# The energy and thermal performance of UK modular residential buildings

by

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# Abstract

This research concerns the in-use performance of light-gauge steel modular construction used for residential purposes. The aim was to investigate ways to reduce the in-use energy consumption of new buildings, while ensuring thermal comfort.

Data were collected from two case study buildings in the UK, one in Loughborough and the other in London, using a variety of methods including building measurement, building monitoring, inspections, and a detailed review of the construction documentation. The case study buildings were monitored using EnOcean enabled wireless sensor networks and standalone temperature sensors. Monitoring data included electricity consumption in individual rooms, often by end use, space heating use, internal temperature and relative humidity, and external temperature. Building measurements included blower door tests to measure fabric air leakage rates, infrared thermal imaging to identify fabric defects and weaknesses, and ventilation system flowrate measurements. Inspections and the review of documentation allowed problems with design, manufacture and construction to be identified. A particular concern for thermally lightweight construction is the risk of overheating, therefore overheating analyses were undertaken.

The research identified weaknesses in the design, construction and operation of the case study buildings resulting in increased energy use and poor thermal comfort, particularly overheating. The modular construction studied requires specific design changes to improve the fabric and building services, in order to reduce energy use. There are also specific recommendations for quality control on site to ensure critical stages are correctly completed, such as installing rigid insulation. There are also more general recommendations for how a company operates because this can influence performance; there ought to be greater attention to holistic design and greater collaboration with suppliers and contractors to determine robust solutions. Overheating was a problem in the London case study, and more research is required to understand the scale of the problem. Avoidance of overheating must be a focus in the design of new buildings. The findings suggest that once the problems with the design and quality control on site are rectified, offsite modular construction can be used to consistently and reliably provide low energy homes.

# Acknowledgements

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# Contents

# Nomenclature

| Symbol | Description | Unit |
|---|---|---|
| A | Area | $m^2$ |
| d | Depth | mm |
| h | Height | mm |
| $h_c$ | Coefficient for surface heat transfer by convection | $W/m^2K$ |
| $h_r$ | Coefficient for surface heat transfer by radiation | $W/m^2K$ |
| $H_e$ | Hour of exceedance for adaptive overheating metric Criterion 1 | hours |
| l | Length | M |
| Q | Fabric heat Loss | W |
| $T_a$ | Air temperature | °C |
| $T_{comf}$ | Comfort temperature | °C |
| $T_e$ | Outside air temperature | °C |
| $T_{ed}$ | 24 hour daily mean external air temperature | °C |
| $T_i$ | Internal temperature measured by sensors during the monitoring studies | °C |
| $T_{max}$ | Upper limit for thermal comfort in a category II building during free-running | °C |
| $T_{min}$ | Lower limit for thermal comfort in a category II building during free-running | °C |
| $T_{op}$ | Operative temperature | °C |
| $T_{rm}$ | Exponentially weighted running mean temperature | °C |
| $T_{st}$ | CIBSE static overheating threshold | °C |
| $T_{upp}$ | Absolute maximum acceptable operative temperature | °C |
| $\Delta T$ | Difference between operative temperature ($T_{op}$) and upper limit for thermal comfort ($T_{max}$) | °C |
| $\Delta T_b$ | Temperature difference | K |
| U | Fabric U-value | $W/m^2K$ |
| v | Air speed | m/s |
| w | Width | mm |
| $W_e$ | Weighted exceedance for adaptive overheating metric Criterion 2 | |
| WF | Weighting factor for adaptive overheating metric | |
| ø | Diameter | mm |
| Ψ | Linear thermal transmittance | W/mK |

# Acronyms

| | |
|---|---|
| AOV | Automatic opening vents |
| CHP | Combined heat and power |
| EEP | EnOcean Equipment Profile |
| Gtoe | Gigatonnes of oil equivalent |
| IR | Infrared |
| LAN | Local Area Network |
| MMC | Modern methods of construction |
| Mtoe | Million tonnes of oil equivalent |
| OSB | Orientated strand board |
| OSC | Offsite construction |
| PV | Photovoltaic |
| SAP | Standard Assessment Procedure |
| TRV | Thermostatic radiator valve |
| [redacted] | [redacted] |
| VCL | Vapour check layer |
| WSN | Wireless sensor network |

# Chapter 1 – Introduction

Buildings are resource intensive both in construction and operation; they account for a significant portion of all the materials and energy used globally. Despite this, buildings often fail to perform as intended, particularly in their ability to provide adequate conditions for thermal comfort throughout the year, often resulting in buildings that are expensive to operate yet uncomfortable. The use of resources for buildings is often inefficient and wasteful, and there is significant scope to reduce the resource intensity of buildings and improve their thermal performance. There are many drivers and motivators for change, but also many challenges and barriers.

This chapter discusses these high level issues; which were fundamental in driving the initiation of this research. It also presents the research aims and objectives, and poses questions which the research seeks to answer.

## 1.1 Scope for Change

This research concerns the energy and thermal performance of UK residential buildings in use, therefore the focus is on scope for improvement in these areas.

Historically, the UK has consistently been one of the largest consumers of primary energy in the world: in 2012 it was the country with the thirteenth highest total consumption, [EIA, 2015]. Since 1970 primary energy consumption in the UK has fluctuated by approximately 20%, averaging 216.3Mtoe (million tonnes of oil equivalent) annually (Figure 1.1). It tended to increase from a low of 196.1Mtoe in 1982 to a high of 236.9Mtoe in 2005, but has since fallen, with energy consumption in 2013 well below the average at 205.9Mtoe [DECC, 2013].

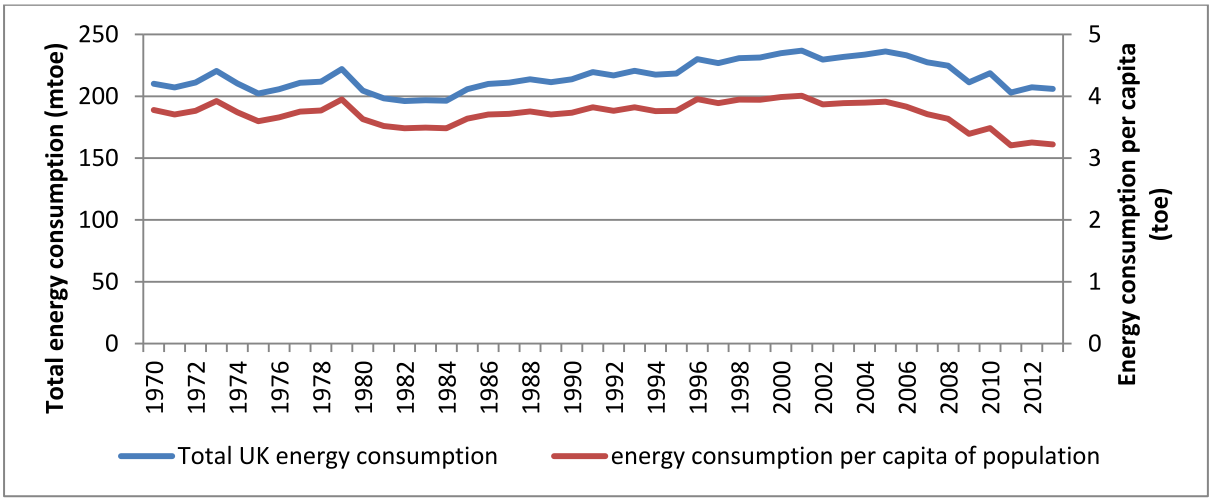



**Figure 1.1: Primary energy consumption in the UK: 1970 – 2013 [DECC, 2013]**

Since 1991 the domestic sector has been the largest consumer of primary energy every year (Figure 1.2), accounting for 31.8% (65.4Mtoe) of total UK primary energy consumption in 2013.

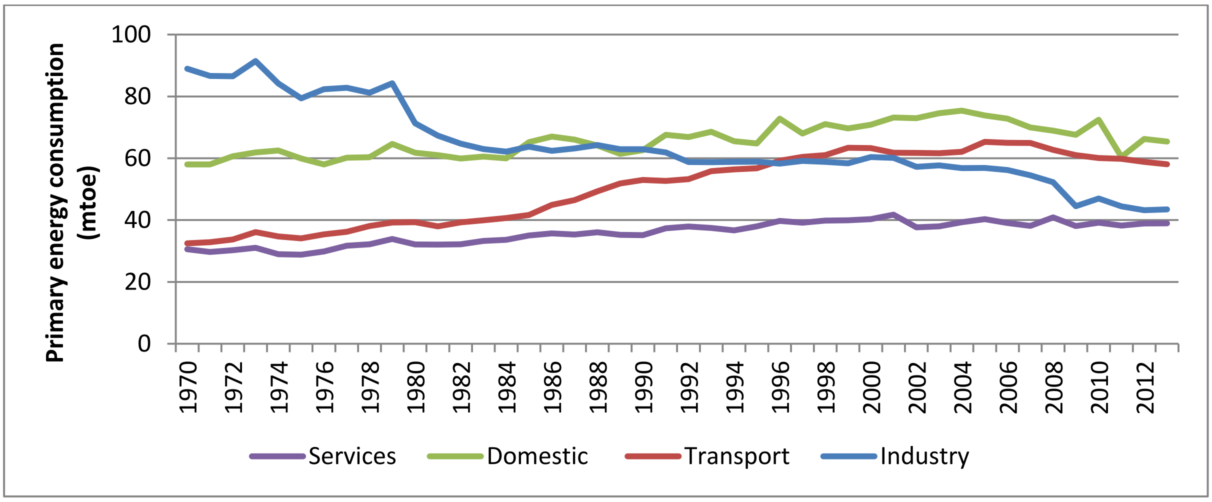



**Figure 1.2: Primary energy consumption in the UK by sector: 1970 – 2013 [DECC, 2013]**

The main driver for energy use in residential buildings is the attainment of thermal comfort of the occupants. More than half of the energy consumed in the domestic sector is used for space heating, 52% on average since 1990, and 54% (35.3Mtoe) in 2013 (Figure 1.3). Therefore, approximately one sixth of primary energy consumption in the UK is used for space heating of domestic buildings. The second largest consumer of energy in the domestic sector is for lights and appliances (28.5% or 18.7Mtoe in 2013), followed by water heating (14.3% or 9.3Mtoe in 2013), and finally cooking (3.2% or 2.1Mtoe in 2013).

Energy used for other end uses can also contribute to the attainment of thermal comfort. Heating water and cooking food is done, in part, for thermal comfort. Many electrical appliances may also contribute to thermal comfort such as fans, portable radiators, air coolers and air conditioners. Therefore, the energy used in the attainment of thermal comfort is higher than the 52% used for space heating.

However, despite the high energy use, domestic buildings often fail to provide adequate levels of thermal comfort during both hot and cold weather, which can be detrimental to the health of occupants. This is because much of the energy used in the domestic sector is wasted due to the poor performance of the building fabric, services and appliances (see Chapter 2 for more details).

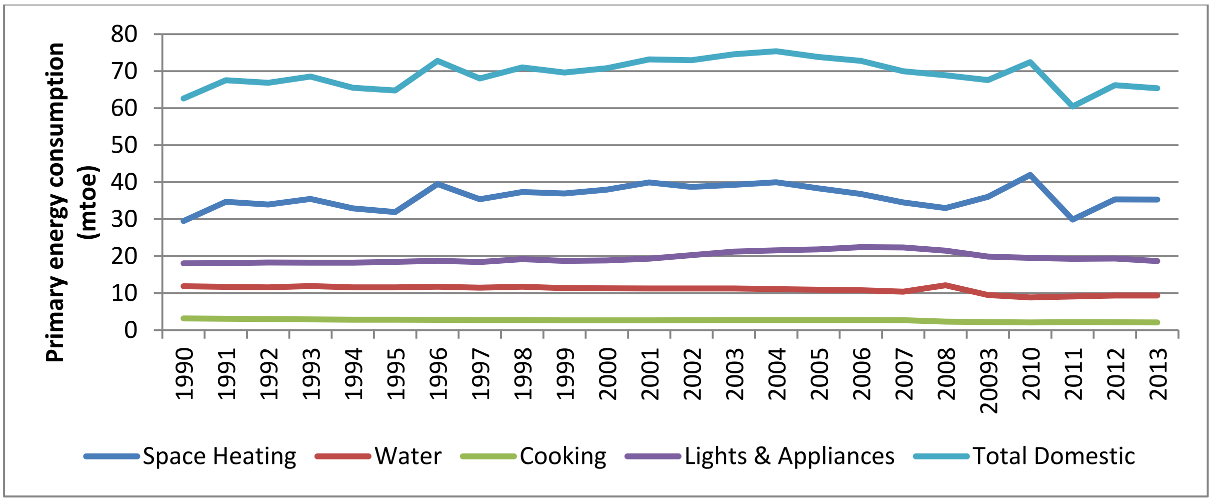



**Figure 1.3: Primary energy consumption in the UK domestic sector by end use: 1990 – 2013 [DECC, 2013]**

Although dwelling performance has improved over time, and energy use has fallen during the last decade, much more needs to be done to make a significant impact upon the total energy consumption for the domestic sector. The technology already exists to construct comfortable buildings that require little or no energy to operate, [ZCH, 2010], which is demonstrated by existing low energy buildings and advanced building standards [BREEAM, 2015; LEED, 2015; NRCan, 2015; Passivhaus 2015]. It is also possible to refurbish existing dwellings to significantly improve thermal comfort and reduce energy use [Boardman et al., 2005]

## 1.2 Drivers and Motivators for Change

There are many reasons to seek to reduce energy use in buildings and improve their ability to provide and maintain thermal comfort for their occupants; and these broadly fall into four categories:

- Resources
- Environmental
- Social
- Energy security

### 1.2.1 Resources

Many of the material resources available on the planet are finite, including minerals and fossil fuels, and their consumption has grown rapidly since the beginning of the industrial revolution. The current consumption of many finite resources is unsustainable [European Commission, 2011], and without change, will become increasingly so as the global population continues to grow. The availability of certain resources could become critical, including fossil fuels [MacKay, 2009; Capellán-Pérez et al., 2014; Shafiee and Topal, 2009;

Hook and Tang, 2013], minerals [Prior et al., 2007; Boryczko, Hołda and Kolenda, 2014] and supplies of clean, fresh water and food [IPCC, 2014].

Without ready alternatives, there could be severe consequences, if resources that the global population depend upon become depleted. There is a twofold approach to avoid this without reducing the current standard of living:

- to make better use of existing resources, by using them more sparingly, with greater efficiency, greater use of local resources, and greater use of recycling and reuse,
- to find alternative resources to replace existing ones, preferably ones which are renewable or replenishable, such as cellulose based plastics in place of petroleum based plastics, and renewable energy in place of fossil fuels.

Energy resources are of key importance in this research, its availability is critical because it is used in every aspect of modern life, and the current human population could not be sustained without it. It is used in the production of food, water, clothing, furniture, appliances, buildings, infrastructure and vehicles. It is also used to transport and distribute these products around the world. Many products also continue to consume energy in use, such as in the heating of buildings, and lighting of streets. The depletion of energy resources would have a critical impact on mankind. Despite awareness of the finite nature of resources, global primary energy consumption has continued to grow, reaching 13.3Gtoe (Gigatonnes of oil equivalent) in 2012 (Figure 1.4). Over the past decade, primary energy consumption has fallen in the UK (despite a rise in population), but this is insignificant compared to growth in other countries, particularly in Asia. Considering current trends, it is vital that technologies are developed to harness sufficient energy from alternative sources, before finite sources become scarce. It is also essential to become less dependent upon energy, because its availability may not be so consistent, predictable or affordable in the future.

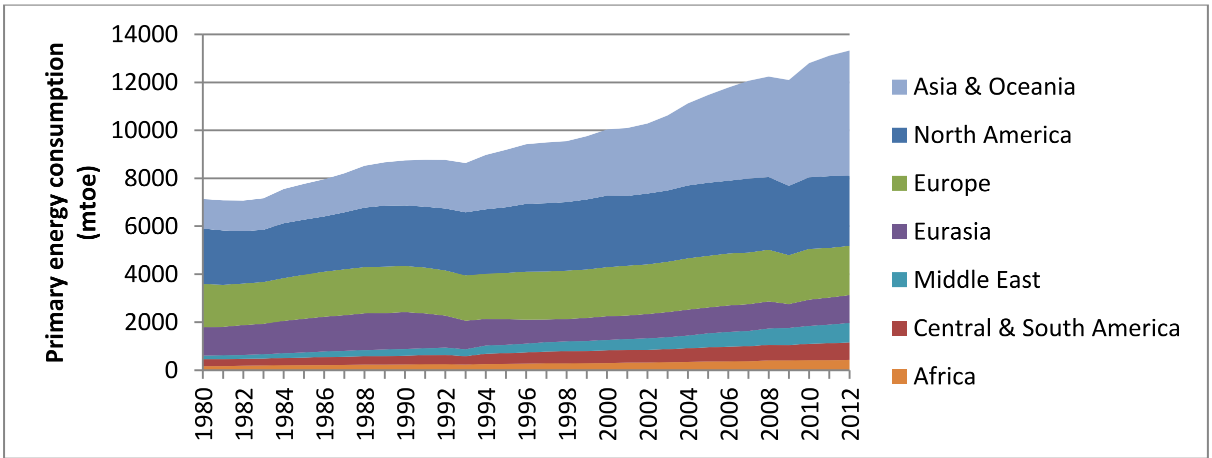



**Figure 1.4: Global primary energy consumption: 1980 – 2012 [EIA, 2015]**

### 1.2.2 Environmental

The environmental impact of human activity is another global problem, and it is directly linked to the consumption of resources: as more resources are consumed, more pollution is created and more habitats are destroyed. This is occurring all over the planet, and like the consumption of finite resources, the situation is unsustainable and becoming critical in many ways.

There are countless ways in which mankind pollutes and destroys the environment. A host of chemicals are constantly being released into the atmosphere, waterways and land. Some forms of pollution are directly detrimental to the health of plants and animals, such as PM10 particulate matter and soils contaminated with heavy metals, whereas others affect the chemical constitution of the environment such as ozone and greenhouse gases which are altering the atmosphere. Whole habitats are also being destroyed, including forests, wetlands and marine habitats. Deforestation to create land for agriculture, the diverting of fresh waterways for industry, and overfishing are just some examples of manmade changes to the biosphere. This negatively impacts biodiversity, and raises concerns about the energy balance of the planet. Mankind is emitting gigatonnes of carbon dioxide into the atmosphere every year whilst removing forests, destroying marine ecosystems, and witnessing the shrinking of the polar ice caps, all of which play a role in determining the Earth's climate.

Since this project concerns energy demand reduction, the environmental impact of fossil fuels is of particular interest. The growing consumption of fossil fuels has resulted in increased greenhouse gas emissions (most notably carbon dioxide), and an increased concentration of these gases in the atmosphere. These changes are altering the thermal properties of the atmosphere, resulting in a general warming of the planet. The concern is that if global warming continues unabated, it could lead to significant changes in climate and an increased occurrence of extreme weather events [IPCC, 2014]. This could have a considerable impact on biodiversity, habitability, and the availability of water and food for large parts of the planet, particularly low lying coastal areas, where large parts of the population live. To mitigate the effects of global warming requires the concentration of greenhouse gases in the atmosphere to stop growing and to stabilise, which requires a significant reduction in greenhouse gas emissions from the burning of fossil fuels and industrial processes [IPCC, 2014]. In terms of the financial implications, it is considered more cost effective to act now to mitigate climate change than to not act and deal with the consequences later [Stern (2007)].

The continued destruction and pollution of the environment may provide short term improvements in standards of living, but in the long term it will ultimately make the planet less habitable for many species, including humans [MA (2005)]. Faced with these problems, there is a real need to assess human behaviour and make changes to ensure a sustainable future [Earth Summit 2012, 2011].

### 1.2.3 Social

The social ramifications of running out of resources or critically reducing the habitability of the planet would be dire on a global scale. But, to many this seems like a far off and uncertain prospect that does not affect people's day to day lives. However, there would also be immediate social benefits to improving the thermal and energy performance of residential buildings in the UK.

There is a shortage of homes in the UK, especially in the South East of England, and in particular a shortage of good quality homes that are affordable to operate and comfortable to live in [CIC, 2013]. Domestic energy prices are high and have been growing steadily for years, making it increasingly expensive for people to heat and power their homes, pushing increasing numbers of people into fuel poverty [Sovacool, 2015; Walker et al., 2014]. Many struggle to afford to heat their homes adequately which means they are living in uncomfortable buildings during colder months, which is detrimental to health. A particular concern is with the elderly who cannot afford to adequately heat their homes, as their age makes them more susceptible to the cold and their reduced social mobility makes it hard for them to find help. Improving the thermal performance of homes so that they require less energy to provide thermal comfort to their occupants would benefit people by reducing fuel costs and providing safer and healthier internal conditions.

### 1.2.4 Energy Security

Reducing energy consumption in the UK would also benefit energy security. The gas reserves are diminishing in the UK: which has been a net importer of energy since 2004 [DECC, 2014], which means it is dependent upon other countries to provide its fuel. While the UK has large reserves of coal, the emissions from coal fired power stations currently make this an unfavourable option for energy production. The dependence on other countries for fuel is cause for concern, because prices and supply can fluctuate, and the situation is likely to become worse as the availability of fossil fuels diminishes. Nationally there is also cause for concern, because many UK coal fired and nuclear power stations are nearing the end of their lives [MacKay, 2009], which means in the future the UK may not have the capacity to generate sufficient electricity to meet demand. The problem of energy security is influenced by many factors, and one way of improving energy security is by reducing demand.

## 1.3 Challenges to Improvement

The reasons to want to reduce energy use and improve internal conditions within UK buildings are clear, however there are many challenges to achieving this. While a comfortable low energy housing stock is technically possible, it is not necessarily straightforward to achieve in reality, for a host of reasons.

The construction of comfortable low energy homes is typically more expensive than standard homes; however the extra performance is often not valued by the market. Therefore, there is no great incentive for house builders to construct buildings to standards above those required by the Building Regulations. To achieve widespread improvements to the existing housing stock and the construction of new low energy homes as the norm requires solutions that are affordable to the industry and consumers.

The uncertain regulatory framework is also a hindrance to progress and it is disappointing that the government recently scrapped zero carbon homes target, a move widely condemned within the industry [UKGBC, 2015] The zero carbon homes target, although challenging, was widely welcomed by the industry, which wants a strong regulatory framework with consistent goals. Significantly improving the performance of buildings is not easy, it requires research and development, which costs money and takes time; a process which was already well underway by the time the targets were scrapped. The industry needs to know the targets that will be required in coming years and to have confidence that these will not change so that it can have confidence to invest in developments.

The complex nature of buildings is another challenge to improving performance. Building physics is complex, owing to the large number of interacting, time dependent variables within a building. Each building is unique, having unique properties, including materials, services, geometry, occupants and geographic location. It is difficult to determine exactly how energy is used and wasted in buildings, and impossible to prescribe a solution that would suit all buildings. There are no ideal or unique solutions for individual building types and multiple approaches could be taken to reduce energy use and improve thermal comfort.

There are also many problems within the construction industry that result in poor quality buildings that underperform. There are also problems with the accurate prediction of building performance, often real performance fails to meet predictions and buildings use more energy than anticipated. There are many reasons why this is the case, which are discussed in Chapter 2.

There are many challenges to achieving a comfortable low energy, housing stock and much research and progress is still required.

## 1.4 Aims and Objectives

The aim of this research was to investigate ways to reduce the in-use energy consumption of light-gauge steel modular construction used for residential purposes, while ensuring thermal comfort. It sought to answer two broad questions:

Does off-site modular construction used for residential buildings lead, per se, to buildings that provide year round thermal comfort with lower energy demand than conventional buildings?

How might the procurement, design, construction of buildings that usemodular methods of construction be improved to ensure a repeatable low energy and thermally comfortable environment?

The work involved collaboration with an industrial sponsor, [redacted], and the research focussed on their modular construction (covered in Chapter 4).

To achieve this aim the following objectives were identified:

1. To conduct a literature review (Chapter 2)
    a. To understand current building performance and the challenges and problems to reducing energy demand and ensuring thermal comfort in residential buildings
    b. To identify appropriate methodologies and methods to adopt
2. To conduct a review of light-gauge steel modular construction (Chapters 2 and 4)
    a. To understand offsite and modular construction and how it differs from traditional construction
    b. To understand the drivers and barriers to the use of modular construction
    c. To achieve in-depth understanding of [redacted], the company and their product
3. To gather data about existing [redacted] buildings (Chapters 7 to 9)
    a. To gain insight into energy consumption within the buildings
    b. To investigate thermal comfort and determine if overheating occurs
    c. To assess the quality of the design and construction
    d. To determine the scale of improvement required
4. To identify weaknesses in the design, construction and operation that result in increased energy use and poor thermal comfort (Chapter 7 to 9)
5. To suggest changes that could lead to improved thermal and energy performance (Chapters 7 to 10)
    a. The main focus to be on changes that can be adopted by [redacted] therefore technical and operational issues.

## 1.5 Chapter Summary

This chapter focused on the high level justification for undertaking this research, before presenting the aims, objectives and research questions. It demonstrated that energy consumption is high in the UK and growing globally; and that a large proportion of the energy consumed is within buildings. However it also showed that energy use is often wasteful and there is significant scope to reduce consumption through improved performance. It discussed the many reasons to want to reduce energy use, including, limiting climate change, reducing environmental impact, improving sustainability, improving building comfort, reducing building operating costs and improving energy security. It also discussed the difficulties achieving low energy, comfortable buildings as the norm, due to the complex and varied nature of the building stock. The challenges mean further research is required, hence why this research was undertaken. This research focuses on modular construction, a modern method of construction, because it could be well suited to tackling some of the problems of the construction industry (which is discussed in Chapter 2).

# Chapter 2 – Literature Review

The reasons for undertaking this research and the decisions about how to conduct it were driven and informed by the issues of the day and from the findings of previous research. This chapter looks at how and why buildings perform poorly and discusses modular construction and overheating, topics which are relevant to this research.

## 2.1 Building Performance

The poor and inconsistent performance of buildings is a key driver for this research, where performance refers to energy consumption, internal environment (thermal comfort and indoor air quality), hygrothermal fabric performance and the performance of building services.

Energy use is high in domestic buildings in the UK partly due to the age of the housing stock and the historically weak requirements of the Building Regulations, however there is also a problem where buildings consume more in use than predicted, whether that is at the design stage for new buildings, prior to refurbishment of existing buildings or with EPCs for existing buildings [Wingfield et al., 2008; Bell et al., 2010a; Bell et al., 2010b]. This has been termed the performance gap and is caused by many factors which broadly fall into three categories: causes linked to the building, the occupants and the prediction methods. The building fabric and services can fail to perform as intended for countless reasons, occupants may use their building in unexpected ways that alters performance, and prediction methods are imperfect which means they contain inherent inaccuracies.

### 2.1.1 Building Fabric and Services

Problems with the underperformance of building fabric and services are common and can lead to high energy use, unsatisfactory internal conditions and fabric degradation.

The main way that fabric underperforms is through high heat losses from inside to outside during the heating season. This can be caused by high air permeability [Grigg, 2004; Wingfield et al., 2008; Stephen 1998; NHBC, 2008], high heat transfer through planar elements and thermal bridges [Bell et al., 2010b; Doran, 2000; Hens et al., 2005; Wingfield et al., 2008], the presence of thermal bypasses [Wingfield et al., 2008; ell et al., 2010b; Wingfield, Miles-Shenton, and Bell, 2009 and 2010] and the occurrence of condensation within the structure (both interstitial and surface) [Oreszczyn et al., 2011; Bell et al., 2005]. The fabric can also underperform in warmer months resulting in overheating; this can be caused by high solar gains, high levels of insulation, low levels of thermal mass and inadequate ventilation. The main ways that building services fail to perform is by failing to achieve their stated efficiencies [Wingfield et al., 2008; Orr, 2009; Carbon Trust, 2007; Bell et al., 2010b], but other problems can exist such as noise which can inhibit use [Bell et al., 2010b].

The reasons why fabric and services underperform are many and varied; the causes span the whole industry from the tendering stage through to handover and into operation.

At the tendering stage there is focus on cost over quality and a false belief that cost equates to value; the best price often wins out even if the costing is unrealistic and the design offers poor performance, [Eigan, 1998]

There are many problems with the design of buildings that affects their performance in use, and much of the recent research comes to the same conclusions [Oreszczyn et al., 2011; Bell et al., 2010a; Bell et al., 2010b; Wingfield et al., 2008]. The design of building fabric in terms of hygrothermal performance often deviates from good practice, for example the continuity of air barriers and insulation layers are rarely clearly marked on drawings, if they are properly designed at all. The buildability of designs is another problem, where it may be possible to draw a particular feature but difficult or impossible to construct it correctly on site. There is also a problem with the provision of accurate and sufficiently detailed drawings for complex features (junctions and interfaces); such that constructors on site are left to improvise important features (or delay work to request suitable drawings). If drawings of complex features are inaccurate or do not exist, then these features may not have been deigned adequately in the first place. If a building design is hygrothermally weak, it does not matter the quality of the work done on site, (if the design is adhered to) it will remain hygrothermally weak.

There are various problems with the design and specification of building services. It is common practice to oversize space heating systems for extremely cold winters but this means that they rarely achieve their stated efficiencies [Carbon Trust, 2007; Carbon Trust, 2011; Bell et al. 2010b]. There are also problems with the optimal specification of building services particularly due to the growing variety and affordability of low and zero carbon technologies, such as heat pumps [Bell et al. 2010b], solar technologies [Bell et al. 2010b; Energy Saving Trust, 2014], and CHP systems [Carbon Trust, 2011] because these technologies are relatively new, complex and require more knowledge and effort to optimise specification.

There are also many problems with the quality of work done on site. The requirement to improve energy performance is relatively new and much of the workforce is inadequately trained to achieve this task, as such there can be a lack of understanding about why certain details are important and how they influence performance [Wingfield et al., 2008; Bell et al., 2010b; Oreszczyn et al., 2011]. There is a culture of substitution and making do on UK construction sites; if the right material is not available at the right time then an alternative will be found [Wingfield et al., 2008; Bell et al., 2010a], this also applies to inadequate construction drawings where solutions are improvised on site rather than in conjunction with the designers [Oreszczyn et al., 2011; Bell et al., 2010b]. There are also problems with the planning and sequencing on site, which can see, for example, features constructed and then demolished to route services and then inadequately reconstructed [Bell et al., 2010b; Wingfield et al., 2008]. There are concerns that building control officers do not prioritise energy performance whilst they inspect for compliance, making it difficult to ensure standards are adhered to and promoting a culture where these standards are not taken seriously [PAC 2009]. There are problems with inadequate commissioning of building services [Wingfield et al., 2008; Bell et al., 2010a; Carbon Trust, 2011] that result in underperformance, where services could work better if time was spent to ensure their correct and optimal setup.

A major problem with the industry is the lack of feedback, a shortcoming that is hindering progress [Bordass and Leaman, 2005; Boardass, Leaman and Ruyssevelt, 2001]. Too little attention is given to the quality and performance of completed buildings: design features and construction methods are assumed to work but little data are collected to confirm or refute this [NAO, 2008; PAC, 2009; Bell et all., 2010a; Bell et al., 2010b]. There is little attempt to identify good approaches from failing approaches or to highlight ways to incrementally improve good approaches: to make improvements there is a fundamental need to assess what works and what does not work in actual buildings [Bell et al., 2010a; Leaman, Stevenson and Bordass, 2010]. The regulatory framework may be partly responsible for the lack of feedback [Bell et al. 2010a], because at present compliance is largely demonstrated through theoretical performance rather than actual performance, with only limited requirement for pressure testing [DCLG, 2015].

The literature clearly shows that building fabric and services underperform; for complex and varied reasons. This results in a building stock that not only performs poorly but does so in an inconsistent and variable manner. Unfortunately these findings are not new [Bonshor and Harrison, 1982; Harrison, 1993; Eigan, 1998], many have been known for decades and many of the problems that existed then continue to exist today. There also continue to be new findings, such as the party wall thermal bypass [Wingfield et al., 2008], and the underperformance of newer technologies such as CHP systems [Carbon Trust, 2007] and heat pumps [Bell et al., 2010a], as well as the newer concerns about overheating (discussed in Section 2.3). It should be noted that similar problems also exist internationally wherever there are attempts to improve the energy use, sustainability, comfort and predictability of buildings [Dall'O et al., 2012; Danielski, 2012; Majcen, Itard and Visscher 2012 and 2013; Ma and Wang, 2009; Parker, 2009; Passe and Nelson, 2013; Saldanha and Beausoleil-Morrison, 2012; Saman, 2013; Sunnika-Blank and Galvin, 2012; Trusty, 2008]. Many changes are still needed across the industry to design and construct better quality housing in order to achieve improvements in energy and thermal performance [Summerfield and Lowe, 2012].

### 2.1.2 Performance Gap

There is often a difference between the predicted performance of buildings and their actual performance, where they tend to consume more energy and lose more heat than predicted. This is a problem for relatively simple tools such as the Standard Assessment Procedure (SAP) [DCLG, 2015] used to demonstrate compliance with the Building Regulations, and with more complex tools such as dynamic thermal building simulations [Bell et al, 2010a and 2010b; Sanders and Phillipson, 2006]. The reasons for this are complex and due in part to the poor and inconsistent performance of buildings and in part due to the prediction methods, tools and approaches used.

As outlined above, it is widely recognised that the performance of building fabric and services is often worse that the design specifications, however the default approach to modelling and prediction is to assume that inputs achieve their best case scenario. This approach is illogical because there can be large uncertainties associated with some parameters (such as air tightness and thermal bridging). If little effort is made to accurately quantify the input parameters, then there can be little confidence in the accuracy of the results. One clear way to tackle this problem is to improve the quality of buildings, which would reduce the uncertainty in input parameters. However, even if quality improves, there will always be some variation in each parameter; and the combined effect could be significant. Therefore, there is a strong argument for developing prediction tools that incorporate the uncertainty in inputs and outputs [Hopfe et al., 2007; MacDonald and Clarke, 2007; Hughes et al., 2013]. It is however challenging to incorporate uncertainty into the compliance tools (SAP and SBEM) which need to be simple and straightforward to use, and it is difficult to correctly quantify the uncertainty in each parameter for every building. One possible solution is the use of confidence factors [Bell et al., 2010a], which are already used in Sweden [Doran, 2000]. They work by applying factors to practices, processes and procedures: if steps are taken to ensure quality then a low factor is applied to the input parameter, if there is no attempt to ensure quality then a high factor is applied. This effectively penalises those that do not take extra steps to ensure the quality of the work and components used in construction, and is a means to improve quality and prediction.

Another key shortcoming with modelling and prediction tools is their treatment of occupants. During their development there has historically been a focus on the deterministic aspects, such as geometry, material properties and building services; and the underlying theory that define these components and their interactions [Clarke, 2001]. However, in dwellings the role occupants play in determining building energy demand, internal gains and the internal environment is significant [Haldi and Robinson, 2011; Schweiker et al., 2012; Hoes, et al., 2009; Schweiker and Shukuya, 2010]. Occupants are also the main drivers for and actors in environmental control in non air-conditioned buildings, such as window opening, where it is occupants that decide whether to open or close windows and they take the action to make the change [Rijal et al. 2007; Rijal et al., 2008a; Rijal et al., 2008b; Gill et al., 2010]. The impact of the occupant could be more significant than potential improvements in the fabric, systems and appliances [Haldi and Robinson, 2012], and it will become increasingly important as the performance of building fabric and services improve [Hoes, et al., 2009]. Improved modelling of occupants at the design stage can result in improved building performance [Schweiker et al., 2012]. However, the key challenges are to better understand occupant behaviour and its impact on energy use, internal gains and environmental control; and how to realistically represent this behaviour in building models [Schweiker et al., 2011]. This is difficult because human behaviour is complex and variable, people have different behaviours, and individuals do not always act in the same way to a given set of circumstances [Widén, Molin and Ellegård, 2012]. Currently much research is being conducted internationally in this area because these weaknesses are prevalent in all prediction tools, because they stem from a lack of knowledge about occupants rather than shortcomings in modelling capabilities [Haldi and Robinson, 2009; Haldi and Robinson, 2012; Rijal et al., 2007; Rijal et al., 2008a, Rijal et al., 2008b; Schweiker et al., 2012; Widén, Molin and Ellegård, 2012: Liao, Lin and Barooah, 2012; Fabi et al., 2012; Virote and Neves-Silva, 2012]. This research tends to use real data from buildings, typically from questionnaires and/or sensors, to improve, modify or calibrate simulation tools and to better understand and predict the role of occupants in building performance. Much work is still needed before the role of occupants is well represented in prediction tools as the norm.

Highlighting the shortcomings in the approaches taken to, and the results obtained from, building models and prediction tools is not to negate their benefit; they are useful, necessary tools that are constantly being improved, they give insight and support research and development. However, it is important to recognise their shortcomings: that they are imperfect tools, that the way they are used impacts the accuracy of the results, and that the data obtained must be interpreted carefully in order to achieve reliable findings.

