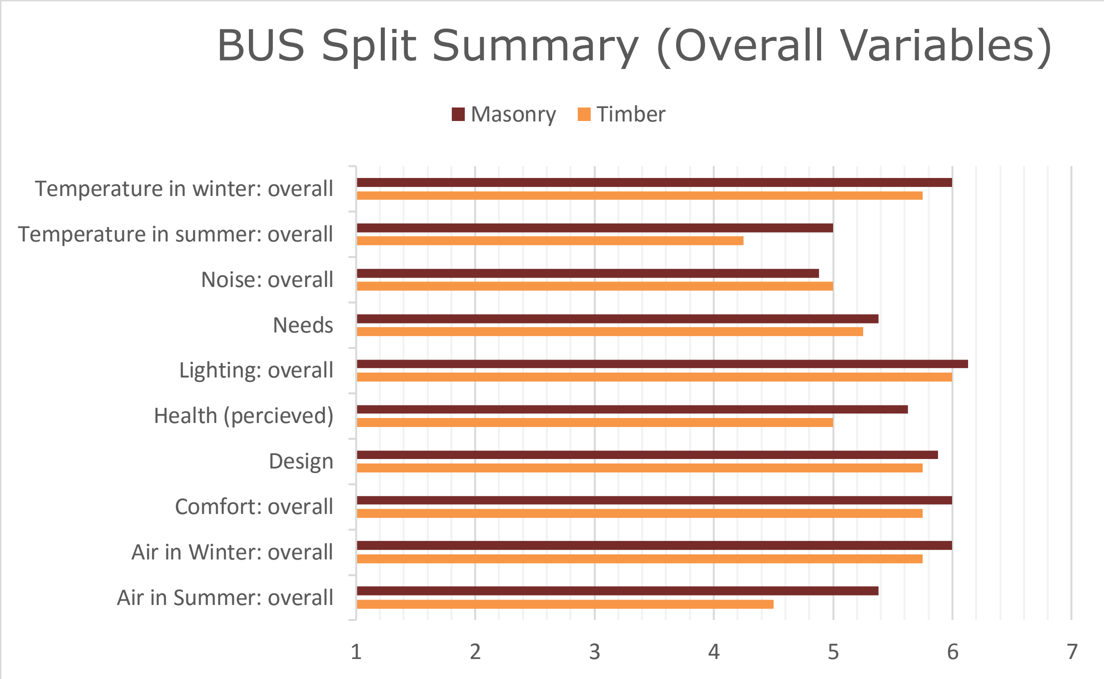

Figure 7.3 Split summary of BUS variables in graphic format

Table 7.1 runs through the actual numbers involved in the conclusions from the BUS questionnaire.

Table 7.1 Split Summary of BUS Variables

	Timber	Masonry
Air in Summer: overall	4.5	5.38
Air in Winter: overall	5.75	6
Comfort: overall	5.75	6
Design	5.75	5.88
Health (perceived)	5	5.63
Lighting: overall	6	6.13
Needs	5.25	5.38
Noise: overall	5	4.88
Temperature in summer: overall	4.25	5
Temperature in winter: overall	5.75	6

Initial impressions are that the average values extracted from the two phases are remarkably alike with no significant differences. This in itself is actually an interesting and revealing statistic as it demonstrates that timber housing from a qualitative owner/occupier perspective is performing to a similar standard as its masonry counterpart. Not better, as research suggests it should, or worse as many in industry and the public would suspect, but just the same.

That being said, upon closer inspection there is a minor, but unusual contradiction in the overall values. For the majority of factors the properties rate highly on the sliding scale, including the overall design of the properties, and yet the occupants simultaneously report issues with cooling of the dwellings, specifically the temperature during the summer months. The graphic readouts are supported by comments recorded on the questionnaires:

- "More solar shading needed."
- "Top floor gets very hot during the day."

In order to gain greater insight into the noise and temperature anomalies highlighted through the slider graphics, these two factors are covered in more detail through percentile graphs which are broken down and defined in Figure 7.4.

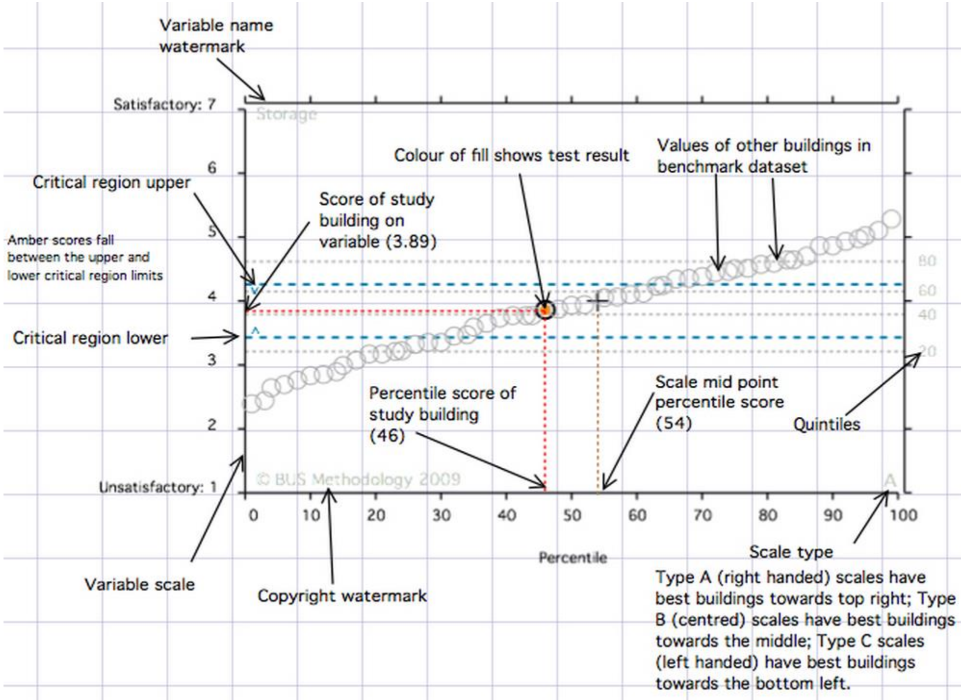

Figure 7.4 BUS Percentile Graphic Details

Figure 7.5 shows the graphical output of the BUS process, in this case looking into how occupants perceive their control over cooling (Cntco) their homes.

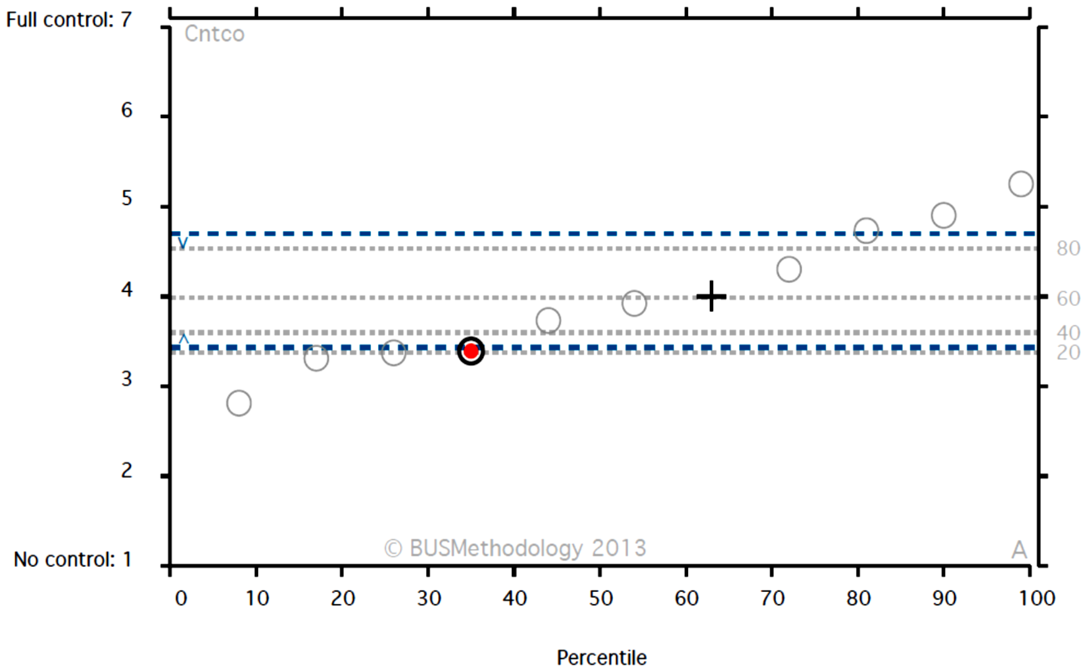

Figure 7.5 Control over Cooling - Percentile Graphic

An overall study mean of 3.42 in the 35 percentile is calculated with respect to a large data base of figures collected from other similar residences located around the UK. The numbers indicate the poor standing of the case study in the context of the researched housing stock and signify that while not unheard of, the control over cooling and high temperatures experienced in the Green Street houses fall below expected performance levels – as indicated by the residents.

Table 7.2 BUS Results for Control over Cooling

Masonry	Timber
3	3
4	3
3	2
N/A	3

Noise is also an issue raised by the occupant's comments, however the percentile graph shows that a score of 5 actually rates the properties within the 72nd percentile.