## 2.2 Modular Construction

This research concerns light gauge steel modular construction, which is an interesting area of research because there is a view that modern methods of construction are well placed to tackle some of the long running problems within the industry.

Modular or volumetric construction is a form of offsite construction (OSC), which is a broad term used to describe a wide range of construction activities and techniques which are carried out prior to reaching the construction site, many of which have traditionally been done on site. There is no agreed, industry wide definition, the terminology is varied with terms such as offsite construction, offsite production, preassembly and prefabrication, offsite manufacturing, and offsite fabrication often used interchangeably in the UK [Gibb, 2001; Goodier and Gibb, 2007; Pan, Gibb and Dainty, 2008]. Offsite Construction can also be described under the wider term Modern Methods of Construction (MMC), which is a newer term that incorporates all aspects of offsite production plus additional modern methods done on site [Goodier and Gibb, 2007].

For the purpose of this research, four categories of offsite construction have been used, and are defined in Table 2.1 [Gibb and Pendlebury, 2006; Goodier and Gibb, 2007]. [redacted] construction includes all four categories: modules form the building structure, but volumetric pre-assembled units, non-volumetric pre-assembled units and component sub-assemblies are also used for various purposes; [redacted] modular design and construction is detailed in Chapter 4.

**Table 2.1: Classification of types of offsite construction**

| Offsite Classification | Description | Examples |
|---|---|---|
| Complete/Modular Buildings | Units that enclose useable space, and form part of the structure of the building, typically factory finished internally | Modular buildings |
| Volumetric Pre-assembly | Units that enclose useable space within or on a building and do not form part of the structure, typically factory finished internally | Bathroom pods<br>Lift shafts |
| Non-Volumetric<br>Pre-assembly | Units that enclose no useable space | Pre-cast panels<br>Building services |
| Component Sub-assembly | Units that are always manufactured and assembled offsite | Structural members<br>Light fittings, windows |

The offsite construction market is diverse, including many types of construction with many differences within each type [Gibb, 1999; Buildoffsite, 2007]. In modular construction the structural component is typically timber, light gauge cold rolled steel, or hot rolled steel. There are many manufacturers of steel modular construction within the UK [[redacted] etc.], but they are not necessarily comparable due to differences in the type of steel, the way load is transmitted through the building, the manufacturing process, the site construction process, the interfacing between building components and the flexibility of the design in terms of internal layout and building size. The products offered by other manufacturers, and their similarities or dissimilarities with the [redacted] product are outwith the scope of this work, which focuses solely on the [redacted] product.

Offsite construction currently represents a small proportion of all building construction activities in the UK, however quantifying the size of the market is challenging and as such there are no up to date figures and certainly not any annual figures [Goodier and Gibb, 2007]. An extensive review in 2004 calculated the value of the UK offsite market (excluding sub-assemblies which are always fabricated offsite) at £2.2billion, accounting for 2.1% of the construction industry, of which modular and portable buildings totalled £0.64billion [Goodier and Gibb, 2004]. When considering only new build construction (excluding civil engineering), the total market was valued £53.3billion, of which 4.1% was offsite; this equates to £2.185billion indicating that the majority of offsite construction is used for new build. Most new build offsite construction is in the non-domestic sector; however exact figures are not available. There are various reasons why the use of offsite technologies is lower in the housebuilding industry, including [CIC, 2013; Egan, 1998]:

- A risk averse industry
- Market forces that dictate the cost benefit of constructing at a given time in a given place
- Low rates of construction despite housing shortages
- Time benefits achieved from offsite construction are not necessarily beneficial for “build for sale” housebuilders who often choose to construct slowly to match the rate of sales
- An industry driven by profits and not performance of the product over its lifetime
- A system whereby properties are valued based on local house prices rather than on quality and performance of the product

For years, the use of offsite construction in housebuilding has been forecast to increase [CIC, 2013; Buildoffsite, 2007], because it offers potential solutions to many of the industry's problems. In particular, offsite construction is often seen as a means to tackling the shortage of housing particularly good quality, affordable housing [CIC, 2013; Housing Trust, 2002, Pan, Gibb and Dainty, 2007]. Offsite construction has historically been used in time of need [Gibb, 1999], and the ongoing housing shortage is a time of need and an opportunity for the offsite market.

In theory, offsite construction can provide many benefits over traditional construction; however benefits are not guaranteed and depend upon project planning and management, as well as the suitability of the offsite method and its integration within the construction process [Gibb, 2001]. There are various advantages, disadvantages, barriers and drivers to the use of offsite construction, that have been well documented in the literature for many years (Table 2.2) [Gibb, 1999; Pan, Gibb and Dainty, 2007; Pan, Gibb and Dainty, 2008; Goodier and Gibb, 2007; CIC, 2013].

While many of the often cited benefits of and drivers for the use of offsite construction do not directly refer to energy use and thermal performance, links can be made. One of the key problems with domestic buildings is poor and inconsistent quality leading to high energy use and poor internal conditions. Quality and consistency is one of the key benefits of offsite construction because many of the problems on a traditional site (such as the use of incorrect materials, illogical sequencing of tasks and difficulties constructing complex details) can be easily controlled or completely removed in a factory setting. Therefore, if offsite construction offers a means to reliably and consistently provide high quality buildings, then it may also offer a means for providing consistent energy and thermal performance.

Offsite construction could also lead to reductions in the whole life cycle impact of buildings, in terms of energy, waste and pollution; and although these topics are not the direct focus of this research, they are still areas where offsite construction can offer benefits over traditional construction. Energy can be saved during manufacture due to high productivity achieved in a factory, by optimisation of factory processes, by a reduction of time spent on site, by a reduction in waste, by maximising recycling of waste, and even by a reduction in transport. Many products manufactured offsite, particularly steel construction, can be dismantled at the end of the building life, allowing materials to be reused and recycled. All of these factors reduce the environmental impact of buildings and improves their sustainability, which can only be beneficial.

**Table 2.2: Drivers and Barriers to the use of offsite construction**

| Driver or Barrier | Examples |
|---|---|
| **Drivers** | |
| Productivity | Greater productivity achieved on a factory production line<br>Automated machinery (e.g. CAD, CAM and CNC machines) performs tasks quicker than people and without error<br>Delays caused by weather are avoided in a factory |
| Accuracy and repeatability | Automated machinery (e.g. CAD, CAM and CNC machines) operates at far higher tolerances than people and without error<br>Processes can be tightly controlled in a factory<br>Workers become more accurate through repetition of task |
| Quality and consistency | The high tolerances achieved in a factory can be used to ensure a high quality product is consistently produced |
| Construction time | Tasks can run concurrently in the factory and on site<br>Offsite buildings can be erected rapidly, reducing time on site |
| Predictable completion times | Delays caused by weather are reduced<br>Delays with one contractor less likely to impact on another since less contractors are required on site |
| Waste | Materials can be cut by machine increasing accuracy and removing human error<br>Materials can be sorted and recycled easily |
| Health and safety | There is no work at height<br>Dangerous machinery can be isolated to avoid accidents<br>Safety procedures are easy to enforce in a factory |
| Standardisation | Greater productivity through repeatability of task<br>Greater quality through repeatability of task |
| **Barriers** | |
| Planning | Offsite technologies need to be incorporated in the project plan early in the design process to maximise time and cost benefits<br>Inability to freeze the construction/planning process early on |
| Negative Perceptions | Poorly performing examples of offsite construction from the past still influence views today<br>A perception that customised solutions cannot be achieved through standardised components and processes |
| Knowledge and information | More information is required to change negative perceptions<br>There is a lack of information about costs, offsite construction process, product interfacings etc.<br>There is insufficient sharing of information between manufacturers which would help inform the market |
| **Driver or Barrier** | |
| Cost | Elemental cost analyses favour traditional methods but whole project cost analyses can find in favour of offsite methods<br>Late adoption of offsite methods can negate cost benefits |
| Transport | Offsite construction reduces transport to site which can benefit access to the site<br>Transport costs may be more or less than a traditional construction, which is project dependent (but rarely accurately calculated) |
| Skills | A skilled workforce close to site can be difficult to find in traditional construction projects<br>Few workers have the correct skills for factory work and need to be trained for the specific tasks |
| Economies of scale | Costs tend to reduce with the purchase of more units, which can be beneficial for large projects but inhibitive for small projects |

Therefore, offsite construction offers the potential to save resources (including energy) and reduce environmental impact in all stages of a building's life. In recent years there has been a growing realisation that low energy, sustainable homes can be achieved through the use of offsite construction methods, [NAO, 2005; Housing Forum, 2002]. Unfortunately, despite the claims, there is little peer reviewed literature that actually measures or tests the performance of offsite construction; while the theoretical benefits exist there is a lack of publicly available data to support or refute their existence in operational buildings. The lack of performance data is an industry wide issue, so it is not surprising that it is also true for offsite construction which represents such as small percentage of the UK building stock. There is of course some literature, but due to the diversity of the offsite market most is not comparable with the energy and thermal performance in use of light gauge steel modular construction in the UK. Research into different offsite construction methods and building types (such as schools) cannot necessarily be compared, nor can most research from abroad (due to differences in climates, regulations and building designs) or research that focuses on different aspects of performance (such as embodied energy and emissions), and much of the literature found fell in to one or more of these categories [Piroozfar, Altan, and Popovic-Larsen, 2012; Cao et al., 2015; Silva et al., 2013; Aye et al., 2012; Bonamente et al., 2014; Hong et al., 2015; Jaillon and Poon, 2014; Li, Shen and Alshawi, 2014; Tam et al., 2007; Lehmann, 2013; Mao et al., 2013; Monahan and Powell, 2011; Rodrigues, Gillott, and Tetlow, 2013; Wang et al., 2013]. By far the most common area of research about offsite construction concerns life cycle analyses where the focus is on benefits reaped from the manufacturing stage and/or from the reuse use at end of life stage, which are reduced embodied energy, reduced embodied emissions, improved sustainability and reduced material wastage.

The literature regarding offsite construction has highlighted many facets of the industry that could lead to the improved energy and thermal performance of dwellings, however there is a lack of data to determine if such theoretical benefits actually result in improved performance, and there is a need to collect data to this affect, which this research aims to do.

## 2.3 Overheating

There is a growing concern in the UK about overheating in buildings, particularly in buildings with low thermal mass which are seen as more vulnerable due to the limited ability to store heat within their fabric [Kendrick et al., 2012]. There are buildings in the UK that overheat at present [Hacker and Holmes, 2007; CIBSE, 2011; Mavrogianni et al., 2011; Tilson, Oreszczyn and Palmer, 2013, Wright, Young and Natarajan, 2005; Peacock, Jenkins and Kane, 2010; Lomas and Kane], and the concern is that the prevalence and severity of overheating could increase in the future for a number of reasons [Hacker and Holmes, 2007, Jenkins et al., 2013; Patidar et al., 2013]. The thermal fabric requirements of new buildings will become more stringent in coming years, which will improve the ability for buildings to retain heat and may increase the risk of overheating during warmer periods [Chvatal and Corvacho, 2009; Gupta an Gregg, 2013]. The climate is predicted to warm and for there to be an increase in extreme weather events, including heatwaves [IPCC, 2014], both of which will raise internal temperatures and increase the potential for overheating [CIBSE, 2005]. The concern about overheating is greatest in the south east of England because it is the warmest part of the UK, and in large urban areas such as London and Manchester [Hacker and Holmes, 2007;] due to the urban heat island effect [Mavrogiannia, 2011; Oikonomou, 2012;]. Urban areas experience increased temperatures compared to rural areas because they generate more heat. The thermal properties of urban areas are also different with more thermal mass and different heat absorption and retention properties which impacts the diurnal temperature fluctuations compared to rural areas, temperature can peak later in the day and may not cool as much at night compared to rural areas, which impacts the internal environment within buildings and can limit the effectiveness of strategies such as night cooling. Some, occasional overheating may be acceptable in buildings, but if the frequency and severity becomes too great then the concern is that there will be a shift in the UK to the widespread uptake of air conditioning [Capon and Hacker, 2009; Hacker and Holmes, 2007; Orme, Palmer and Irving, 2003]. This is not desirable because buildings already consume too much energy and it will be difficult to reduce energy use in the domestic sector if there is widespread uptake of air-conditioning. It is possible to construct buildings with little risk of overheating without the use of air conditioning, and this ought to be a priority for the industry to avoid the uptake of air conditioning.

The occurrence of overheating is a problem for occupants because it causes them thermal discomfort, it is not a problem for the building fabric or structure. Thermal comfort is defined as:

“That condition of mind which expresses satisfaction with the thermal environment.” [British Standards Institution, 2005]

If the majority of occupants in a building feel uncomfortably warm or hot then the building is said to be overheating [Nicol, Humphreys and Roaf, 2012]]. There are a wide range of temperatures that humans can find comfortable, as evidenced by the diverse climates in which mankind has learned to thrive [Nicol, Humphreys and Roaf, 2012]. However, the human body can only operate within a relatively narrow range of core temperatures, therefore temperature regulation is necessary, which occurs through subconscious thermoregulation (such as sweating) and conscious actions (such as opening windows).

There are many physical parameter that influence thermal comfort which include [CIBSE, 2015]:

- Air temperature
- Mean radiant temperature
- Humidity
- Air movement
- Metabolic rate
- Clothing

These parameters are constantly changing (even in air-conditioned building where most parameters are fairly stable, metabolic rate will still vary), therefore thermoregulation is constant process where the aim is to maintain a constant core temperature (homeostasis) in a constantly changing environment. The body generates heat from fuel and movement, and exchanges heat with the environment based on the temperature gradients between the body and its surroundings. A person can influence the exchange of heat by their choice of clothing, activity level, calorie intake, hydration level and by adjusting their environment to suit their needs, such as by opening windows, using fans or turning on heating [Nicol, Humpreys and Roaf, 2012]. If a person cannot achieve homeostasis through thermoregulation or conscious actions, then the result will be to experience thermal discomfort.

A key purpose of buildings is the attainment of thermal comfort as they protect from the harshness of the environment, which includes hot and cold external temperatures, high wind speeds, rain and humidity. However, there is now a growing concern that buildings can cause thermal discomfort due to various factors that influence the internal environment of buildings [CIBSE, 2005]:

- Building fabric, particularly insulation, thermal mass, and glazing
- Heat gains from occupants, lights, appliances, solar radiation and thermal gradients
- Ventilation rate
- Building form and orientation

Until relatively recently there was little concern about overheating in UK buildings, therefore little attempt to understand it, calculate it or avoid it. The standard approach was to determine overheating based on the extent to which internal temperatures exceed static temperatures [CIBSE, 2006], but there was never any regulatory requirement to demonstrate that a design will not overheat. In recent years there has been increasing recognition that overheating represents a growing problem and steps should be taken at the design stage to avoid it [Nicol et al., 2009]. However, there is still little regulatory requirement to ensure buildings avoid overheating, there are no maximum allowable internal temperatures [CIBSE, 2011], and there are only simple requirements to limit solar gains and insulate mechanical services [DCLG, 2015]. The determination of overheating based on static temperatures is now widely viewed as unacceptable. Thermal comfort is highly subjective, and there is not one set of perfect conditions in which all people will experience comfort [CIBSE, 2011]. It has been found that the conditions deemed comfortable by occupants vary throughout the year because people adapt to their changing environment [Nicol and Humphreys, 2002]. This is the adaptive approach to thermal comfort, is based on the principle of adaptation:

*"If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort."* [Nicol and Humphreys, 2002]

People can react in two basic ways [Humphreys, Rijal and Nicol, 2013]:

- By taking action to feel more comfortable in the prevailing conditions, such as by changing clothes, adjusting posture, changing activity levels, drinking and eating
- By taking action to alter the prevailing conditions, such as by opening windows, closing blinds or turning on fans

Because people can adapt to their changing environment, the temperatures at which they experience comfort and discomfort changes throughout the year, and an internal temperature of 26°C might cause discomfort in May but not in August.

Based on the adaptive approach, it has been found in free-running buildings that the comfort temperature is linearly proportional to the exponentially weighted running mean of the daily mean outdoor temperature, $T_{rm}$ (from herein referred to as running mean temperature) [Nicol and Humphreys, 2002; Nicol, Humpreys and Roaf, 2012; CIBSE, 2015]. The running mean temperature is defined as:

$$T_{rm} = (1-\alpha)(T_{ed-1} + \alpha T_{ed-2} + \alpha^2 T_{ed-3} \dots) \quad \textbf{Equation 2.1}$$

Where α is a constant between 0 and 1 which governs how the running mean temperature responds to the daily mean external temperature, where 0.8 is the recommended value [British Standards Institution, 2007; CIBSE 2015; CIBSE, 2013]

The comfort temperature can be calculated from the running meant temperature, there are different equations based on the standard used [ASHRAE, 2013; British Standards Institution, 2007]. The European standard [British Standards Institution, 2007; CIBSE 2015; CIBSE, 2013] defines the comfort temperature as:

$$T_{comf} = 0.33T_{rm} + 18.8$$ **Equation 2.2**

From the comfort temperature a band of acceptable temperatures can be calculated based on the category of the building:

$$T_{comf} = 0.33T_{rm} + 18.8 \pm 2$$ …For a Category I Building **Equation 2.3**

$$T_{comf} = 0.33T_{rm} + 18.8 \pm 3$$ …For a Category II Building **Equation 2.4**

$$T_{comf} = 0.33T_{rm} + 18.8 \pm 4$$ …For a Category III Building **Equation 2.5**

The categories of building are described in Table 2.3 [CIBSE, 2013] ,

**Table 2.3: Categories of building for determining the adaptive thermal comfort band of temperatures**

| Category | Comfort Band (K) | Description |
|---|---|---|
| I | ±2 | High expectation: For occupants sensitive and fragile to thermal comfort |
| II | ±3 | Normal expectation: New and renovated buildings |
| II | ±4 | Moderate expectation: Existing buildings |
| IV | >4 | Values outside of criteria: acceptable for short periods only |

The use of the adaptive model of thermal comfort for the determination of overheating is growing and is becoming increasingly mainstream [Humphreys, Rijal and Nicol, 2013; Nicol et al., 2013], and was recently incorporated into CIBSE Guide A replacing the static temperature recommendations [CIBSE, 2006 and 2015].

Environmental measurements are an indirect measure of thermal comfort, because comfort is a human perception, and environmental conditions merely indicate the likelihood that people will feel comfortable or not. Occupant surveys, questionnaires and interviews are another key approach to understanding thermal comfort [Nicol, Humphreys and Roaf, 2012]. This research focuses more on the environmental conditions that can be measured, so will not describe the various qualitative approaches to investigating thermal comfort and overheating. However, there have been many interesting findings from quantitative (or mixed methods) approaches that have ramifications for building design and operation. In addition to the well established factors (temperatures, air speed, humidity, clothing and metabolic rate), other less tangible factors have been shown to influence human perception of and satisfaction with the environment within buildings. It has been found that occupants feel comfortable in a wider range of conditions if they have control over their environment and in a narrower range of conditions if they have no means of control [Leaman and Bordass, 2007]. This means in a building where the occupants are able to take adaptive action (such as turn on fans, open windows, change activity level or clothing level), such as in free-running buildings, occupants feel comfortable in a wider range of conditions. And, in a building where occupants have limited ability to take adaptive action, such as an air-conditioned workplace (where occupants may not be able to open windows, or adjust the air-conditioning settings or the level or activity or clothing for example), the range of conditions in which they feel comfortable is narrower. The literature also shows that even in buildings where the occupants have means of control, if they do not understand those controls (perhaps how to use them or their purpose), then they feel comfortable in a narrower range of conditions [Leaman and Bordass, 2007], and if they come to understand those controls and how to use them then the range of temperatures in which they feel comfortable grows. The literature even suggests that other, seemingly unrelated factors can influence thermal comfort, such as noise, smells, the suitability of the environment to the role (e.g. a cramped work desk), and floor layout [Leaman and Bordass, 2007]. It also shows that occupants may be more forgiving of low energy buildings if they view low energy buildings a beneficial to the environment [Deuble and de Dear, 2012; Leaman and Bordass, 2007]. These findings are significant because it suggest that tightly controlled thermal conditions within a building are not the ideal to aim for, that occupants may be more comfortable in variable conditions. It also suggests that occupants prefer to have means of control and therefore complex building services that remove control may not be ideal. It also highlights the importance of architectural delight within buildings, if occupants like a building they are more likely to feel comfortable; good buildings have a positive impact on people.

Determining if a building design will overheat or if an existing building currently overheats, and to what extent, is problematic, there are many approaches and all are time consuming. Much research is currently being conducted in this area, to better understand occupants, which conditions class as overheating, how to design buildings to avoid overheating and how establish methods to use at the design stage to ensure buildings will not overheat when constructed and into the future [Jenkins et al., 2013, Jentsch, Bahaj and James, 2008].

Of specific interest to this work is the research focused on design solutions, with some looking at specific approaches such as thermal mass [Hacker et al., 2008], phase change materials [Voelker et al., 2008], and solar control [Khun et al., 2001]. Whereas other research take a more objective view, using parametric studies to investigate which solution or range of solutions is most suitable for minimising the risk of overheating [Orme et al., 2003; Capon and Hacker, 2009; Porritt et al., 2012; Kendrick et al., 2012; Tilson, Oreszczyn and Palmer, 2013].

It seems that over the coming years much is set to change with regard to the treatment of thermal comfort and overheating in buildings. This is being driven by increased knowledge on the subject as well as an increased requirement to tackle these issues due to an increased risk of overheating.

## 2.4 Chapter Summary

This chapter presented the findings from the literature review, which helped to formulate the research, to focus efforts on areas that are lacking and to conduct research that yields meaningful, reliable results that can facilitate improved performance of [redacted] buildings. It first outlined the complex and varied reasons that buildings underperform, highlighting that much work is still required to achieve a comfortable, low energy housing stock. The performance gap and the reasons for its existence were then discussed: the challenges in accurately predicting building performance with models lead to the decision to focus the research on the actual performance of existing buildings, rather than to rely on modelling and assumptions that the buildings perform the way they were intended to at the design stage. The chapter then went on to discuss modular construction and the offsite construction market more generally, presenting the often cited advantages and disadvantages of offsite construction. It explained how offsite construction is often seen as offering solutions to many of the problems with building quality and sustainability, but that much of the research has focused on benefits gained in the manufacture/construction and end of life stages, and not on the performance in use. This research focuses on the performance in use of modular construction, and therefore aims to provide information and data in an area that is currently lacking. Finally, the chapter discussed overheating in buildings and thermal comfort, which are complex subjects influenced by building design and operation, location, human physiology and perception. The literature suggests that people are comfortable in a wider range of conditions in free-running buildings that they like and understand, and in which they have the ability to take adaptive action. Understanding this is important when formulating the final recommendations of this research because it suggests that complex, tightly controlled internal environments are not ideal, and that simple, adaptable, free-running buildings may be preferable. The findings from the literature review were vital for shaping the research, understanding the current challenges, and identifying the areas where research and data are lacking.

# Chapter 3 – Methodology and Methods

This chapter presents the methodology and methods used to achieve the research aims and objectives, and it explains why they were chosen. The choice of methodology and methods is fundamental to the type of research conducted, the data collected from it, the analyses that can be undertaken, and the conclusions that can be drawn.

## 3.1 Methodology

The aim of this research was to investigate ways to reduce the in-use energy consumption in light-gauge steel modular construction used for residential purposes, while ensuring thermal comfort and affordability. This is an applied problem because the energy use, comfort and affordability of homes are all issues currently faced by house builders and occupants. It is an open-ended problem, because there is no unique solution that could be applied to all building types, geographic locations and occupants; and there are multiple approaches that could achieve the same result. Decisions about how to achieve the research aim were based on:

- the literature review,
- the manufacturer and their goals, and
- the philosophical perspective of the researcher.

The literature review highlighted a number of issues which influenced the objectives formulated, and the methodology and the methods adopted, because it negated many approaches. The existence of a gap between predicted and achieved performance means it is difficult to confidently predict building energy consumption or the risk of overheating through theoretical approaches alone, such as building simulations. Instead, it was deemed more reliable to choose methods that focus on existing buildings and how they perform in reality, such as building monitoring and measurement.

The manufacturer wanted to collaborate on research aimed at improving and ensuring the energy performance of their product. While the research was not dictated by the manufacturer, their involvement influenced the objectives, methodology and methods. Collaborating with the manufacturer largely meant that the improvements sought were of a technical nature, and would focus on changes that the manufacturer could adopt.

The philosophical view of the researcher was equally as important in formulating the objectives and methodology [Dainty, 2008; Guba and Lincoln, 1994; Guba 1990]. This project was conducted within a postpositivist philosophical framework. The postpositivist world view evolved from positivism and an attempt to resolve many of the problems with positivism, and as such postpositivism and positivism share many facets, but also many differences [Philips and Burbules, 2000, Guba and Lincoln, 1994; Guba 1990]. The postpositivist ontological view adopted is critical-realism, which shares the realist view of positivism, of a single physical reality separate from human existence, but it deviates from positivism in that it believes perception of reality can differ between people and that it is never possible to correctly and entirely understand reality, due to the complexity of reality and the subjective nature of human experience, however the aim is still to strive for this ideal. [Guba and Lincoln, 1994; Guba 1990].

The epistemological view of knowledge is linked to the ontological view of reality, and in this project a modified-objectivist stance was adopted; in which the objectivist ideal is shared with the positivist paradigm, but seen as unattainable in reality [Guba and Lincoln, 1994; Guba and Lincoln, 2000: Guba 1990]. The ability to gain knowledge about the world in a completely objective way is ideal, but achieving this is extremely difficult because it requires a separation of a researcher's views, knowledge and experiences from the problem to look at it objectively. There are also issues such as measurement error and uncertainties that make it difficult to obtain completely objective data. Objectivism is still the goal, but the modified-objectivist stance realises the difficulties in achieving it completely.

The postpositivist world view with its ontological and epistemological positions leads to the adoption of certain methodologies for inquiry, those supported by the paradigm. A modified-experimental methodology was adopted [Guba and Lincoln, 1994; Guba 1990], which is an evolution from the tightly controlled laboratory experiments used by positivists, to experiments conducted in more natural settings with little or no control over various parameters. This evolution is born out of problems with the positivist experimental approach to inquiry, which include: context stripping in controlled experiments, the complexity of real world problems, the inapplicability of general data to individual cases, the underdetermination of theory and the value and theory ladenness of facts, among others [Philips and Burbules, 2000: Guba and Lincoln, 1994; Guba 1990], The problem with controlled laboratory experiments is that they seek to simplify and control conditions to analyse individual or limited numbers of parameters to identify causative relationships. And, while this approach is perfectly acceptable for certain forms of inquiry, it is not necessarily the best approach to all research problems. The energy and thermal performance of buildings is complex and dynamic, and influenced by hundreds of parameters many of which are unpredictable, uncontrollable and not necessarily transferrable to a laboratory, most notably occupants and weather. Laboratory experiments have lead to advances in building physics, but they have also lead to an over-simplification of the processes involved and a tendency to focus on the structure and systems and to exclude the occupants.

Another facet implied by a postpositivist world view is the emphasis on “critical-mutliplism” which Guba (1990) describes as a “form of elaborated triangulation”. Since the view is that data, data collection methods, human intelligence and objectivity are imperfect and fallible, then it is logical that there should not be too heavy a reliance on individual data sources, and it is preferable to collect data from multiple sources. The logic is that the findings are more reliable if multiple sources of data confer, than if there is only one source of data pointing to a given conclusion.

## 3.2 Case Study Research

Based on the research aims and objectives, the findings from the literature review, the collaboration with the sponsor, and the philosophical worldview, it was decided that the best way to achieve the research aim was through the use of case studies.

Yin (2014) has a twofold definition for a case study:

*“A case study is an empirical enquiry that investigates a contemporary phenomenon (the “case”) in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident*

*A case study inquiry copes with the technically distinctive situation where there will be many more variables of interest than data points, and as one result relies on multiple sources of evidence, with data needing to converge in a triangulating fashion, and as another result benefits from the prior development of theoretical propositions to guide data collection and analysis.”*

Case studies are in-depth studies that typically utilise data from multiple methods and sources [Yin, 2014; Proverbs and Gameson, 2008]. Multiple sources of evidence allow triangulation to be used as a data analysis method, where data and findings from different sources converge to reach the same conclusion [Yin, 2014; Proverbs and Gameson, 2008, Fellows and Liu, 2008]. The benefit of triangulation is that convergent findings from multiple sources of evidence lead to greater confidence in the findings, because the data from one source are corroborated and supported by the data from other sources.

The use of case studies as an approach to inquiry is very well aligned with the postpositivistic paradigm, due to the preference for natural settings, the minimal control over parameters, and for the collection of data from multiple sources. The reasons for choosing to conduct case study research were also motivated by the aims and context of the research problem. Yin (2014) describes the conditions under which various research methods might be adopted, advising that the case study method is best suited for research questions that seek to answer "how" and "why" questions for contemporary problems for which there is no control over events. This research concerns the energy and thermal performance of existing buildings, and therefore concerns contemporary events. There is also no desire to control the factors which influence energy and thermal performance within [redacted] buildings, because to control them would create an unnatural situation and the data would not be objective or representative of real building use or real performance. The research also seeks to answer "how" and "why" questions in addition to "what", "where", "how many", "how much" questions. The aim is to determine not only how much energy is used, but also why that much energy is used, not only if overheating occurs, but also why it may or may not occur, and not only how the fabric performs well, but also why it performs as such. The aim is not simply to quantify energy and thermal performance, but to delve deeper into the causes, in order to make suggestions to the manufacturer on how to improve their product.

Another reason why case study research is so suited to the research aims and objectives is the complexity of the problem. There are hundreds of interacting variables that influence energy use and thermal performance in buildings, which are context dependent: the same building in another location would perform differently, a different building in the same location would perform differently, and the same building with different occupants would perform differently. The energy and thermal performance of a building is a function of the fabric, the systems, the location, the weather, the occupants, and the interaction between these factors; to change any of these would change the performance in some way. It is not straightforward to separate these factors and how they interact, to rank them, and to focus on only one issue in isolation from the rest. Nor were there any reliable data or evidence that there should be a focus on a particular aspect of performance to the exclusion of others. Therefore, it was deemed best to investigate the whole system.

Yin (2014) explains that case study research:

*"benefits from the prior development of theoretical propositions to guide data collection and analysis."*

The findings from the literature allowed the creation of theoretical propositions that helped guide the inquiry. For instance, the literature shows that there is potential for increased quality and repeatability in products manufactured offsite compared to on site, and therefore it could be hypothesised that this increased quality could result in improved fabric performance because there are less fabric defects. The literature also shows that the risk of overheating is greater in thermally lightweight buildings, particularly in cities and especially in London; and given that [redacted] buildings are thermally lightweight and often located in cities, it could be hypothesised that they overheat at some point during the year. However, there was no clear evidence specific to [redacted] buildings to formulate hypotheses, only theoretical propositions (which were used to help formulate the research questions outlined in Chapter 1.5).

While the research was to be conducted in natural settings, the approach is experimental, where aim is for researcher to be separate from the subject, to be impartial, objective and to not directly influence the results. The research design used was based on the experimental approach, it was approximately linear and separated into distinct stages (Figure 3.1).

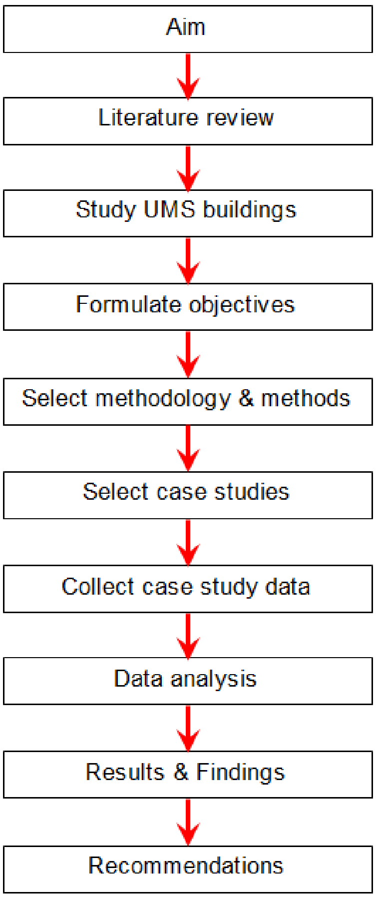



**Figure 3.1: The research process - Linear experimental**

## 3.3 Data

Case study research requires in-depth knowledge about each case, therefore it typically involves the collection of data from multiple methods.

The methods chosen were based on the data required to answer the aims and objectives. Many parameters can give insights into building performance, but it was only practical to collect data from a limited number of parameters. The data chosen for collection and the reasons for their selection are summarised in Table 3.1. This data will give insight into the energy and thermal performance of the buildings in use, and the design, manufacture and construction of light-gauge steel modular buildings. With this dataset, the focus is on technical changes that could be made to the design, manufacture and construction of the modular buildings to improve energy and thermal performance in use.

**Table 3.1: Data selected for collection and the reasons for selection**

| Data collected | Reason for collection |
|---|---|
| Internal temperature | • To understand the thermal behaviour of a building<br>• To calculate the occurrence of overheating |
| Relative humidity | • Primarily collected because the sensors measured temperature and humidity<br>• To understand the internal environment of a building: too dry or too humid are both unwanted |
| External temperature | • To understand the thermal behaviour of a building<br>• To calculate comfort temperatures for overheating analyses |
| Electricity consumption | • To understand how occupants use buildings<br>• To understand electric space heating use<br>• To calculate internal gains within a building |
| Window opening | • To understand how occupant use buildings, specifically occupant controlled natural ventilation<br>• To identify the occurrence of simultaneous space heating and window opening |
| Fabric air leakage rate | • To understand the thermal behaviour of the building<br>• To identify faulty design, materials or workmanship |
| Ventilation system flow rates | • To quantify ventilation rates<br>• To identify faulty design, materials or workmanship |
| Infrared thermographic images | • To investigate thermal performance of the facade<br>• To identify faulty design, materials or workmanship |
| [redacted] construction details (e.g. AutoCAD drawings, design and construction details, compliance test results<br>photos, observations, site measurements, information from informal conversations) | • To understand design, manufacture and construction of the buildings<br>• To quantify thermal performance of the fabric design<br>• To identify faults with design, manufacture and construction<br>• To understand how buildings are used by occupants and operated by managers<br>• To understand design constraints<br>• To garner any additional information that may be pertinent to the project |
| Weather conditions | • To understand the impact that weather has on the thermal behaviour of the buildings<br>• To create an EnergyPlus weather file for simulations (not presented in the thesis) |

## 3.4 Methods and Tools Overview

The data to be collected, largely dictate the method to be used, for example IR thermographic images must be taken with a thermal imaging device, and temperature must be measured with a sensor. However, it does not dictate the specific tools that should be selected, or how the method will be used in practice.

The methods deemed most suitable to for this project were:

- Building measurement and monitoring
- [redacted] construction review
- Occupant questionnaires

The methods, tools and data collected in this project are summarised in Table 3.2.

Occupant questionnaires were created, but due to dissemination problems the response rate was unsatisfactorily low and the results were excluded.

Building measurement involves the one-off measurement of a parameter in a building, and building monitoring refers to repeated measurements over time, typically at regular intervals; both require the use of measurement tools. The measurement and monitoring data collected were mostly quantitative; however some of the methods selected also produce qualitative data, such as IR thermal imaging and identification of air leakage paths from blower door tests.

A comprehensive review of the [redacted] construction was selected as a method for identifying weaknesses in design, manufacture and construction that could lead to poor energy or thermal performance in use. This involved the collection and analysis of data from many sources to provide a complete and in-depth understanding of the [redacted] construction. Data were obtained from technical design documentation, and visits to the [redacted] factory, construction sites and operational buildings. A range of methods and tools were used to extract data, which produced both qualitative and quantitative data.

**Table 3.2: Methods and tools selected for data collection**

| Method type | Tool | Data collected |
|---|---|---|
| Building monitoring | EnOcean enabled wireless sensor networks | • Internal temperature<br>• Internal relative humidity<br>• Electrical power use<br>• Electrical energy<br>• Window opening |
| Building monitoring | MadgeTech temperature loggers | • Radiator surface temperature |
| Building measurement | Minneapolis blower door test kit | • Fabric air permeability<br>• Air leakage paths |
| Building measurement | Alnor rotating vane - balometer | • Ventilation system flowrates |
| Building measurement | FLIR IR thermal camera | • IR thermal images of facade |
| External monitoring | Hobo temperature loggers | • External temperature |
| Third party weather monitoring | Met office land based weather stations [UK Met Office, 2014c and 2014d] | • Varies[1] |
| [redacted] construction review (analysis of technical details, visit to sites and factories) | Various including:<br>• AutoCAD drawings<br>• Photos<br>• Test results<br>• Design details<br>• Observations<br>• Notes and measurements<br>• Conversations | • Construction methods<br>• Construction details<br>• Material properties<br>• Calculated U-Values<br>• Design constraints<br>• Building operation details<br>• Insight into thermal comfort<br>• Measurements (e.g. degree of window opening) |

[1] *Data available varied by station, data collected included: air temperature, dew point temperature, relative humidity, air pressure, cloud cover, wind speed, wind direction, global horizontal radiation, precipitation, and snow cover (which were used to create EnergyPlus weather files for building monitoring). The research presented in this thesis used only the external temperature data from the weather stations.*

Two case study buildings were selected, the first, In Loughborough, was the main study, and second, in London, acted as a supplementary study. Details about the case study buildings, and the reasons for their selection, are given in Chapter 5. Some of the methods used and data collected differed between the case studies (Figure 3.2) because it was not possible to use the same methods in each study for a number of reasons (primarily due to differences in the buildings, resource limitations, access restrictions).