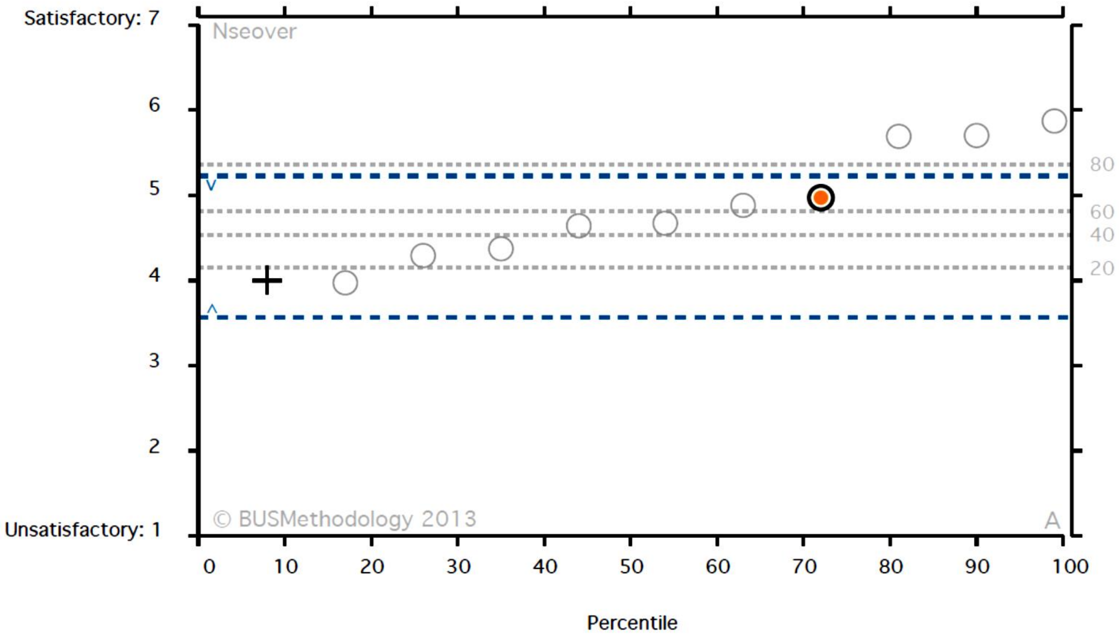

Figure 7.6 Noise Overall - Percentile Graphic

Looking back at all the comments made on the questionnaires, the feedback varies widely from house to house.

- Generally very quiet. (Timber)
- Love how quiet it is, but sometimes hearing neighbours is comforting. (Timber)
- Noise between floors is terrible - every word, sound and movement. (Timber)
- Noise on first and second floor is too much. (Masonry)
- Really great sound muffling materials. Never hear neighbours, or outside. (Timber)
- Lots of noise between rooms and neighbours. (Masonry)

To make any definitive conclusions would require sound testing the properties which is unfortunately beyond the remit of this project, however it is interesting to note that despite a lighter construction method, there does not seem to be any bias against the timber and noise interference between the properties, in fact quite the opposite is visible in Table 7.1. Acoustic performance is listed as a significant perceived barrier and any evidence from a real development that indicates otherwise is worth noting.

Both the BUS survey and the BUS Supplementary survey provided some key insight into the opinions, and beliefs held by the occupants regarding their properties and the general attitude towards the benefits and barriers facing TPC.

7.3.1.2 Building Use Survey Supplementary Questionnaire – Answer Summary

Table 7.3 BUS Supplementary Questionnaire – Answer Summary

	Occupants of Timber Houses (1-4)					Occupants of Masonry Houses (5-8)				
Questions	1	2	3	4	Comments	5	6	7	8	
What do you see as a more sustainable form of construction? (Masonry/Timber)	N/A	Timber	N/A	Timber	I believe it is timber.	Timber	Timber	N/A	Brick	
Did the house construction type in any way affect your decision to purchase the house? (Yes/No)	No	No	Yes	No		No	Yes	Yes	Yes	
Has the house construction type in any way affected your daily routine? (Yes/No)	No	Yes	No	No		No	No	No	Yes	
Does the housing construction type in any way impact your future plans for the property? (Yes/No)	Yes	Yes	Yes	No	Aim to move before render cracks.	Yes	No	No	No	
Did you have trouble finding a mortgage due to the house construction? (Yes/No)	No	No	No	No	Insurance costs more.	No	No	N/A	N/A	
What do you estimate is the lifespan of your house?	0-40	0-60	N/A	0-100yrs	Feels weak at times. Brick lasts longer.	0-100yrs	0-100yrs	0-40	0-100	
Have there been any structurally related problems since your occupation of the property? (Yes/No)	No	No	Yes	No	Leaks	No	No	Yes	Yes	

The BUS supplementary questionnaire was designed to address the subject of barriers to integration for TPC in a wider context within the British construction industry and expand on specific topics not addressed in the narrow scope of the standardized BUS questionnaire. The majority of these barriers are outlined in section 2.5. The idea is to understand if these theoretical barriers still exist in the modern age of timber construction from the perspective of the house buyer or client. This section covers each question from

Table 7.3 in turn, commenting on what the answers reveal about the general attitude towards that particular element of TPC.

- *What do you see as a more sustainable form of construction? (Masonry/Timber)*

  The actual sustainable credentials of housing materials depend on a vast amount of factors, one of the greatest being not the material itself, but how far it has to travel. Timber is almost always seen as a more environmentally friendly material – the questionnaire corroborates this fact, however evidence from section 6.3 quantifiably refutes this supposition.
- *Did the house construction type in any way affect your decision to purchase the house? (Yes/No)*

  Typically the results show that those in the timber housing generally didn't care as to the nature of their housing fabric and those in the masonry did. This doesn't really reveal too much about the changing perception towards timber, only that the construction method is not seen as inferior by those who choose to live in it.
- *Has the house construction type in any way affected your daily routine? (Yes/No)*

  There seems to be little to no impact on people's day to day lives based on the construction of their houses. These are early days, however, and maintenance routines synonymous with timber housing have yet to come into play. These may change resident's attitudes towards timber properties and this question should be posed again after a few years in order to gauge the resident's ongoing feelings toward housing maintenance.
- *Does the housing construction type in any way impact your future plans for the property? (Yes/No)*

A clear majority of the "yes" answers lie with TPC signifying that these homeowners are already thinking ahead about the properties and what they may want to do with them in the future – the comment in

Table 7.3 is particularly revealing and speaks to the perceptions of durability still ingrained within the British psyche. The general consensus seems to be that people are obviously still unsure as to how to treat the properties from an investment perspective and are aware that as time goes by no one knows how the houses will fare from a durability standpoint. This may be reading into things a bit too much, and it could have more to do with the nature and lifestyles of the occupants, but the comment that was already mentioned seems to suggest otherwise.

- *Did you have trouble finding a mortgage due to the house construction? (Yes/No)*

  Section 2.5 goes into great detail as to the reticent nature of the various financial institutions that play a part in buying and owning a house. There is anecdotal evidence that suggests perceptions are changing with respect to the perceived financial viability of TPC and therefore new homeowners are finding it easier to both buy and insure their homes and the survey data seems to support this conclusion. Section 7.3.1.3 elaborates on this point a little further.

- *What do you estimate is the lifespan of your house?*

  This is a very simple and intentionally blunt question probing how occupants perceive durability within the different construction types. As expected the masonry housing in generally perceived to last longer than the timber, however the fact that 2 of the 3 timber answers are over 60yrs indicates that people acknowledge that timber housing has made some significant advances over the past few decades. The comment provides an interesting insight into the psychology behind the durability perceptions.

- *Have there been any structurally related problems since your occupation of the property? (Yes/No)*

  Since this survey was conducted there have been significant changes concerning the subject of structural reliability in both the timber and masonry properties, predominantly focused around water leaking through the flat roofs of the properties, roofs which were later found to be missing the appropriate vapour barrier. This however was a common occurrence across both house fabric types and are therefore unrelated to the aims of this project.

7.3.1.3 Building Use Survey Analysis

The BUS analysis revealed that the design of the housing in both phases in theory is good, comfort is rated highly, lighting is rated highly, even ventilation is rated highly, however this did not translate into to positive feedback on the summertime ventilation and temperatures. Looking back at the individual hard copies of the questionnaires and Table 7.1 there is no strong correlation between construction type and cooling. This would seem to support the conclusion that temperature control is more likely to be an occupant driven issue rather than fabric dependant. The results of a handover review conducted by the author of this project (Bailey, et al., 2013) concluded that the occupants were never taught how to efficiently cool their properties through the variety of design features and technologies built into the dwellings. Thus the BUS methodology results are likely the result of a lack of appropriate occupant education rather than a reflection on the housing fabric. Over all there is very little discussion within the BUS survey answers which highlights the difference in construction materials or build process, and in a way that is a very revealing conclusion as it suggest that occupants ultimately don't really care about the underlying structure as long as the performance is on par with their expectations. These conclusions however, must be placed within the context of an audience which has invested heavily in their respective properties and thus the answers they provide may lean toward a positive bias.

The BUS supplementary questionnaire broached many of the key qualities associated with TPC, covered in section 2.5, from the perspective of the literature review. This includes issues of financing, durability, longevity and sustainability. The idea was to understand, albeit from a small subset of the population, how these characteristics are portrayed and viewed in the modern age of mainstream timber construction from the perspective of the house buyer or client. The conclusions seemed to suggest that perceptions and barriers have remained similar (Section 2.5) but they simply don't have the same level of influence over the public's decision making.

- Timber is seen as more sustainable construction material.
- There are still reservations from throughout the development regarding the longevity and durability of the timber construction despite the advances in modern construction methods and the obvious acceptance of the material by those who have invested in buying the phase 1 houses and significant developments in the Passivhaus movement for example.
- The feedback from the survey is mixed regarding the financial hurdles associated with buying TPC housing. There is a clear and encouraging consensus in this study regarding the availability of mortgages, however there is a key comment that suggests the insurance companies have yet to come to the same conclusions about TPC as the banks. This is potentially down to the ongoing perceived fire risk and durability concerns associated with timber housing brought about through a lack of education and historical precedence. It is unlikely that prices will come down until TPC becomes a staple of the British housing market and proves itself to be the equal of its masonry counterpart resulting in a bit of a "chicken and egg" situation.

7.3.2 Design Team Review and Retrospective

The design team review and retrospective tests were the most challenging of the qualitative data gathering procedures due to the inherently invasive nature of the testing into the lives of very busy individuals, all with different schedules and priorities. In particular the coordination of industry elements and the residents of the development proved to be a challenge as discussed in greater detail in section 7.3.2.2. Ultimately these complications resulted in a poor rate of response for the interviews and created a ridged timeframe precluding adaptation of the TSB's design team retrospective methodology, which despite initial appearances and intentions, delivered little, if any, relevant data. While the amount of information gleaned from each study was less than the original target (substantially so in the walkthrough), the design team review revealed some very valuable insight into the project, covered in the following section.

7.3.2.1 Project Management Interviews

The project management interviews were targeted at the key members of the design, management and construction team who would be able to answer detailed questioning concerning their direct experiences and involvement with the project, with an obvious emphasis on fabric comparison. Out of the relevant individuals identified in section 7.2.2.1 only 2 ultimately agreed to take place in the study, architect, Julian Marsh and project surveyor Jonathan Edwards. The following is a collection of relevant remarks and interesting comments expressed throughout the semi-structure interview process by John Edwards, quantity surveyor and Julian Marsh, architect. The full interview protocol is displayed in full in Appendix A.