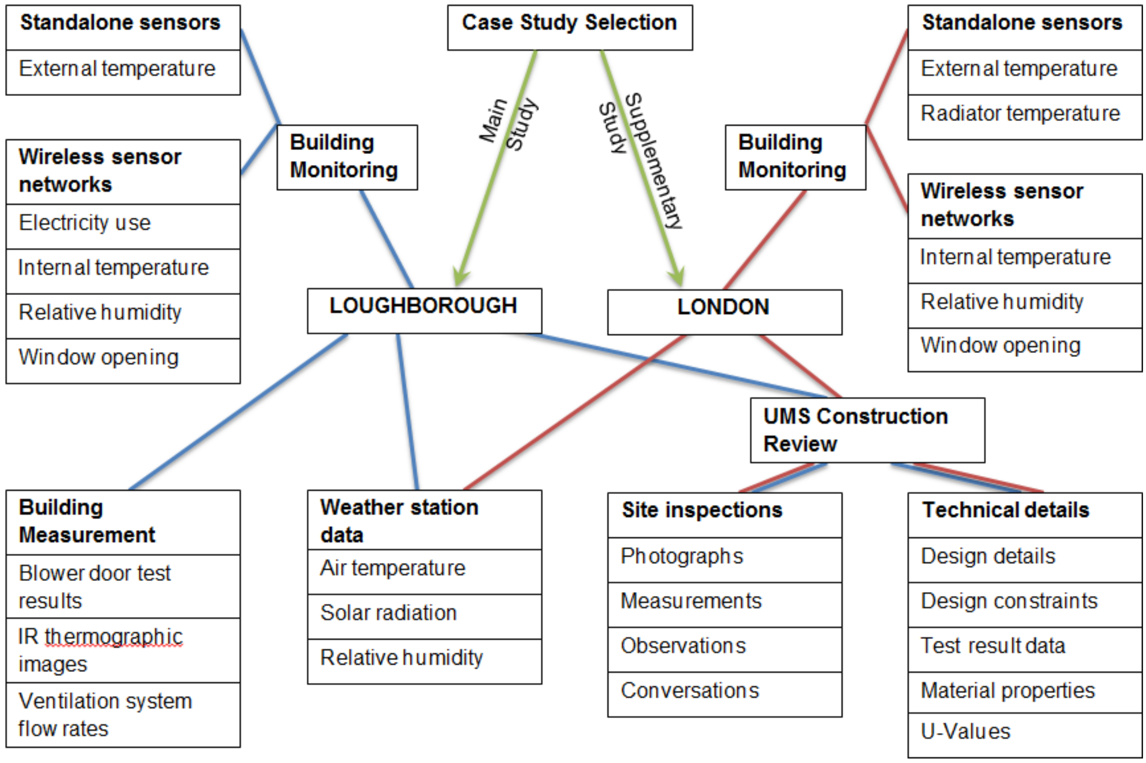



**Figure 3.2: Methods used and data collected in each case study**

## 3.5 Building Monitoring: Wireless Sensor Networks

EnOcean Enabled Wireless sensor networks (WSNs) were used in both case study buildings to monitor a number of parameters over a period of months, (Table 3.3).

**Table 3.3: Data in each case study using wireless sensor networks**

| **Loughborough case study**<br>5th March to 28th June 2013 | **London case study**<br>8th March to 25th September 2013 |
|---|---|
| Internal air temperature | Internal air temperature |
| Internal air relative humidity | Internal air relative humidity |
| Window opening[1] | Window opening[1] |
| Instantaneous electricity consumption | |
| Total electricity consumption | |
| [1] *There were uncertainties over the accuracy of the window opening data, therefore the window data were removed from most analyses.* | |

### 3.5.1 Equipment

The EnOcean technology is particularly attractive because equipment is interoperable between manufacturers so there is a large range of equipment, and most sensors harvest their own energy so do not require regular battery changes.

The reasons for choosing EnOcean WSNs and some technical details about the technology are given in Appendix A.

To setup an EnOcean WSN, the following types of equipment had to be sourced, purchased and installed:

- Network controller
- Sensors
- Repeaters

The most important aspect of equipment selection was specification of the controller, due to large variations in functionality from different manufacturers. Selection of sensors and repeaters was less crucial because their technical specifications are essentially fixed, and do not vary between manufacturers (Appendix A). Various controller options were considered, and three were tested before the final specification was made. The equipment selected is outlined in Table 3.4.

**Table 3.4: EnOcean equipment purchased by type and manufacturer [EnOcean Alliance, 2014]**

| **Equipment description** | **Manufacturer** |
|---|---|
| Can2Go universal controller | SCL Elements (now owned by Schneider Electrics and rebranded as SmartStruxture Lite) |
| Repeaters | BootUp |
| Temperature and relative humidity sensors | Smart buildings Ltd (now Ecologix Controls Ltd.) |
| Window contacts sensors | Eltako and Peha |
| Electricity meters | Eltako |

### *Can2Go Universal Controller*

The Can2Go controller (Figure 3.3) was selected because of its supposed superiority over the typical generic controller offered by most manufacturers. It does not require a computer to operate, it has no software, it does not require a license, it does not restrict access to sensor data and it offers full interoperability.

**Figure 3.3: Can2Go Universal Controller [EnOcean Alliance, 2014]**

It is powered directly from the mains electricity and can be used on its own to collect data from sensors in the network.

The controller has no software; rather it contains an embedded web server. The server can be accessed with a web browser, either directly by connecting the controller to a computer, or remotely over the internet by connecting it to a Local Area Network (LAN). The benefit of this setup is that the controller can be accessed remotely over the internet at any time using any device by any person with login credentials.

The controller uses coded scripts, written in the Lua programming language, to communicate with equipment in the sensor network, such as to collect data from sensors and send commands to actuators. The controller is truly interoperable (unlike those from many other manufacturers) and can receive all the data transmitted by all EnOcean equipment.

A further benefit of the Can2Go controller is that multiple controllers can be used together to create large networks, controllers can communicate using ZigBee, CANbus or Ethernet protocols, allowing networks ranges far beyond what is practical using only the EnOcean protocol. The controllers can also be integrated into standard building management systems.

The main drawback to using the Can2Go controller is the expertise required. It offers far greater functionality than perhaps any other EnOcean controller, but it requires significantly more skills to operate. Its operation is not intuitive, and it requires knowledge of Lua programming, computer networking, the EnOcean communication protocol and EnOcean Equipment Profiles. These skills are not required for most EnOcean controllers. The Can2Go controller was only selected because no other option within budget offered the required functionality (namely interoperability and full access to the data).

### *Temperature and Humidity Sensors*

The EnOcean temperature and relative humidity sensors were small and simple in design, and cheap in cost and construction, (Figure 3.4 and Table 3.5).

Various tests were conducted to calculate the accuracy of the temperature measurements, which determined the sensors were correctly calibrated and performed within the stated accuracy. The accuracy of the humidity measurements was not tested.

**Figure 3.4: EnOcean temperature and humidity sensor [EnOcean Alliance, 2014]**

Once the solar cell is charged sufficiently to operate, the sensor begins functioning, measuring the temperature and humidity and transmitting the data wirelessly. There is no way to control the sensor, to start it or stop it; when it has power it automatically works, and when the charge is depleted it stops.

The temperature and humidity sensors were fixed to wardrobes and doors in the Loughborough case study and to cork boards in the London case study. The temperature sensor is located within a plastic housing which is fixed to a surface, therefore it will not be a true measurement of air temperature, and will include a radiant component. EnergyPlus simulations were undertaken on a calibrated model of the Loughborough case study building which predicted small differences between operative, air and radiative temperatures, typically 0.5°C or less (less than the accuracy of the sensors). Therefore, it was deemed insignificant that the sensors measured a combination of air and radiative temperatures.

**Table 3.5: Technical specifications: EnOcean temperature and humidity sensors [EnOcean Alliance, 2014]**

| **Parameter** | **Specification** |
|---|---|
| Dimensions (h*w*d) | 32mm*53mm*9mm |
| Measured parameters | Temperature and Relative Humidity |
| Measurement range | Temperature: 0°C – 40°C; Humidity: 0% – 100% |
| Measurement accuracy | Temperature: ±0.5°C; Humidity: ±5% |
| Measurement resolution | Temperature: 0.157°C; Humidity: 0.392% |
| Charge time | Bright light for approximately 5 hours |
| Charge duration | Approximately 4 days from full charge |
| Light level required to maintain charge | Daily average of 200lux |
| Transmission type | Bi-stable: when temperature change > 0.3°C or 1000 seconds has passed since last transmission |
| Maximum transmission frequency | 100 seconds |
| EnOcean Equipment Profile (EEP) | A5-04-01 |

### *Window Contact Sensors*

Contacts were purchased from two manufacturers, (Figure 3.5), Eltako contacts were used in the Loughborough study, and Peha contacts in the London study. The technical specifications are identical, the only difference is the sensor housing and dimensions, (Table 3.6). The contacts sensors have two parts, the sensor and the magnet. One part is fixed to the frame and the other to the window or door. When the two parts are brought together or separated the sensor is triggered and a wireless telegram is transmitted.

**Figure 3.5: Peha contact left and Eltako contact right [EnOcean Alliance, 2014]**

They begin to work automatically once the solar charge is sufficient, and cannot be stopped or started by the user. The contacts are essentially binary devices with only two states, giving them a low power consumption compared to analogue sensors such as the temperature and humidity sensors.

**Table 3.6: Technical specifications of Eltako and Peha EnOcean contact sensors [EnOcean Alliance, 2014]**

| **Parameter** | **Eltako specification** | **Peha specification** |
|---|---|---|
| Dimensions (h*w*d)<br>• Sensor<br>• Magnet | <br>75mm*26mm*12mm<br>23mm*14mm*6mm | <br>110mm*19mm*15mm<br>23mm*14mm*6mm |
| Measured Parameters | Window or door opening | Window or door opening |
| Measurement range | Open or closed | Open or closed |
| Measurement accuracy | N/A | N/A |
| Charge time | Bright light for approximately 10 minutes | Several hours in daylight (to reach full charge) |
| Charge duration | A number of days | A number of days |
| Light level required to maintain charge | Low (no specific details) | Low (no specific details) |
| Transmission type | Bi-stable: Triggered if there is a state change or if 1000 seconds has passed since last transmission | Bi-stable: Triggered if there is a state change or if 1000 seconds has passed since last transmission |
| Maximum transmission frequency | Transmits upon a change of state | Transmits upon a change of state |
| EEP | D5-00-01 | D5-00-01 |

### *Electricity Meters*

Inline electricity meters were used (Figure 3.6 and Table 3.7), which meant the metered electricity supply had to be wired through the meter. An electrician was required to install and removed the meters. They are DIN rail mountable, allowing for easy installation into distribution boards and consumer units in buildings. They have a CE marking, which meant they were safe to install. They are not powered through energy harvesting; instead they use the mains supply to which they are connected.

**Figure 3.6: Eltako electricity meters [EnOcean Alliance, 2014]**

Two ratings were purchased: 16A and 65A, but some higher rated meters (of at least 100A), would have been useful for this project. Attempts were made to source higher rated meters, however there were problems procuring them within a suitable timeframe.

The researcher tested all meters in the laboratory, for safety purposes a laboratory electrical technician was required to wire the meters into a test rig so testing could be done. The first stage of testing was to determine how to decode the wireless data from the meters, because there was initially some uncertainty about how to do this due to the minimal information provided by the manufacturer. The second stage of testing was to determine if the meters were accurate by using a range of household appliances and comparing the loads measured by the meters to those measured by a calibrated meter. Functioning meters were found to operate within their stated accuracy. Three meters were found to be faulty, while they were physically safe to install, they did not transmit wireless data correctly, only sending it sporadically.

The meters automatically begin working when they receive power, there is no way to control the operation, they function when they have power and stop when they do not. The meters transmit electrical power and energy consumption data.

**Table 3.7: Technical specifications of Eltako EnOcean electricity meters [EnOcean Alliance, 2014]**

| **Parameter** | **Specification** |
|---|---|
| Dimensions (h*w*d)) | 80mm*18mm*58mm<br>(DIN EN 60715 TH35 rail mounting) |
| Measured parameters | Instantaneous electricity consumption (W)<br>Total electricity consumption (kWh) |
| Measurement range | 16A Meter: 0kW – 5.28kW<br>65A Meter: 0kW – 21.48kW |
| Measurement resolution | Instantaneous electricity consumption: 1W<br>Total electricity consumption: 0.1kWh |
| Measurement accuracy | 1% |
| Power consumption | 0.5W |
| Transmission type | Bi-stable: Triggered if there is a change of more than 10% or if 10 minutes has passed |
| Maximum transmission frequency | 20 seconds |
| EEP | A5-12-01 |

### *Repeaters*

Repeaters from BootUp (Figure 3.7 and Table 3.8) were selected because they could be supplied with a USB power cable and therefore could be easily connected to the mains power supply with a USB plug. Most repeaters need to be hardwired into a building's electricity supply, which is logical for a permanent installation, but was not ideal for this project where equipment was only installed for months.

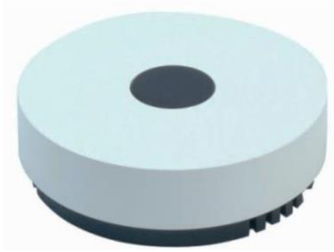


**Figure 3.7: BootUp repeater [EnOcean Alliance, 2014]**

The repeaters have a switch at the back to choose whether they operate in level 1 or level 2 mode. In level 1 mode repeaters only repeat data directly from sensors actuators and controllers. In Level 2 mode repeaters also repeat data from other repeaters.

The repeaters work seamlessly with the other equipment, the controller treats data received from repeaters as though they have been received directly from the sensors, there is no need to decode data from repeaters separately or differently from the sensors.

**Table 3.8: Technical specficiations of BootUp EnOcean repeater [EnOcean Alliance, 2014]**

| **Parameter** | **Specification** |
|---|---|
| Dimensions (ø*d) | 93mm*29mm |
| Measured parameters | Repeats data in Level 1or 2 mode |
| Measurement range | N/A |
| Measurement accuracy | N/A |
| Power consumption | 3.5W |
| Transmission type | Repeats all data based on the level setting |
| Maximum transmission frequency | N/A |
| EEP | N/A |

## 3.5.2 Monitoring Preparation

Before the WSNs could be installed in the case study buildings several initial stages had to be completed. The building owner and landlord, [redacted] had to agree to the planned installation. The building monitoring required sensors to be fitted within bedrooms, and for data to be collected over a period of months. This could only be done with the occupants' permission and cooperation; therefore participants were required for the monitoring aspects of the case studies. Securing participants involved numerous stages including planning an ethical study, highlighting target participants, making contact with occupants, data protection, and securing a final agreement for participant involvement, all of which are discussed in Appendix B.

On a technical level, many decisions had to be made before the monitoring could begin including: selecting suitable equipment, testing equipment, conducting a pilot study, planning the installation, arranging permission, and sourcing an electrician. Safety was of the upmost importance, and required special attention for the electricity monitoring because it involved modifications to the electrical services. The technical preparations for the building monitoring are discussed in Appendix C.

Once the volunteers were arranged and equipment tested, the installation date was arranged and the equipment prepared for each case study. The solar powered sensors were charged in bright light in the days leading up the case studies. The controllers were setup with the correct network settings, to access to the internet via the LAN in the case study building. Sensor ID numbers were input into the controller, to identify each sensor in the case study. Lua scripts (see Appendix D) were written in the controller to obtain data from each sensor and to write that data temporarily into unique locations for each measurement. Log functions were setup in the controller to extract data from these unique locations, different log frequencies were chosen for different types of sensors:

- Temperature: every 5 minutes
- Relative humidity: every 10 minutes
- Window state: every 2 minutes
- Instantaneous electricity consumption: every 60 seconds for most meters, and every 30 seconds for meters measuring kitchen electricity consumption
- Total electricity consumption: every 30 minutes

It was not possible to only log data when new data were received because the Lua code that extracted the sensor data and the log functions that saved the sensor data operated separately within the controller, and no way was found to link them. The bi-stable operation of the EnOcean sensors (Appendix A) meant that it was not possible to predict when new data would be received, because data were often transmitted based on a change of state and not a fixed time interval. In contrast, the logging function within the controller was only capable of logging at fixed intervals. Therefore, logging could not be made to occur only when sensor data had been received and it was necessary to log more frequently than data were likely to be received from the sensors to avoid missing data. This was not ideal and there are likely to have been times when data were lost. Perhaps there is a way to log data as it was received from the EnOcean sensors, but at the time there was limited publicly available documentation on how to operate the controller or write Can2Go specific syntax in the Lua language, making it difficult to determine any other method for logging.

### 3.5.3 Equipment Installation

On the day of installation, the controller was setup first, by connecting it to the mains power supply and the correct LAN Ethernet socket. The sensors and repeaters were then installed. An electrician installed the electricity meters according to the agreed method statement.

Window contacts, temperature and humidity sensors, and repeaters were fixed using double sided adhesive foam tape. The window contacts were fitted to window frames (aluminium and UPVC), and the temperature and humidity sensors were fixed to wardrobes and doors in the Loughborough case study and cork boards in the London case study. These locations were chosen to facilitate removal and avoid damaging painted walls. Repeaters were stuck to false ceilings and door frames in the Loughborough study, and in internal cupboards in the London study. Care was taken to fix repeater wires to walls with masking tape so they could not be caught or tripped over.

### 3.5.4 Equipment Performance

Remote access to controllers allowed the performance of the WSNs to be observed. In both studies there were network problems remote access allowed this to be identified and efforts to be made to resolve the problems by moving controllers and repeaters. The problems encountered and their impact on analysis are discussed in Appendix E, reflections about the suitability of the monitoring method are discussed in chapter 10.5.

### 3.5.5 Advantages and Disadvantages

***Advantages***

- Remote access provides instant access to data and details about network performance, which saves trips to buildings to check performance and download data
- Continuous access to data allows problems to be identified during the study, allowing them to be rectified during the study, rather than afterwards when it is too late
- Storing data centrally in the controller means data are not lost if sensors are lost
- Not needing batteries means visits are not needed to check battery level and change those depleted, this also helps to minimise disruption to occupants
- Equipment is interoperable, which means there are hundreds of sensors to choose from, and a large number of repeaters and controllers
- The equipment is cheaper than many standalone sensors and other wireless networks, particularly for electricity monitoring
- The quantity of data that can be logged is not restricted by sensor logging capacities, which are often prohibitively small

***Disadvantages***

- WSNs are subject to interference and shielding which can result in loss of data
- It is difficult to anticipate or predict the occurrence of interference or shielding
- The energy harvesting sensors can become depleted in certain circumstances
- The technology is relatively new and complex to fully understand, this project required decoding of EnOcean telegrams and writing code in the Lua programming language, which required far more work than standalone sensor options
- The bi-stable nature of the sensors' data transmissions combined with the looping of code in the Can2Go controller meant that no two data readings had the same time stamp, which required significant pre-processing before data analysis could begin

## 3.6 Building Monitoring: Radiator Surface Temperature

Temperature sensors were fitted to radiators in student bedrooms in the London study to infer space heating patterns. Tests showed that space heating patterns could be determined from a temperature sensor fitted to a radiator, and could give some indication of the radiator setting (e.g. high or low TRV settings), however it could not be used to quantify the actual radiator temperature or the energy used. Ideally space heating use would have been monitored more accurately, but it was difficult because the wet heating system was not sub-metered anywhere in the building, there was restricted access to the occupied spaces, and time and budget limitations did not allow for more sophisticated approaches.

### 3.6.1 Equipment

MadgeTech Temp101A standalone temperature loggers were used, (Figure 3.8 and Table 3.9). The EnOcean temperature sensors did not measure high enough temperatures, so were not suitable. The MadgeTech sensors were chosen because they had a large logging capacity, long battery life, were flat so could be fitted easily to radiators, and were within budget.


**Figure 3.8: MadgeTech Temp101A temperature sensor [MadgeTech, 2014]**

A number of sensors were tested using a laboratory water bath, and were found to be properly calibrated and performed well within the stated accuracy. Further tests were conducted using all temperature sensors (including the EnOcean sensors), which found they all compared very well, with little variation between the readings at any time.

To launch sensors or download data, each sensor has to be individually connected to the software on a computer via a USB adapter.

**Table 3.9: Technical specifications of MadgeTech 101A temperature sensors [MadgeTech, 2014]**

| Parameter | Specification |
|---|---|
| Dimensions (h*w*d) | 36mm*56mm*16mm |
| Measured parameters | Temperature |
| Measurement range | -40°C to 80°C |
| Measurement accuracy | ±0.5°C |
| Measurement resolution | 0.01°C |
| Memory | 1 million readings |
| Battery life | 10 years at 15 minute logging frequency |

### 3.6.2 Operation

All sensors were set to launch at the same time and log every two minutes, to facilitate data comparison. Prior to installation it was not clear what the most suitable logging frequency should be, therefore a high logging frequency was selected. Double sided adhesive heat conducting tape, was used to fix the sensors to radiators. This tape is designed for fixing heat sinks to CPUs in computing, and was selected for its good heat conduction and adhesive properties. Each sensor was fitted to the internal face of a radiator, so it was out of the way and less likely to be knocked off. They were fitted in the middle at the bottom of the radiator because radiators heated up from bottom to top, so the bottom would change temperature quicker than the top.

As with the building monitoring using WSNs, the monitoring of radiator temperature was done in occupied rooms, therefore this required participation from volunteers (Appendix B).

### 3.6.3 Advantages and Disadvantages

***Advantages:***

- Cheap
- Easy to use
- Accurate
- Long battery life
- Large logging capacity
- Sensor shape made them easy to fix to radiators

***Disadvantages:***

- No remote access to the data, if sensors go missing the data would be lost
- No remote access so if a sensor develops a fault there is no way of knowing, and data would be lost

## 3.7 Building Monitoring: External Temperature

The external temperature was monitored on site during both case studies.

### 3.7.1 Equipment

Onset Hobo Pendant temperature loggers were used (Figure 3.9 and Table 3.10). The accuracy of the loggers was tested, only those that performed within their stated accuracy and compared well to the MadgeTech sensors (which had been tested in the laboratory water bath) were used. To launch sensors or download data, each sensor has to be individually connected to the software on a computer via a USB adapter.


**Figure 3.9: Hobo Pendant Logger [Onset, 2014]**

**Table 3.10: Onset Hobo Pendant Temperature Logger Technical Specifications [Onset, 2014]**

| **Parameter** | **Specification** |
|---|---|
| Dimensions (h*w*d) | 58mm*33mm*23mm |
| Measurement range | -20°C to 70°C |
| Measurement accuracy | ±0.53°C between 0°C and 50°C |
| Measurement resolution | 0.14°C at 25°C |
| Memory | 6500 readings |
| Sample rate | 1 second to 18 hours |
| Battery life | 1 year typical |

### 3.7.2 Operation

Two sensors were used at each case study site, in case one sensor developed a fault or ran out of power. A suitable location had to be found to fix the sensors, a place that was shaded from the solar radiation or other sources of heat, but not overly shaded by adjacent objects from air flow. The sensors were set to log every 15 minutes.

### 3.7.3 Advantages and Disadvantages

***Advantages:***

- Waterproof, so suitable for external temperature measurement
- Cheap
- Easy to use
- Sensor housing makes it easy to hang the sensor from objects

***Disadvantages:***

- No remote access to the data, if sensors go missing the data would be lost

- No remote access so if a sensor develops a fault there is no way of knowing until data are downloaded
- Logging capacity is low

## 3.8 Building Measurement: Ventilation System Flow Measurements

The volumetric flowrate in ventilation systems was measured in a number of student flats in the Loughborough case study.

### 3.8.1 Equipment

An Alnor Rotating Vane RVA501 was used to take the flowrate measurements.

It is a simple tool comprising a handheld rotating vane wired to a handheld computer (see Figure 3.10, and Table 3.11).

The equipment was subject to regular testing to ensure calibration, so accuracy could be relied upon.

**Figure 3.10: Alnor rotating vane RVA501 [TSI Alnor, 2014]**

**Table 3.11: Alnor rotating vane RVA501 technical specifications [TSI Alnor, 2015]**

| Parameter | Specification |
|---|---|
| Velocity range | 0.25m/s to 30m/s |
| Velocity accuracy | ±1% of reading ±0.02m/s |
| Duct size | $0m^2$ to $46.45m^2$ |
| Volumetric flowrate range | Varies as a function of velocity and duct area |
| Temperature range | 0°C to 60°C |
| Temperature accuracy | ±0.5°C |
| Temperature resolution | 0.1°C |

### 3.8.2 Operation

The rotating vane is quick and easy to operate.  The only data inputs are the shape and dimensions of the ventilation duct measured.  The vane also measures temperature which it uses to determine volumetric flowrate.  The measurements are taken by holding the vane close to and in line with the duct.  The vane will begin to rotate due to the airflow that is drawn across it due to airflow through the duct, the computer measures the speed of the vane and air temperature to provide a measurement for volumetric airflow.

A flow hood can be fitted to the vane to make the measurements easier, quicker and less prone to error.  However, the hoods could not be used for the majority of measurements in this project due to obstructions and restrictions near many ducts.

### 3.8.3 Advantages & Disadvantages

***Advantages:***

- Easy to use
- Small and portable
- Readily available

***Disadvantages:***

- The hoods cannot be used in all locations, where fans are too close to adjacent surfaces or other obstructions
- Measurements without the hoods are more time consuming, and can be more prone to error if due care is not taken
- The length of wire made it difficult to take measurements with the telescopic handle fully extended
- Hoods did not secure adequately to the vane and had a tendency to fall off

## 3.9 Building Measurement: Blower Door Tests

Blower door tests were conducted in a number of student flats in the Loughborough case study to measure building air permeability and locate air leakage sights.

### 3.9.1 Equipment

The Minneapolis Blower Door Model 3 was used to take the measurements (see Figure 3.11) [The Energy Conservatory, 2014].  The equipment comprises the following components:

- Fan
- Test instrumentation
- Fan speed controller
- Aluminium door frame
- Nylon door panel
- TECTITE software

**Figure 3.11: Minneapolis blower door model 3 during testing**

### 3.9.2 Operation

The tests were conducted using the standard method outlined in British Standard "*BS EN 13829:2001 Thermal performance of buildings. Determination of air permeability of buildings. Fan pressurization method*" [British Standards Institution, 2001].

All tests were conducted under depressurisation. Individual student flats were tested, and treated as single zone buildings by making adjustments to the adjacent flats (zones) to normalise pressure (blower door test setup and results are detailed in Chapter 7.1).

Tests were conducted using both Test Method A (test of the building in use) and Test Method B (test of the building fabric). Test Method B is the same as Test Method A with the added step of sealing ventilation ducting in the test flats.

### 3.9.3 Advantages and Disadvantages

***Advantages:***

- The equipment and measurement method are standard, and widely used today, so there is a wealth of information available about how best to undertake tests
- The equipment was readily available to use
- The test provides data that cannot be obtained by another means
- The test is useful for locating design and construction problems, such as gaps in fabric

***Disadvantages:***

- The equipment is large, heavy and difficult for one person to move
- The tests are disruptive to any occupants
- Running multiple tests can take a long time
- Weather conditions can impact the accuracy of the tests (primarily wind speed, but also temperature and atmospheric pressure), it is necessary to be aware of this and conduct tests when the conditions are suitable
- Due to the large number of parameters required to calculate air leakage rates, and the uncertainties inherent in each of these, it means that the uncertainty in the final result is variable and large (less than ±15% in calm conditions to more than ±40% in windy conditions [British Standards Institution, 2001]
- Testing one zone in a multi-zone building creates problems with interpretation of data as air leakage may come from adjacent zones as well as the external facade

## 3.10 Building Measurement: Infrared Thermal Imaging

An infrared thermal camera was used to take thermographic images of the external facade of the Loughborough case study building in winter. It was not possible to take thermal images internally at the same time because the building was occupied and access was not permitted; some limited images were taken inside when the building was vacant in summer.

### 3.10.1 Equipment

The images were taken using a FLIR T640bx camera with a standard lens, (see Figure 3.12 and Table 3.12).

**Figure 3.12: FLIR camera: T640bx [FLIR, 2014]**

**Table 3.12: FLIR camera T640bx technical specifications [FLIR, 2014]**

| **Parameter** | **Specification** |
|---|---|
| Accuracy | ±2°C or ±2% of reading, whichever is greater, at 25°C nominal |
| Thermal Resolution | 307,200 (640 × 480) |
| Thermal Sensitivity | <0.03°C @ 30°C |
| Temperature Range | -40°C to 2,000°C |
| Measurement Pre-sets | 6 pre-sets: centre spot; hot spot (box max); cold spot (box min); no measurements; user pre-set 1; user pre-set 2 |
| Min. Focus Distance | 0.25 m |
| Battery Operating Time | >2.5 hours |
| Built-in Digital Camera | 5 MP |
| Digital Zoom | 2×, 4× and 8× |
| Weight (including battery) | 1.3 kg |

### 3.10.2 Operation

The imaging was done on cold, dry, overcast winter days, early in the morning shortly after sunrise. The time of year ensures there is a large temperature difference between inside and outside which maximises heat losses, making them easier to observe in the thermal images. The weather was dry because rain wets the facade, interfering with the ability to assess the fabric performance, due to uneven wetness, absorption and evaporation of water on the facade. The weather was overcast and the time of day early to avoid any thermal effects of solar radiation on the facade, which also negatively affects the images taken.

The camera was straightforward to setup and operate. The following inputs were required:

- Temperature of the atmosphere
- Relative humidity
- Emissivity of the surface
- Distance between the camera and surface
- The reflected apparent temperature of the surface

The reflected apparent temperature was uncertain, and the process required to estimate it was not undertaken. The reflected temperature (IR radiation) could have originated from the cold sky at dawn, from adjacent objects such as buildings, people and foliage, or from the ground, all of which have different temperatures. It is also likely that different parts of the building would reflect IR radiation from different sources, (such as the top floor would likely reflect the sky temperature and the ground floor would reflect adjacent objects or the ground), which means there is not one correct value for the reflected apparent temperature. The inability to quantifying the apparent reflected temperature with certainty means that the analysis of thermographic images must be qualitative in nature, rather than quantitative. It was possible to analyse temperature differences but not absolute temperatures.

### 3.10.3 Advantages and Disadvantages

***Advantages:***

- Simple and non-destructive technique
- Equipment was readily available to use
- Provides visualisation of heat transfer and heat distribution through a building's fabric, for which there is no other method

***Disadvantages:***

- Interpretation of the images requires skill and results can be confused
- The images are best taken under certain conditions, and avoided in other conditions, so the imaging must be planned around the weather and time of day

## 3.11 Analysis of [redacted] Modular Design

The manufacturer provided access to their factory, construction sites, buildings in use, and a wealth of design documentation. Access to this level of detail is not always available when researching buildings in operation, and it provided the opportunity to gain in-depth knowledge of the buildings.

Three methods were used:

- Observation: through visits to the factory and sites (construction and completed buildings in use)
- Document analysis: through access to detailed design and construction documentation
- Visual analysis: through access to photos and AutoCAD drawings

Information was also obtained through informal conversations with various parties, although these conversations were not planned or arranged as a method, but still provided useful insight in some instances.

### 3.11.1 Equipment

The main tools used when visiting the factory or sites were a camera and a notepad and pen. A camera allowed visual documentation of processes, and notes were used to record any interesting information uncovered during the visits, such as from observation or discussions with factory or site personnel.

The equipment used for the analysis of documents and photographs varied. AutoCAD files, PDF files and photographs were the main sources of technical data. Some data were easy to understand, and required no analysis, and simply needed to be read and noted. Other data were more technical, and required detailed knowledge of the design to understand the information presented. The technical details were analysed and the information collated to create a full understanding of the modules and modular buildings.

### 3.11.2 Operation

Documentation was obtained from [redacted] early in the project. Initially the design and installation manuals were examined, which detailed module dimensions and materials, test results, and the construction of modules on site. Individual project files were later examined, initially to help select case study buildings, and then to better understand the case studies. The documentation was used again in the later stages of the project to better understand and explain the data collected by other methods, such as the IR thermographic images and the blower door test results.

The factory was visited on two occasions. On both occasions a tour was given, and the manufacturing processes in each area of the factory were explained in detail. On the second visit, access was allowed to the factory to work alone and observe and record the various stages of manufacture, as deemed fit.

One construction site was visited. A [redacted] employee provided a tour which covered each stage in the construction process.

Three buildings in use were visited; two were the case study buildings. Initially, visits to buildings involved an informal tour, providing access to student flats, and plant and boiler rooms, to observe the design of the building and its operation. Upon commencement of the case studies, unaccompanied access was often allowed to the buildings, or parts of the buildings. Visits to buildings allowed additional information to be obtained, much of which was qualitative such as the quality of the construction or the operation of building services. Quantitate data were also collected, such as the extent of window opening, and the electrical rating of services and appliances, such as light bulbs and ventilation systems.

### 3.11.3 Advantages and Disadvantages

***Advantages:***

- Provides the opportunity for in-depth understanding of the design, manufacture and construction of [redacted] buildings
- Design documentation provides details that cannot be obtained easily from visiting or measuring existing buildings, which aids in-depth understanding
- Access to sites makes it easier to decipher the design documentation, through first-hand experience of each stage, which aides in-depth understanding

***Disadvantages:***

- The quantity of design documentation was large, making it impossible to look at it all
- Data quality was at times a problem, with contradictions between different documents, this created uncertainty, and a lack of confidence in some details
- Some of the documentation required specialist knowledge to understand, such as structural integrity and fire safety tests
- The interpretation of the data could be subjective, and the data and sites selected for analysis could be subject to personal bias
- The observations may be project or site specific, so are not necessarily universally applicable

### 3.12: Chapter Summary

This chapter has outlined the methodology and methods adopted during this research, and the reasons for choosing them. It detailed how a critical realist methodology was chosen; influenced by the research aims and objectives, the findings from the literature review, the collaboration with the sponsor, and the philosophical views on reality and knowledge. It explained how the critical realist methodology led to the decision to use case studies for data collection, because the facets of case study research aligned well with those of critical realism. It presented the numerous data collection methods selected including: electricity monitoring, internal temperature and humidity monitoring, IR thermal imaging, blower door tests, ventilation system flowrate measurements, review of design documents and photograph analysis. It explained how each method was used, the data collected from them, and any advantages and disadvantages associated with their use. The methods chosen yielded a mixture of qualitative and quantitative data, where the aim was to gain in-depth understanding of the thermal and energy performance of the case study buildings, to understand how the buildings perform and why they perform as they do.

# Chapter 4 – [redacted] Construction

This research concerns light gauge steel modular construction manufactured by [redacted]. This chapter outlines the design and fabrication of [redacted] modules and their incorporation into buildings. It discusses [redacted] as a company, their motivations for undertaking research, how they operated, their relationship with [redacted] (their main client and owner), and their financial problems that resulted in their sale. It was vital to understand how the buildings were designed and constructed in order to identify weaknesses in design and construction which can lead to underperformance, to effectively analyse and interpret data, and to ensure suggested design changes are suitable for [redacted] construction.

## 4.1 [redacted]

[redacted] was a manufacturer of light gauge steel modular construction. They were setup in 2002 [redacted]. [redacted] constructed approximately 40 student halls of residences with [redacted] (Figures 4.1 and 4.2). [redacted] also worked on a small number of other projects, providing modules for other halls and hotels; however their main client was [redacted]

[redacted] made significant losses in [redacted], and in [redacted] sold them to [redacted] [[redacted]], but [redacted] entered administration within months. [redacted]

Before [redacted] were sold they recognised the need to diversify, and were keen to branch into a new market, the low energy housing market. However, to achieve this, the energy performance of their buildings would have to improve significantly. They would have to move away from a product that typically only aimed to comply with the energy and thermal performance standards required by the Building Regulations, towards a product that aimed to meet the highest standards, such as the Code for Sustainable Homes for new domestic buildings [BREEAM, 2015]. This research was undertaken to investigate how [redacted] could change their product to provide low energy, comfortable homes. The main focus was on technical changes to the product that could improve energy and thermal performance.

[redacted] were sold after the research had begun, after the methods and case studies had been selected, and the first orders had been placed for monitoring equipment. Therefore, it was too late to make significant changes to the research plan. The sale of [redacted] impacted on the research as it removed access to the factory and to [redacted] expertise and data, which would have been beneficial during data analysis and the formulation of recommendations. It increased the workload (because extra time was spent trying to answer certain questions that could have been answered quickly by [redacted] it created uncertainties (because many questions could not be answered with certainty without input from [redacted] and it limited the extent to which the recommendations could be completely tailored to the [redacted] design (because input from [redacted] would have been required in the latter stages to achieve this).

While there was no longer the opportunity to be involved in making direct improvements to the [redacted] design, the literature review revealed a lack of data about the energy and thermal performance of modular construction in use, and this research can still be used to provide data about the performance of modular buildings. While this research only considered the [redacted] product, the findings could be relevant to other manufacturers of modular construction and steel construction, if they share similarities.


**Figure 4.1 (left): [redacted] building during construction [[redacted] 2012]**
**Figure 4.2 (right): The same [redacted] building after construction [[redacted] 2012]**

## 4.2 [redacted] Modular Design

The [redacted] design featured components from all four categories of offsite construction, [Goodier and Gibb, 2007]:

- Volumetric units that form the structure of the building: **Modular rooms**
- Volumetric units that do not form the structure of the building: **Shower pods**
- Non-volumetric units: **Corridor cassettes and panels**
- Component sub-assemblies: **Light fittings, windows, etc.**

Modular rooms, corridor cassettes and corridor panels were manufactured by [redacted] in their factory in [redacted], (Figures 4.3 and 4.4). The shower pods and sub-assemblies were purchased from other manufacturers and fitted into modules by [redacted]

The modules and corridor components formed the main structure of a building and could be used alone to construct fully modular buildings, or in combination with other construction methods, such as structural steel.

**Figure 4.3 (left): [redacted] factory floor, showing panel framing machine**
**Figure 4.4 (right): [redacted] factory floor, showing module near completion**

## 4.3 Modular Room Design

In student halls of residences, modules were used for bedrooms, kitchens and studio flats. They were four sided volumetric units, constructed from four wall panels, one floor panel and one ceiling panel (Figure 4.5). Modules were produced in a range of sizes, which varied between projects; the maximum dimensions were limited by the size that could be transported by lorry. Modules could not be used to create large open-plan spaces, because each module required four wall panels.

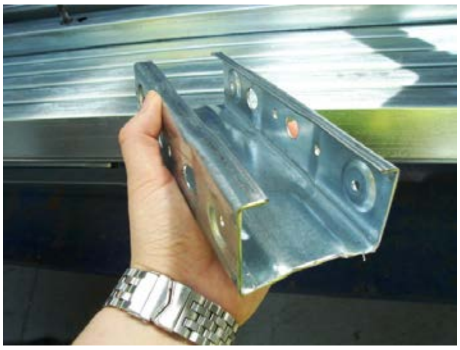
**Figure 4.5: [redacted] factory floor, showing four-sided module during manufacture [[redacted] 2012]**

Modules could be opened partially to adjacent modules through the use of large archways, as was the case with studio flats. The modules were fully fitted in the factory, with mechanical and electrical services, flooring, paintwork, furniture, appliances and shower pods (Figures 4.6 and 4.7), which meant typically no work was required within the modules on site. The specification of the final fit out varied based on the project requirements.

**Figure 4.6 (left): Fully fitted bedroom module, showing curved shower pod wall [[redacted] 2015]**
**Figure 4.7 (right): Fully fitted kitchen module**

### 4.3.1 Module Structure

Structurally the modules panels comprised light gauge galvanised steel. The steel was cold-formed into C-sections (Figure 4.8), 75mm thick for wall and ceiling panels, and a 150mm thick for floor panels (Figure 4.9).



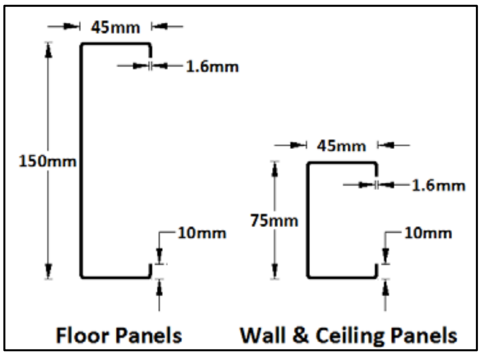



**Figure 4.8 (left): Small steel C-section for wall panel**

**Figure 4.9 (right): Steel C-section dimensions**

The steel C-sections were riveted together to form a frame (Figure 4.9), which then had various layers of boarding and insulation fitted to them to form the panels, (Figure 4.10). The arrangement of steel in the frames, and the layers of boarding and insulation fitted to them varied based on type of panel and the height of the modular construction.

There were two module designs, based on the height of the building:

- a low-rise design for buildings up to 18 metres tall, and
- a medium-rise design for buildings between 18 metres and 30 metres tall.

The medium-rise design used different and additional materials and features to resist the increased lateral loads experienced at increased height, and to improve the fire rating of the structure (as required at increased height).

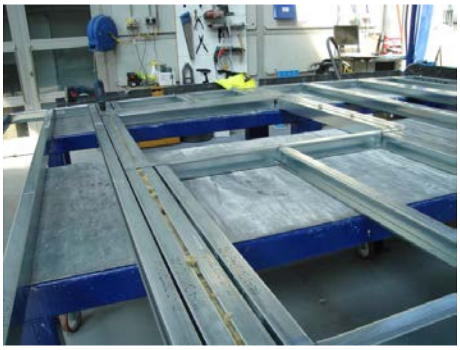


**Figure 4.10 (left): Steel frame for a wall panel with a window**

**Figure 4.11 (right): Steel frame floor panel with rigid insulation nailed to the underside**

### 4.3.2 Module Testing

The modules and their design were subjected to a range of tests conducted by third parties, including: fire safety tests, structural analysis tests and calculations, acoustic tests, U-Value calculations, thermal bridging calculations and condensation analyses. These tests ensured that the designs met various requirements set out in the Building Regulations. Of most relevance to this work are the thermal properties of the modules and modular buildings.

### 4.3.3 Module Dimensions

The size of modules was restricted by the size that could be transported by lorry. Modules could be no higher than 4.95m and no longer than 14.4m long, however most modules were around 3m high and 7.5m at longest, so the restrictions had little impact on height and length. In contrast, width restrictions did impact on the width of modules. There is no restriction on the transport by road of modules up to 3m wide. Widths between 3m and 5m require 2 days police notice. Widths between 5m and 6.1m require 2 days police notice, and 10 days Highways Authority notice [Highways England, 2015]. Widths above 6.1m are possible but may not be granted and therefore are not guaranteed. Above widths of 3m, the police may also place restrictions on the timing of transportation. Most [redacted] modules were no wider than 3.15m.

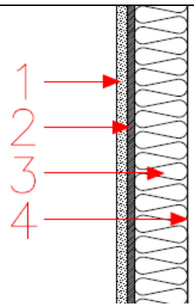
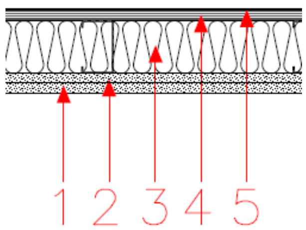
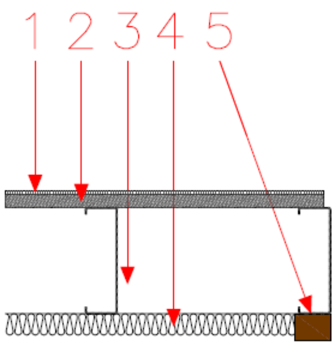
### 4.3.4 Design Uncertainty

Despite access to a wealth of information regarding the modular design and construction there remain some uncertainties. The design evolved over time but when exactly changes occurred is unclear, as these were not documented. The module design documentation was out of date, and did not reflect the most up to date design. Many architects' drawings were lacking in detail or were found to contain errors. Some of the details used for tests and calculations by third parties were contradictory regarding the type and thicknesses of materials used in the modules. These uncertainties make it difficult to have absolute confidence in understanding the modular design. The design presented here is based on the design observed in the factory in 2011.

### 4.3.5 Low-Rise Design

The low-rise module design is outlined in Table 4.1. The structural integrity of the modular buildings is discussed further in Appendix F.

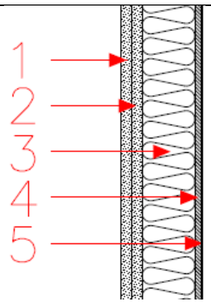
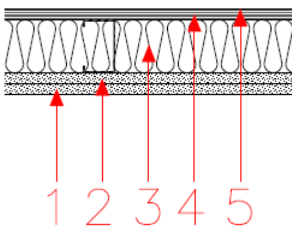
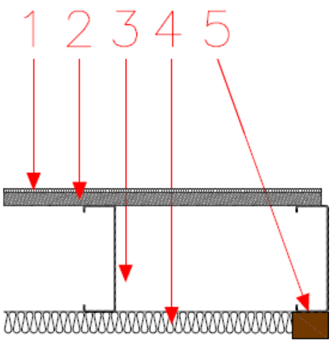
**Table 4.1: Low-rise modular panel design**

| **Wall Design** | **No.** | **Material** |
|---|---|---|
|   | 1 | 15mm plasterboard |
| | 2 | 10mm cement particle board (CPB) |
| | 3 | 75mm steel stud frame with 60mm Rockwool between studs |
| | 4 | 0.4mm breather membrane |
| **Ceiling Design** | **No.** | **Material** |
|   | 1 | 15mm plasterboard |
| | 2 | 12.5mm plasterboard |
| | 3 | 75mm steel joist frame with 60mm Rockwool between studs |
| | 4 | 15mm oriented strand board (OSB)<br>[To allow light passage over the module during construction on site] |
| | 5 | 0.4mm breather membrane |
| **Floor Design** | **No.** | **Material** |
|   | 1 | Flooring (varies by room type and project) |
| | 2 | 18mm tongue and groove chipboard |
| | 3 | 150mm steel joist frame<br>[Insulation may be fitted between joists in ground floor module to achieve required U-Value] |
| | 4 | 30mm rigid insulation |
| | 5 | 38mm floor skid |

### 4.3.6 Medium-Rise Design

The medium-rise module design is outlined in Table 4.2. Compared to the low-rise design, thicker boards are used on the internal surface of wall and ceiling panels, and the wall panels have racking board fitted to their external surface. The floor panels used for the medium-rise construction are same as for the low-rise construction.

**Table 4.2: Medium-rise modular panel design**

| **Wall Design** | **No.** | **Material** |
|---|---|---|
|  | 1 | 15mm plasterboard |
| | 2 | 15mm plasterboard with a foil backed vapour control layer |
| | 3 | 75mm steel stud frame with 60mm Rockwool between studs |
| | 4 | 10mm OSB racking board |
| | 5 | 0.4mm breather membrane |
| | | |
| **Ceiling Design** | **No.** | **Material** |
|  | 1 | 15mm plasterboard |
| | 2 | 15mm plasterboard with a foil backed vapour control layer |
| | 3 | 75mm steel joist frame with 60mm Rockwool between studs |
| | 4 | 15mm OSB |
| | 5 | 0.4mm breather membrane |
| | | |
| **Floor Design** | **No.** | **Material** |
|  | 1 | Flooring (varies by room type and project) |
| | 2 | 18mm tongue and groove chipboard |
| | 3 | 150mm steel joist frame [Insulation may be fitted between joists in ground floor module to achieve required U-Value] |
| | 4 | 30mm rigid insulation |
| | 5 | 38mm floor skid |

### 4.3.7 Thermal Properties

U-Value calculations were undertaken by a third party for the low- and medium-rise module designs. The calculations were for floors, walls and ceilings of the modules alone, and within a typical construction, (Tables 4.3 to 4.5). The assumed thermal properties of the materials are given in Appendix G.

These calculations demonstrated that the construction could easily achieve the U-Values required by the Building Regulations. Variations in the design would require additional calculations to be undertaken to demonstrate compliance. The design of the roof, foundations and cladding often varied between buildings, and therefore new U-Value calculations were regularly required.

**Table 4.3: Calculated U-Values calculated for modular floors**

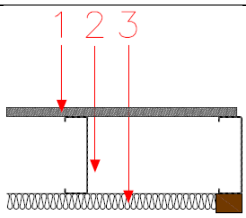
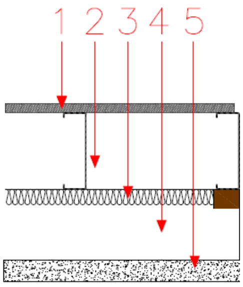
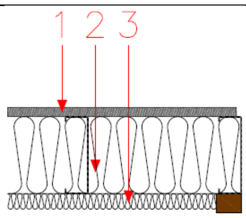
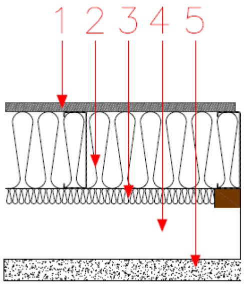
| **Floors** | | |
|---|---|---|
| **Description and U-Value ($W/m^2K$)** | **Section** | **Layers** |
| Low and medium-rise module floor<br>**U-Value = 0.77** |  | 1. 18mm chipboard<br>2. 150mm steel studs<br>3. 30mm rigid insulation |
| Low and medium-rise module floor over ventilated floor void<br>**U-Value = 0.29** |  | 1. 18mm chipboard<br>2. 150mm steel studs<br>3. 30mm rigid insulation<br>4. Ventilated void<br>5. Foundations |
| Low and medium-rise enhanced module floor<br>**U-Value = 0.48** |  | 1. 18mm chipboard<br>2. 150mm steel studs with 150mm Rockwool insulation<br>3. 30mm rigid insulation |
| Low and medium-rise enhanced module floor over ventilated void<br>**U-Value = 0.25** |  | 1. 18mm chipboard<br>2. 150mm steel studs with 150mm Rockwool insulation<br>3. 30mm rigid insulation<br>4. Ventilated void<br>5. Foundations |

**Table 4.4: U-Values calculated for modular walls**

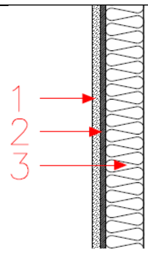
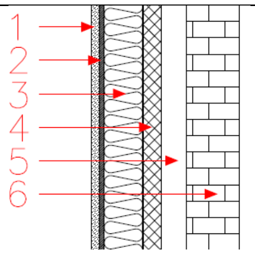
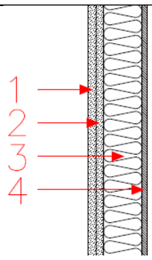
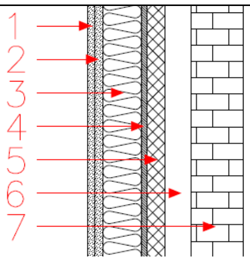
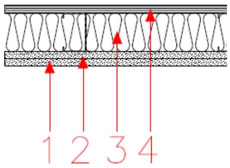
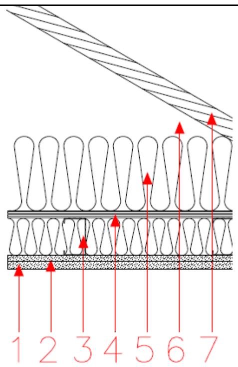
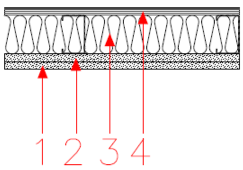
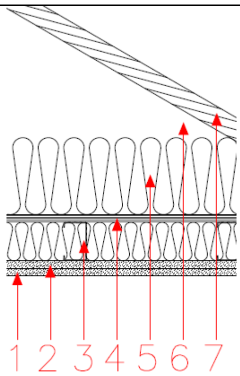
| | Walls | |
|---|---|---|
| **Description and U-Value ($W/m^2K$)** | **Section** | **Layers** |
| Low-rise module wall<br><br>**U-Value = 0.87** |  | 1. 15mm plasterboard<br>2. 10mm cement particle board (CPB)<br>3. 75mm steel studs with 60mm Rockwool insulation |
| Low-rise module wall with partially filled cavity and brick outer leaf<br><br>**U-Value = 0.29** |  | 1. 15mm plasterboard<br>2. 10mm CPB<br>3. 75mm steel studs with 60mm Rockwool insulation<br>4. 35mm rigid insulation with low emissivity, vapour control foil facing<br>5. Air gap (>24mm)<br>6. 102mm brick, medium weight |
| Medium-rise module wall<br><br>**U-Value = 0.79** |  | 1. 15mm plasterboard<br>2. 15mm plasterboard with a foil backed vapour control layer<br>3. 75mm steel studs with 60mm Rockwool insulation<br>4. 10mm OSB |
| Medium-rise module wall with partially filled cavity and brick outer leaf<br><br>**U-Value = 0.28** |  | 1. 15mm plasterboard<br>2. 15mm plasterboard with a foil backed vapour control layer<br>3. 75mm steel studs with 60mm Rockwool insulation<br>4. 10mm OSB<br>5. 35mm rigid insulation with low emissivity, vapour control foil facing<br>6. Air gap (>24mm)<br>7. 102mm brick, medium weight |

**Table 4.5: U-Values calculated for modular ceilings and roofs**

| Ceilings and roofs | | |
|---|---|---|
| **Description and U-Value ($W/m^2K$)** | **Section** | **Layers** |
| Low-rise module ceiling<br><br>**U-Value = 0.81** |  | 1. 15mm plasterboard<br>2. 12.5mm plasterboard<br>3. 75mm steel studs with 60mm Rockwool insulation<br>4. 15mm OSB |
| Low-rise module ceiling with roof insulation, ventilated void and pitched tiled roof<br><br>**U-Value = 0.16** |  | 1. 15mm plasterboard<br>2. 12.5mm plasterboard<br>3. 75mm steel studs with 60mm Rockwool insulation<br>4. 15mm OSB<br>5. 150mm insulation<br>6. Loft space<br>7. 40mm roof tiling including batten space (30° pitch) |
| Medium-rise module ceiling<br><br>**U-Value = 0.80** |  | 1. 15mm plasterboard<br>2. 15mm plasterboard with a foil backed vapour control layer<br>3. 75mm steel studs with 60mm insulation between joists<br>4. 15mm OSB |
| Medium-rise module ceiling with roof insulation, ventilated void and pitched tiled roof<br><br>**U-Value = 0.16** |  | 1. 15mm plasterboard<br>2. 15mm plasterboard with a foil backed vapour control layer<br>3. 75mm steel studs with 60mm insulation between joists<br>4. 15mm OSB<br>5. 150mm insulation<br>6. Loft space<br>7. 40mm roof tiling including batten space (30° pitch) |

### 4.3.8 Modular Windows

The windows used within modules varied based on project requirements, in terms of size, appearance and thermal properties. There were restrictions on the size and location of windows within modular walls, for structural reasons. Some projects included large windows that required alterations to the modular design, but typically windows were kept within the standard limitations to avoid the extra time and cost involved in redesigning the modules. Typically aluminium framed double glazed window units were used, of a standard thermal performance, (with a U-Value of 2.0–2.2 $W/m^2K$), but many projects also had different windows. Module windows were installed in the factory, but no generic design or manufacturing documents were found, however there were detailed drawings for some projects which show a number of installation options. The windows had steel angles fitted to them (Figure 4.12), and these were then bolted to the steel frame, (Figure 4.12), they could be fitted in-line with the module wall (Figure 4.12), protruding past the module wall (Figure 4.12), or anywhere in-between. The quality of this detail is discussed in Chapter 7.



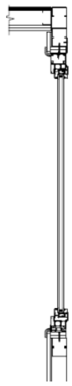
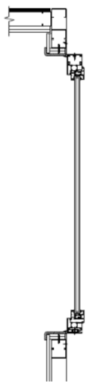



**Figure 4.12 (far left): Modular windows with steel angles and DPC fitted prior to delivery to [redacted] factory**
**Figure 4.13 (centre left): Window fitted to module in factory so it protrudes past wall**
**Figure 4.14 (centre right): Section drawing of modular window fitted in-line with module wall [[redacted] 2012]**
**Figure 4.15 (far right): Section drawing of modular window fitted to protrude past module wall [[redacted] 2012]**

## 4.4 Corridor Panel and Cassette Design

Wall panels, floor cassettes and ceiling cassettes were used to create the corridors between modules. Floor cassettes were used on all storeys to create the corridor floors (Figure 4.16). Ceiling cassettes were used on the top floor only. Corridor panels were used to divide the corridors between flats and for external walls where the corridor met the external facade (Figure 4.17). Corridors could also be provided in modular form, but it appears that panelised corridors were used for all [redacted] projects.

The corridor components utilised the same steel C-sections as the module panels. However, unlike the modules, they were not finished in the factory, and required work on site; typically the addition of plasterboard, insulation, flooring, paint, mechanical and electrical services, and false ceilings.

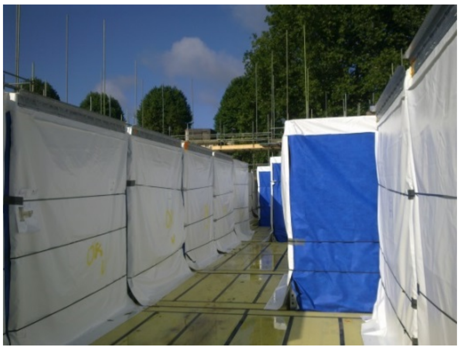



**Figure 4.16 (left): Corridor onstruction on site – floor casettes fitted between modules [[redacted] 2012]**
**Figure 4.17 (right): Corridor construction on site – corridor wall panels and floor cassettes [[redacted] 2012]**

## 4.5 Shower Pods

Shower pods were used in all bedroom and studio flat modules (Figure 4.18). [redacted] initially manufactured their own shower pods, but later switched to purchasing them from other manufacturers. They were purchased fully fitted including plumbing and electrical wiring, and simply had to be installed within the module. The size and internal finish of the shower pods varied by project, for example the pods used for hotel projects were larger with a higher specification of fittings compared to student halls.

**Figure 4.18: Shower pod [[redacted] 2012]**

## 4.6 Component Sub-assemblies

The use of component sub-assemblies is standard in all construction projects, and therefore all buildings use this form of offsite construction. However, the type of sub-assemblies used in offsite construction can differ from those used on a traditional construction site, such as modular wiring systems, (Figure 4.19).

**Figure 4.19: Modular wiring system**

## 4.7 [redacted] Modular Fabrication

The modules and cassettes were manufactured in a factory in [redacted]. The factory operated a production line, with the factory floor divided into areas, each dedicated to different tasks (Figure 4.20 and Table 4.6). Machinery was used to automate much of the construction process. When the factory was operating at maximum, one module could be completed every 55 minutes. Employees typically worked in one area, repeating the same task or set of tasks throughout the day. Employees were typically unskilled or semi-skilled; they were fully trained in the factory to perform the tasks required. Over time, some employees were trained to work in more than one production area.

Module fabrication in the factory is detailed in Appendix H. Once module fabrication was complete, the modules were transported to site by lorry for installation. The modular construction process on site is detailed in Appendix I.

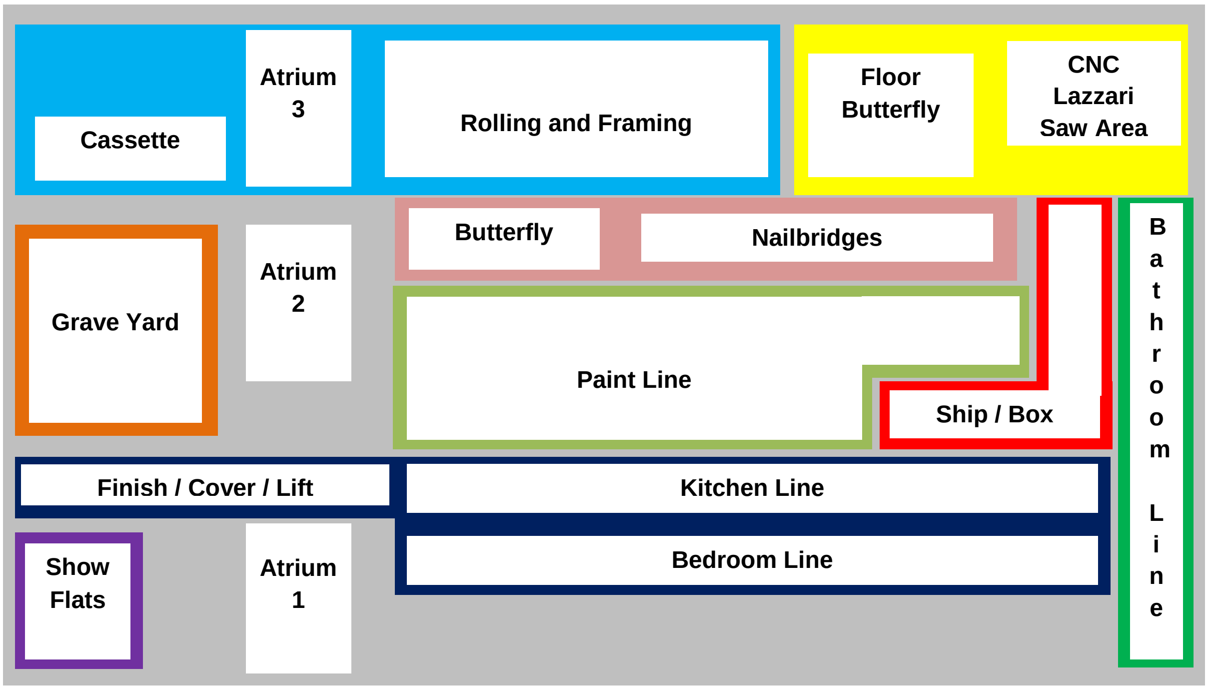



**Figure 4.20: [redacted] factory floor schematic layout – based on [redacted] floor plan [[redacted] 2012]**

**Table 4.6: Overview of tasks undertaken in each [redacted] factory production area**

| Production Line Area | Tasks Performed in Area | Automated |
|---|---|---|
| Rolling | Steel cut and rolled into C-sections | Yes |
| Framing | Steel C-sections connected together to create structural frames, for wall, ceiling and floor panels. | Yes |
| CNC Lazzari Saw | Boards cut to size using a CNC driven saw | Partly |
| Nailbridges | Boards and some insulation nailed to the steel frames to create panels | Yes |
| Butterfly and Floor Butterfly | Joints between boards on the panels sealed<br>Heating pipework fitted within floor panels<br>Electric wiring fitted within ceiling panels<br>Fire insulation fitted between studs in ceiling panels<br>Panels moved to the next part of the production line using a machine called a butterfly | No |
| Paint Line | Wall and ceiling panels painted and dried | |
| Ship/Box | Floor panel completed, then shower pod fitted to it, followed by four wall panels and finally one ceiling panel to create a module | No |
| Bathroom Line | Bathroom pods stored here and lifted onto the floor panel on the Ship/Box line | No |
| Kitchen and Bedroom lines | Modules fitted out internally, with electrics, radiators, plumbing, flooring, furniture and appliances.<br>Electrics and plumbing tested | No |
| Finish/Cover/Lift | Windows fitted<br>Fire insulation fitted between wall studs<br>Racking boards fitted if required<br>Waterproof membrane fitted | No |
| Cassette | Steel C-sections used to create the floor, wall and ceiling panels for corridors | Partly |
| Show flats | Show modules completed to different specifications | N/A |
| Graveyard | Material storage area<br>Area for miscellaneous tasks, such as fitting out structural steel modules for modular stairwells | N/A |
| Atria | Access for lorries to deliver equipment and load completed modules for transport to site | N/A |

## 4.8 [redacted] Operation and Management

As a company, [redacted] operated as a sub-contractor, and they had little involvement in the design or construction of buildings unless it directly related to the modular construction. Each project would follow the traditional construction process. The building would be designed by the architect to meet the project brief; this design would then be "modularised" by [redacted] (Figures 4.21 and 4.22). Modularisation involved dividing the internal space into modular units, quantifying the number and size of modules and corridor components required, and their interfacing within the building. Modularisation was an iterative process, involving collaboration between [redacted] and various parties such as the architect, structural engineers, structural contractors, consultants, window suppliers etc. This process ensured the modularised design met all requirements, primarily safety and regulatory requirements, but also interfacing requirements between components.

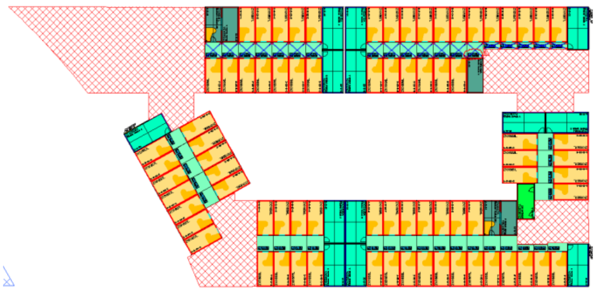



**Figure 4.21 (left): Drawing of architect's building design [Architect 1, 2009]**
**Figure 4.22 (right): Drawing of [redacted] modularisation of architect's design [[redacted] 2012]**

## 4.9 Standard [redacted] Product

In total, [redacted] constructed around 40 halls of residences using [redacted] modular construction. These halls are all unique, and no two projects were identical, although many were of a similar style and appearance (Figures 4.23 to 4.26). Different architects were used for different projects, although some architects worked on a number of projects for [redacted] It appears that the decision to use modular construction was not necessarily pre-determined from the inception of a project, and [redacted] had to compete for tendering with other contractors.

**Figure 4.23 (left):** [redacted] **hall of residence in** [redacted] **[**[redacted] **2012]**
**Figure 4.24 (right):** [redacted] **hall of residence in** [redacted]

**Figure 4.25 (left):** [redacted] **hall of residence in** [redacted] **[**[redacted] **2014]**
**Figure 4.26 (right):** [redacted] **hall of residence in** [redacted] **[**[redacted] **2014]**

Most [redacted] halls of residences comprised a combination of modules and structural steel, in varying proportions. The structural steel was often used to create large open plan areas on all or part of the ground floor; these normally formed the non-lettable areas such as:

- Entrance halls
- Offices
- Staff kitchens
- Laundry facilities
- Plant and boiler rooms
- Common rooms
- Bike stores
- Bin stores
- Stairwells

The modules were used to provide the lettable floor area of the buildings:

- Bedrooms
- Studio flats
- Kitchen-living rooms

However, for some projects, some rooms were constructed from structural steel. This was usually for structural reasons, with these spaces acting as cores or shear walls to resist lateral loads in taller buildings. Sometimes non-modular rooms were used for large or non-uniform kitchen-living rooms that would have been difficult to transport to site as modules.

While many [redacted] halls have different external appearances and internal layouts; the modular rooms were often very similar, if not identical. [redacted] and [redacted] had agreed a standard which outlined module types, dimensions, and internal finishes. There were four types of modules in the standard: bedrooms, kitchens, studio flats and micropad flats. The bedrooms, kitchens and micropads were constructed from individual modules. The studio flats were constructed from two bedroom sized modules, connected together on site and open to each other via an arch in the joining walls.

The standard specified default dimensions for each type of module (Table 4.7). It also specified the internal fit including the type of shower pods, windows, carpets, furniture, heating, ventilation, appliances and even curtains. There was also a premium standard with slightly larger modules, and often a higher specification of internal fittings.

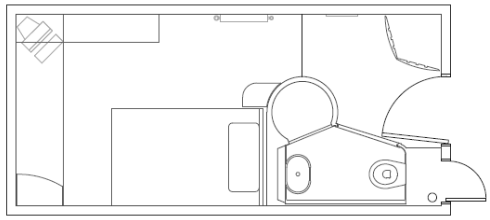
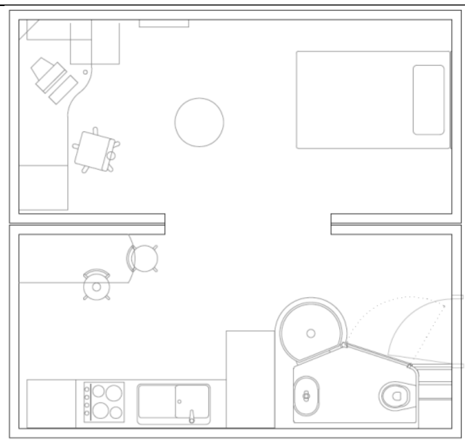
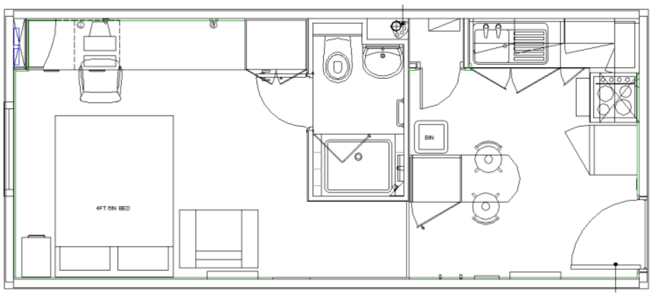
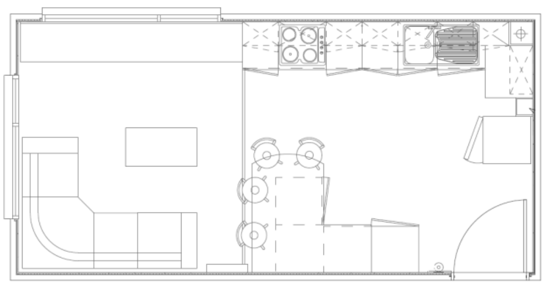
Despite the agreed standards, many [redacted] projects actually did not conform to the specification. The module dimensions and windows often varied between projects. The internal fit out varied to a lesser extent, but it did seem to evolve over time.

The external wall design of [redacted] halls of residences varied between projects. Modules always had rigid insulation fitted to their external walls on site, the thickness varied by project. The rigid insulation was then clad, with or without a cavity between the cladding and the insulation, depending on the design. Cladding materials varied, including:

- Brick
- Rendered block
- Rendered rigid insulation
- Rainscreen of various types
- Weatherboarding

Curtain walling was often used where corridors met the external facade. Roofs were pitched or flat, with taller buildings always having flat roofs.

**Table 4.7: Standard [redacted] module specifications [[redacted] 2012]**

| **Details** | **Floor plan** |
|---|---|
| **Standard Bedroom**<br>Internal floor area:<br>5.35m by 2.4m = 12.84$m^2$<br>Room contents: Shower pod, queen size bed, desk, cupboard, drawers, shelf, cork board, radiator |  |
| **Single Studio Flat**<br>Internal floor area:<br>5.35m by 4.8m = 25.68 $m^2$<br>Room contents: Shower pod, queen size bed, desk, cupboard, drawers, shelf, cork board, radiators, kitchen, breakfast bar, seating area |  |
| **Micropad Flat**<br>Internal floor area:<br>7.55m by 3.15m = 23.78 $m^2$<br>Room contents: Shower pod, queen size bed, desk, cupboard, drawers, shelf, cork board, radiators, kitchen, breakfast bar, seating area |  |
| **Standard Kitchen**<br>Internal floor area:<br>6.48m by 3.14m = 20.35 $m^2$<br>Room contents: Kitchen (with oven, hob, sink, 2 fridge freezers, kettle, toaster, microwave, extract ventilation, cupboards), breakfast bar, seating area with sofas and table |  |

## 4.10 Chapter Summary

This chapter concerned [redacted] modular construction. It provided information about [redacted] as a company, that they were established [redacted] to construct halls of residences, constructing around 40 halls for [redacted] but that they became loss making when the demand for new halls fell. The chapter explained how [redacted] wanted to diversify into the low energy housing market, which is why this research was initiated, to help identify ways to achieve this; however [redacted] was sold before this could be realised. The chapter also detailed the design and fabrication of the modules, including the thermal properties of the materials. It explained how [redacted] and [redacted] had an agreed standard for different types of modules, and that the modules in many buildings were very similar even if the layout and appearance of buildings differed.

It was necessary to understand the design, fabrication and construction of [redacted] modules and buildings in order to identify weaknesses in design and construction, to effectively analyse and interpret data obtained during the project, and to ensure suggested design changes are suitable for [redacted] construction.

# Chapter 5 – Case Study Details

A case study approach was taken to data collection (Chapter 3.2); this chapter provides details of the two case studies chosen, including their location, age, size, fabric, occupancy, buildings services.

The first case study was in Loughborough and the second in London, (Figure 5.1), both were modular student halls of residences, [redacted].


**Figure 5.1: Case study locations: 1=Loughborough, 2=London [Mapbox,2014]**

The Loughborough study was the larger of the two, where the full range of methods was used. It was chosen largely out of convenience, its location providing easy access, which helped facilitate an in-depth study. The London study was smaller in scope and was selected to supplement the main study. It was chosen due to its contrast with the Loughborough study, which provided the opportunity to investigate additional parameters, such as overheating.

The buildings in each study vary in age, size, fabric, location, occupancy and services, but each represents a typical type of [redacted] hall of residence: the low rise building with a masonry facade and the medium rise building with a clad or rendered rigid insulation facade (Table 5.1).