1. *In your mind, why was timber chosen as the primary material for Phase 1?*
   The developer (Blueprint) was always open to adopting whatever construction style best suited the site and expressed this during the tendering stage. Marsh Grochowski, the winning architecture firm designed the whole site to be in masonry. The reason phase 1 was changed to timber was due to a deadline placed on the spending of a grant from the HCA. The grant was required to make the project viable, thus the money had to be spent by the deadline. Upon consulting the contractors (Lovell) the suggestion was to build phase 1 out of timber as it was seen as a faster method of construction which would ensure that the money from the grant was spent in time. The money was spent in time, but the change from masonry to timber frame construction had a significant amount of unforeseen implications, principally the light weight construction's lack of thermal mass and the potential for overheating within the house. Numerous solutions were suggested including the inclusion of PCM and internal masonry walls the full height of the housing however the final solution selected to combat the potential overheating of the properties were external electronic shutters on windows on the Southwest façade.

2. *What was the basis for the decision to adopt masonry construction in Phase 2?*

The extra implications associated with the change to timber in Phase 1 (program disruption, cost, aesthetic impact of the external blinds) actually made it far more complicated than originally planned and defeated the whole ethos behind using the timber frame method. Lovell approached the developer and suggested moving back to traditional masonry build with which they had far more experience.

3. *Can you list 3-5 key advantages of using timber construction?*

- Perceived as a sustainable material.
- Potential for lighter foundations
- Theoretically more airtight
- Theoretically higher levels of insulation
- Factory work should make construction quicker (roof on quicker, water tight quicker etc.)
- "Obviously" lower carbon construction.
- Theoretically cost benefits.
- Reduced program on site – dependant on a decent lead in. Green Street did NOT see this. Yes the money was spent, but there was too much time on site. Green Street needed more time off site preparing in order to see the real advantages of reduced program. The problems associated with thermal mass may not have been an issue if there had more time to speak with timber developers and work out a better solution.

4. *Can you list 3-5 key disadvantages of using timber construction?*
- Keeping it dry during construction
- Difficult to adapt and to manipulate on site.
- Less thermal mass.
- Post occupancy movement, structural shifting.
- Potentially a general feeling that the technique lacks solidity. Less dense, an overall conception of lightweight construction.
- Easy to poorly install the vapour barrier and membranes – results in much higher risk of degradation than traditional masonry and the potential for poor airtightness. Only a problem on timber frame, built half in factory and half on site. Modular design leaves the factory much more complete mitigating the potential for poor practice

5. *Why do you believe the UK builds primarily in masonry housing?*

   Partly because most houses are built by the large house builders, it's what they are used to, it is what their procurement systems are set up for. They have teams of subcontractors etc. already sorted. It is easier for them to stop start small scale builds on this basis. Greater flexibility for them. To get the true economies of scale required to appreciate the benefits of timber you need larger developments which are just not that prevalent in this economic climate.

   Just tradition. It's just what we have always done.

6. *What key challenges do you see as standing in the way of the integration of timber construction into mainstream housing construction in the UK?*

   It comes down to site skill most of all. Until we can get the same level detail and focus that you get in the factory, actually on site when the thing arrives then the performance benefits theoretically associated with TPC will struggle to be realised. Completely modular construction is the best. Frames and panels are still too open to construction error. Half and half is where you get the problems.

   The preconceived notions of poor longevity and durability. Telling people that the timber house has a 60 year guarantee doesn't actually instil much faith in the construction. People are living in Edwardian houses which they subconsciously perceive as simply being around forever (this is not the case when they are actually examined closely – foundations bad, timber joists above windows etc. – not as solid as they actually think.) However people always think of a house lasting for centuries and then you give them only a 60 year warranty and it causes them to rethink things (when coupled with the timber construction;) even though 60 years is actually a good guarantee and you wouldn't really expect anything more. People equate the poor performance of post war prefabrication units with modern methods of construction and immediately question its long term viability.

   Thermal mass is a big issue – we need ways of keeping the houses cool in summer.

Big house builders will need to construct large factories, but the reason that they haven't done this is piecemeal nature of the construction industry. Often companies are on a site for many years, selling houses a few at a time and then building a few more etc. There are no cost savings to be made through off site timber construction because the company is already on site. Essentially it is not a technical problem, it's the way the market is structured and how houses are sold, at least over the past few years. Higher densities in the future will push for larger developments and thus better conditions for large scale timber construction.

7. *Given these challenges, do you personally see timber fabrication as a viable alternative to traditional masonry construction?*

   Yes, but depends heavily on site conditions, timeframe, volumes. Social housing schemes might be a good opportunity to evaluate TPC. They appreciate the cost benefit of less time on site, they have plenty of lead in time and they are not sales led – it's construction program led.

   Yes, but obviously only when mixed with traditional masonry. Thermal mass remains a significant issue. It's not as simple as sticking a load of PCM on the wall. Even if we go for external timber (as opposed to timber frame with brick skin) houses should still contain massive masonry cores – concrete stairs or lightweight concrete floor panels for example. There has to be something in there which has to be thermally massive. BedZED used concrete ceilings.

   Green Street theoretically is a good site for timber due to its density and volume, the problems emerged due to the last minute decision to change to timber without enough planning and forethought.

7.3.2.2 Project Management Interviews Analysis and Conclusions

While the data gathering process did not go quite as planned, this section yielded some of the most insightful and valuable conclusions, albeit from a limited cross section of interviewees.

The interviews revealed the motivations behind the adoption of TPC in phase one were very simple – speed of construction. There was no complex design strategy or in-depth consideration of the pros and cons associated with the adoption of timber as the primary construction material, it was simply viewed as a rapid construction technique. This was later called into question as the shortened schedule had a knock on effect on the design timetable, which in turn left inadequate time to prepare solutions for the light weight construction's lack of thermal mass and the potential for overheating within the house. This highlighted the need for perhaps a little more forethought in a construction technique where measuring twice and cutting once can save money, time and the environment. The complications associated with phase 1, coupled with the removal of the expedited timetable and the contractor's experience with masonry construction resulted in the decision to revert back to masonry construction in phase 2. This could be indicative of building sites across the country, dipping their preverbal toes into the TPC industry, only to find that it is not exactly how they expected it to be, and immediately reverting back to their old ways. This conclusion is supported by the answer to question 5, which pinpoints the motivations behind the majority of the UK housing industry using masonry construction, namely they are just more comfortable with masonry because it is "what we have always done."

The advantages and disadvantages highlighted in this section mirrored those of the literature review and occupant questionnaires, however, there was a lot of "theoretically…" or "potential/perceived…" benefits, only reinforcing the need for projects like this, converting theory into fact through applicable and relevant POE of mainstream developments. The themes of precision and the need for specific and relevant skills are once again emphasised within this section with a particular emphasis on the need for a greater level of factory based modularisation within the industry in order to combat some of the site based weaknesses. The issue of durability and longevity in TPC dwellings is laid bare in comments by Jonathan Edwards, citing the identical warranty period for both traditional masonry construction and TPC, yet at the same time acknowledging the fact that people still equate the poor performance of post war prefabrication units with modern methods of construction and immediately begin to question its long term viability. Finally the subject of thermal mass was raised as a particular obstacle in the way of the mass integration of TPC, however as Julian Marsh put it: "The problems associated with thermal mass may not have been an issue if there had more time to speak with timber developers and work out a better solution." Essentially, given enough time, it is usually possible to design a solution for the lack of thermal mass instead of just immediately reverting to brick and mortar construction.

7.3.2.3 Design Team Retrospective Walkthrough and Conclusions

In theory the design team walkthrough was a good idea, developed by the TSB (TSB (b), 2011) to better understand the original aspirations for the project and then work through the process of design, construction and occupancy to better understand how those aspirations were realized and where they differ from the delivered building thereby revealing gaps between design and delivery performance.

Even the brief provided by the TSB indicated that the walkthrough represented a valuable opportunity to gather information on the successes and failures associated with the different construction types in Phase 1 and 2:

> *The purpose of the walkthrough is to compare design intent with reality and why there is a gap between the two. Explore the degree to which the design intent has been followed through in terms of delivery and subsequent adoption by the occupant(s). Focus on what constraints or problems they had to accept or address in delivering the project.*
>
> *Cover construction team issues and how these were cascaded through the project for example: training for design team on utilising specific technologies and new materials, sequencing of trades. Describe and evaluate the documentation generated to confirm and record the commissioning and hand-over from specialist contractor to house builder.* (TSB (d), 2011, p. 3)

In reality, the TSB protocol, used as the questioning framework, was too heavily focused on systems maintenance, management and performance. It contained very little fabric related enquiry and was considered by some of the research team, to be very awkward and less than optimal in its implementation. Unfortunately running this phase of the research, gathering all the necessary people and coordinating access to the representative houses was only possible under the guise of the TSB project, and thus the line of questioning was inextricably tied to the TSB protocol. The following is a very brief summary of relevant information salvaged from the full audio recordings, which can be made available for future research project with a greater focus on systems management, maintenance and renewable technologies. The interviews were conducted in Houses 1 and 6, representing each phase and attended by representatives from the architecture firm, developers, surveyors and agent, dwelling owners and research team.

Masonry Housing:

The only fabric related discussion concerned the perceived durability of the housing: "I think we have a very solid house, I do appreciate that it has the solid block construction." There seems to be no movement and both the contractor and occupant were encouraged by the fact that there was little to no movement in the house post-construction.

Timber Housing:

- No noticeable problems with settling or movement in the timber as of yet.
- There is little to no acoustic transmission between the housing, however between floors is rated as being simply adequate.
- The occupant has never really even considered that the house is made from timber. The house "feels solid." No issue with the construction fabric or type.
- It was difficult to install the MVHR in the timber housing as often the timber structure interfered with the optimum ducting path and it is simply unsafe to be cutting through potentially structurally integral beams.
- The blinds are actively used to reduce the temperature in rooms.

7.3.3 Industry Overview

Once the development of the questionnaire was complete (see methodology) the second step was to compile a list of just under 100 timber frame manufacturers, builders, suppliers, designers, essentially representatives from every stage of the supply chain in order to get as well a rounded collection of answers as possible. Table 7.4 gives an example of a few of the companies targeted.