**Table 5.1: Comparison of case study sites**

| | **Loughborough** | **London** |
|---|---|---|
| Building constructed | 2006 | 2011-2012 |
| Number of buildings | 2 | 2 |
| Number of storeys | 3 in each building | 6 and 12 |
| Number of occupants | 160 | 529 |
| Module construction | Low rise design | Medium rise design |
| External facade | Partially insulated cavity wall with outer leaf of brick, rendered block and timber cladding | Rendered and clad rigid insulation |
| Roof | Pitched tiled roof | Flat |
| Space heating | Electric radiators | Hydronic radiators powered by CHP plant |

The London study was chosen because it was believed to provide a better opportunity to study overheating for three reasons:

- It was occupied for 50 weeks a year, and therefore was occupied during the warmest months when overheating is most likely to occur.
- The buildings are large, densely occupied, have low thermal mass and high levels of insulation; putting them at increased risk of overheating.
- Buildings in London are considered at greater risk of overheating compared to other locations in the UK, due to the southerly yet inland location, and the urban heat island effect caused by a large city.

## 5.1 Case Study 1: Loughborough

The Loughborough case study comprises two buildings constructed in 2006, both have three storeys and a similar layout and floor area (Figures 5.2 and 5.3). The northernmost building was the main focus of the study, where the majority of data were collected, which was largely due to practicalities and resources.

**Figure 5.2 (left): Loughborough study – North building**

**Figure 5.3 (right): Loughborough study – South building**

### 5.1.1 Location

The site is [redacted], (Figure 5.4, 5.5, and 5.6).

[redacted]

**Figure 5.4: Loughborough case study location: [redacted] [Google Maps, 2014a]**

[redacted]

**Figure 5.5 (left): Satellite image of Loughborough case study location [Google Maps, 2014a]**

**Figure 5.6 (right): Satellite image showing Loughborough case study buildings [Google Maps, 2014a]**

### 5.1.2 Internal Layout and Structure

The southernmost building contains only modular student accommodation whereas the northernmost building also contains a reception/common area which are not modular but structural steel, (Tables 5.2 and 5.3).

**Table 5.2: Use of space within the Loughborough case study buildings**

| **Number of:** | **North Building** | **South Building** |
|---|---|---|
| | | |
| *Flats in Total* | 16 | 15 |
| *Ground floor flats*<br>*(Beds each)* | 4<br>(5,5,5,5) | 5<br>(5,5,6,6,6) |
| *1st Floor Flats*<br>*(Beds each)* | 6<br>(1,5,5,6,6,6) | 5<br>(5,5,6,6,6) |
| *2nd Floors Flats*<br>*(Beds each)* | 6<br>(1,5,5,6,6,6) | 5<br>(5,5,6,6,6) |
| | | |
| *Studio Flats* | 2 | 0 |
| *5 bed flats* | 10 | 6 |
| *6 bed flats* | 4 | 9 |
| | | |
| *Kitchen Modules* | 14 | 15 |
| *Bedroom Modules* | 74 | 84 |
| *Studio Modules* | 4 (2 bedroom, 2 kitchen) | 0 |
| *Stairwells* | 2 | 2 |
| *Other Spaces (non-modular)* | Common/Reception Area which includes: common area, reception, office, staff kitchen, student laundry, plant room, boiler room, accessible WC | 0 |

**Table 5.3: Floor layout for Loughborough case study, highlighted modular components [Architect 2, 2006]**

| Details | Floor Plan |
|---|---|
| **<u>Ground Floor:</u>**<br>All residential areas are modular<br>All non-residential areas are structural steel: the reception/common area and stair cores<br>Each building has two stair cores, creating two blocks in each building, with different entry points to the flats in different block | ***Copyrighted content redacted*** |
| **<u>1st to 2nd Floors:</u>**<br>All residential areas are modular<br>There is a warden's flats on each floor in the northernmost block, which is a standard studio comprising two modules<br>Stair cores are structural steel | ***Copyrighted content redacted*** |

The modules were designed and constructed according to the standard specification agreed between [redacted] and [redacted]. The bedroom, kitchen and studio modules are all the standard size (Table 4.7 in Chapter 4.9), with standard furniture, appliances and services (Figures 5.7 to 5.10). The module structure followed the standard low rise design (Table 4.1 in Chapter 4.3.4). Each flat has its own private corridor constructed with [redacted] corridor cassettes. The flat corridors have lighting and power sockets; some have windows to outside and others do not (Figure 5.11).


**Figure 5.7 (left): Loughborough study – Student kitchen: View 1**

**Figure 5.8 (right): Loughborough study – Student kitchen: View 2**



**Figure 5.9 (left): Loughborough study – Student bedroom: View 1**

**Figure 5.10 (centre): Loughborough study – Student bedroom: View 2**

**Figure 5.11 (right): Loughborough study – Flat corridor with no fenestration**

The external facade was fitted on site to form a partially insulated cavity wall; the outer leaf of the wall features a range of materials and designs (Figure 5.12):

- Modular wall with a partially insulated cavity and brick outer leaf (Table 5.4)
- Modular wall with a partially insulated cavity and rendered block outer leaf (Table 5.5)
- Modular wall with a partially insulated cavity and timber clad outer leaf (Table 5.6)
- Block inner leaf with a partially insulated cavity and brick outer leaf, in the non-modular walls used in communal areas. (Table 5.7)
- Curtain walling for flat corridors and stair cores


**Figure 5.12: Loughborough study – External facade materials**

The exact design of the facade is not certain as the design and construction drawings are lacking in detail, and contain errors and contradictions. There are few details about the dimensions of facade materials and no details about their thermal properties.

The thicknesses of the cavity wall insulation and render were not clear in the drawings and have been determined from observations made during inspections and by information provided in the generic design documentation.

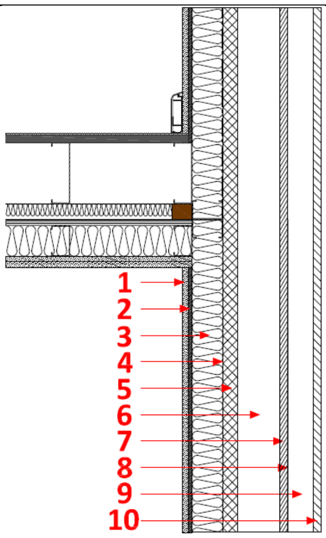
The details of the timber cladding are uncertain, the only drawing that details the design provides limited information, is not to scale, contains errors, and therefore cannot be relied upon.

The construction drawings of the cladding suggest the masonry outer leaf is attached to the modules with wall ties, but there is no reference to any masonry support system. However, it is believed a masonry support system was used, a view supported by the presence of weep holes in the brick cladding at approximately ceiling height on each storey, indicating the presence of cavity trays (Figure 5.13). Cavity trays are required above bridges through the cavity, and in brick walls cavity trays require weep holes. The presence of weep holes at ceiling height on each storey indicates the presence of repeating bridges in the cavity, and these are believed to be masonry support systems. Wall ties would also have been used across the facade.

**Figure 5.13: Loughborough study – Location of weep holes in brick facade indicated in yellow**

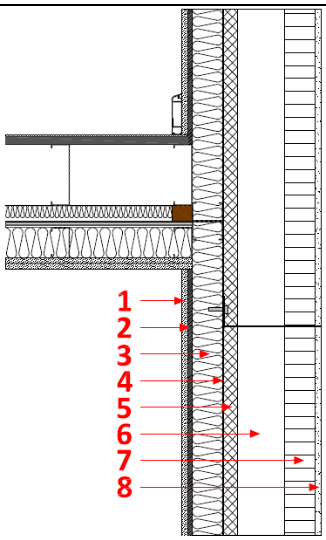
Since limited information is available about the external cladding, assumptions have been made about the design, dimensions and thermal properties (Tables 5.4 to 5.7). The details of the timber cladding are the most uncertain. The curtain walling and fenestration are described in the next section.

**Table 5.4: Loughborough study – Details of modular external wall: timber clad facade**



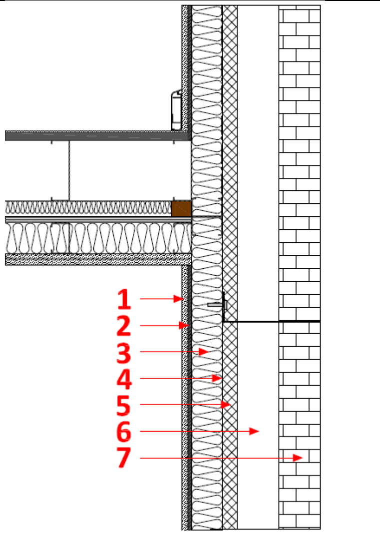

| No. | Timber Clad Facade | Thickness (mm) |
|---|---|---|
| 1 | Plasterboard | 15 |
| 2 | Cement particle board | 10 |
| 3 | Steel stud wall panel<br>filled with Rockwool | 75<br>60 |
| 4 | Breather membrane | 2 |
| 5 | Rigid insulation with low emissivity, vapour control facing | 35 |
| 6 | Air gap - cavity | 102.5 |
| 7 | Sheathing board | 19 |
| 8 | Breather membrane | 1 |
| 9 | Drained and ventilated cavity (Batten orientation unknown) | 61 |
| 10 | Timber cladding | 19 |

**Table 5.5: Loughborough study – Details of modular external wall: render facade**



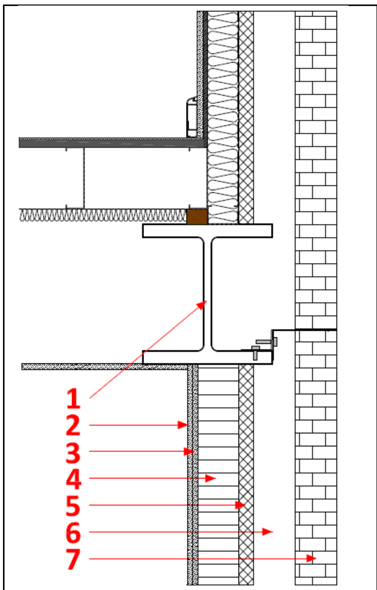

| No. | Render Facade | Thickness (mm) |
|---|---|---|
| 1 | Plasterboard | 15 |
| 2 | Cement particle board | 10 |
| 3 | Steel stud wall panel<br>filled with Rockwool | 75<br>60 |
| 4 | Breather membrane | 2 |
| 5 | Rigid insulation with low emissivity, vapour control facing | 35 |
| 6 | Air gap - cavity | 112.5 |
| 7 | Concrete blockwork | 75 |
| 8 | Render | 15 |

**Table 5.6: Loughborough study – Details of modular external wall: brick clad facade**




| No. | Brick Facade | Thickness (mm) |
|---|---|---|
| 1 | Plasterboard | 15 |
| 2 | Cement particle board | 10 |
| 3 | Steel stud wall panel<br>filled with Rockwool | 75<br>60 |
| 4 | Breather membrane | 2 |
| 5 | Rigid insulation with low emissivity, vapour control facing | 35 |
| 6 | Air gap - cavity | 100 |
| 7 | Brick | 102.5 |

**Table 5.7: Loughborough study – Details of external wall in non-modular ground floor areas**




| No. | Non-modular facade | Thickness (mm) |
|---|---|---|
| 1 | Structural steel (beams and columns) | 305 x 305 x 198 UC[1] |
| 2 | Cement particle board | 12.5 |
| 3 | Cement particle board | 12.5 |
| 4 | Concrete block | 100 |
| 5 | Rigid insulation with low emissivity, vapour control facing | 35 |
| 6 | Air gap | 102 |
| 7 | Brick | 102.5 |

[1]British Standards Institution, 2005

### 5.1.3 Fenestration

The Loughborough case study buildings feature three types of fenestration

- Module windows: fitted in the factory to all modules (Figure 5.14)
- Curtain walling: fitted on site in the flat corridors and stair cores (Figure 5.15)
- Standard windows and glazed doors: fitted on site in the non-modular reception/common area (Figure 5.16)

Construction drawings indicate that there are lintels above each window in the brick and render facades, but not above those in the timber clad facades.

**Figure 5.14 (left): Loughborough study – Modular windows**

**Figure 5.15 (centre): Loughborough study – Curtain walling in stair core**

**Figure 5.16 (right): Loughborough study – Standard windows and glazed doors on ground floor**

### *Modular Windows*

Three sizes of modular windows were used based on location and module type (Figure 5.12 above and Table 5.8). Windows were fitted to modules in the factory, and the facade was constructed around them on site. It was determined from observations that the windows were installed in-line with the modular wall (Chapter 4.3.8); there were no drawings of this detail for this project. The external wall is thick at 339.5mm, which means the windows are recessed within the facade, and partly shaded by it (Figure 5.17). Little is known about the interfacing between the modular windows and the cladding, there is only one simple drawing of this detail, which suggests the window reveal is supported by steel angles attached to the modules; there are weep holes in the brick work which support this view (Figure 5.17).

**Figure 5.17: Loughborough study – Recessed modular windows recessed with weep holes below marked**

**Table 5.8: Loughborough study – Modular window types and dimensions**

| Modular window type | Opening size (width*height) | Glazing area |
|---|---|---|
| Bedrooms and studios | 910mm *1210mm | 0.72m$^2$ |
| Ground floor kitchens | 1585mm * 1210mm | 1.25 m$^2$ |
| First and second floor kitchens | 1585mm * 1890m | 2.19 m$^2$ |

Other than size, all module windows have the same specifications:

- Powder coated aluminium frames
- 4mm-18mm-6mm double glazed unit
- U-Value of 2.2 W/m$^2$K
- Top hung opening
- Degree of opening restricted to 30cm horizontal (Figures 5.18 and 5.19)


**Figure 5.18 (left): Loughborough study – Extent of modular window opening**
**Figure 5.19 (centre): Loughborough study – Modular windows fully open at 30cm**

### *Curtain Walling*

The curtain walling is used in the corridors in student flats and in the stair cores (Figure 5.20). It was fitted on site, and is essentially in-line with the outer leaf of the cavity wall, although slightly recessed within it (Figure 5.21). The curtain walling in the stair cores also contains the entry doors for the blocks of flats. The flat corridors vary in width, and so does the curtain walling used to enclose them. The curtain walling specifications are the same as the modular windows except for the glass thickness:

- Powder coated aluminium frames
- 6mm-18mm-6mm double glazed unit
- U-Value of 2.2 W/m$^2$K
- Top hung opening
- Degree of opening restricted to 14cm horizontal (Figure 5.22)

There are limited details about the interfacing between the curtain walling, the modular structure and the external facade. Drawings show the flat corridors have walls panels fixed to their ends where the corridors meet the external facade, but there is no information about the design or these panels, how they were constructed or by who, or how they interface with other components. The only detail about the corridor end panels is in two drawings, one section and one elevation drawing, but they contradict one another about the dimensions, which leads to uncertainty. The section drawings show that the curtain walling is fixed to the corridor end panels on each storey (and I-beams in the non-modular construction) with steel angles.



**Figure 5.20 (left): Loughborough study: curtain walling within student flat**
**Figure 5.21 (centre): Loughborough study: Curtain walling slightly recessed within facade**
**Figure 5.22 (right): Loughborough study: Degree of window opening of curtain walling**

### *Standard Fenestration*

Nothing is known about the window and door specification used in the reception/common area. However, they have a similar appearance to the module windows and curtain walling (Figures 5.23 and 5.24), and therefore it is assumed that they also have a U-Value of $2.2W/m^2K$, which was the minimum standard required by the Building Regulations for metal framed windows at the time of construction [DCLG, 2015].


**Figure 5.23 (left): Loughborough study: Curtain walling to left and standard window to right**
**Figure 5.24 (right): Loughborough study: Internal view of reception/common showing windows**

### 5.1.4 Mechanical and Electrical Services

#### *Space Heating*

Space heating is provided by electric radiators within each module, they are individually controlled in each room via a control panel on the wall near the radiator, (Figures 5.25 and 5.26). The thermostat is located within the control panel. To activate the heating the occupant must press the "Touch" button, which heats the room to a predefined setpoint for a predefined duration. This type of heating control is common in hotels and some halls of residences.


**Figure 5.25: Loughborough study – Radiator and control panel in bedroom**

**Figure 5.26: Loughborough study – Individual radiator control panel in each module**

Although the control panel has an adjustment knob indicating "MIN" and "MAX", the occupant has no knowledge of, or control over what these values are. The "MIN" and "MAX" values are not known, and were set prior to construction. The heating duration has been predefined at two hours, which is the maximum duration of heating that can be received from one push of the "Touch" button. If the thermostat setpoint is reached before two hours has passed then the radiator will automatically turn off, otherwise it will turn off after two hours even if the thermostat setpoint has not been reached. The occupant can continue to reactivate the heating indefinitely as long as the thermostat measures below the setpoint, however if the internal temperature is above the setpoint then it is not possible to activate the heating. The controls also provide a frost protection function which activates after 48 hours of inactivity of the heating system. The control panel will switch the radiator on if the temperature drops below the frost protection temperature, which is also predefined and unknown, but is typically around 5°C [Prefect, 2011].

This type of control means that it is not possible for the occupants to heat their rooms to excessive temperatures or for excessive durations, or to heat their room when they are not there. There is no space heating in the flat corridors or the stair cores.

### *Hot Water*

The hot water is provided centrally from gas boilers located in the plant room in the North building. It is used by sinks in the kitchen modules, and by sinks and showers in the bedroom modules. It is also used in the staff kitchen and the accessible toilet in the common/reception area.

### *Ventilation*

Each flat in the building has its own ventilation system powered by a central unit in the kitchen of each flat. The systems extract air from extract vents in the showers of bedroom modules (Figure 5.27), and from the cooker hood in the kitchen modules (Figure 5.28). The kitchen modules also have inlet ventilation (Figure 5.29). The systems are permanently switched on to provide background ventilation; there are three speed settings which alter the flowrate. The speed controls are located in a recessed area at the top of the cooker hood in the kitchen, and are not immediately obvious. There is nothing to indicate that these switches in the cooker hood control the whole ventilation system. The only way to switch off the ventilation system is at the circuit breaker in the distribution board in the kitchen.



**Figure 5.27 (left): Loughborough study – Extract ventilation in showers in bedroom modules**
**Figure 5.28 (centre): Loughborough study – Ventilation system cooker hood extract in kitchen modules**
**Figure 5.29 (right): Loughborough study – Inlet ventilation in the kitchen modules**

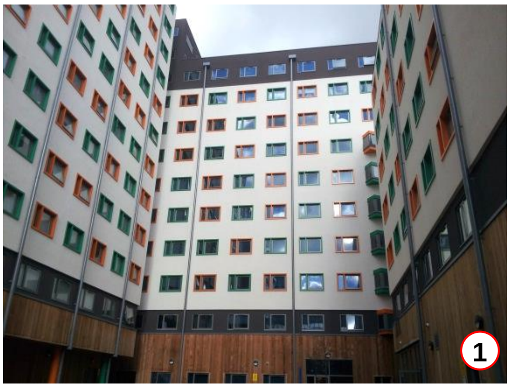
## 5.1.5 Occupancy

The buildings are occupied by students [redacted], predominantly undergraduate students from the UK. The buildings are occupied for 39 to 40 weeks a year, from late September to late June, coinciding with the academic year. The tenancy covers periods when students are undertaking lessons and exams, and also the Christmas and Easter vacations. While the buildings may be occupied throughout this period, many students go elsewhere during the vacations, and a significant proportion may not be present during the entire exam period. The buildings are unoccupied during summer; however staff continue to work in the office preparing for the next academic year, which includes organising any refurbishments or repair to the buildings.

## 5.2 Case Study 2: London

The London case study comprises two buildings, constructed in 2011 and 2012 (Figures 5.30 to 5.35). Block A has seven storeys and the smaller floor area, Block B has 12 storeys and the larger floor area. The floor area in Block B decreases on the upper storeys, with the top floor approximately two thirds the area of the ground floor. Only Block B was included in the study, due to the small size of the study and the need to keep the distance between wireless sensors and the controller to a minimum.

***Copyrighted content redacted***





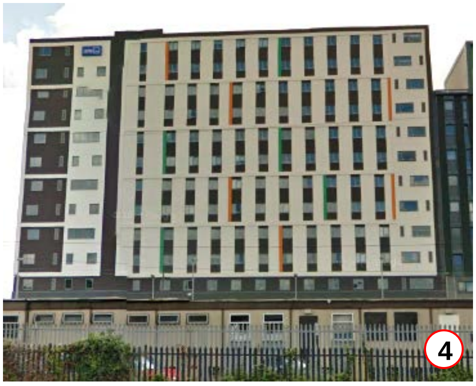





**Figure 5.30 (top left): London case study site plan, with view points indicated [Architect 3, 2011]**
**Figure 5.31 (top centre): View 1 showing Block A and Block B from within the courtyard**
**Figure 5.32 (top right): View 2 of Block A and Block B from within courtyard**
**Figure 5.33 (bottom left): View 3 showing Block A and Block B from the east**
**Figure 5.34 (bottom centre): View 4 showing Block B from the west [Google Maps, 2014b]**
**Figure 5.35 (bottom right): View 5 showing Block B from the north-west [Google Maps, 2014b]**

### 5.2.1 Location

The London case study buildings are [redacted] in [redacted] London, [redacted] (Figures 5.36 to 5.39). [redacted]

[redacted]

**Figure 5.36 (left):** [redacted] **[The National Archives, 2014]**

**Figure 5.37 (right): Map of showing London case location in** [redacted] **London [Mapbox, 2014}**

[redacted]

**Figure 5.38 (left): Satellite image of** [redacted] **London study buildings marked [Google Maps, 2014b]**

**Figure 5.39 (right): Aerial Photograph of** [redacted] **London study buildings marked [**[redacted]**, 2014]**

### 5.2.2 Internal Layout and Structure

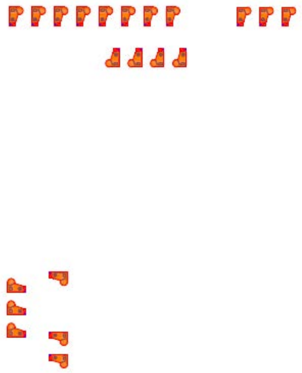
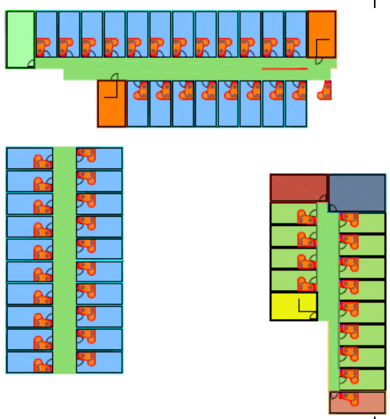
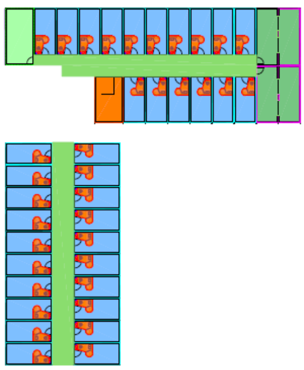
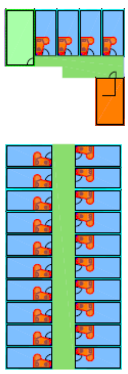
Parts of the buildings were not modular, including the ground floors, the stair cores, the majority of kitchens in Block B, and six bedrooms in Block B. It is believed these areas were constructed using steel reinforced precast concrete beams, columns and panels (Figure 5.40). Non-modular stair cores, kitchens and bedrooms were for structural purposes, to resist the lateral loads in a building of this height. The ground floors primarily comprise non-residential spaces, however Block B also has four student flats, and although they are not modular they have the same layout and dimension as the modular rooms on the storeys above, and contain identical shower pods. The first floor and above are used entirely as student accommodation, and are predominantly modular in construction (Tables 5.9 and 5.10).

**Figure 5.40 : London study – Block B non-modular cores completed and modules partly installed [[redacted], 2014]**

**Table 5.9: Use of space within the London Case study buildings**

| **Number of:** | **Block B** | **Block A** |
|---|---|---|
| Flats in Total | 55 | 12 |
| Ground Floor Flats (Beds each) | 4 (5,5,7,9) | 0 |
| 1st-6th Floor Flats (Beds each) | 5 (3,10,10,10,10) | 2 (5,9) |
| 7th-9th Floor Flats (Beds each) | 5 (3,7,7,10,10) | N/A |
| 10th-11th Floor Flats (Beds each) | 3 (5,10,10) | N/A |
| 3 Bed Flats | 9 | 0 |
| 5 Bed Flats | 4 | 6 |
| 7 Bed Flats | 7 | 0 |
| 9 Bed Flats | 1 | 6 |
| 10 Bed Flats | 34 | 0 |
| Modular kitchens | 17 | 12 |
| Non-modular kitchens | 38 | 0 |
| Modular bedrooms | 413 | 84 |
| Non-modular bedrooms | 32 | 0 |
| Studios | 0 | 0 |
| Stair cores | 1 | 1 |
| Other Spaces (e.g. laundry) | Plant Room, Common Room, Comms Rooms, Cycle Store | Entrance, Office, Laundry, Sub-Station, Switch Room, Comms Room, Disabled WC, Bin Store |

**Table 5.10: Floor layouts for London case study buildings, highlighting modular components**

| Details | Floor Plan [Architect 3, 2011] | Offsite Modular Components [redacted] 2012] |
|---|---|---|
| **<u>Ground Floor:</u>**<br>The ground floor is not modular, it is believed to be reinforced precast concrete<br><br>There are 4 flats in Block B, the bedrooms all feature shower pods, constructed offsite and provided by [redacted]. | ***Copyrighted content redacted*** |  |
| **<u>1st to 6th Floors:</u>**<br>All bedrooms and kitchens in Block A are modular.<br>On each floor in Block B, all but one of the bedrooms are modular, the non-modular bedrooms have a shower pod provided by [redacted].<br>Only one of the five kitchens on each floor in Block B is modular. | ***Copyrighted content redacted*** |  |
| **<u>7th to 9th Floors</u>**<br>On each of these floors all bedrooms are modular.<br><br>Three of the five kitchens on each floor are modular. | ***Copyrighted content redacted*** |  |
| **<u>10th to 11th Floors</u>**<br>On each of these floors, all bedrooms are modular.<br><br>One of the three kitchens on each floor is modular. | ***Copyrighted content redacted*** |  |

The majority of modular bedrooms are of the standard size with an internal floor area of 5.35m by 2.4m (Figure 5.41); there are also twenty-two modular accessible bedrooms, where the module and the shower room are larger to allow for wheelchair access. Accessible modular bedrooms were included, in limited numbers, in many [redacted] halls.

The kitchen modules vary in size depending on the number of bedrooms in each flat (Figure 5.42), and none are of the standard size. Since more than half of the kitchens were not modular and were constructed on site, the modular kitchens were provided to site without the standard internal fit and finish so they could be completed on site to the same specification as the non-modular kitchens.

Each flat has its own private corridor which is behind the locked entry door to each flat. They have lighting and power sockets, but no windows, because none have external walls.

**Figure 5.41 (left): London study – Standard modular bedroom [[redacted], 2015]**
**Figure 5.42 (right): London study – Large kitchen [[redacted], 2015]**

Block A is a low rise building and Block B is a medium rise building, they have different modular designs because the difference in height meant each building had different structural requirements. Only Block B was included in the case study so the structure of Block A is not important. Block B may not feature the standard medium rise design (Chapter 4.3.5). There is conflicting information in the technical documentation which makes it difficult to have absolute confidence. Based on various details, it is believed that the walls followed the standard medium rise design with two layers of 15mm plasterboard internally, but that the ceiling featured the low rise design (Chapter 4.3.4), with plasterboard of two different thicknesses (15mm and 12.5mm). In fact the low rise ceiling design was observed in drawings for other medium rise projects, and [redacted] may actually have used both ceiling designs in medium rise construction.

The external facade was fitted on site and comprises rigid insulation fixed to the modules with various types of render and cladding fitted to it (Table 5.11). The types of facade materials and their dimensions are known from technical drawings, however nothing is known of their thermal properties.

**Table 5.11: London study – Facade materials**

| Facade Materials | Image reference |
|---|---|
| PPC extruded aluminium cladding panel in orange and green | A |
| Glass-fibre reinforced concrete (GRC) rainscreen cladding panel | B |
| Western red cedar timber rainscreen cladding | C |
| Trespa Meteon exterior rainscreen cladding panel | D |
| Dark grey render system | E |
| White render system | F |
| Glazed curtain walling (see section 5.2.3 Fenestration) | Figure 5.46 |

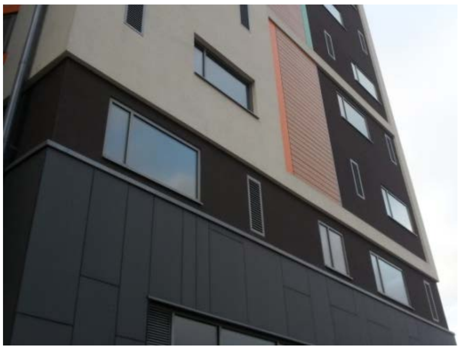

Block B East facing facade facing the courtyard


Block A East facing facade dacing the street

The white render system is the predominant facade material followed by the grey render system, because all rooms that face the courtyard have rendered facade, as do many that face outwards. The glazed curtain walling is used only in some parts of the ground floor: in the common room, main entrance and offices. The GRC and timber rainscreen cladding systems are used only on the ground floor and approximately the bottom half of the first floor. The Trespa Meteon rainscreen cladding and the PPC extruded aluminium cladding are used in small quantities on facades that face outwards, they are not used on the facades that face the courtyard. Some individual modular rooms actually have three or four different types of facade material attached to their external wall, but the majority have one or two (typically the white and/or grey render systems).

Not only is the use of materials varied across the facade, the thickness of the facade also varies. Four thicknesses of rigid insulation were used, resulting in a variable wall thickness across the facade (Figures 5.43 and 5.44). From the limited information available, it appears that the thickness of rigid insulation is linked to the facade materials used, and that only the white render system uses 200mm thick insulation, only the grey render system uses 100mm thick insulation, and the cladding is always fitted to 60mm thick insulation with an air gap in between (Tables 5.12 to 5.15). The white render system is also used with the 150mm thick insulation, but it is not clear if it is also used with the grey render system.

The thermal implications of using various facade materials and various insulation thicknesses are not clear. None of the documentation obtained from [redacted] mentions thermal performance or external wall U-Values, but this does not mean that these aspects were not considered. The different thicknesses of rigid insulation could have been selected to have different thermal properties so that all sections of wall have similar U-Values, however this is merely conjecture, and the real design considerations are unknown.



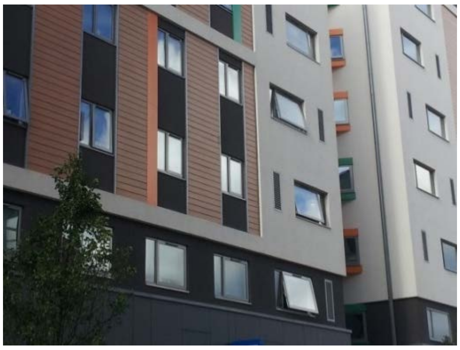
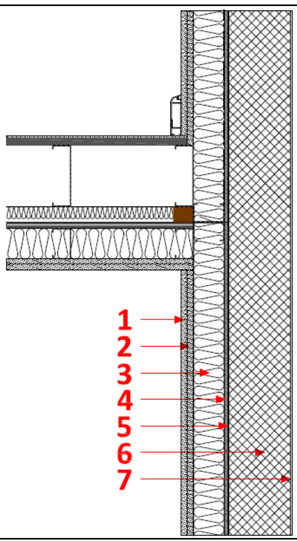


**Figure 5.43 (left): London study – Block B east facing facade showing variable facade thickness**

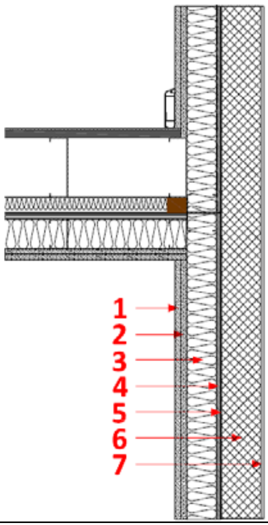
**Figure 5.44 (right): London study – Block A and B east facing facades showing variable facade thickness**

**Table 5.12: London study – Details of modular external wall: grey render on 150mm insulation**



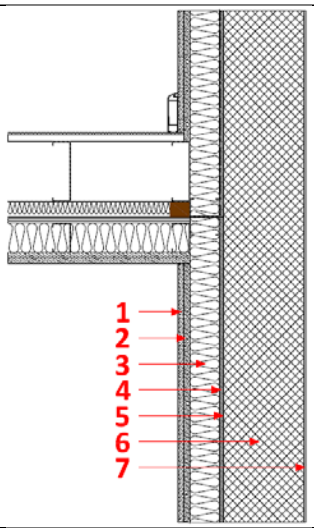

| No. | Render on 150mm insulation facade | Thickness (mm) |
|---|---|---|
| 1 | Plasterboard | 15 |
| 2 | Plasterboard with foil backed VCL (vapour control layer) | 15 |
| 3 | Steel stud wall panel<br>filled with Rockwool | 75<br>60 |
| 4 | Racking board | 10 |
| 5 | Breather membrane | 2 |
| 6 | Rigid insulation with low emissivity, vapour control facing | 150 |
| 7 | White render and perhaps grey render | 6 |

**Table 5.13: London study – Details of modular external wall: grey render on 100mm insulation**



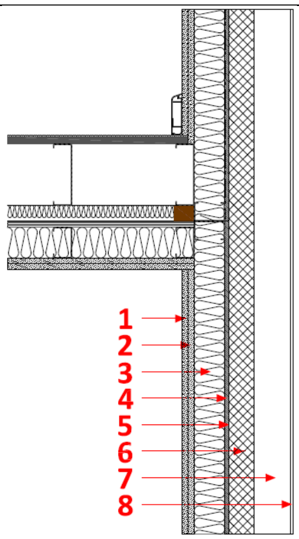

| No. | Render on 100mm insulation facade | Thickness (mm) |
|---|---|---|
| 1 | Plasterboard | 15 |
| 2 | Plasterboard with foil backed VCL | 15 |
| 3 | Steel stud wall panel (filled with Rockwool) | 75 (60) |
| 4 | Racking board | 10 |
| 5 | Breather membrane | 2 |
| 6 | Rigid insulation with low emissivity, vapour control facing | 100 |
| 7 | Grey render | 6 |

**Table 5.14: London study – Details of modular external wall: white render on 200mm insulation**




| No. | Render on 200mm insulation facade | Thickness (mm) |
|---|---|---|
| 1 | Plasterboard | 15 |
| 2 | Plasterboard with foil backed VCL | 15 |
| 3 | Steel stud wall panel (filled with Rockwool) | 75 (60) |
| 4 | Racking board | 10 |
| 5 | Breather membrane | 2 |
| 6 | Rigid insulation with low emissivity, vapour control facing | 200 |
| 7 | White render | 6 |

**Table 5.15: London study – Details of modular external wall: Cladding systems**




| No. | Cladding facade | Thickness (mm) |
|---|---|---|
| 1 | Plasterboard | 15 |
| 2 | Plasterboard with foil backed VCL | 15 |
| 3 | Steel stud wall panel (filled with Rockwool) | 75 (60) |
| 4 | Racking board | 10 |
| 5 | Breather membrane | 2 |
| 6 | Rigid insulation with low emissivity, vapour control facing | 60 |
| 7 | Air gap | 90 |
| 8 | Cladding systems:<br>• PPC aluminium rainscreen<br>• High pressure laminate rainscreen<br>• Western red cedar timber<br>• Trespa Meteon | 6 |

### 5.2.3 Fenestration

The buildings contain 21 different styles of windows plus curtain walling (Figures 5.45 to 5.47). The style of glazing used varies based on the type of room and location in the building:

- Double glazed window with top hung opening in bedrooms and kitchens
- Opaque windows that do not open in stair cores
- Curtain walling in reception area and common room on the ground floors

There are also five different glazing specifications and four trickle vent specifications, which means two windows may have the same appearance but different properties. The reason for this is the different acoustic requirements of windows in different locations. A train line runs adjacent to the west side of the site, to minimise noise the bedrooms in Block B that face north and west have thicker glazing and acoustic trickle vents. The kitchens have lower specification glazing and trickle vents, presumably because occupants do not sleep in the kitchen so there is not the same requirement to block noise from these spaces.

There are no windows in the flat corridors because they have no external walls.

There are no details about the thermal performance of any of the windows, or whether the use of different types of glazing affects heat transfer through otherwise identical windows. The Buildings Regulations at the time of construction [DCLG, 2015] require a U-Value no higher than 2.2W/m$^2$K for windows and curtain walling.

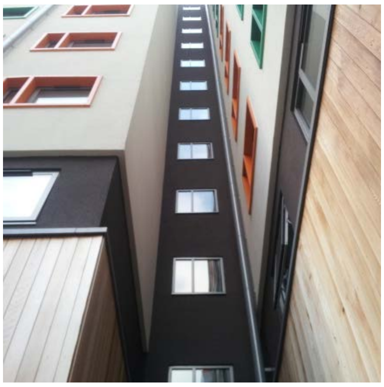
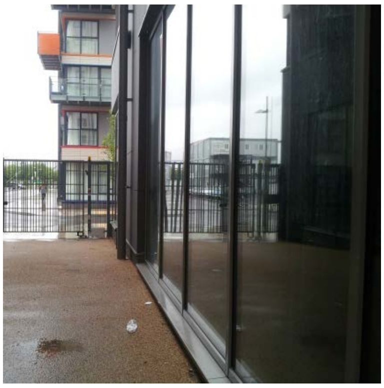




**Figure 5.45 (left): London study – large bedroom windows left & right, stair core opaque windows centre**
**Figure 5.46 (centre): London study – ground floor curtain walling in office in Block A**
**Figure 5.47 (right): London study – oriel windows in highly shaded south facade in Block B**

#### *Bedroom and Kitchen Windows*

In general, the windows that face the internal courtyard are larger, and those that face outwards are smaller. All bedrooms and kitchens have venetian blinds.

The windows were fitted in the factory to the external face of modules (Figures 5.48, and Chapter 4.3.8) There are no details showing how windows were fitted on site in non-modular bedrooms and kitchens.  Due to the variable thickness of the external walls, some windows are recessed within the facade and some are not. Windows in walls with 200mm thick insulation are recessed within and partly shaded by the facade, whereas those within 100mm thick rigid insulation are not (Figures 5.49 and 5.50).

**Figure 5.48: Window fitted to external face of module in factory**

The degree to which windows can open has been restricted for safety, as is typically the case.  The drawings suggest that windows should be able to open at the bottom horizontally 150mm beyond the external facade, however since the thickness of the facade varies and hence relative position of the window within the facade varies, this would result in a variable degree of opening based on the type of facade adjacent to the window.  The drawings show that a window next to an external facade with 200mm thick insulation should be able to open horizontally by 100mm more than a window next to a facade with 100mm thick insulation. However, observations on site do not agree, and suggest all windows are restricted to open horizontally by 150mm from the window frame rather than the external facade (Figures 5.49 to 5.51).  This means the windows within the walls with 200mm thick rigid insulation barely open past the facade (Figure 5.50).

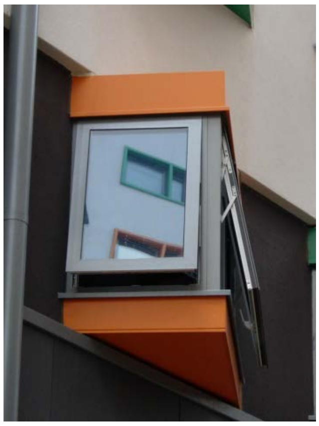


**Figure 5.49 (left): London study – Module window not recessed in facade – extent of window opening**

**Figure 5.50 (centre): London study – Module window recessed in facade – extent of window opening**

**Figure 5.51 (right): London study –opening Orial windows – extent of window opening**

### *Stair Core Opaque Windows*

Externally the stair cores have windows with opaque glazing (Figure 5.45 above), however internally there are no windows in these areas, they do not penetrate through the external wall into stair cores, and they seem to have no function but to provide the external appearance of windows. The fenestration in the stair cores is interesting because the architect's drawings show louvered panels which would have provided ventilation; however the final construction has false windows that provide no ventilation.

### *Curtain Walling*

There is curtain walling on the ground floor in the entrance area and the common room, but there are no details about the system used or its installation, however since it is used in non-modular, non-residential parts of the buildings it is not important to this project.

## 5.2.4 Mechanical and Electrical Services

The space heating and hot water are provided by a CHP plant used by the [redacted] site, it is believed to use biomass fuel. Heat from the CHP plant is transferred to the case study buildings via a heat exchanger in the plant on the ground floor of Block B. The buildings have a BMS system, which is managed by a third party.

### *Space Heating*

Space heating is provided by a wet heating system; each bedroom and kitchen has a radiator, there are no radiators in corridors or stair cores. Details of the radiators were found in the design documentation:

- Kitchen radiator – 520mm x 1800mm, 1417watts
- Bedroom radiator – 600mm x 600mm, 807watts (Figure 5.52)

Thermostatic radiator valves (TRVs) on each radiator are the only means of occupant control. Space heating is available whenever the external temperature is below 15°C, which is measured by an external temperature sensor connected to the BMS system.

**Figure 5.52: Promotional image showing the placement of the radiator within the bedroom [[redacted], 2015]**

### *Hot Water*

The hot water is believed to be provided by the [redacted] CHP district heating system. It is used by sinks in kitchens, staff office and accessible toilet in the reception area, and by sinks and showers in bedrooms.

### *Ventilation System*

As is typical with [redacted] halls of residences, each flat has its own ventilation system, centrally powered from the kitchen. There is extract ducting in kitchens, bedrooms and flat corridors; it is not clear if there is any inlet ducting. The extract ventilation is via the cooker hoods in the kitchens and via vents in the corridor and in the shower pods in the bedrooms.

### 5.2.5 Occupancy

The use of the buildings was not restricted to one institution, and occupants attended a range of different universities. The buildings were occupied for 50 weeks and five days in the year, and were only completely vacant for around ten days in early September. The tenancy therefore essentially covers the whole year, and not only the academic year. These longer tenancies are common with [redacted] halls, with most ranging from 44 to 51 weeks. While it is assumed that students will occupy the buildings during term time, when they have classes and exams; it is not known to what extent the buildings are occupied during holidays and in the summer, when students may choose to go elsewhere for some or all of the time.

## 5.3 Chapter Summary

This chapter detailed the two case studies selected for this study, providing information about their location, design, occupancy and building services. It explained that the Loughborough study was chosen largely for convenience due to its location, and the London study was chosen to investigate overheating because its size and location were though to put it at greater risk. It outlined how the two studies are both typical forms of [redacted] construction but are quite distinct in their size, age, fabric, occupancy and services, which presents the opportunity to investigate performance in different contexts. Knowledge about the design and use of the case study buildings was necessary for successfully planning and implementing the data collection methods, analysing the data, and formulating the recommendations; because all of these stages relied upon in-depth knowledge of the cases.

# Chapter 6 – External Temperatures during 2013

Weather can have a significant impact on the thermal comfort and energy consumption of buildings, particularly temperature and solar gains, but also other parameters such as wind speed, wind direction and rainfall. Therefore, it is important to understand the prevailing weather conditions during the case studies, and how they compare with average conditions.

This chapter focuses on the external temperatures during the case study periods. While solar radiation is also important, the weather data were obtained some distance from the case study sites and there is no way of knowing how well the solar radiation data compare with the study sites because at any time cloud cover can vary significantly over short distances. Therefore, the focus of the chapter was on temperatures during the case study periods, which were from March to June 2013 for the Loughborough study and from March to September 2013 for the London study.

## 6.1 National Temperatures

The UK temperatures statistics show that March was the third coldest, and July was the third hottest since the record period began in 1910 [UK Met Office, 2014]. This was very fortunate, that in such short case studies extreme conditions were able to be observed.

The Met Office have no formal definition for a heatwave, however they did class conditions in July as a heatwave [UK Met Office, 2014]: it had a long duration, lasting from 6$^{th}$ to 24$^{th}$ July, but was not particularly extreme. Over these 19 days, a daily maximum temperature of at least 28°C was measured at one or more locations in the UK. The maximum temperature recorded during this period was 33.5°C on 22$^{nd}$ July, and this was recorded at two stations: Heathrow and Northolt.

While national statistics are useful, local weather anomalies mean different patterns can occur regionally; therefore it is more useful to understand and use local weather data.

During this project two types of weather data were used:

1. Regional temperature data, to compare the weather for 2013 with historic temperature data to determine if the patterns were typical or atypical
2. Weather station data for 2013 from sites near the case study buildings, used primarily for the overheating analyses

## 6.2 Regional Temperatures

### 6.2.1 Temperature Anomalies: The Midlands – Loughborough Case Study

For the Midlands region [UK Met Office, 2014a], the temperature patterns were much the same as they were nationally. July 2013 was the third hottest month on record for the region (Figure 6.1), and March 2013 was the second coldest on record for the region (Figure 6.2).

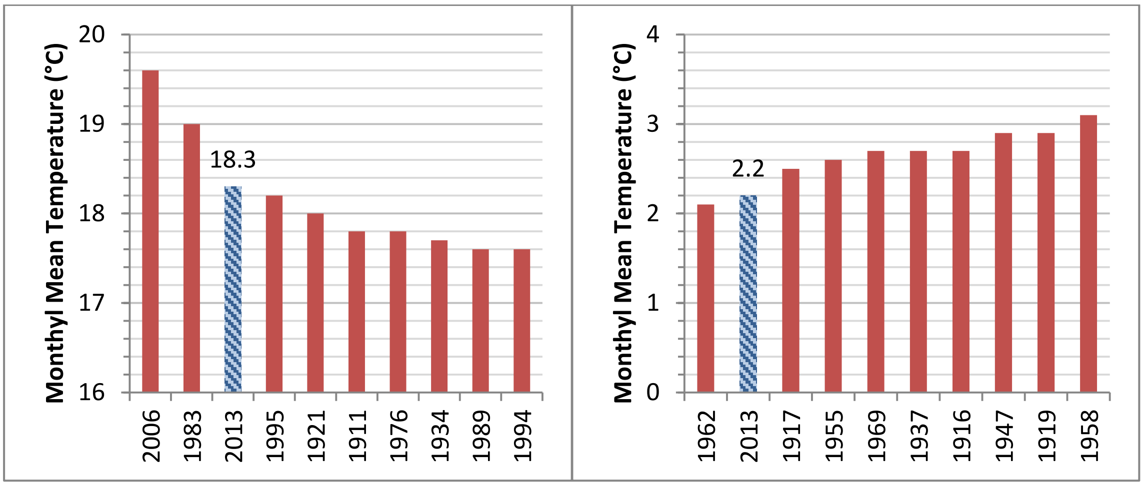



**Figure 6.1 (Left): Hottest July on record: The Midlands region**

**Figure 6.2 (Right): Coldest March on record: The Midlands region**

The first six months of the year were colder than average; as was November (Figures 6.3 and 6.4). July, August, October and December were warmer than the 30 year average period (1981-2010), and September was typical of the average period. The largest deviation was in March, where the mean monthly temperature was 3.9°C colder than average.

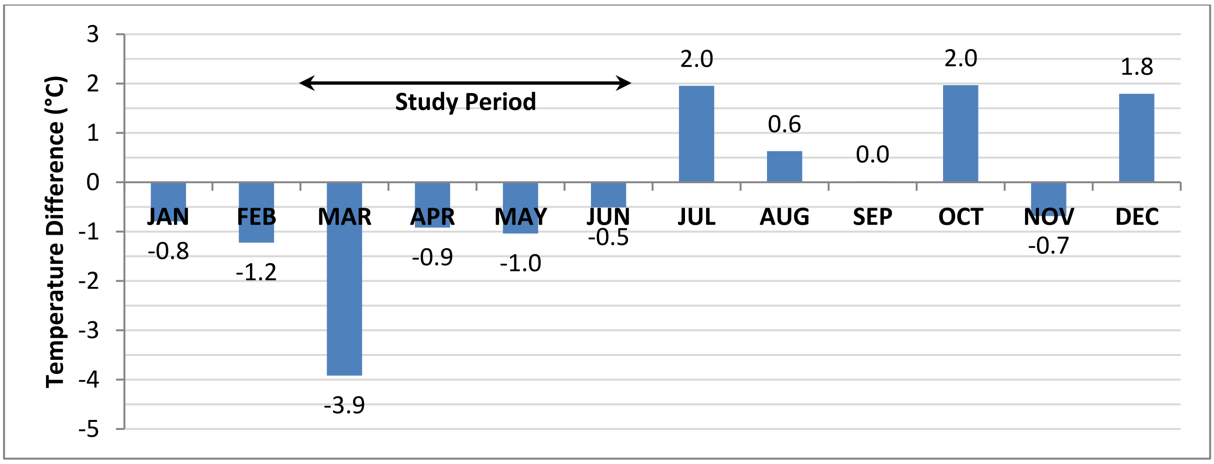



**Figure 6.3: Difference between monthly mean temperature for 2013 and 30 year average (1981-2010) – The Midlands**

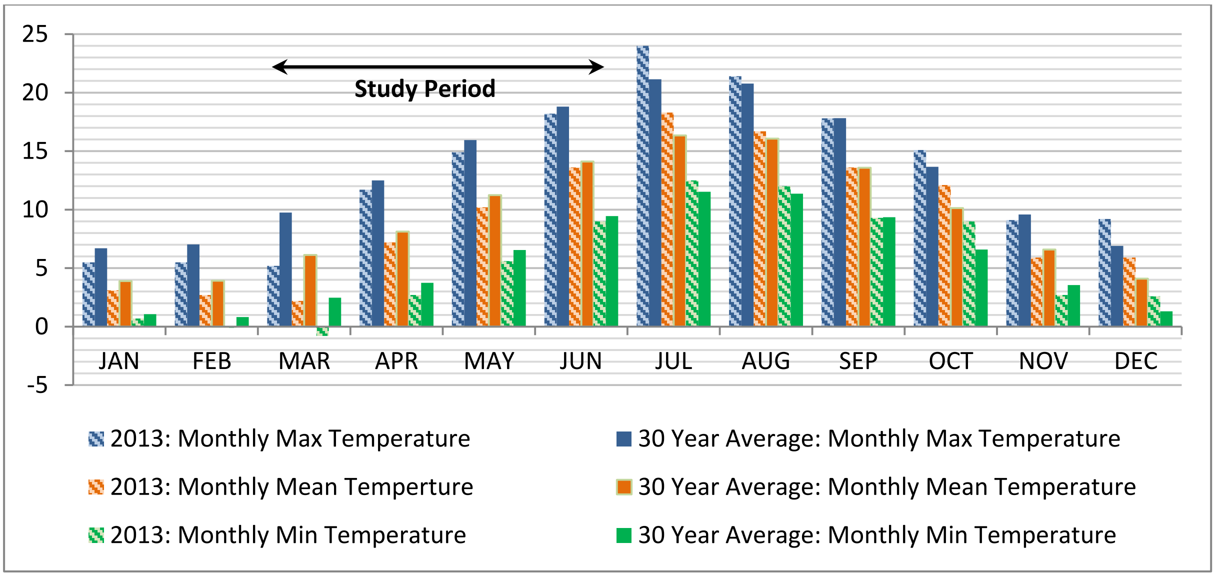
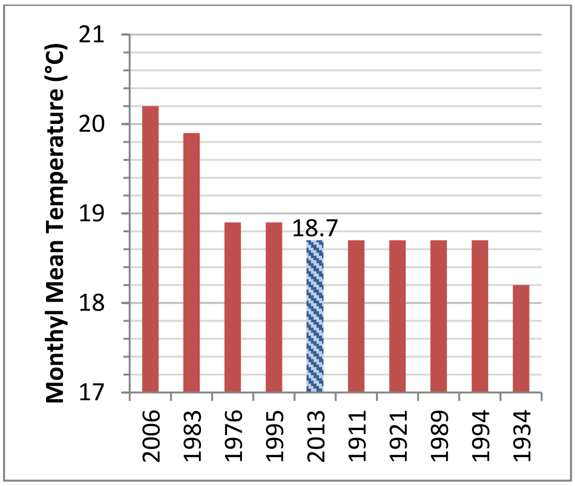



**Figure 6.4: The Midlands 2013 temperature data compared with 30 year averages (1981-2010)**

### 6.2.2 Temperature Anomalies: South East and Central – London Case Study

For the region of South East and Central England [UK Met Office, 2014a], the temperature patterns were much the same as nationally. July 2013 was the fifth hottest month on record since records began in 1910, equalling 1911, 1921, 1989, and 1994 (Figure 6.5). March 2013 was the fourth coldest on record, and the coldest in over 50 years, (Figure 6.6).



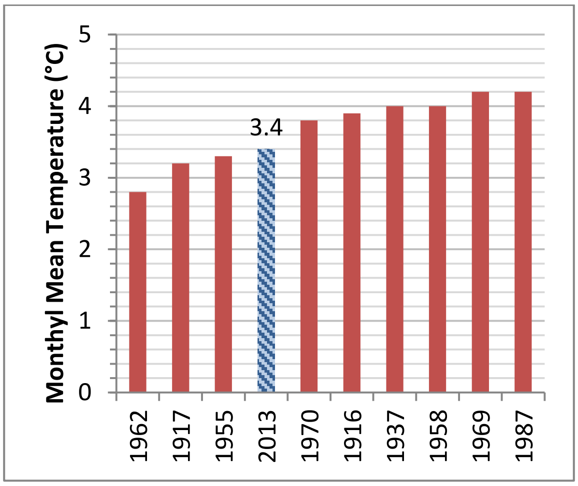




**Figure 6.5 (Left): Hottest July on record: South East & Central Region**

**Figure 6.6 (Right): Coldest March on record: South East & Central Region**

For the region, the first six months of the year were cooler than the 30 year average, as was and November (Figures 6.7 and 6.8). July, August, October and December were all warmer than the 30 year average, and September was very close to the average. The biggest deviation from the 30 year average was during March, where monthly mean temperature was 3.4°C below average. These are the same patterns observed in the Midlands.

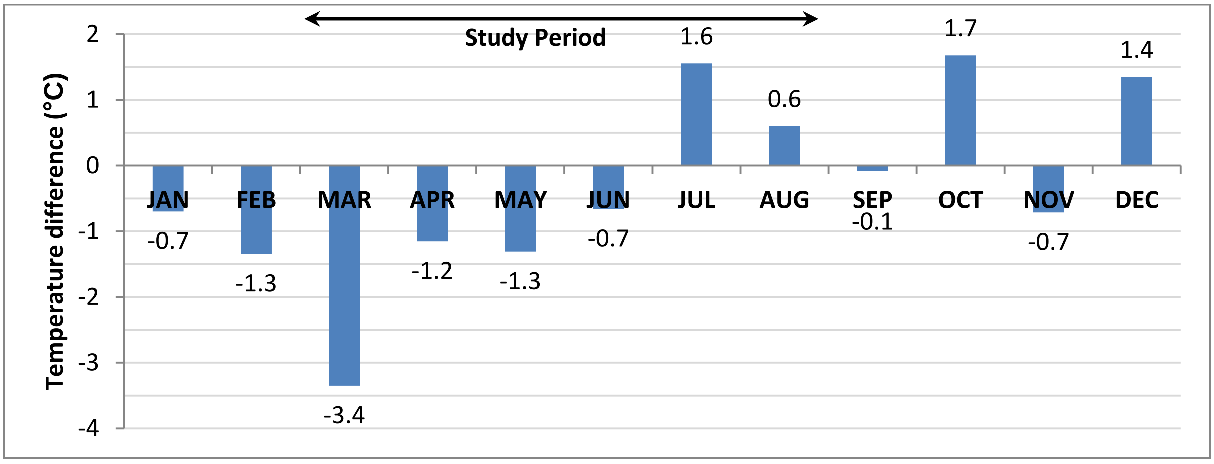



**Figure 6.7: Difference between monthly mean temperature for 2013 and 30 year average (1981-2010) – South East & Central**

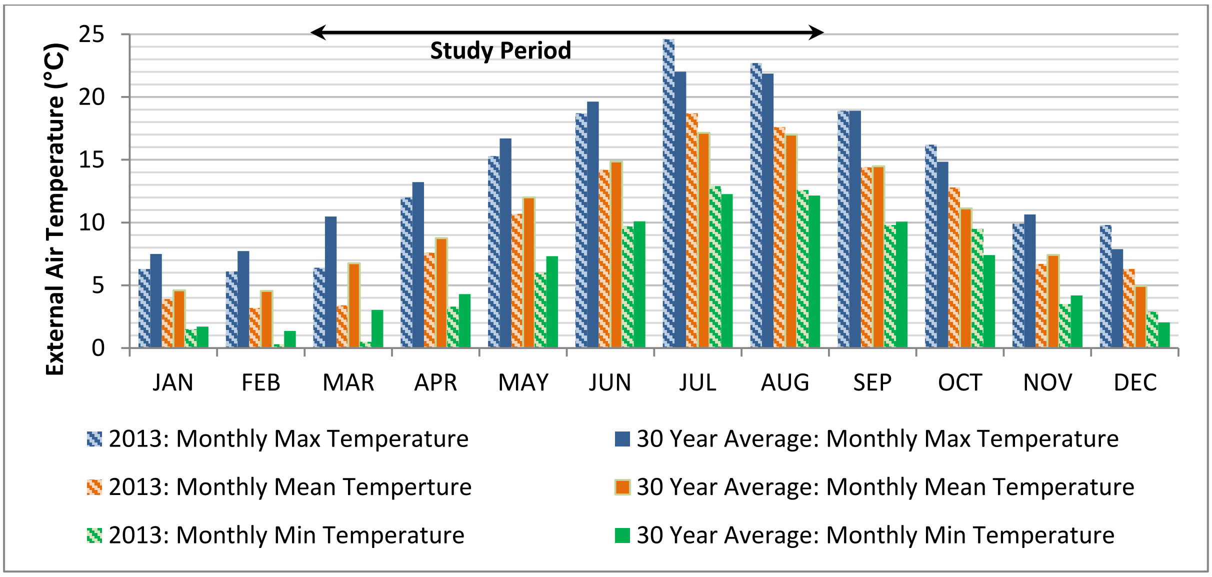



**Figure 6.8: South East & Central 2013 Temperature data compared with 30 year averages (1981-2010)**

## 6.3 Local Weather Station Data

External temperature was measured on site for both case studies; however there were problems with their placement on both sites resulting in unreliable data. Therefore, data were obtained from Met Office land based weather stations [UK Met Office, 2014c and 2014d].

### 6.3.1 Loughborough Case Study

Two standalone Hobo Pendant loggers were fixed to a tree near the case study buildings in March. By the time the sensors were removed the surrounding area had become overgrown with shrubs which increased shading and minimised air flow near the sensors thus creating a thermal buffer. Therefore, there was a concern that the temperature measured on site may not have been reliable throughout the study.

Four local weather stations were identified (Figure 6.9):

1. Loughborough University Campus
2. Sutton Bonington [UK Met Office, 2014c]
3. East Midlands Airport [UK Met Office, 2014c]
4. Nottingham Watnall [UK Met Office, 2014c]

Air temperature measured on site compared well with the three Met Office weather stations, but less so with the campus weather station (Figure 6.10). Concerns over the accuracy of the campus weather station data led to its exclusion.

[redacted]

**Figure 6.9: Local weather stations: 1=Campus station, 2=Sutton Bonington, 3=East Midlands, 4=Nottingham Watnall**

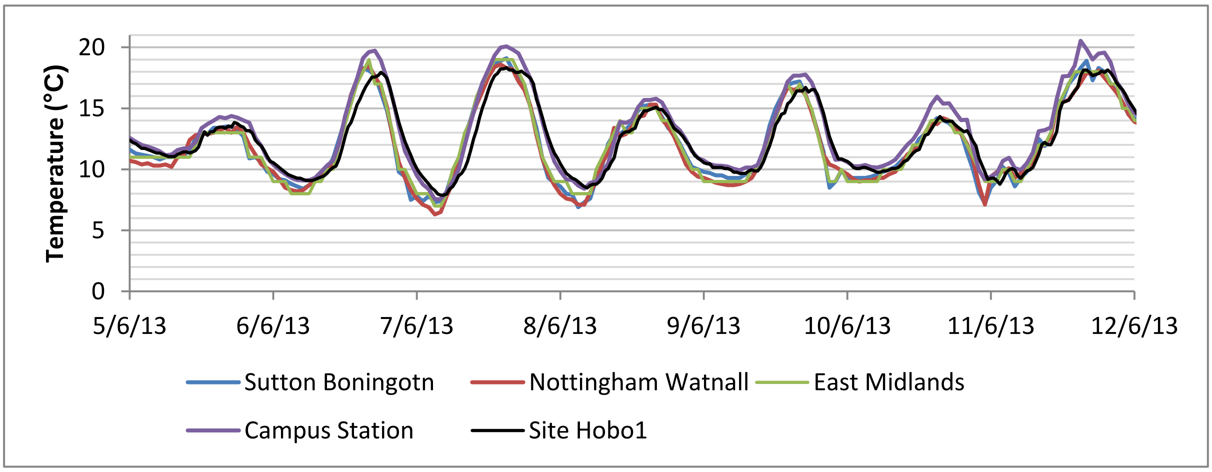



**Figure 6.10: Air temperature data compared between case study site and local weather stations**

A comparison of the three remaining weather stations showed that most measured parameters compared well with each other (Table 6.3); however, temperatures at Sutton Bonington often dropped lower at night, perhaps due to its rural location, and East Midlands station had many gaps in the data that made it unusable. Ultimately, the Nottingham Watnall weather station data were chosen, because although it was furthest away, the site was more comparable and there were few gaps in the data.

**Table 6.1: Local weather station comparison for Loughborough case study**

| Weather Station | Distance (km) | Conclusion |
|---|---|---|
| Loughborough University | 0.98 | Inaccurate data<br>Long gaps in data |
| Sutton Bonington | 7.25 | Night time temperatures low, too rural a site<br>Gaps in data |
| East Midlands Airport | 12.8 | Temperature compared well with site data<br>Frequent gaps in data |
| Nottingham Watnall | 26 | Temperature compared well with site data<br>Least gaps in data<br>All parameters measured including solar radiation |

The Nottingham Watnall weather station data show that the temperature was less extreme than the regional average during 2013, with lower maximum temperatures and higher minimum temperatures than the regional data, (Figure 6.11).

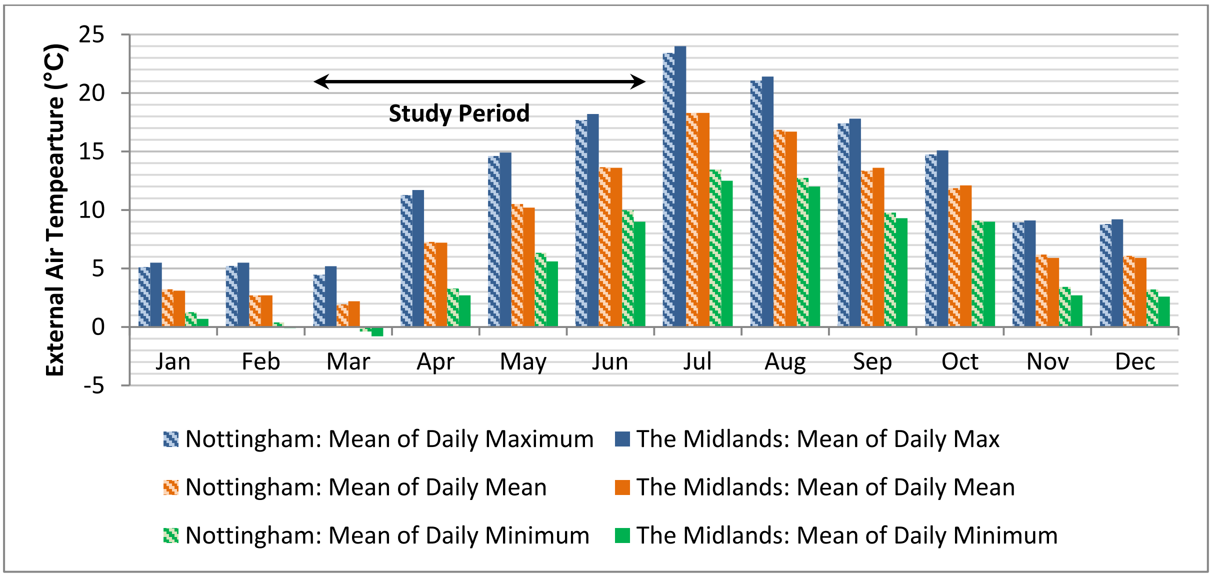



**Figure 6.11: Monthly averages of daily weather data 2013: Nottingham Watnall vs. The Midlands**

The temperature varied by 37.1°C in 2013 (Figure 6.12), from a low of -6.5°C on 17th January to a high of 30.6°C on 1st August. It temperature varied by 26.8°C during the study from a low of -3.9°C on 31st March to a high of 22.9°C on 19th June. It is irrelevant whether there was a heatwave in Loughborough in July because the case study had already ended.

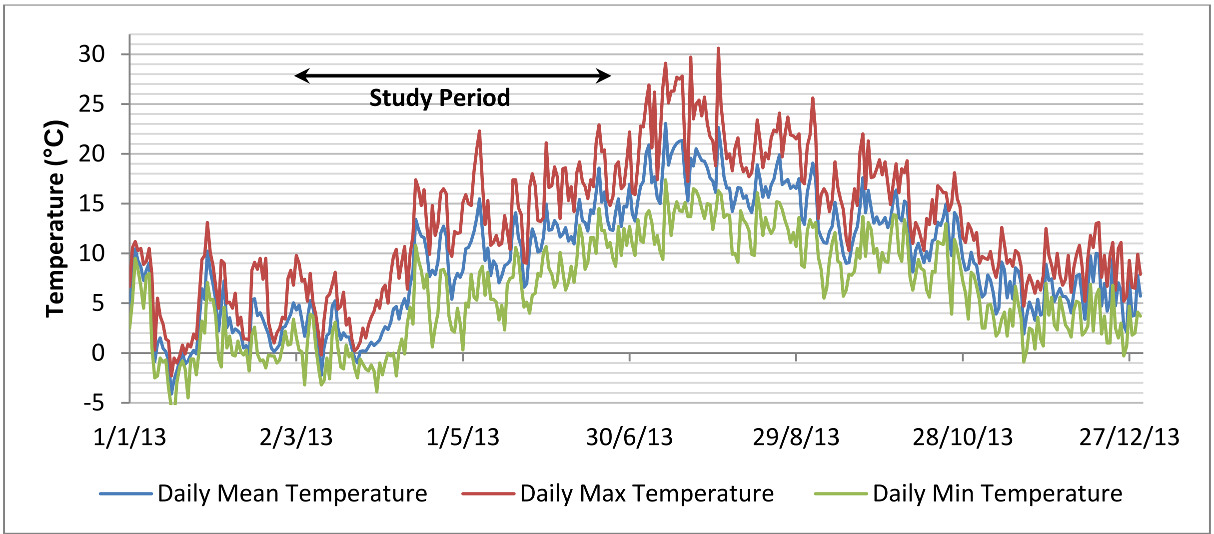



**Figure 6.12: Daily maximum, minimum and mean temperature: Nottingham Watnall weather station 2013**

### 6.3.2 London Case Study

Two standalone Hobo Pendant loggers were fixed to a drain pipe on the north facing façade of the smaller building, which is not truly north facing, but was thought to be sufficiently so to avoid solar insolation. Analysis of the data showed that on sunny mornings the sun perhaps shone onto the sensors, causing readings to spike, (Figure 6.13). This means that the data have errors early in the day, however it is believed that the daily maximum and minimum temperatures are representative of the temperature on site.

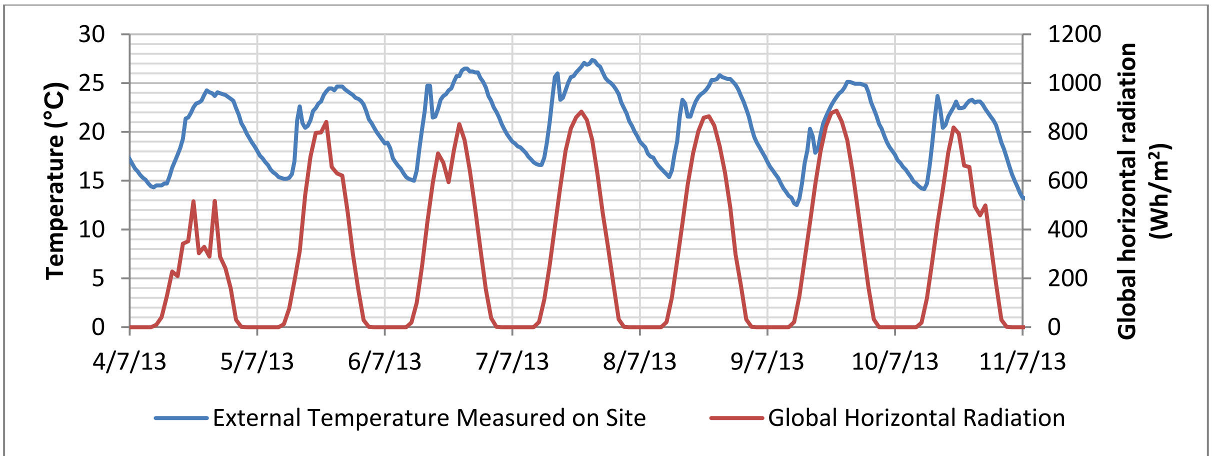



**Figure 6.13: External temperature measured on site showing temperature spikes on sunny mornings**

Four local weather stations were identified (Figure 6.14) [UK Met Office, 2014d]:

1. Kew Gardens
2. St James's Park
3. Hampstead
4. London City

[redacted]

**Figure 6.14: Local weather stations:**
**1=Kew Gardens, 2=St James's Park, 3=Hampstead, 4=London City**

The air temperature measured by the local weather stations was compared well with temperature measured on site, (Figure 6.15).

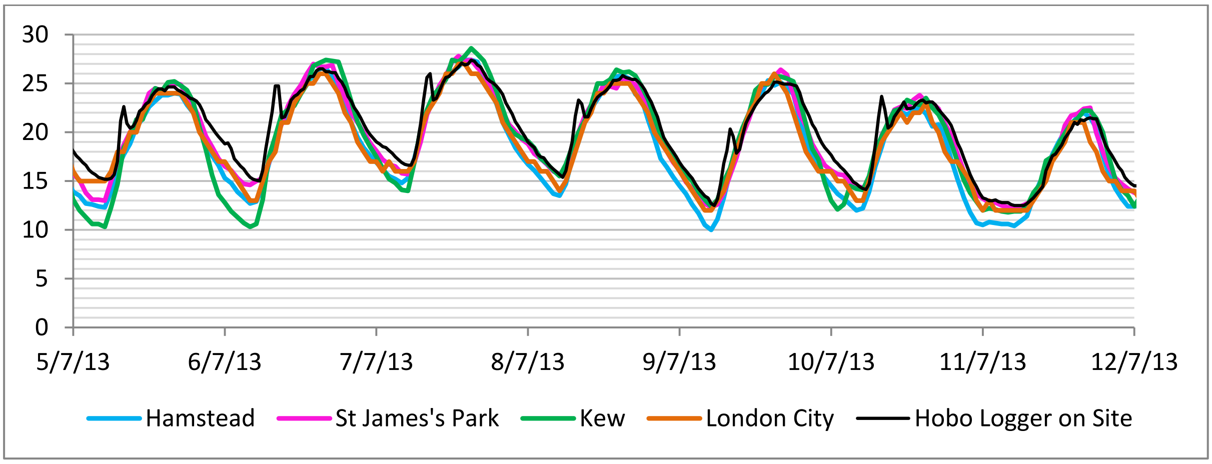



**Figure 6.15: Air temperature data compared between case study site and local weather stations**

The St James's Park weather station was deemed most suitable, (Table 6.3). Although Hampstead was closest to the case study site, it regularly measured lower temperatures at night (as did Kew Garden's weather station).

**Table 6.2: Local weather station comparison for London case study**

| Weather Station | Distance (km) | Conclusion |
|---|---|---|
| Kew Gardens | 20.22 | Night time temperatures typically lower than on site |
| St James's Park | 10.81 | Data compare well |
| Hampstead | 8.92 | Night time temperatures typically lower than on site |
| London City | 12.07 | Data compare but not accurate enough: only whole numbers |

The St James's Park weather station data show that the temperature within London is higher than the regional average, during every month of 2013, (Figure 6.16). This is to be expected since London is a large city with a concentrated population, thermal mass and energy use: whereas the regional data will include both rural and urban data.

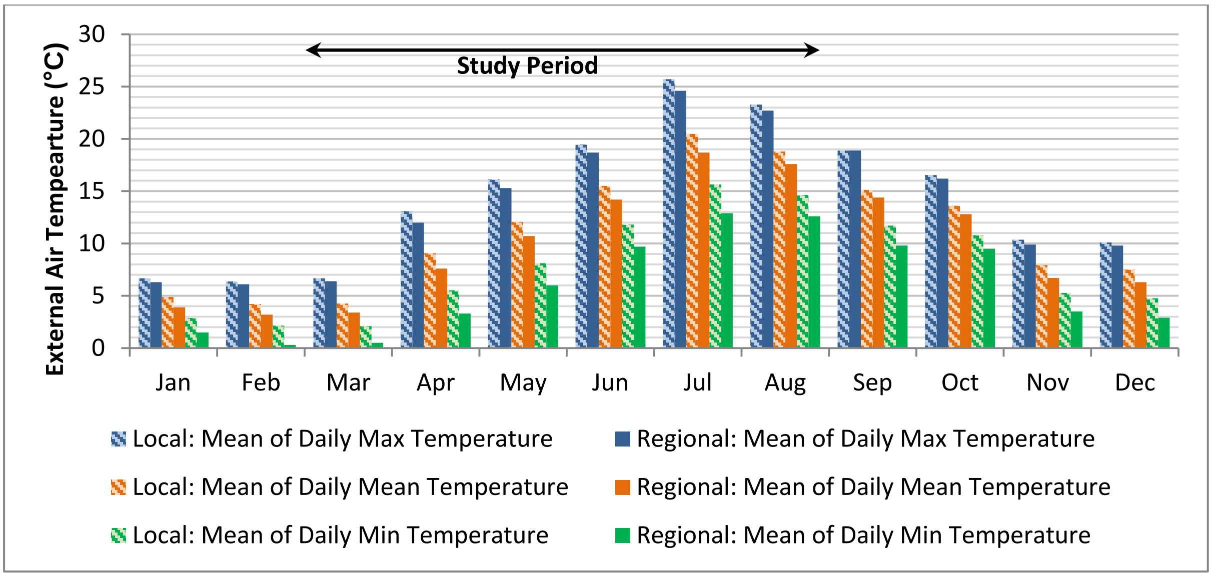



**Figure 6.16: Monthly averages of daily weather data 2013: London compared with Regional**

The temperature varied by 36.3°C during 2013 (Figure 6.17), from a low of -3.5°C on 22nd January to a high of 32.8°C on 22nd July; the lowest temperature measured during the study was -1.4°C on 12th March.