Table 7.4 Selection of Companies Canvased for Industry Overview

Advanced Panel Systems Ltd	**Advanced Timber Craft Ltd**	**Alexanders' Timber Design Ltd**	**Aspire Timber Structures Ltd**	**Bellwood Timber Frame**
Crendon Timber Engineering	**Crocodile Timber Frame Ltd**	**Crown Timber Plc**	**Cygnum Timber Frame Ltd**	**Deeside Timberframe Ltd**
Falcon Panel Products Ltd	**Faloowfield Projects Ltd**	**Fawcett Construction Ltd**	**Fforest Timber Engineering Ltd**	**Fleming Buildings Ltd**
Gibbs Timber Frame Ltd	**Goodwins Timber Frame**	**Guildford Timber Frame Ltd**	**Guildway Ltd**	**Harlow Bros Ltd**
Kilbroney Timber Frame Ltd	**Kingspan Off-Site Ltd**	**Kirkwood Homes Ltd**	**Lewis Timber Frame Ltd**	**Lincolnshire Timber Frame Ltd**
Muir Timber Systems	**Neatwood Homes Ltd**	**New World Timber Frame Ltd**	**Northwest Timber Frame Scotland Ltd**	**Oakworth Homes Ltd**
Roe Timber Frame Ltd	**RTC Timber Systems**	**Scotframe Timber Engineering Ltd**	**Setanta Construction Company Ltd**	**Sevenoaks Timber Engineering Ltd**
Boise Engineering Wood Products Ltd	**BSW Timber Plc**	**Ccg (Osm) Ltd**	**Clarke and Sons Ltd**	**Covers Timber Structures Ltd**
Donaldson Timber Engineering Ltd	**Drumbow Timber Frame**	**Eco Timber Frame Ltd**	**Ecoframes Ltd**	**Eleco TimberFrame Ltd**
Fleming Homes Ltd	**Flight Timber Products Ltd**	**Forever Warm Homes Ltd**	**Frame UK**	**Frame Wise Ltd**
Heritage Designs	**Holbrook Timber Frame Ltd**	**Howarth Timber Engineering Ltd**	**Ijm Timber Frame Ltd**	**Ipswich Timber Frame Ltd**
Maple Timber Frame of Langley Ltd	**Masterframe UK Limited**	**Mk Timber Systems Ltd**	**MandM Timber Frame**	**Moreys Timber Engineering**
OFP Ltd	**Pace Timber Systems**	**Pattrick and Thompsons Ltd**	**Pinewood Structures Ltd**	**Rob Roy Homes Ltd**
Skye Homes Ltd	**Southern Timber Frame Ltd**	**Spruce Timber Frame Ltd**	**Stewart Milne Group**	**Swift Timber Homes Ltd**

Of the companies selected, 35 actually responded to phone calls and e-mails requesting a direct contact to whom the questionnaire could be targeted. E-mails with the questionnaire were subsequently sent out to both respondents and the general enquiries accounts for companies who never communicated.

Unfortunately, despite the amount of companies identified and approached for the survey there was very limited response rate as often companies were reluctant to give out personal e-mail addresses so the surveys could be better targeted. Out of the 96 companies identified there was a response from only 7. Nevertheless the following is a compilation of their answers to the survey questions and their comments on the subjects raised by the questions. Where the answers or scale for the answer is not clear please see the italicized comments for clarification.

1. **Good environmental performance is driven by a wide range of variables. Please rate the following factors in relation to their influence over the environmental performance of a dwelling where 1 is the highest impact.**

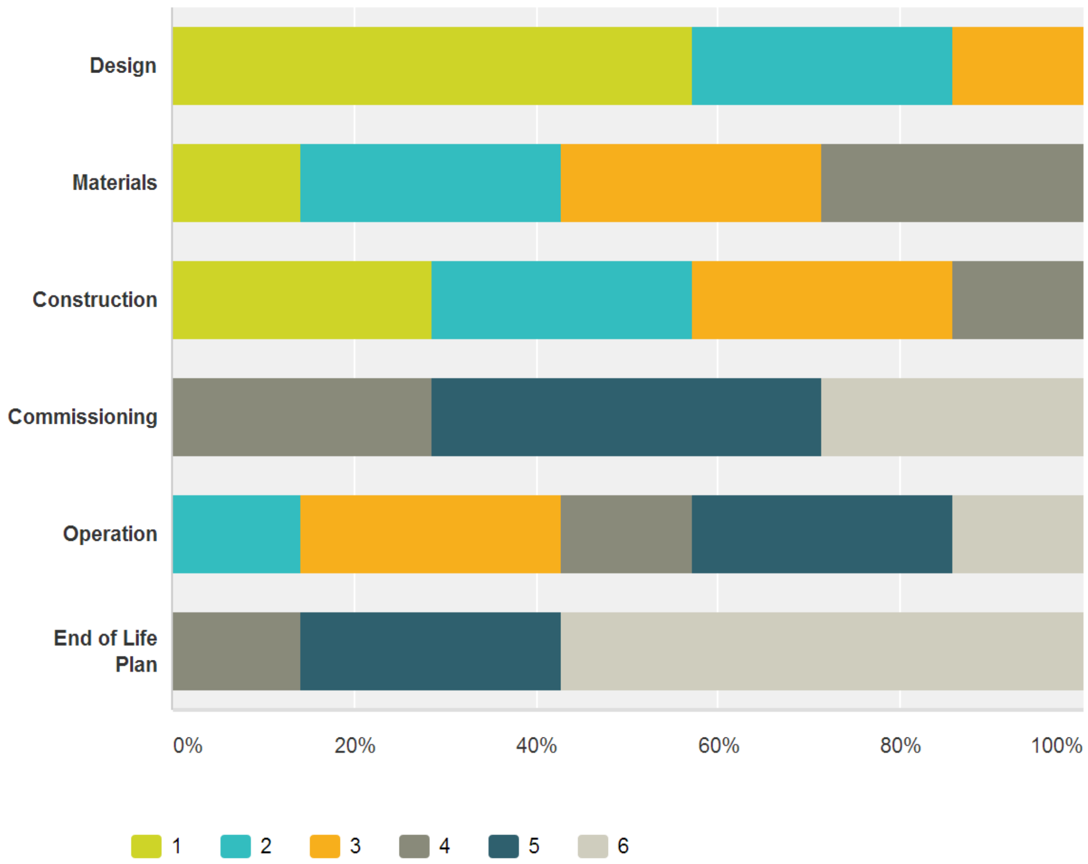

Figure 7.7 Industry Overview Question 1 Answers

For clarification, the top bar of the graph indicates that 60% of respondents felt that design had the greatest impact on environmental performance as indicated by the green bar which corresponds to the number 1. A further 25% on this bar felt that design was secondary to another factor and finally, 15% felt that there were at least 2 other factors which impacted environmental performance more than design – materials and construction. As there were 7 total respondents, these results represent the views of 4, 2, and 1 person respectively.

2. **The following are integral components of energy performance in modern housing. Please indicate on the scale the extent to which you believe houses built using TRADITIONAL MASONRY CONSTRUCTION methods are achieving each of the elements:**

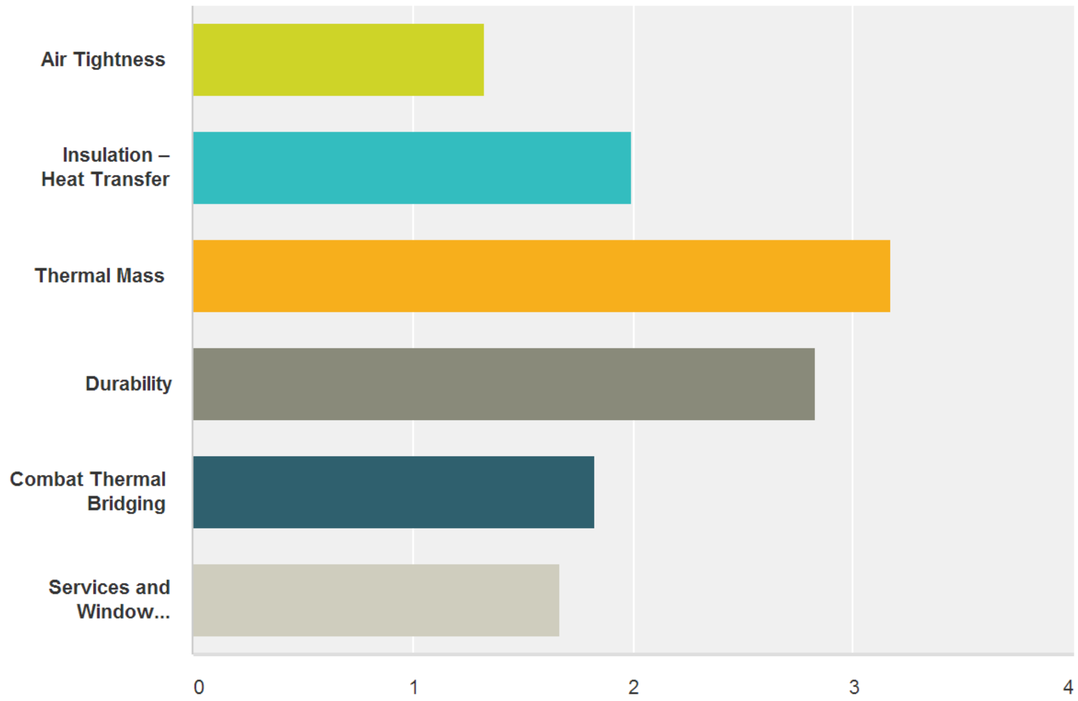

Figure 7.8 Industry Overview Question 2 Answers

(0- Poor,1- Satisfactory,2- Good,3- Very Good,4- Perfect)

Results for question 2 are the average rating given by the 6 respondents who answered this question. Traditional masonry construction is seen to provide only satisfactory air tightness, whereas it scores very highly on thermal mass and durability.

3. **The following are integral components of energy performance in modern housing. Please indicate on the scale the extent to which you believe houses built using TIMBER FABRICATION construction methods are achieving each of the elements:**

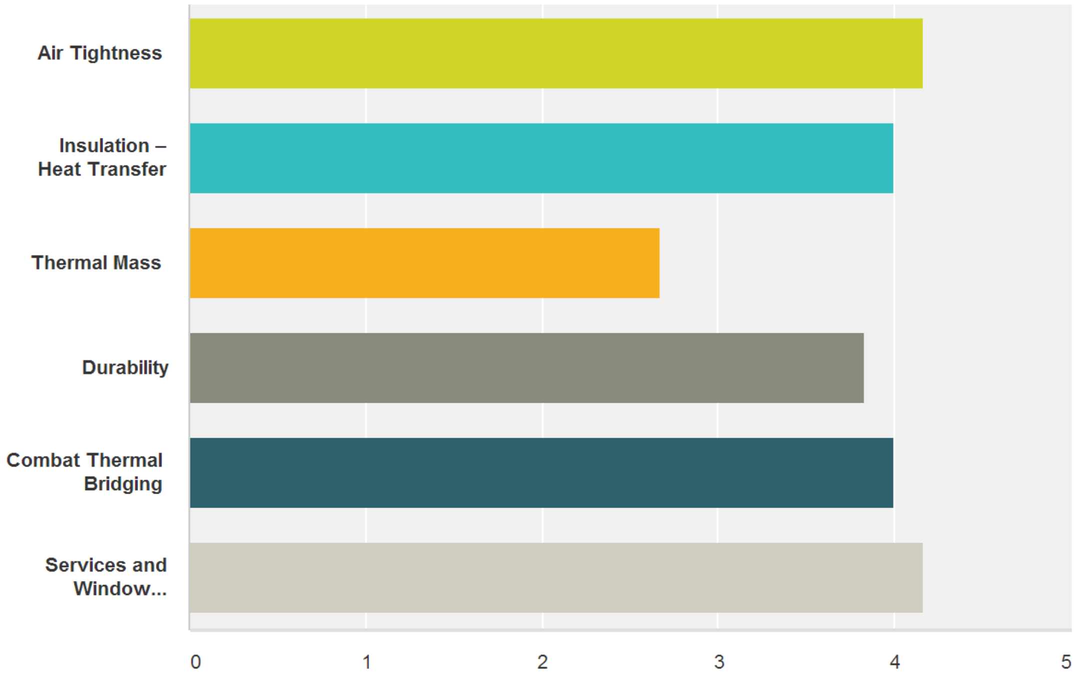

Figure 7.9 Industry Overview Question 3 Answers

(1- Poor,2- Satisfactory,3- Good,4- Very Good,5- Perfect)

4. **In answering questions 2 and 3 were your decisions based primarily on experience and quantifiable evidence or hypothetical reasoning and logical deduction from the build process? Essentially if you rated one construction type higher than another in a particular component, what was that decision based on?**

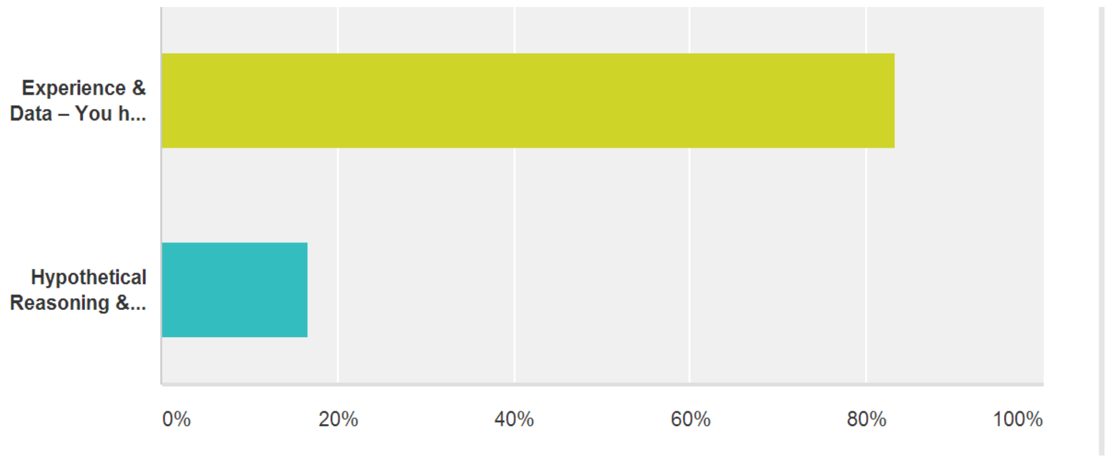

Figure 7.10 Industry Overview Question 4 Answers

- *Experience and Data – You have seen first-hand one type of construction perform better or have evidence to prove it.*
- *Hypothetical Reasoning and Logical Deduction – Obviously one type of construction will perform better than the other because of the way it is employed and executed.*

All questions included the option for commenting if the respondent wanted to add any extra feedback. The following comments pertain to question 4.

"Not all my answers where from experience and data. Some were from hypothetical and logical deduction. Note that some of these items can be equally as good or poor in both systems however it all comes down to detailing."

"We have vast experience of both traditional and timber frame construction. T.F. [timber frame] is by far the winner PROVIDING it is well manufactured and erected with care. Attention to detail and use of market leading membranes gives the most excellent of results. Please note the answers to T.F. questions are based on the previous mentioned being followed to the last letter of the law. Unfortunately in our experience there are still some very light weight manufacturers and erectors in the market with ridiculous prices and low quality product."

"A bit of both of the above actually…"

5. The following are a list of potential obstacles which have historically stood in the way of achieving high levels of performance in timber

housing. Please indicate the impact you believe they have in the modern timber fabrication industry.

Table 7.5 Industry Overview Question 5 Answers

OBSTACLES	No Impact / No longer presents a problem in modern industry	Minor Impact / Will affect performance in a small number of instances	Significant Impact / Widespread problem but is being dealt with and getting better	Major impact / Fundamental problem in the industry, needs immediate attention
A lack of proper factory facilities and equipment to achieve the strict levels of accuracy.	66.67%	33.33%	0%	0%
A lack of specialized expertise in fabricating the timber building components.	66.67%	0%	33.33%	0%
A lack of specialized expertise in erecting timber building components.	50%	33.33%	0%	16.67%
A lack of scale – greater scale helps to work out problems and refine the product.	33.33%	50%	16.67%	0%
Underdeveloped supply chain and lack of standardisation.	50%	33.33%	16.67%	0%
The introduction of services and subcontractors who are unfamiliar with timber fabrication during the construction phase.	16.67%	50%	33.33%	0%

Once again, respondents felt inclined to expand upon their numerical feedback with the following comments.

"Personally I feel another issue to date is the lack of expertise to design good timber frame kits. It is increasingly hard to find skilled designers as the job is becoming increasingly more difficult as the way we build becomes more complex. I fear there is also a huge lack of training available and there will be a large shortfall of a skilled workforce in the future."

"Erecting is a problem for the major sites, or so the big developers will tell you, mainly due to their historic lack of planning and resistance to change, but smaller sites simply do not suffer at all."

6. **In your opinion where does responsibility lie if a housing development of either construction type is found to be underperforming?**

7. Table 7.6 Industry Overview Question 6 Answers

Answer Choices	Responses
Developer	3
Architect	3
Supplier	0
Contractor	3
Subcontractor	1
Regulatory Body	0

Comments from one of the respondents shed light on some of the thinking behind what led to their decision:

"To answer question 6 correctly I have indicated the architect however this is not strictly true. I believe that it is the reasonability of the "Building Designer" this might not always be the Architect, others involved in the project may assume this role. It is ultimately their responsibility to bring the building as a whole together."

Despite the concerted effort to secure a high response rate on the survey the lack of contributions severely impacted the gravity of the conclusions from this section. In addition to this, to get a truly accurate picture of industry feedback it would only be fair to offer the questionnaire to masonry builders as well, however time constraints and the logistics of distribution, exacerbated by the fact that masonry house builders are probably less likely to respond to a questionnaire regarding timber frame construction meant that this phase of the research has been delayed until a later date. Thus, while the results from this section cannot claim to represent a comprehensive overview of industry perspectives and opinion, the numbers, and particularly the comments go a long way in helping to reveal the timber house builders outlook on TPC and explain some of the potential pitfalls in timber design and construction.

Question 1. Design, construction, and materials are rated first second and third respectively in their perceived influence over the development of a sustainable dwelling; greater than the impact of building operations, commissioning issues or an end of life plan. This is somewhat at odds with the results of the rest of this project which suggest the highest impact comes from the construction and the operation of the dwelling. The material impact is actually quantifiably compared to the operational energy of the dwelling and was shown to have a proportionally tiny impact in a dwelling of this standard. (See Table 6.6) The questionnaire results may obviously contain a slight bias due to the nature of the applicants and this may have contributed to the higher ranking of the materials influence.

Questions 2-4. The timber housing outperformed the masonry housing in all factors except durability and thermal mass, which as this study concluded, is a relatively trivial issue when counteracted with sufficient insulation and good design techniques. These opinions from the respondent were based for the most part on actual experience and data, which is important as this entire thesis revolves around establishing how TPC in the UK performs in reality, not through hypothetical reasoning or foreign precedence. Multiple respondents enforced the idea that their answers from questions 2 and 3 were directly proportional to the accuracy, and precision afforded to the timber dwelling during the construction process, thereby suggesting that without these high tolerance standards the performance benefits immediately being to lessen and degrade.

Question 5. The questionnaire respondents highlighted the potential obstacles which remain as significant barriers within the modern timber fabrication industry. Among these, and the only major impact chosen, was a lack of specialized expertise in erecting timber building components. Other factors such as a lack of specialized expertise in fabricating the timber building components and the introduction of services and subcontractors who are unfamiliar with timber fabrication during the construction phase helped to support the conclusion that once again, the quantitative shortcomings associated with the data collected from phase 1 of the case study are likely to come, at least in part, from poor construction practice which is predicated by this gap in specialized knowledge. Considering the UK's history with timber construction and the learning exercise that represented, not to mention the vast amount of knowledge and experience literally a few hundred miles away in Europe, this gap should be relatively easy to fill once it is recognised and highlighted as a key stumbling block through research such as this.

Question 6. An absence of any consensus on question 6 seems to be indicative of some confusion and refusal to take responsibility for the actual as-built state of a dwelling. This could lead to problems if POE uncovers performance variation between design and as built dwellings.

7.4 Qualitative Results - Conclusion

Chapter 7 comprises of 4 separate qualitative studies in consultation with three groups of individuals who directly and indirectly impact the goals of this project.