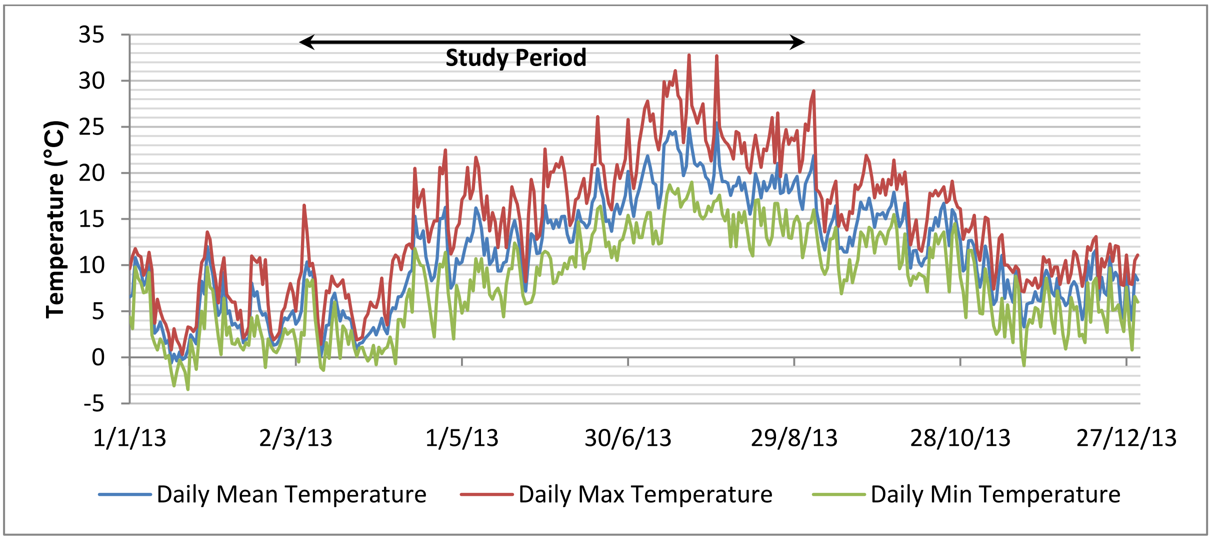



**Figure 6.17: Daily maximum, minimum and mean temperature: St James's Park weather station 2013**

In London the July heatwave did not follow the same pattern as the nationally averaged statistics, (where a temperature of 28°C or above was measured each day from 6th to 24th

July inclusive). The temperature in London only reached above 28°C for five consecutive days from 13th to 19th July inclusive, (Figure 6.18).

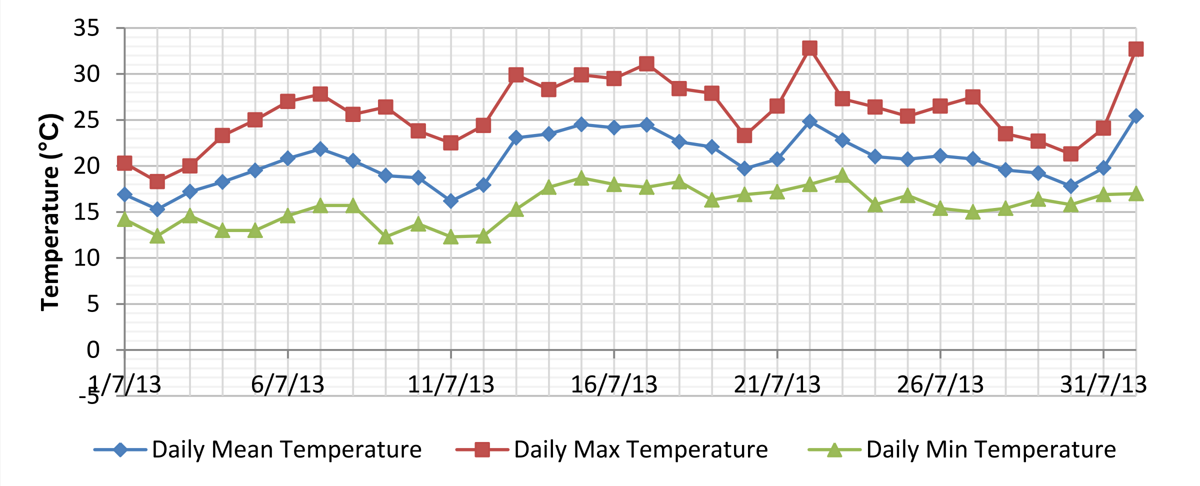



**Figure 6.18: Daily maximim, minimum and mean temperture: St James's Park weather station July 2013**

While The Met Office does not have a formal definition of a heatwave [UK Met Office, 2015], they cite they definition from The World Meteorological Organizarion [WMO, 2015]:

*"…when the daily maximum temperature of more than five consecutive days exceeds average maximum temperature by 5 °C, the normal period being 1961-1990"*

The average maximum temperature for July for the 1961-1990 averaging period is:

- 21.2°C for the South East and Central Region
- 22.2°C for London (measured by the Greenwich weather station)

This means that a temperature in excess of 27.2°C for five consecutive days will class as a heatwave in London. In London temperatures were in excess of 27.2°C for seven consecutive days from 13th to 19th July inclusive, the lowest daily maximum temperature during this period was 27.9°C on 19th July. Therefore, according to the definition, a heatwave did occur in London during July 2013.

Using a more recent data averaging period, (1991-2010), would raise the average maximum temperature in London for July from 22.2°C to 23.2°C. However, the criterion would still be failed on six consecutive days from 13th to 18th July inclusive, and therefore a heatwave would still be deemed to have occurred.

### 6.3.3 London Vs Loughborough

Comparing the temperature data used for both sites shows that London was nearly always warmer than Loughborough, on average 1.8°C warmer in 2013, (Figure 6.19). This confirms that London is a more suitable location to investigate overheating than Loughborough.

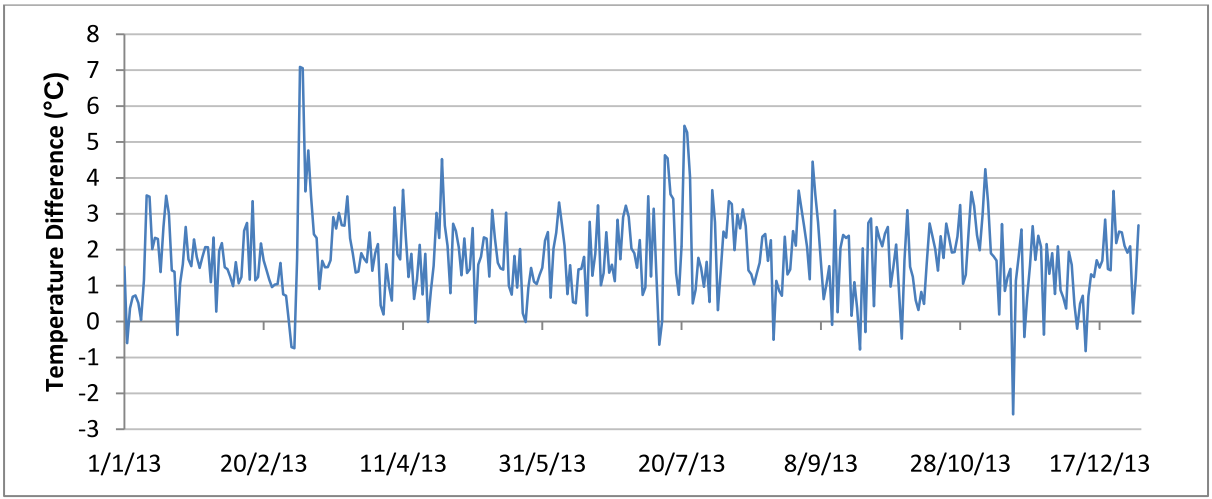



**Figure 6.19: Difference in daily mean temperature: London minus Loughborough**

## 6.4 Adaptive Thermal Comfort

In order to conduct an overheating analysis using the adaptive approach it is necessary to calculate the exponentially weighted running mean of the daily mean outdoor temperature, $T_{rm}$ (from herein referred to as running mean temperature) [CIBSE, 2015]:

$$T_{rm} = (1 - \alpha)(T_{ed-1} + \alpha T_{ed-2} + \alpha^2 T_{ed-3} \ldots)$$ **Equation 6.1**

The running mean temperature is calculated using the daily mean temperature, which was calculated from hourly temperature data from the local weather stations [UK Met Office, 2014c and 2014d]. The running mean temperature was calculated for each day in both studies using the preceding 30 days of data, (the simplified calculation was not used, 30 days of data were used for each calculation). A value of 0.8 was used for α, other values were tested but had little impact on the overheating results.

The band of comfort temperatures and the upper allowable temperature ($T_{upp}$) were calculated from the running mean temperature for a category II building from 1st May until the 30th September (Figures 6.20 and 6.21) [CIBSE 2015]:

$$T_{comf} = 0.33T_{rm} + 18.8$$ **Equation 6.2**

$$T_{max} = T_{comf} + 3 = 0.33T_{rm} + 21.8$$ **Equation 6.3**

$$T_{min} = T_{comf} - 3 = 0.33T_{rm} + 15.8$$ **Equation 6.4**

$$T_{comf} = 0.33T_{rm} + 18.8$$ **Equation 6.5**

$$T_{upp} = T_{max} + 4 = 0.33T_{rm} + 25.8$$ **Equation 6.6**

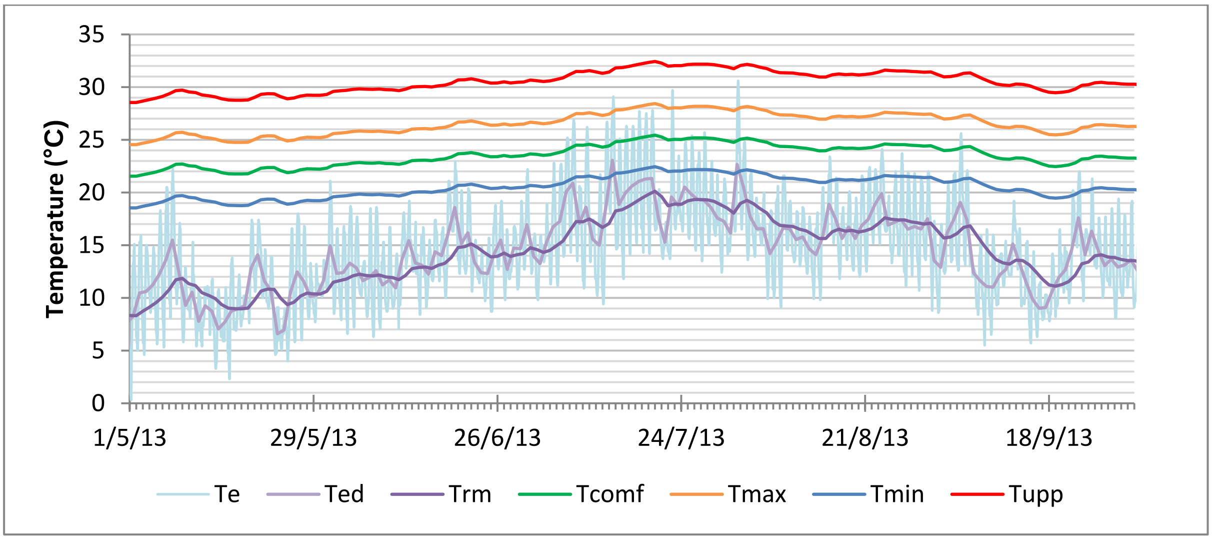



**Figure 6.20: Loughborough adaptive thermal comfort temperatures: 2013 – Category II building**

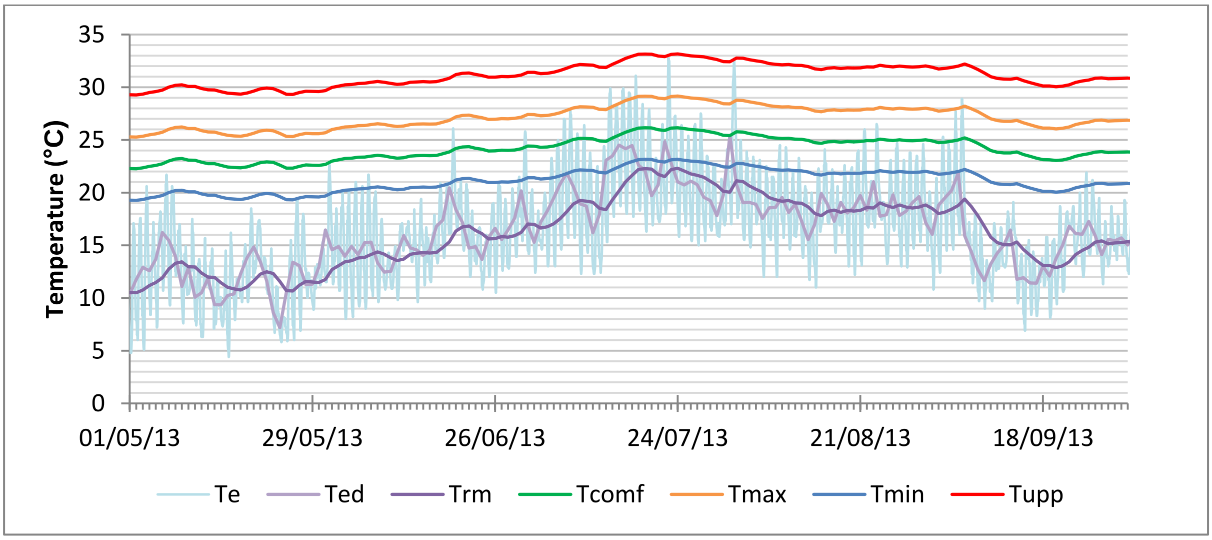



**Figure 6.21: London adaptive thermal comfort temperatures: 2013 – Category II building**

From May to September 2013 the temperature in London was, on average, 1.84°C higher than in Loughborough, however the comfort temperature in London was only 0.6°C higher on average than in Loughborough due to relationship between comfort temperature and running mean temperature (Figure 6.22).

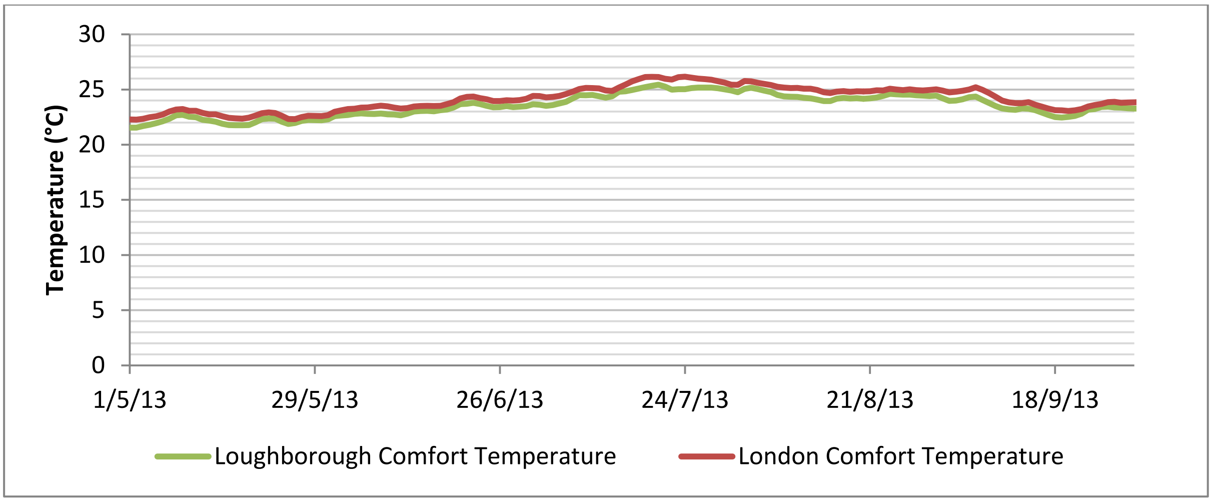



**Figure 6.22: London and Loughborough adaptive thermal comfort temperatures compared**

## 6.5 Chapter Summary

This chapter has focused on the external temperatures during the case study periods. It provided information about national temperature statistics for the period, followed by regional data for the Midlands and for South East and Central England, and finally data from local weather stations. It showed that in 2013 in both regions (as well as nationally), March was especially cold and July was especially warm to the extent that there was a heatwave. The chapter finished by discussing adaptive thermal comfort, and how comfort temperatures were calculated using temperature data from weather stations near the case study sites. It was essential to understand the weather conditions during the study periods, because the building thermal performance is influence by the weather, because temperature data were needed for the overheating analyses, and because it is important to put the results in context, to understand if the data were collected during average or extreme conditions.

# Chapter 7 – Fabric Thermal Performance

This chapter presents the findings with regard to the fabric thermal performance of [redacted] buildings. It primarily uses data from the Loughborough case study, and therefore the main focus is on those buildings; however it was also possible to draw some conclusions about [redacted] buildings in general.

The data used came from numerous methods:

- Blower door tests
- Infrared thermal imaging
- Building inspection
- Photographs from construction sites
- Design and construction documentation

Data from individual methods led to findings about fabric thermal performance, such as sources of air leakage from blower door tests, and the presence of thermal bridges from IR thermal images. Triangulation of data from multiple methods also led to further and more detailed findings, which could not be reached from individual methods alone. This chapter begins by detailing the data collection methods, before presenting findings about specific aspects of building thermal performance, namely:

- Airtightness
- Thermal bridging
- The breather membrane
- Installation of insulation
- Design and construction quality
- Project management and responsibilities

## 7.1 Data Collection Methods

### 7.1.1 Blower Door Tests

Blower door tests were carried out in three individual flats in the north building in August 2013 while the building was vacant (Figure 7.1).

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**Figure 7.1: South facing elevation of north building indicating blower door test flats [Architect 2, 2006]**

The advice for testing student halls of residences is to test whole blocks, but the fan equipment was too small to achieve pressurisation of whole blocks, so only individual flats could be tested. This meant that the blower door equipment had to be fitted to the main entrance door of the test flats, which were internal doors (Figures 7.2 and 7.3). The pressure tubing supplied with the equipment was short, and it was not possible to place the external tubing outside the building; instead it was placed in the stair core (Figure 7.3), which was normalised with atmospheric pressure as much as possible by opening the external door and windows in the stair core. The test flats were selected for the following reasons:

**Figure 7.2: Blower door equipment setup in main entrance door of test flat**

- The flats have a large area of external walls and small area of internal party walls, which is important because the test aims to measure the external fabric
- The test flats were fully modular, so the tests focus on modular performance
- The flat entrance door aligned with the flat corridor, which helps fan pressurisation
- The stair core had a simple layout, helping to normalise pressure with outside

There were uncertainties about how best to conduct the tests; primarily in how to treat the adjacent flats. Multiple tests were carried out, with variable door and window positions (open or closed) in the adjacent flats, to determine the optimal setup. The variation in results between different setups was very small, and it was concluded that the setup of the adjacent flats was not critical, other than to ensure to repeat the same setup for each test so the results could be compared.

The three flats were tested using test method A (ventilation ducting and trickle vents unsealed), only Flat 4 was tested with test method B (ventilation ducting and trickle vents sealed), due to difficulties sealing the extract vents in the shower pods.  The surface area used in the calculations was for the whole area of surfaces that bounded the tests zone, including the floor (100.9$m^2$), ceiling (100.9$m^2$), internal walls (37.6$m^2$) and external walls (74.7$m^2$), which is the advised approach for non-standard tests [British Standards Institution, 2001; DCLG, 2016].

All tests had the following features:

- Multi-point depressurisation test
- Horizontally and vertically adjacent flats: All windows and doors closed
- Stair core: All windows and main door open

There were no issues with the quality of the data obtained from the blower door tests.  The external wind speed was low during testing, averaging between 3.6m/s and 4.2m/s, with a maximum of 5.1m/s on the third test day [UK Met Office, 2014c], therefore it did not impact on the accuracy of the test.

***Copyrighted content redacted***

**Figure 7.3: Architect's plan drawing marked to show setup of blower door equipment for testing individual flats [Architect 2, 2006]**

### 7.1.2 Infrared Thermography

The infrared thermal images were taken of the external facade on two days: the 8th and 12th of February 2013. The imaging of the external facade was intentionally done on cold, dry, overcast winter days, early in the morning shortly after sunrise, for the reasons described in Chapter 3.10.

In hindsight the images taken could have been improved. Inexperience in optimising images meant that many images were not taken perpendicular to the facade, which is ideal. There was no possibility to retake the images after this was realised. However, the same temperature variation patterns were observed irrespective of angle; therefore the angle did not appear critical, and the images were deemed to be acceptable.

### 7.1.3 Building Inspections

The Loughborough study was inspected internally and externally with the aim of identifying anything that could be detrimental to fabric thermal performance. While multiple visits were made to the London study, inspection of the fabric was not really possible because the near constant occupancy did not allow access inside modular rooms, and it was difficult to inspect the external fabric from the ground floor (particularly because the cladding on the non-modular ground floor differed from the modular storeys above). Therefore findings from inspections relate to the Loughborough study only.

### 7.1.4 Review of Construction Photographs

A review of the photographs from the factory and construction sites was conducted to investigate the thermal performance of the fabric.

Photographs taken during visits to the factory helped provide a detailed understanding of the modules, but they yielded few findings about fabric thermal performance. The visits were made in the early stages of the research; the aim of those visits was to gain a general understanding of the design and manufacture. Therefore, the data collected were not best suited for assessing thermal performance, because there was insufficient focus on the relevant details, such as junctions.

Construction site photographs were included in the design documentation obtained from [redacted] however there was no consistency between the documents for different buildings, some contained many photographs, and others none. The majority of images focussed on the modular construction (module installation and modular interfaces); there were far fewer of cladding, roofs, foundations, non-modular construction, curtain walling, and the interfaces between these features and the modular construction. Therefore, it was not possible to analyse all aspects of construction on site using the photographs.

### 7.1.5 Review of Design and Construction Documentation

[redacted] provided access to much of their documentation, which included generic documentation and project specific documentation.

The generic design and construction documents detailed the standard module design (for low and medium-rise construction), dimensions, materials, fire testing, acoustic testing, structural integrity, U-Value calculations, interstitial condensation analyses, thermal bridging calculations, and manufacturing drawings used in the factory.

Project specific documentation was obtained for most [redacted] buildings, and primarily comprised AutoCAD drawings detailing various design aspects, but also meeting minutes, costing information, photographs, material specifications, structural analyses etc. The types, quantity and quality of documentation varied significantly between projects.

Time was spent reviewing these documents, particularly for the case study buildings, to understand the design of the buildings and to assess the quality of the design in terms of thermal performance and buildability.

## 7.2 Findings on Airtightness

Good airtightness of a building's envelope helps minimise heat losses, keep energy use low, avoid the occurrence of condensation and optimise the operation of mechanical ventilation. Data from various methods were used to identify specific air leakage routes that if eliminated would improve airtightness.

The blower door test measured Q50 air leakage rates at 7-9$m^3/(h.m^2$ surface area) (Table 7.1). The airtightness required by the Building Regulations at the time of construction was 10 $m^3/(h.m^2$ surface area) [DCLG, 2016]. Flat 4 on the ground floor performed worst, Flat 5 performed slightly better, and Flat 6 performed notably better than Flats 4 and 5. It is unclear whether this is a trend, with better performance on higher storeys; it was not possible to undertake additional tests. Since whole blocks could not be tested, the tests were not ideal, and the results were not only a measure of air leakage through the external fabric, but also of the partitions between adjacent zones. It is unclear how much air was drawn through the external envelope from outside, and how much was drawn through the internal fabric from adjacent zones; therefore the tests are not an accurate measure of air leakage through the external fabric, and they cannot be compared with the results from other tests or benchmarks.

**Table 7.1: Blower door test results: Loughborough case study**

| Flat | Test method | Airflow at 50Pa | | | | Leakage Areas | |
|---|---|---|---|---|---|---|---|
| | | V(50) $m^3/h$ | **n50 ACH (1/h)** | w50 $m^3/(h.m^2$ floor area) | **q50 $m^3/(h.m^2$ surface area)** | Canadian EqLA @ 10Pa | **LBL ELA @ 4Pa** |
| Flat 4 | **A** | 2811 | **11.41** | 27.86 | **8.95** | 1088.4 | **574.6** |
| Flat 4 | **B** | 2797 | **11.35** | 27.72 | **8.90** | 1102.1 | **587.8** |
| Flat 5 | **A** | 2687 | **10.90** | 26.63 | **8.55** | 1102.6 | **601.7** |
| Flat 6 | **A** | 2219 | **9.00** | 21.99 | **7.06** | 870.0 | **462.7** |

The tests were however useful for determining the location of air leaks, by depressurising each test flat to approximately 20-30Pa; the majority of leaks were identified by hand. A limited number of IR thermal images were taken under depressurisation, but a fault with the camera meant extensive imaging was not possible. Air leakage paths can be convoluted, blower door tests do not fully explain how air permeates through the fabric, but through the triangulation of data from other methods identification of some air leakage paths was possible. Two key areas of weakness were identified: at the party wall junctions between modules and at the curtain walling.

### 7.2.1 Party Wall Junction between Modules

Within the modules strong air leaks were found coming through the various sockets (Figures 7.4 and 7.5). No other leaks were detected, including around the windows or at the junctions between walls, floors and ceilings.

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**Figure 7.4 (left): Air leakage path through sockets in modules: Loughborough case study**

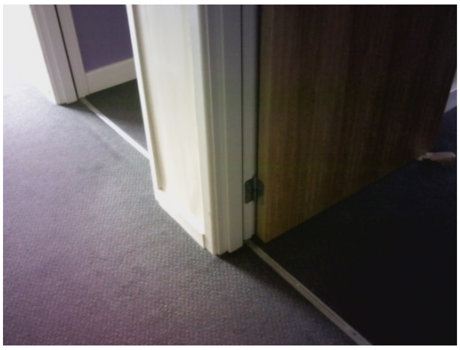
**Figure 7.5 (right): Architect's plan drawing marked to indicate the location of sockets in bedroom and kitchen modules [Architect 2, 2006]**

Air leaks were also detected along the full length of the corridor at floor and ceiling level where the corridor and modules interface (Figures 7.6 and 7.7).

**Figure 7.6 (left): Air leakage paths along corridor ceiling indicated in red**

**Figure 7.7 (right): Air leakage paths along the corridor floor indicated in red**

Along the corridors, the leaks were strongest at ground level around the door frames where two modules interface (Figures 7.8 and 7.9).



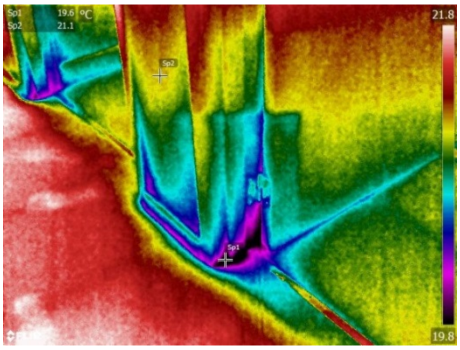



**Figure 7.8 (left): Air leakage paths around module door frames and corridor floor**

**Figure 7.9 (right): Corresponding IR thermal image showing corridor floor and module door frames**

In the IR thermographic images of the external facade interesting variations in apparent temperature were seen, corresponding to the vertical party wall junctions between modules (Figures 7.10 to 7.13). These patterns are indicative of hot plumes of air rising in the cavity and hitting the outer leaf of the wall, and suggest that hot air is escaping from inside the building at these locations. The plumes vary in their occurrence and intensity, and were not observed at every party wall junction between modules, which suggests a variation in the quality of the construction in these areas, with some junctions performing better than others.

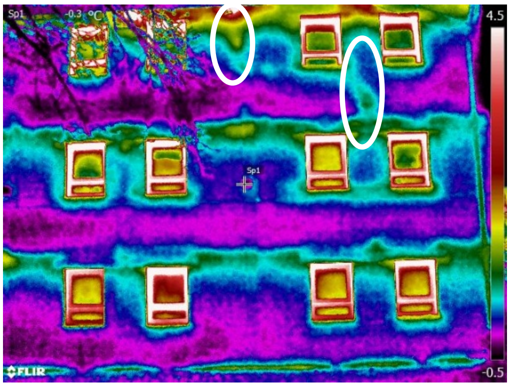


**Figure 7.10 (left): IR thermal image of modular walls with windows with brick cladding, plumes marked**
**Figure 7.11 (right): Corresponding photograph showing position of lintels and masonry support system**

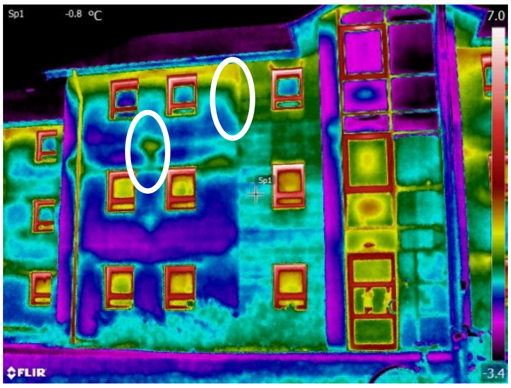


**Figure 7.12 (left): IR thermal image of brick and timber clad wall, plumes marked**
**Figure 7.13 (right): Corresponding photograph of brick and timber clad wall**

Analysis of the generic and project specific documentation obtained from [redacted] (which included documents from contractors) found no mention of an air barrier, and no drawings detailing its design, its location within the external envelope, or how continuity should be achieved across the envelope. Some [redacted] buildings may have an air barrier, if other members of the design team (such as the principal contractor or architect) ensured it was designed and constructed. However, the failure to find any mention or drawing of air barriers in any documents suggests that its design may typically have been overlooked, and that many (or perhaps all) [redacted] buildings contained no intentionally designed air barrier, including the Loughborough and London case studies.

Air barriers can be provided by dry lining, such as within each module, if the joints and penetrations are correctly sealed. This explains why few leaks were detected within the modules under depressurisation with the blower door kit. However, at the party wall junctions between modules, there are no materials that can act as an air barrier. There is a

25mm air gap at the party wall junction between modules; at each end of these junctions are voids measuring 100mm by 175mm (Figures 7.14 and 7.15). The externally facing voids are filled with rock wool insulation before being covered with rigid insulation and cladding. The internally facing voids are simply covered with two layers of plasterboard, which form the corridor walls. No evidence was found of any further measures taken to seal the party walls junction between modules.

**Figure 7.14: Air gap at party wall junction between modules [[redacted] 2012]**

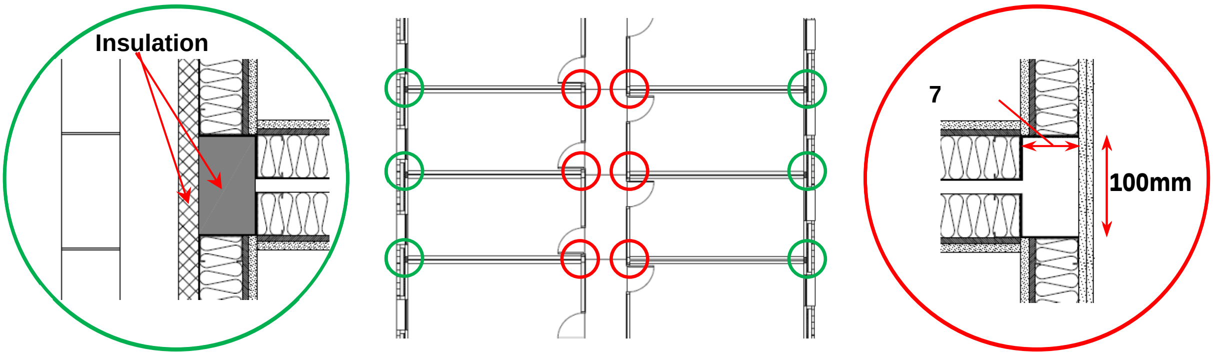
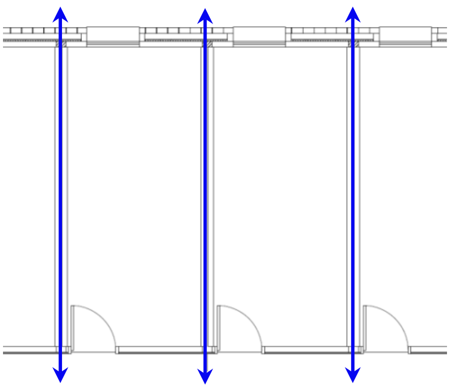



**Figure 7.15: Plan drawings detailing the party wall junction between modules**

The insulation used externally cannot act as an air barrier, and while the dry lining used internally could, the detailing is not sufficient to achieve this (and would actually be quite difficult to achieve even with concerted effort, furthermore it would not be the preferred location for the air barrier [DCLG, 2007]). This means that air can exchange between the internal and external environments via the party wall junction between modules (Figure 7.16). This conclusion is supported by the location of air leaks detected during depressurisation with the blower door kit, which were through the sockets in module walls and along the corridor floor and ceiling where it interfaces with the modules, (Figure 7.17).



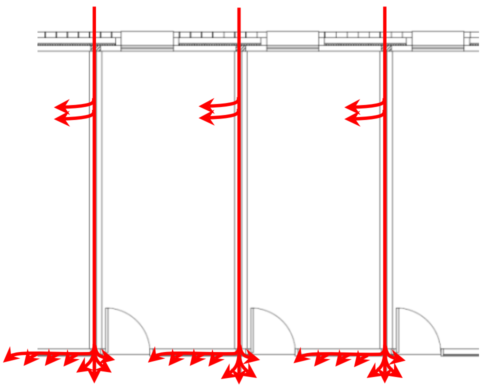


**Figure 7.16 (left): Plan drawing of modules showing air leakage paths through cavities in the party walls**
**Figure 7.17 (right): Plan drawing of modules showing air leakage paths under depressurisation**

This conclusion is also supported by the IR thermographic images that show plumes of hot air at the wall junctions between modules. [redacted]

[redacted]

The insulation, if correctly fitted may slow the transfer of air, but any gaps in the insulation act as thermal bypasses, which create routes of minimal resistance for the air to escape (Figure 7.19). That plumes were evident at only some junctions, [redacted].

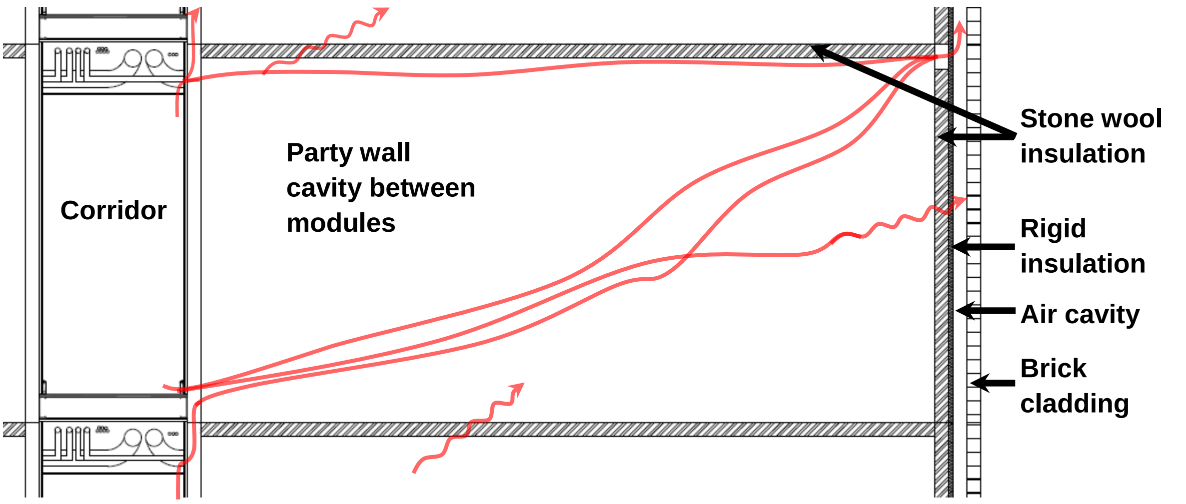



**Figure 7.19: Section drawing of the party wall junction showing thermal bypasses**

### 7.2.2 Curtain Walling

During depressurisation with the blower door kit large quantities of air were found leaking through the interface between the curtain walling and the corridor, both horizontally and vertically (Figures 7.20 and 7.21).