Section 7.3.1 delves into the results from the BUS and BUS Supplementary, conducted to better understand the attitudes and perceptions of housing occupants in order to better interpret performance attributes displayed in the quantitative data gathering portion of the research. Despite some setbacks associated with the third party data compilation, the BUS surveys revealed that while occupants scored the design of the housing, the ventilation, lighting and comfort highly overall, there was simultaneously negative feedback regarding summertime ventilation and temperatures in particular. It was hypothesised that this dichotomy of results stemmed, not from a poor design choice or materials, but from the lack of appropriate education during the handover process. Ultimately the responses to the core BUS survey contained very little discussion pertaining to the construction materials or build process, which in itself suggested that occupants fundamentally did not really care about the underlying structure as long the housing performed in line with their expectations. The supplementary survey attached to the formalised BUS methodology was written to ascertain the current perspective of typical homeowners regarding many of the barriers traditionally associated with constructing, buying and owning timber housing. The conclusions seemed to suggest that these barriers simply don't have the same level of influence over the public's decision making.

Section 7.3.2 is divided into 2 explicit tests, the project management interviews and the design team retrospective. While not as well populated as originally planned, the quality of the feedback from the project management interviewees was exceptional – feeding directly into many of the explanations surrounding the quantitative findings and revealing some interesting facts about the motivations and practicalities of the Phase 1 timber housing.

Key themes from this section included:

- The role of industrial inertia in holding back the integration of timber construction in the mainstream house builders.

- The need for a longer and more detailed planning stage when dealing with timber construction.
- The importance of a relevant skill set and the impact that poor practice can have on a build such as Green Street
- The necessity for more factory based fabrication so as to avoid the greater tolerances often associated with on-site construction and visible in Green Street Phase 1.
- The importance of more research to clarify what are real benefits associated with timber construction in the UK and what are simply theoretical or perceived benefits, generally drawn from foreign precedence or specialised research housing.
- The inconsistent and somewhat illogical prejudice associated with the durability and longevity of TPC – the NHBC issues identical warranty periods for both traditional masonry construction and TPC.
- The issue of thermal mass in TPC is not actually an issue if given adequate time to design a house accordingly. Building with masonry seems to be more of a knee jerk reaction to this problem rather than a reflection of the state of modern housing design.

Unfortunately, while the concept of the design team retrospective was good, the reality was a failure whose sole relevant contribution to the TPC and masonry debate was that the occupants felt that both construction types felt durable and that the materials for the TPC housing was never really a factor in day to day life.

Section 7.3.3 rounds off the qualitative analysis chapter by revealing an interesting, if not exactly comprehensive view into the industry perspectives of TPC.

Design, construction, and materials are rated by industry as having the greatest influence on development of a sustainable dwelling. This is somewhat at odds with the results of this study which suggest the highest impact is often the result of actions during the operational phase of the dwelling lifecycle. It is thought that perhaps the question was unclear or an industrial bias informed the answers of the first question.

The timber housing outperformed the masonry housing in all factors except durability and thermal mass. The results of these questions were found to be based almost explicitly on actual industrial experience as opposed to hypothetical reasoning or foreign precedence. Multiple respondents enforced the idea that the superior performance of TPC (with respect to air tightness, insulation, durability, lack of thermal bridging and services and window integration accuracy) is entirely subject to the precision and tolerances of the fabrication procedure thereby suggesting that these performance benefits are only available to heavily standardised, assembly line production dwellings, predominantly fabricated in a factory – mirroring comments already made by Julian Marsh.

The questionnaire respondents highlighted the foremost obstacles that remain as significant barriers within the modern timber fabrication industry

- A lack of specialized expertise in erecting timber building components
- A lack of specialized expertise in fabricating the timber building components
- Services installers and subcontractors who are unfamiliar with timber fabrication

These findings supported the quantitative shortcomings associated with the data collected from phase 1 of the case study placing blame, at least in part, on poor construction practice, predicated by this gap in specialized knowledge.

The wording and response rate somewhat invalidated the results of this question, however the subject of POE and the industry's reaction to potentially sensitive POE performance data is a contentious issue which should be addressed. With houses subject to ever greater scrutiny and more regulations governing their sustainable performance, it is important that accountability for be correctly apportioned in the event of a house underperforming. To whom do the consumers – the home owners – turn if their product/house is found to not actually do what it says on the tin?

This section can be summarised by the comment by one respondent "*We reiterate the need for expertise in the manufacturing and erecting with the finest of detail attention."* These conclusions, when applied to the more quantitative data recorded on the case study site, seem to suggest that the somewhat underwhelming performance characteristics of the timber construction may stem simply from a lack of expertise and the subsequent errors during the construction/erection phase.

8 Summary and Conclusions

This project was created and moulded in response to a clear and significant gap in research outlined by work from Wingfield et al. (2011). Information pertaining to successful, practical examples of sustainable TPC within medium to large scale (greater than 20 houses) mainstream UK housing developments, not research housing or purpose built eco villages, is almost non-existent and the research that does exist is often fragmented (EST, 2008) and focused on the design and delivery phase, rarely incorporating post occupancy evaluation or life cycle analysis. This lack of relevant, modern and standardised data represents a substantial barrier to the integration of what research suggests is a very promising construction technique – TPC.

The research aim therefore is to provide a record of standardised data, comparing energy usage, performance characteristics and qualitative evidence from environmentally certified timber and masonry fabricated housing to establish the ecological viability of timber prefabricated housing. This focus on the environmental impact and practical performance of TPC deliberately excludes the financial implications of the building process from this stage of the research, instead viewing this project as a prerequisite step in the development of a much larger comprehensive case considering the merits and pitfalls of adopting TPC on an industry wide scale.

Ultimately, conclusions drawn from Chapter 2 support a premise that timber frame dwellings should perform to ecologically similar or higher standards than an identical masonry counterpart, with better airtightness, stricter tolerances and lower overall fuel consumption. The case study data from this project and those that follow will simply be used to substantiate or refute this position while simultaneously providing a clear and relevant body of knowledge to which architects, developers, contractors and clients can turn when considering TPC as an alternative to traditional masonry construction.

Chapters 3 - 6 break the quantitative discussion and conclusions down into two distinct lines of enquiry– a comparative analysis between the two fabric types and a more introspective investigation into the theorized gap between design and performance for both construction types. The rationale behind adopting a more complicated comparative analysis, as opposed to simply testing a set of exclusively timber housing, is based on the target audience for whom the research is intended – the UK housing industry. By comparing TPC with the well-established and well respected traditional masonry construction methods the results have a greater authority and influence in the masonry dominated industry. Chapter 7.3 delved into the qualitative side of the research exploring many of the underlying causes that most profoundly impact the TPC performance profile thereby exploring and supporting hypotheses developed throughout the quantitative data analysis.

8.1 Final Conclusions

The final conclusions contained within this chapter draw on both the quantitative and qualitative data analysis to develop and identify some constructive resolutions for narrowing both the gap between design and performance and the gap between research theory and reality in the case of TPC; resolutions that can then be easily disseminated and applied within industry. Throughout the testing, data gathering, data analysis and these conclusions it is understood that the Green Street case study is made up of only 8 houses. The conclusions represented through this research are therefore based on a small data set and are subject to the inherent statistical variance that accompanies a small data set. However, when this is put into the context of other POE projects, which so often focus on only 1 or 2 houses, the information in the following paragraphs actually represents a significant step in establishing verifiable, quantifiable conclusions from mainstream, UK based evidence.

From a comparative energy performance standpoint the simple conclusion is that throughout the heating season the timber houses perform better, requiring less energy per degree difference between inside and outside temperatures. Following on from that, the heat loss over time between the two fabric types is very similar, calling into question the overarching assumption that the greater thermal mass of masonry and brick construction equates to less thermal degradation over time. The assumption is, that the greater insulation in the TPC construction (an extra 55mm over the masonry walls) counteracts the lack of thermal mass, helping to slow the heat degradation to a similar rate as the masonry construction. During the cooling season the diurnal temperature swing is noticeably greater in Phase 1 (timber) but the temperature in the timber housing remains consistently lower throughout the vast majority of the testing period thus when taking into account the contributing factors such as shading and orientation of the building, results in the conclusion that with the correct design and planning, timber housing can in fact perform on par or in some cases better than its masonry counterpart.

The LCA revealed lower CO_2e values exhibited by the timber walls. Although the individual outcome varies from house to house the Phase 1, timber housing performed worse in air permeability testing with the average results across the fabric types revealing that overall the timber housing performs worse than its masonry counterpart. A comparison of the design and as built HLC for the two building fabrics clearly reveals that the masonry housing proportionally outperforms the timber frame construction. Essentially, when the design HLC for each house is replaced by the measured HLC, there is a significant change in the outcome of the SAP calculated energy expenditure, a deviation of 59.1% (timber) and 31.85% (masonry) between the design and as built emissions – amounting to a maximum 500kg of CO_2 emissions per year for Phase 1. This discrepancy can obviously impact how the housing is rated, for example reducing the houses from CSH level 4 to CSH level 3 across the board.

Addressing the qualitative results, the BUS methodology found that occupants were ultimately indifferent to the underlying structure (timber or masonry) of the dwelling. The conclusions seem to suggest that many of the perceptions and barriers from Section 2 have remained the same but they simply don't have the same level of influence over the public's decision making.

The thermography results from both phases reinforced some of the assumptions from earlier tests, specifically the apparent lack of precision and workmanship demonstrated by recognisable and ubiquitous areas of thermal ingress. Ultimately, the sustainable standards required in modern housing demand higher tolerances than ever before, and elements such as poorly fitting sliding doors simply can't be a part of that. The responses to industry questionnaires stressed the need for greater expertise in the manufacturing and construction of timber framed dwellings and a greater emphasis on precision and accuracy. This mirrored feedback from the project management interviews which also reinforced the themes of precision and the need for specific and relevant skills, adding the suggestion that a greater level of factory based modularisation within the industry could serve to combat some of these evident site based weaknesses. These conclusions, when applied to the more quantitative data recorded on the case study site, seem to suggest that the somewhat underwhelming performance characteristics of the timber construction may stem simply from a lack of expertise and the subsequent errors during the construction/erection phase.

The quantitative analysis concludes that in this instance, while there was no clear overall leader in performance, the timber prefabrication technique produced dwellings that perform ecologically on par and in some cases better than their masonry counterparts. The subsequent response to the research question is that TPC should not be used as an alternative to existing methods, rather, the nature and strengths of the current masonry focused industry cannot be ignored and would be supported by the TPC technique, rather than replaced by it. The TPC industry within the UK is still young and there are many lessons to be learned before ecological performance of TPC can reliably be said to exceed that of the more traditional masonry methods of housebuilding.

As part of the final dissemination objective in Section 1.5, some of these lessons are addressed with industry focused solutions which directly combat some of the gaps in performance identified through the quantitative data gathering and analysis, thereby closing the loop of problem identification and problem solving. The following suggestions certainly do not represent an exhaustive list of potential solutions, however they are founded entirely on the hard evidence and conclusions gathered throughout the project.

1. There is a skills shortage associated with TPC. The solution is simple, provide more fabric specific training. There is a vast amount of knowledge and experience to draw on from other countries both in Europe and further afield – Japan, the USA & Canada. But more fundamental than that, the teaching must also instil an inherent culture of precision, of accuracy within all parties involved with site work, from the brick layers and carpenters to the plumbers

and electricians. Precision driven sustainability is a holistic goal, and requires the full motivation of all those involved.

2. There needs to be more layers of on-site checks and accountability throughout the construction phase of a housing development. In this day and age of computer aided modeling and performance analysis the design stage of a dwelling or building is often subject to the utmost scrutiny, tested, modeled and re-tested before even thinking about site execution. Ultimately the design stage of a project is flexible, amendable and fluid and yet still goes through this process. Once those drawings and specifications hit the site and start to emerge as solid reality, they are far less flexible and can be very hard to monitor. Ultimately the execution phase of a build must mirror the design intentions and a simple way to ensure that precision is maintained throughout the project is to create greater accountability on site and post construction through testing, including but not limited to, air permeability, thermography and co-heat analysis POE.

3. The findings of the air permeability study highlight the need for a more strategic approach when dealing with post-construction testing and more importantly the devolvement of responsibility. The findings of this study mirror that of a study of timber framed housing by Alan Clarke (2009, p.9):

> *The problems aren't physical, but rather are down to the system of subcontracting and of responsibility and supervision on site. When educated and motivated, builders have been able to deliver good results, but lack of responsibility or care from other contributors to the build can undo the good work. This suggests that the best results will be obtained with different contractual structures, say with a low-energy building specialist overseeing the whole build and enforcing airtightness standards on the various trades. It is also indicates that what looks fine on the drawing also needs to stand up to the conditions on site, and be both testable*

and repairable if necessary. The identification of increased leakage owing to service penetrations shows these to be significant, and meriting specification of reliable and easily installable seals, plus training and monitoring of the work.

4. TPC, and specifically the timber frame subset of TPC which currently dominates the UK market is inherently resistant to bad onsite practice due to its predominantly offsite construction. However greater levels of offsite work would further remove this potential for on-site imprecision and modularisation of the entire construction process would result in even greater tolerances. This can only be achieved through investment in larger factories, factories which can ensure a high level of standardisation, whilst still maintaining the ability to customise and contextualise each house for the specific site it will be built on.

5. There needs to be a better understanding of the impact that occupants have on sustainable dwellings. This is not a fabric specific solution, but it is a clear outcome of this project. The interactions and effects of occupants on the energy performance in these dwellings is quantifiably massive. (section 0) Sustainable building research has a tendency to gravitate towards producing fabric and technologically driven solutions, however, the evidence suggests that these solutions may prove superfluous if not developed within the context of a typical home owner and their interactions with the dwelling. Ultimately, if housing is designed to be sustainable it cannot just be sustainable in isolation, as a fabric or empty envelope. It must maintain the same level of performance regardless of vacancy or occupation or else how can it be deemed truly sustainable?

Historically POE was never an issue as housing wasn't under such scrutiny and pressure to perform, it is only the recognition of global warming, predicating the need for established performance benchmarks, which has initiated this movement.

Timber prefabrication is a great example of a technology or process being implemented to achieve the so called "sustainable home" and this research project has used POE to establish if it genuinely achieves these sustainable design intentions. However the timber prefabrication process (while significant in the fabric first approach to sustainable housing) is only one tiny component of the sustainable housing movement – it is well known that there is not one simple solution to creating a sustainable house, it is a combination of processes and technologies.

However while this one site was tested and evaluated who is testing the rest of the sustainable designs and components, not just in a lab, but on the ground, in real houses built under real market conditions and occupied by real people? The answer is, almost no one – the very implementation and existence of the TSB BPE is evidence of this as it seeks to fill the void of knowledge generated by a substantial lack of relevant POE information pertaining to sustainable residential construction. There are unique conditions associated with a mainstream building project, conditions that are often absent in a lab or research housing, which is frequently built on an individual scale and occupied by environmental specialists. A lack of mainstream oriented data is often justified through the difficulty in obtaining relevant housing and the cooperation of occupants, but the simple fact is, without it, without relevant realistic POE, there is absolutely no guarantee that a technology or process tested under laboratory conditions or modelled on a computer will actually perform in the environment for which it is actually intended.

POE will have to become an essential component of sustainable housing development, regardless of fabric type. Post occupancy testing and evaluation must become as fundamental as good insulation or energy efficient appliances. It will need to be streamlined and standardised so that benchmarks across the industry can be established, but ultimately those who claim to build sustainable housing will no longer be able to hide behind theoretical benefits and computer models. They will held accountable for their actual practices and products, this is the only way to ensure truly sustainable construction in the UK.

8.2 Dissemination of Work

There are commonly considered to be 3 fundamental components to a PhD:

1. The concept phase –discovering and understanding a gap in current research, and using it to inform a research question which sets the context for the project.
2. The data gathering and testing phase – Exploring the research question through novel and applicable testing methodology, collecting quantitative and qualitative data.
3. Conclusion Phase - critically analysing the data and developing informed conclusions and theories in response the original research question.

However this section deals with a 4^{th} vitally important component – the dissemination of the work in a useful and productive manner. Identifying the avenues of publication and information distribution is seen as an absolutely crucial element in research such as this.

There are three primary ways in which this research is looking to make a tangible impact.

1. Standardisation of testing methodology. Throughout the testing phase of the research every effort has been made to standardise each testing protocol. The reasoning behind this is that the information and data collected can then be distributed to the building research field as a whole where it will then be analysed, added to data banks and be used to develop benchmarks on a national scale. This is important as the case study around which this thesis is built, only includes 8 houses. While this provides a good indication of general trends, it remains a representative housing development and is far from a comprehensive analysis of the UK housing industry. Given the resources and timeframe available this would be an impossible undertaking, but by standardising the production of data it ensures that the research completed during this project does not remain an isolated piece of work.

2. Working closely with industry partners. In the case of this project the site developers, Blueprint have engaged with the academic research and conclusions to the extent that their practice has already with regard to their handover procedures, their air-tightness regulations and their overall communications chain on site. As the research project moves to a close the conclusions are informing and potentially impacting the fabrication of future developments by Blueprint. The following is an exerpt from the TSB BPE Full Application completed by Blueprint during the tender stages of acquiring funding through the BPE program. It details the value of working with this project and exactly how the information acquired through the research will feed back into their company, their partners and others involved with the Green Street case study.

> *"Because the Green Street project has proved so popular with the market, uses tried and tested mechanical and electrical technolgies and has been a commercial success for Blueprint in what is a deprived inner-city area, it is a highly replicable model for future energy efficient housing developments by members of the project team. The results of the study have the potential to directly influence the construction type of this model. The make up of the project team (and their partnership organisations), means the findings from the study would transfer in to many of the key areas of the sector - Institutional Investor (Aviva Investors), Academia (University of Nottingham), Architect (Marsh Grochowski), Developer (Blueprint, Igloo Regeneration, ISIS Waterside Regeneration) , Consultant (Gleeds, Eye Developments), Contractor (Lovells and Morgan Sindell Group) and Public Sector (Homes and Communities Agency and East Midlands Development Agency).*
>
> *Blueprint has developed around 100 housing units in the last 18 months and is at initial design stage on two housing developments comprising around 50 units. Lovell build around 500 housing units per annum. The combined output of the project team including all partnership / affiliate organisations however, is likely to amount to many hundreds if not thousands of housing units per annum.*

The study would be used to inform current and future developments being built or designed by Blueprint, Lovells, Gleeds and Marsh:Grochowski and their affiliated organisations. All team members are fully engaged in the debate regarding the benefits of low energy housing, heavy vs. lightweight construction and of off-site vs. on site construction methods.

Specifically, Blueprint are currently at feasibility stage on two housing developments within the City of Nottingham comprising around 50 housing units. The results from this study have the potential to influence design factors and construction methods for these projects.

Knowledge gained from the study would be disseminated through team member's organisations (and their affiliates) via a variety of media. These could include the electronic distribution of findings to all relevant staff members, presentations at team, board and departmental meetings and the uploading of findings to organisation's internal and external websites. The University of Nottingham will also use seminars, lectures and open days to present the findings of the study.

The results of the study will directly influence both the advice given and construction methods used in future housing developments by the team members and their affiliates."

(No reference is available as much of the document is classified however, evidence of its existance can be provided on request)

3. Finally the research will contribute toward a portfolio of published work for circulation within the academic environment. In this manner, the work can be analysed and built upon by peers within the academic sphere while simultaneously being available for access by industry as a reliable, reviewed source of information. Currently this project has produced 2 published papers with contributions to a third – the NHBC Foundation's Co-Heating Test Research Project 2011-12. This test formed part of a wider research

programme involving other organisations and institutions, which aimed to evaluate the use of co-heating methodology to assess building fabric heat loss. While the results of the program were originally confined to academia and research institutions such as the BRE, they are now available through a report by Butler and Dengel (2013). The aim is to develop an optimal testing methodology based around the co-heat test that will one day form an integral part of building regulations, much like the current utilization of air testing in new properties. And finally there are an additional 6 papers planned toward the end 2014 with details available in the following section.

8.3 Publications and Future work

This is just a short section which covers the current and upcoming publications directly associated with this research project.

Completed Publications:

- Bailey, D., Gillott, M., Wilson, R. (2012). Designing out risk using post-occupancy evaluation methods in domestic construction. *Proceedings of The 11th International Conference on Sustainable Energy Technologies.* Vancouver.
- Bailey, D., Gillott, M., Wilson, R. (2013). The Process of Delivery – A Case Study Evaluation of Residential Handover Procedures in Sustainable Housing. *Sustainability in Energy and Buildings.* (pp. 95-105). Stockholm, Sweden: Springer Link.
- Bailey, D., White, J., Gillott, M. (2012). NHBC Foundation Co-Heating Test Research Project 2011-12 Data Analysis Report - University of Nottingham. Nottingham, UK: University of Nottingham
  This was an unpublished contribution to a piece of work by Butler and Dengel (2013) which subsequently acknowledges the contribution from these authors.

Upcoming and Planned Publications:

- Following on from the handover paper – "Soft Landings for Domestic Application" – A paper looking at how to best regulate and perform residential handovers using the established commercial handover process as a framework. More details are available within the original handover paper.
- A partially complete paper, the product of the unusual findings throughout the airtightness testing procedures. The paper is a commentary on the regulations and the reality of onsite practices.
- In reviewing various airtightness literature it quickly became apparent that there was little information regarding the airtightness degradation over time in modern, sustainable timber and masonry construction. Ongoing yearly measurements over the coming years should provide a clear degradation profile which can be extended for as long as the occupants remain amicable and willing to cooperate.
- A review of regulations pertaining to the insulation requirements of integral garages – instigated by the findings of the thermography testing.
- An expansion on the WHLC concept introduced in Chapter 3 – more research required on the concept, but should the model hold up under additional tests there is significant implications for the value within post-occupancy evaluation of dwellings.
- A review of existing site control and accountability measures on housing development building sites. As such a prominent factor in ensuring the precision and accuracy of future developments, it is important to first understand exactly what measures are currently in place to combat poor construction practices, then look to create a specific strategy of how to upgrade these measures to meet the standards of modern sustainable construction.

As demonstrated, through the plans for ongoing and future publications, this project was never intended as a finite piece of work. Housing development and construction is a changing and fluid industry and this work will inevitably be superseded by others. While this research does serve its purpose in providing at least some tangible, relevant data to which those with questions can fall back on, the author is realistic in his ambitions and acknowledges that there still remains much work to be done.

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APPENDIX

APPENDIX A. Interview Protocol for Project Management Interview

Green Street Housing Development

In recent years the UK housing industry has been forced to explore increasingly diverse methods of achieving ecological methods in response to the government's ever more stringent environmental policies. One of these avenues of innovation is the use of timber as the primary material for both the structure and envelop of domestic applications. As a representative mainstream housing development, incorporating both traditional masonry and innovative timber construction techniques the Green Street project provides a unique research opportunity. Your professional experience on this project is invaluable in providing a context to the qualitative data gathered through the monitoring in Phases 1and2 of the development. The primary purpose of the interview is to establish your views on timber construction in relation to your direct involvement with the Green Street project.

Interviewee Name:

Date:

Tracking information source.

Profession:

Individual's background and capacity to answer the questions professionally.

Role and responsibilities within the Green Street Project

1. At what stage did you join the project?
2. What do you see as your role and responsibilities in this project?

Building Fabric.

3. In your mind, why was timber chosen as the primary material for Phase 1?

    a) Did it achieve this ambition?
    b) If not, for what reason(s) did it not?

In a mainstream housing development what are the motivations for using timber construction? It is important to establish if the theoretical attributes of timber construction, as displayed by the motivations of the client and architects, are substantiated in the reality of the construction environment.

4. What was the basis for the decision to move over to masonry construction for Phase 2?

    a) Did it achieve this purpose?
    b) If not, for what reason did it not?

The move back to brick is somewhat unusual in the middle of a building project. What were the thought processes behind the move? Who was behind this decision and at what stage of construction was it made?

Material Awareness/Understanding

5. Can you list 5 key advantages of using timber construction?
6. Can you list 5 key disadvantages of using timber construction?

Deals with the perception of timber in the UK.

7. How many of these advantages and disadvantages were actually displayed in this project?

Looks at the reality of timber in the UK.

The Market

8. Why do you believe the UK builds primarily in masonry housing?

   Establishes base conditions – why current methods exist.

9. What key challenges do you see as standing in the way of the integration of timber construction into mainstream housing construction in the UK?

   Establishes base conditions – why current masonry construction methods dominate the market.

10. Given these challenges, do you personally see timber fabrication as a viable substitute for traditional masonry construction?

    Important to understand the position of representatives from the various stages of construction (Developer, Architect, Contractor).

The Performance

11. From your perspective which building fabric (masonry or timber) made it easiest to achieve Code for Sustainable Homes (CSH) Level 4 accreditation and why?

    Environmental performance is the fundamental variable in question within this study. It is vital to understand its weaknesses in respect to its direct competitor. Thus if brick was better, how was it better and what can timber do to emulate this? If timber was better, then what are the barriers that continue to hinder its mainstream integration?

Open ended time – reflections on this type of building

Allows participants to voice any aspects of the case study and building process not yet covered. This feedback section is vital in creating a comprehensive analysis.

APPENDIX B. Publication Abstracts

The Process of Delivery – A Case Study Evaluation of Residential Handover Procedures in Sustainable Housing

David Bailey, Mark Gillott, Robin Wilson

Energy and Sustainability Group, Built Environment, Nottingham University, Nottingham NG7 2RD, UK

Abstract. At present research groups are developing a growing body of evidence quantitatively demonstrating through post occupancy evaluation, a significant gap between the actual physical performance characteristics and the design predictions of sustainable dwellings. In examining this documented performance variability this paper argues that a substantial proportion of this gap may be the result of mismanagement and misuse of sustainable systems by the occupants who have received little to no training in the specialised equipment and design techniques regularly employed in modern sustainable housing. Specifically this paper looks into the training and guidance given to new house owners during the critical handover phase. The research adopts a direct observational methodology in conjunction with a suitable housing case study and the associated handover process. By recording and analysing the handover procedures of a representative housing developer the study hopes to gain valuable insight into the current technological training and guidance provided to new tenants of modern ecologically certified housing. The study finds occupants are not receiving adequate training and guidance with regard to the sustainable measures employed in their housing. In addition the survey suggests that residents struggle to absorb the information provided in the current format. Ultimately the study proposes a complete reform of the handover process, based on existing commercial precedence and focusing on both the accessibility and content of the handover procedure.

DESIGNING OUT RISK USING POST-OCCUPANCY EVALUATION METHODS IN DOMESTIC CONSTRUCTION

David Bailey*, Mark Gillott*, Robin Wilson**

*Energy and Sustainability Research Division, **Architecture and Urbanism Research Division, Faculty of Engineering, University of Nottingham , Nottingham NG7 2RD, UK

Abstract. This position paper introduces a methodology for the novel application of post-occupancy evaluation (POE) data with the aim of proactively reducing operational performance errors in sustainable domestic construction through better materials selection. The theory is based on the premise that a significant gap exists between the actual physical performance characteristics and the design predictions of sustainable dwellings. This gap is quantifiable through POE, such as co-heating tests which measure the heat loss coefficient of an entire dwelling, post-construction allowing comparison against the UK"s Standard Assessment Procedure (SAP) design values. The proposed methodology suggests that this gap is proportionally different for housing constructed using different materials and different fabrication methods, given a standard air tightness. A proportionally smaller gap between design and actual performance of housing built using a particular fabrication method would indicate a more accurate method of construction. Subsequently if one construction method is found to have a proportionally smaller gap, it would suggest that future developments should possibly use the more accurate material as the basis for their construction in order to achieve compliance.

University of Nottingham

Version 1.0 – May 2012

David Bailey, Jenny White, Mark Gillott

Energy and Sustainability Group, Built Environment, Nottingham University, Nottingham NG7 2RD, UK

The University of Nottingham was commissioned by the NHBC Foundation to undertake a coheating test on House No.4 at the BRE site at Garston, Watford. This test formed part of a wider research programme involving other organisations and institutions, which aimed to evaluate the use of co-heating methodology to assess building fabric heat loss.

The testing period extended from 23rd April – 8th May 2012 (16 days). The initial heat-up period of two days, and the final de-rig day were not included in the analysis, with data for the period 25th April-7th May being the relevant period for this study.

This report comprises of a brief explanation of the methodology used, issues encountered, and a discussion of the resulting dataset. In addition, it includes a proposal for an adjustment to the data analysis protocol which aims to reduce the scope for experimental error, whilst also simplifying the testing and evaluation process.

The data collected during the study resulted in a calculated measured heat loss coefficient of 73.89W/K, a difference of 12% from the specified design value of 65.92W/K.

APPENDIX C. SAP Worksheet Summary

The following is a compilation of the key relevant data associated with this research project and extracted from the SAP sheets of Phase 1 and 2 of Green Street. This format was deemed more appropriate than including all 5 pages of for each of the 8 houses, however should the raw data be required it may be requested. Some information is available within the main body of the thesis within the results chapter.

Green Street Phase 1 and 2 Key SAP Data

SAP Variable	House 1	House 2	House 3	House 4	House 5	House 6	House 7	House 8
Floor Area (m^2)	123	107	107	107	121	121	121	121
Dwelling Volume (m^3)	329	283	283	283	313	313	313	313
Sides which are sheltered	2	2	2	2	1	1	1	2
Shelter Factor	0.85	0.85	0.85	0.85	0.92	0.92	0.92	0.85
Window Area (m^2)	33.10	29.65	30.12	29.65	39.15	39.74	52.59	39.15
Total area of heat loss perimeter (m^2)	231	184	185	184	288	280	282	288
Fabric heat loss (W/K)	73.5	63.5	64.1	63.5	82.1	81.5	93.4	82.1
Thermal bridges (W/K)	18.5	14.7	14.8	14.7	23.1	22.4	22.6	23.1
Total fabric heat loss (W/K)	92	78	79	78	105	104	116	105
Ventilation heat loss (W/K)	23.3	20.1	19.9	20.1	23.5	23.7	23.3	22.9
Heat loss coefficient (W/K)	115	98	99	98	129	128	139	128
Heat loss parameter (HLP), W/m^2K	0.93	0.92	0.92	0.92	1.06	1.06	1.15	1.06
Useful Solar gains (W)	1042	931	937	931	1317	1312	1457	1314
Mean Internal Temp (°C)	18.9	18.9	18.9	18.9	18.6	18.9	18.6	18.9
Temperature rise from gains (°C)	9.04	9.47	9.48	9.47	10.24	10.28	10.46	10.26
Base Temp (°C)	9.47	9.05	9.03	9.04	8.34	8.31	8.13	8.32
Space Heating fuel requirement, kWh/year	2620	2048	2052	2046	2296	2260	2370	2277
Main Space Heating (kg CO_2/year)	508	397	398	397	445	438	460	442