**Figure 7.20 (left): Air leakage paths shown in in red around bottom of curtain walling**

**Figure 7.21 (right): Air leakage paths shown in red around top of curtain walling**

The strongest air leak was at the interface with the floor (Figures 7.22 and 7.23). The curtain walling is connected to the corridor with a wooden frame, but there was no evidence of any seals between them, so air can pass freely into and out of the flat at this interface.

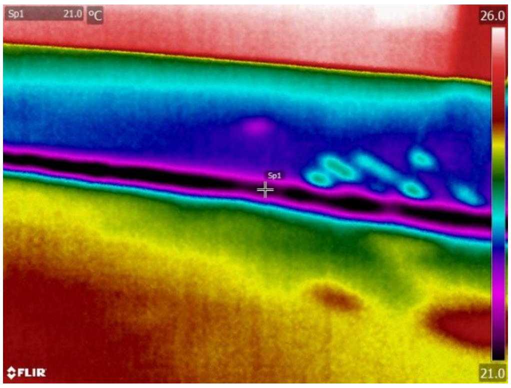



**Figure 7.22 (left): photo of curtain walling indicating location of spot on IR thermal images**

**Figure 7.23 (right): IR thermal image of curtain walling showing main leakage path**

The detailed section drawings of the curtain walling show a design that is weak in terms of thermal performance (Figures 7.24 and 7.25). The curtain walling is in-line with the external cladding and there is a large gap between the curtain walling frame and the corridor end panels that leads directly into the cavity in the external wall, this gap has basically just been boxed in with a wooden frame. The drawings show no sealing around the wooden frame and no evidence of an air barrier, which would stop the exchange of air with between the internal environment and the cavity in the wall. It is also likely that air can exchange between the corridors on different storeys via the unsealed wooden frames.

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**Figure 7.24 (left): Section drawing of curtain walling interface with corridor [Architect 2, 2006]**

**Figure 7.25 (right): Plan drawing of interface between curtain walling, module and cladding, edited to show module wall layers and steel [Architect 2, 2006]**

The IR thermal images taken externally of the curtain walling appear to agree, that there is air movement between the internal environment and the cavity wall around the curtain walling. The apparent temperature distribution around the curtain walling is irregular, particularly at the junctions between floor and ceiling, and this indicates that hot air is escaping from the internal environment in these areas (Figures 7.26 to 7.29).

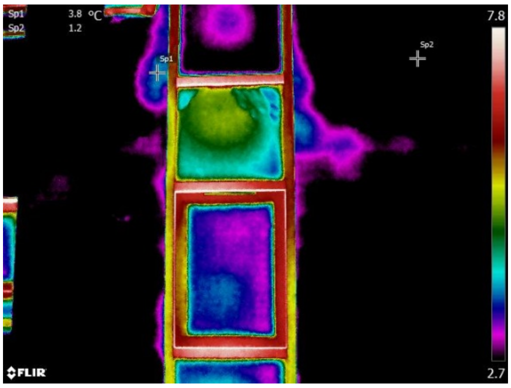

**Figure 7.26 (left): IR thermal image of curtain walling – irregular temperature indicates air leakage**

**Figure 7.27 (right): Corresponding photograph of curtain walling in render clad wall**

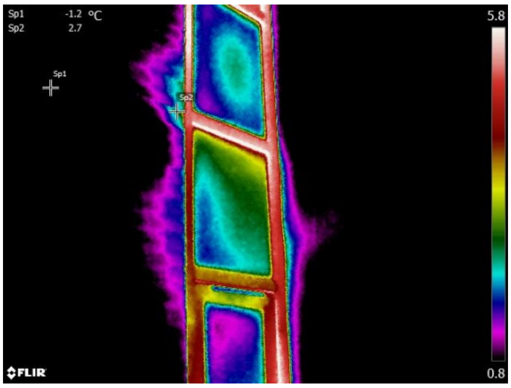

**Figure 7.28 (left): IR thermal image of curtain walling – irregular temperature indicates air leakage**

**Figure 7.29 (right): Corresponding photograph of curtain walling in render and brick clad wall**

### 7.2.3 Airtightness Discussion

By combining data from multiple methods, air leakage routes were identified at the party wall junction between modules and at curtain walling where it interfaces with modules and cladding. It was determined that there is no continuous air barrier in the external envelope, individual modules have good airtightness due to the dry-lining that comprises the internal surfaces (with the exception of air leaks through the plug sockets), but the spaces between the modules are not airtight. [redacted] informed that they had pressure tested individual modules (but they did not provide the data), indicating they had clearly thought about airtightness, but it appears only at the modular level, and not between modules or in panelised corridors. Within construction projects, [redacted] acted as a sub-contractor, supplying offsite modules and corridor panels, they explicitly stated that they had no responsibility for the airtightness of whole buildings. However, [redacted] were well placed to devise standard solutions between modules and where corridors interface with external walls. Based on the data from multiple sources it seems likely that airtightness between modules and in corridors was either overlooked altogether, or there was the misconception that the performance achieved by individual modules translated to the whole structure. There may also be other weak areas in the external envelope, such as at interfaces with the ground and roof, but this cannot be determined with confidence with the data available. The correct design and construction of the air barrier is essential if energy use is to be minimised within buildings, possible solutions are discussed in Section 7.9 Recommendations.

## 7.3 Findings on Thermal Bridging

Large quantities of heat can be lost through thermal bridges in the external envelope, condensation can also form around bridges which can lead to fabric degradation, damp, and further reductions in fabric thermal performance. To minimise the energy use of buildings, it is necessary to minimise thermal bridging. Data from various methods were used to identify the following thermal bridges that, if minimised or removed would improve fabric thermal performance: masonry support systems, lintels, modular windows, and curtain walling.

### 7.3.1 Masonry Support Systems

As discussed in Chapter 5.1, the presence of certain weep holes in the external facade indicates that masonry supports systems were used in the Loughborough study; it is believed they were typically used in all [redacted] buildings with masonry cladding. The IR images agree with this view, revealing horizontal lines with elevated apparent temperatures at approximately ceiling height on each storey confirming that masonry supports are present and that they act as thermal bridges (Figures 7.30 to 7.33). In the IR images, the masonry supports typically had apparent temperatures 1-2°C higher than the coldest parts of the wall.

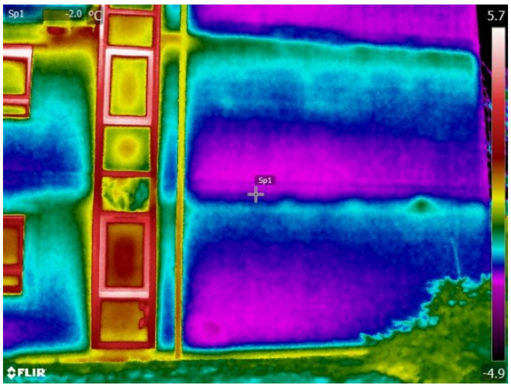

**Figure 7.30 (left): IR thermal image shows elevated temperatures due to masonry supports**

**Figure 7.31 (right): Corresponding photograph with masonry support thermal bridges marked in red**

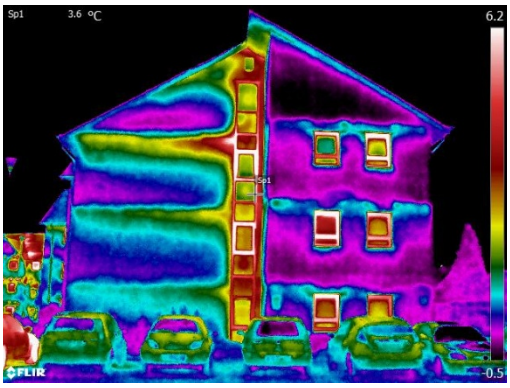

**Figure 7.32 (left): IR thermal image shows elevated temperatures due to masonry supports**

**Figure 7.33 (right): Corresponding photograph with masonry support thermal bridges marked in red**

The design documents for the Loughborough study [redacted] were little help in determining the presence or design of the masonry supports. There were however some details of masonry support systems in the generic documentation and in the documentation for other projects provided by [redacted] including photographs from another construction site showing masonry supports (Figure 7.34). Based on these data it was determined that the masonry support systems are typically steel angles fixed directly to the modular frame.


**Figure 7.34: Construction site photograph showing numerous steel angles fixed directly to modules [[redacted] 2012]**

### 7.3.2 Lintels

The IR thermographic images identified thermal bridging through lintels above windows in the masonry clad walls (Figure 7.35), because the walls had elevated apparent temperatures where the lintels are located. The masonry support systems do not appear to be present above the lintels, only in sections of wall where there are no lintels, and this makes sense because the lintels and masonry supports perform the same function so there is no need to use both on the same vertical section of wall. Figure 7.34 above shows that the lintels and the masonry supports are actually identical steel angles, their design and function is the same and they differ only in name. The images show that the masonry support system is at approximately ceiling height, but the lintels are at a lower height. The combination of thermal bridging from window lintels and the masonry support system, results in a stepped line of increased apparent temperature running horizontally along the length of the walls on each storey (Figure 7.36). In the IR images, the lintels typically had apparent temperatures 1-2°C higher than the coldest parts of the wall.

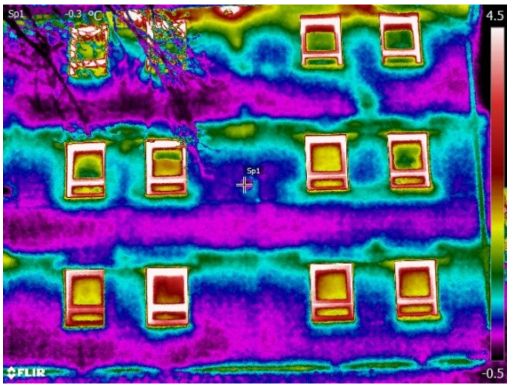


**Figure 7.35 (left): IR thermal image of modular walls with windows with brick cladding**

**Figure 7.36 (right): Corresponding photograph showing position of lintels and masonry support system**

The construction drawings show that there are no lintels above windows in the timber clad walls, and the IR thermal images support this conclusion (Figures 7.37 and 7.38)

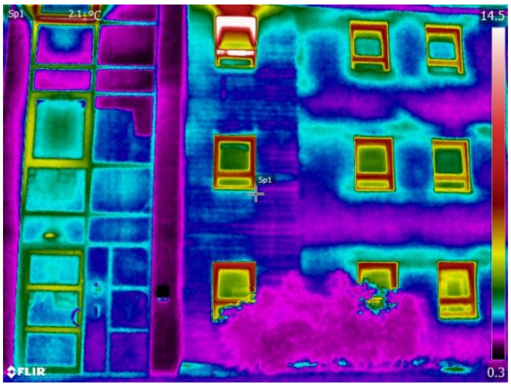


**Figure 7.37: IR thermal image showing no evidence of lintels in timber clad section of wall**

**Figure 7.38 Corresponding image of timber clad and brick clad sections of wall**

### 7.3.3 Modular Windows

The frames of the windows, doors and curtain walling were the features in the facades with the highest apparent temperatures, and this is to be expected because the fenestration has higher U-values than other features in the external envelope. The apparent temperatures were highest where the frames are thinnest (Figure 7.39 to 7.41), typically 7-10°C hotter than the coldest parts of the cladding on the same wall, (but in some instances as much as 12-14°C higher). The cladding nearest the fenestration had elevated apparent temperatures indicating heat was being transferred from the frames into the cladding.

**Figure 7.39: Greatest heat losses at thinnest part of frames – marked red**

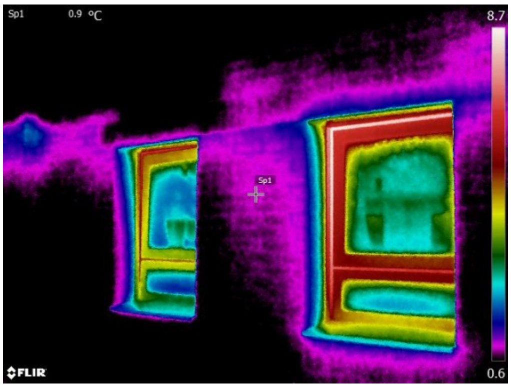


**Figure 7.40 (left): IR thermal image of modular bedroom windows**

**Figure 7.41 (right): Corresponding photograph of modular bedroom windows**

From the IR thermal images alone it is not certain that the elevated apparent temperatures of the modular windows and the surrounding cladding is anything more than would be expected; however when combined with data from other sources it was concluded that thermal bridging through modular windows is a significant problem.

The main concern is how the modular windows interface with the modules and cladding. Data from visits to the factory and from [redacted] generic design documentation revealed that windows are bolted directly onto the modules using steel angles (Figures 7.42 to 7.44). The steel angle is bolted to the window frames on one side and the module frame on the other. There is no feature for limiting heat transfer between the window frames and the module walls, so heat can readily transfer between them.

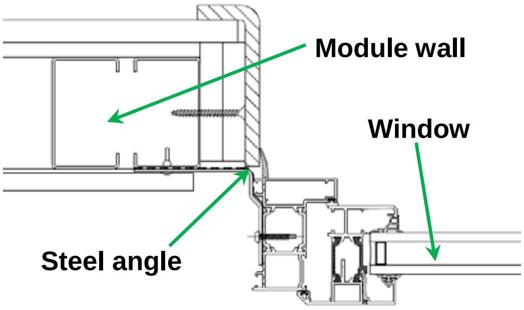


**Figure 7.42 (left): Windows in the [redacted] factory with steel fixing angles fitted**

**Figure 7.43 (centre): Window fitted to module in factory with steel angles**

**Figure 7.44 (right): Plan section of steel angle connection between window and module [[redacted] 2012]**

The [redacted] generic design documents concern only the modular construction, and do not cover how cladding and rigid insulation could be interfaced around the windows, [redacted]. In the Loughborough study there were two basic plan drawings detailing the interfacing between modules, cladding and modular windows (Figures 7.45 and 7.46); there were no corresponding section drawings. The drawings [redacted] provided little information about how the windows interfaced with the cladding, or about the design of lintels, cavity trays, weep holes, insulation, cavity barriers, sealant, window sills or reveals. The drawings do not show any insulation between cladding and windows, [redacted] the data suggest that the windows are acting as a direct thermal bridge between the internal modular structure and the cladding.

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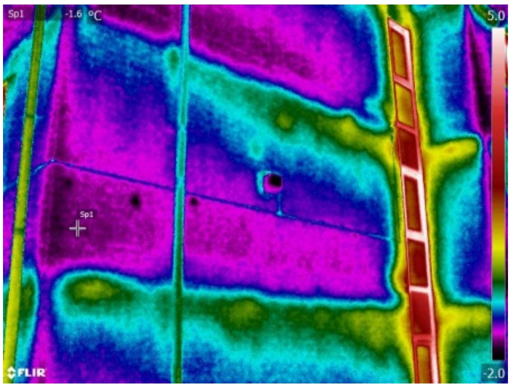
**Figure 7.45 (left): Plan drawing of window jambs from Loughborough study [Contractor 1, 2006]**

**Figure 7.46 (right): Plan drawing of window jambs from Loughborough study [Contractor 1, 2006]**

### 7.3.4 Curtain Walling

The curtain walling was identified as another area of avoidable thermal bridging. As with the modular windows, the curtain walling frames were at elevated apparent temperatures (Figure 7.47 and 7.48), and were as much as 10°C higher than the surrounding walls.



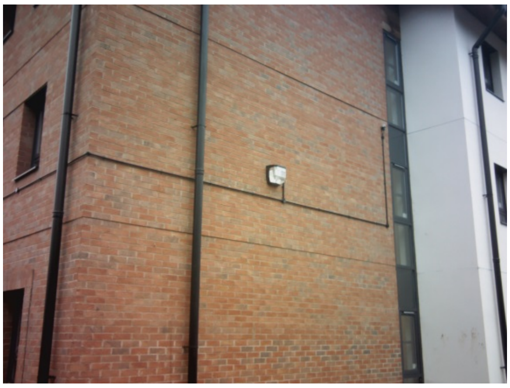



**Figure 7.47 (left): IR thermal image shows curtain walling at elevated apparent temperatures**

**Figure 7.48: (right) Corresponding photograph of curtain walling in brick and render clad walls**

The design drawings reveal that curtain walling is simply fixed to the modular structure using steel angles (Figure 7.49). There is no thermal separation between the steel modular structure and the aluminium frames of the curtain walling, so heat can readily transfer between the two. By comparing the drawings with the thermal images it became apparent that the steel angles supporting the curtain walling are likely to be the masonry supports. They are not simply the same in design; it appears that the masonry and curtain walling are literally supported by the same steel angles. This is evident in the thermal images, because the interfaces between curtain walling and masonry supports were at far higher apparent temperatures than other regions of the masonry supports or curtain walling (Figure 7.50).

***Copyrighted content redacted***

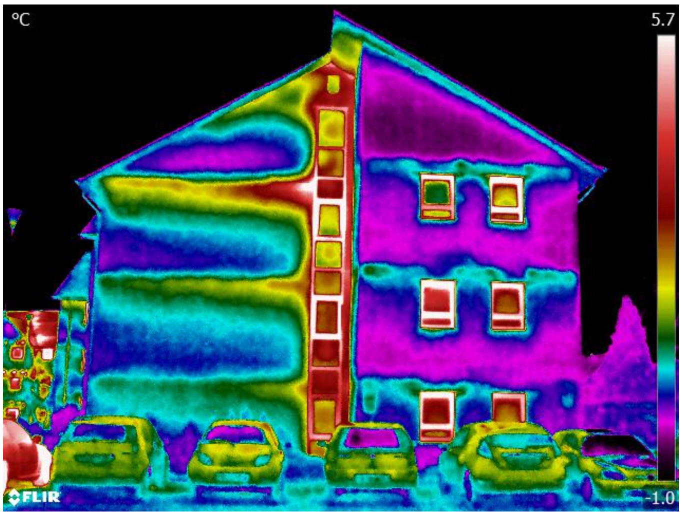



**Figure 7.49 (left): Section drawing shows curtain walling fixed to modular structure with steel angle [Architect 2, 2006]**

**Figure 7.50 (right): IR image of elevated temperatures at curtain walling – masonry support junctions**

### 7.3.5 Thermal Bridging Calculations

[redacted] employed a third party to carry out finite difference modelling for the medium-rise design to determine the thermal performance of specific junctions within the modular construction due to non-repeating thermal bridges. Undertaking the modelling is a means of demonstrating compliance with Criterion 4 of Approved Document Part 2LA of the Building Regulations, in the requirement that reasonable provision be made to limit thermal bridging and ensure reasonable continuity of insulation over the facade. [DCLG, 2016]. Reasonable provision can be demonstrated by showing that the temperature factor is no worse than 0.75 in residential buildings [Ward and Sanders, 2007; Ward, 2006].

The linear thermal transmittances and temperature factors were calculated for nine types of thermal bridge (Table 7.2). The conclusion was that all junctions were found to satisfy the requirements of Approved Document L, by achieving a temperature factor equal to or greater than 0.75. Of the nine junctions modelled, five have better linear thermal transmittances than the default values for the approved construction details [Ward, 2006], resulting in high temperature factors between 0.84 and 0.93, which is a positive indication about the thermal performance of the modular design.

However, the masonry support systems were not modelled at all, but since they penetrate the insulation layer and are large and numerous in masonry clad walls they should have been modelled. Similarly, there were no models for any of the junctions between corridors and modules, or between corridors and curtain walling, and this is a shortcoming because the former are present in all [redacted] buildings and the latter are present in most.

The models used for the window calculations [redacted] assumed that there was no heat transfer between windows and walls, and so the windows were not explicitly modelled. This is a standard assumption [Ward, 2006] however the data show that the windows are fixed directly to the module walls with no thermal separation, so it is not a valid assumption for this construction. Secondly, while the models were for a brick clad wall, steel supports do not appear to have been modelled, not as lintels above the windows or as masonry supports below the jambs and sills. The model results use the term “window header”, which is not typical; it is believed this junction is normally classed as a “lintel”. However, lintels typically have far higher linear thermal transmittances than the value calculated for the window header, which further supports the view that lintels were not modelled above the windows. Based on the data available it was concluded that the models of the sills, jambs and window header are not a true reflection of the actual construction, and there are serious doubts that the linear thermal transmittances and temperature factors calculated using them are indicative of the actual performance at these junctions.

**Table 7.2: Thermal bridging results for the medium-rise design**

| Description | [1]Linear thermal transmittance, Ψ (W/mK) | [1]Minimum surface temperature (°C) | [1]Temperature factor $f_{Rsi}$ | [2]Default for approved construction details | [2]Default SAP 2012 |
|---|---|---|---|---|---|
| Corner | 0.074 | 16.87 | 0.84 | 0.09 | 0.18 |
| Party wall junction | 0.041 | 18.43 | 0.92 | 0.06 | 0.12 |
| Wall –floor | 0.027 | 18.49 | 0.93 | 0.07 | 0.14 |
| Window sill | 0.145 | 14.96 | 0.75 | 0.04 | 0.08 |
| Window header | 0.045 | 17.74 | 0.89 | ? | ? |
| Window jamb | 0.046 | 17.76 | 0.89 | 0.05 | 0.10 |
| Wall-roof | 0.055 | 17.52 | 0.88 | 0.06 | 0.12 |
| Ground floor outer | 0.338 | 16.74 | 0.84 | 0.16 | 0.32 |
| Ground floor inner | 0.373 | 14.94 | 0.75 | 0.16 | 0.32 |
| Lintel | ? | ? | ? | 0.3 | 1.0 |

[1] *Data from third party employed by* [redacted] *to undertake modelling*
[2] *BRE, 2014*

### 7.3.6 Fabric Heat Loss Calculations

With knowledge of the calculated U-values through planar walls and linear thermal transmittances at thermal bridges calculated by third parties, it is possible to calculate total heat losses through the fabric of the walls [LeedsBeckett, 2016]:

$$Q = \left[\sum(U_i \cdot A_i) + \sum(\Psi_j \cdot L_j)\right] \cdot \Delta T_b \qquad (W)$$ **Equation 7.1**

This does not include heat losses due to ventilation, only heat losses through the fabric.

The heat loss was calculated for two sections of walls, one with windows and the other without (Figures 7.51 to 7.53). Since no modelling was done for masonry supports, it was assumed they have a linear thermal transmittance of 1W/mK, based on the SAP 2012 recommendations for lintels [BRE, 2014] and because it is believed the masonry supports are the same as the lintels (essentially steel angles). For the wall with windows, two calculations were done, one with the window header and no lintels, and one with lintels and no window header, due to the belief that the window header modelled is not accurate.

It was not possible to calculate heat losses for the whole buildings because nothing is known about the thermal bridging in the corridors, curtain walling, roof and stair cores, and the calculation would contain too many assumptions to have confidence in the results.

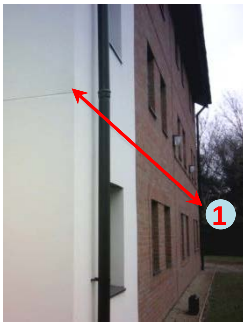



**Figure 7.51 (left): Plan of Loughborough south building – walls indicated for heat loss calculations [Architect 2, 2006]**

**Figure 7.52 (centre): Wall with windows used in heat loss calculations**

**Figure 7.53 (right): Wall without windows used in heat loss calculations**

The wall with windows was seven modules wide and three high, representing 21 modules with 21 windows. The heat loss was calculated separately for the planar elements (Table 7.3) and the thermal bridges (Table 7.4). Although the windows have an area less than one fifth of the walls they lose 19.4% more heat than the walls. Similarly, even if lintels are neglected and the linear thermal transmittance for the window header is assumed to be correct, 18.6% more heat is lost through thermal bridging than through planar walls. If lintels are included in place of the window header then the heat losses from thermal bridging increase significantly to 71.74W/K, 61% more than the planar walls.

**Table 7.3: Heat losses through planar walls and modular windows in wall with windows**

| Description | Area ($m^2$) | U-value ($W/m^2K$) | Heat loss (W/K) |
|---|---|---|---|
| Walls | 127.33 | 0.35 | ***44.57*** |
| Windows | 24.18 | 2.2 | ***53.20*** |

**Table 7.4: Heat losses through thermal bridges in wall with windows**

| Description | Linear thermal transmittance, Ψ (W/mK) | Total length (m) | Heat loss - header no lintels (W/K) | Heat loss – lintels no header (W/K) |
|---|---|---|---|---|
| Corner | 0.074 | 16.65 | 1.23 | 1.23 |
| Party wall junction | 0.041 | 49.95 | 2.05 | 2.05 |
| Wall –floor | 0.027 | 54.6 | 1.47 | 1.47 |
| Window sill | 0.145 | 19.74 | 2.86 | 2.86 |
| Window header | 0.045 | 19.74 | 0.89 | 0 |
| Window jamb | 0.046 | 51.45 | 2.37 | 2.37 |
| Wall-roof | 0.055 | 18.2 | 1.00 | 1.00 |
| Ground floor outer | 0.338 | 18.2 | 6.15 | 6.15 |
| Lintel | 1 | 19.74 | 0 | 19.74 |
| Masonry support | 1 | 34.86 | 34.86 | 34.86 |
| | | ***Total*** | ***52.88*** | ***71.74*** |

Heat losses were calculated for the wall with no windows because the thermal bridging is at a minimum in these walls. Windowless walls represent the long walls of the modules, and they all share a junction with corridors and curtain walling, but nothing is known about the properties of these bridges. To be conservative, the linear thermal transmittance of the module-corridor-curtain walling junction was assumed to equal the window jamb. It was determined that thermal bridging accounted for 26.8% more heat losses than the planar walls (Table 7.5 and 7.6).

**Table 7.5: Heat losses through planar walls in wall without windows**

| Description | Area ($m^2$) | U-value ($W/m^2K$) | Heat loss (W/K) |
|---|---|---|---|
| Walls | 46.20 | 0.35 | ***16.17*** |
| Windows | 0 | 0 | ***0*** |

**Table 7.6: Heat losses through thermal bridges in wall without windows**

| Description | Linear thermal transmittance, Ψ (W/mK) | Total length (m) | Heat loss (W/K) |
|---|---|---|---|
| Corner | 0.074 | 8.33 | 0.62 |
| Party wall junction | 0.041 | 0 | 0 |
| Wall –floor | 0.027 | 16.65 | 0.45 |
| Window sill | 0.145 | 0 | 0 |
| Window header | 0.045 | 0 | 0 |
| Window jamb | 0.046 | 8.33 | 0.38 |
| Wall-roof | 0.055 | 5.55 | 0.31 |
| Ground floor outer | 0.338 | 5.55 | 1.88 |
| Lintel | 1 | 0 | 0 |
| Masonry support | 1 | 16.65 | 16.65 |
| | | ***Total*** | ***20.28*** |

In both calculations, heat losses from thermal bridging are dominated by losses from the masonry support systems. It is possible that the linear thermal transmittance assumed is higher than in reality, but because [redacted] did not have this thermal bridge modelled, there is no option but to assume the default value. If the masonry supports were assumed to have the default value for accredited lintels (0.3W/mK), the heat losses would drop significantly to 64-75% of the heat from the wall (depending on window header/lintel assumptions), which is still significant. Clearly the heat losses through fenestrations and thermal bridging should not be neglected, and it is important to aim to reduce heat losses through the fenestration, thermal bridges and planar walls.

### 7.3.7 Thermal Bridging Discussion

The data from multiple methods were used to identify significant thermal bridges at the masonry supports, lintels, modular windows and curtain walling. These interfaces are particularly problematic because they are areas where steel angles are fixed directly to the steel modular structure and to the cladding, with no insulating materials to stop the flow of heat between them. Limiting thermal bridges is important in all construction, but it is particularly important in steel construction. Thermally all of the steel within the modular construction is connected, so the thermal bridges do not just have a localised impact, they draw heat from the whole modular structure into the external environment and the cladding. This is particularly problematic due to the high thermal conductivity of steel (50W/mK) and aluminium (160W/mK) compared to other construction materials such as brick (0.752W/mK), which means these bridges can draw significant heat out from the structure. While [redacted] had undertaken thermal bridging calculations, the problematic bridges identified were either not modelled or not modelled correctly, so as to neglect or overestimate the performance of these bridges. To reduce the energy consumption of [redacted] buildings requires these thermal bridges be minimised or removed, recommendation are given in Section 7.9

## 7.4 Findings on the Breather Membrane

[redacted]

As discussed in Chapter 4, each module has a breather membrane fitted in the factory as the last step in module fabrication; it remains fitted throughout construction, and forms part of the fabric of the completed building. The purpose of the membrane is twofold: to protect the module from moisture during transit and construction, and to control the movement of moisture through the wall during operation to minimise the chance of surface condensation on the building materials and interstitial condensation within them. The membrane is semi-permeable, designed to allow moisture to pass from inside the building to outside, but to stop moisture from outside reaching the modular construction. To achieve its function, the membrane must be continuous over the external envelope; [redacted].

The membrane closes at the corners with Velcro, which is permeable to moisture allowing the ingress of water; furthermore, site photographs show open Velcro corners, [redacted] (Figures 7.54 and 7.55). [redacted] The photographs of poorly closed corners and a lack of lapped and sealed joints do not prove that these failures are present in the final building, because they could have been remedied before cladding installation; however they do suggest that this is an issue.

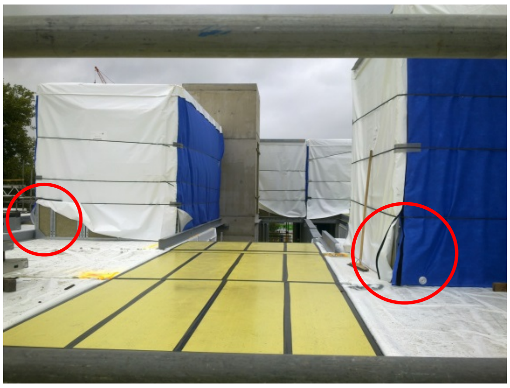


**Figure 7.54 (left): Open Velcro corners in breather membrane revealing modules below [[redacted] 2012]**
**Figure 7.55 (right): Breather membrane not lapped and sealed revealing modules below [[redacted] 2012]**

The membrane is intentionally punctured during construction to connect modules with corridors, roofs, cladding and adjacent modules (Figures 7.56 and 7.57). The membrane is also prone to accidental tearing, although the occurrence of tearing appears small compared to the intentional puncturing for interfacing. [redacted]

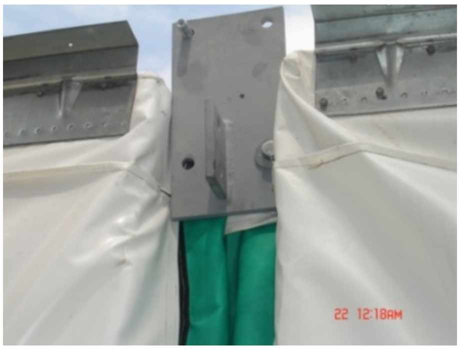



**Figure 7.56 (left): Steel supports connectors puncturing the breather membrane [[redacted] 2012]**
**Figure 7.57 (right): Holes cut in membrane to connect lifting equipment used on site [[redacted] 2012]**

[redacted] The windows were covered by the membrane during transit which had to be cut on site to reveal them. [redacted] From the site photographs it appears that holes were simply cut in the membranes during cladding construction (Figures 7.58 to 7.60). [redacted]



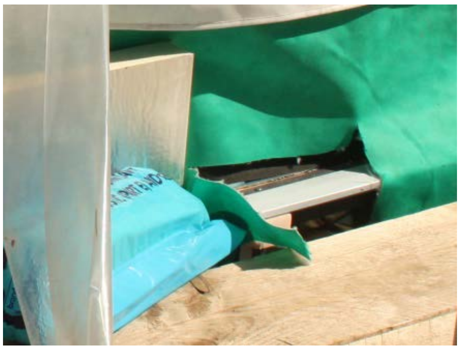


**Figure 7.58 (left): Breather membranes still visible after cladding construction [[redacted] 2012]**

**Figure 7.59 (centre): Breather membranes still visible during cladding construction [[redacted] 2012]**

**Figure 7.60 (right) Breather membrane crudely cut at the top of a window and not sealed [[redacted] 2012]**

[redacted] A second problem is that the membranes are loose fitting around the modules (Figures 7.61 and 7.62), making it difficult to accurately fit insulation on site (which is discussed next in Section 7.5).

[redacted]

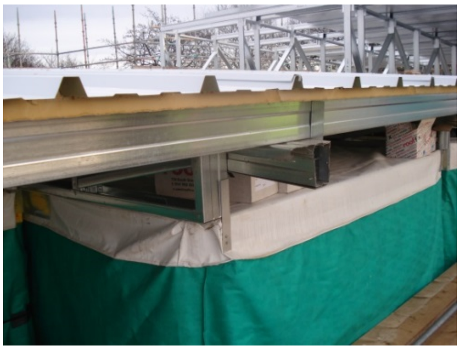



**Figure 7.61 (left): Loose fitting breather membrane [[redacted] 2012]**

**Figure 7.62 (right): Loose fitting breather membrane trailing onto corridor floor [[redacted] 2012]**

## 7.5 Findings on Insulation

The correct installation of insulation is important if good fabric thermal performance is to be achieved.

Fire insulation was fitted within the modules in the factory by [redacted] stone wool insulation and rigid insulation were fitted on site by other contractors. Observations from the factory were that fire insulation was well fitted (Figures 7.63 and 7.64), with strips of insulation cut especially to fit into each void between in the steel frame. While this insulation helps to reduce heat transfer through the module, its main role is for fire protection, so it is vitally important it is properly fitted.


**Figure 7.63 (left): Fire insulation neatly fitted in module floor panel in factory**
**Figure 7.64 (right): Fire insulation neatly fitted in wall panel with holes cut for services [[redacted] 2012]**

[redacted] The insulation that is fitted into the void at the party wall junctions between modules was of insufficient length in all photographs (Figures 7.65 to 7.68). The thermal bypasses this creates have already been discussed in section 7.2 Airtightness. [redacted] the loose fitting breather membrane appears to make it impossible to correctly fit the rigid insulation to the external walls of the modules, because the membrane bunches up and the rigid insulation cannot be fitted flat against the module (Figures 7.66 to 7.68). [redacted] many of the rigid insulation boards are not taped at their joints (Figures 7.68 to 7.70).



**Figure 7.65 (left): Insulation of insufficient length revealing party wall junction behind [[redacted] 2012]**
**Figure 7.66 (centre): Insulation of insufficient length and ill-fitting rigid insulation [[redacted] 2012]**
**Figure 7.67 (right): Insulation of insufficient length and ill-fitting rigid insulation [[redacted] 2012]**

**Figure 7.68 (left): Ill-fitting, un-taped rigid insulation and unsufficient length of insulation [[redacted] 2012]**

**Figure 7.69 (centre): Un-taped rigid insulation between boards and around services [[redacted] 2012]**

**Figure 7.70 (right): Un-taped rigid insulation visible during cladding construction [[redacted] 2012]**

In the Loughborough study it was possible to inspect the cavity wall in the non-modular construction via the boiler room because parts of the walls were not properly enclosed. A section of wall had an opening at the top, which revealed that the rigid insulation was not fixed to the internal leaf of the wall, the gap between them was approximately 25mm (Figure 7.71), [redacted].

**Figure 7.71: Gap between concrete block inner leaf and insulation**

The errors of installation identified are basic deviations from good practice [DCLG, 2007b] and should not be allowed to occur; they make the insulation less effective by creating thermal bypasses, and increasing heat losses, thermal bridging and the risk of condensation.

[redacted] employed third parties to undertake U-value, thermal bridging and condensation calculations; these calculations all have one finding in common, the absolute importance of the rigid insulation fitted on site. They all conclude that if the insulation is poorly fitted it would increase wall U-Values, thermal bridging, and the occurrence of condensation. Condensation risk would increase not only due to the thermal bridges and bypasses created, but because the vapour control foil facing on the rigid insulation is the dominant vapour resisting material in the wall and must be taped at junctions to perform as intended.

While it was not the responsibility of [redacted] to fit insulation on site, its optimal installation is vital to achieving good fabric thermal performance of the modular construction. [redacted]

## 7.6 Findings about Design Quality

The impact that the design quality and the provision of adequate design details [redacted] as on building thermal and energy performance was discussed in Chapter 2. If designs are thermally weak or design drawings are poorly rendered, then achieving a well performing building can be difficult. Some problems with the quality of design have already been discussed such as the lack of air barrier, the [redacted] breather membrane, and the thermal bridging through fenestration, lintels and masonry supports. [redacted]

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### 7.6.3 Design and Construction Quality Discussion

[redacted] Robust design is required to consistently achieve good energy and thermal performance of buildings; it is not something that will happen on its own, it needs specific attention. Care and attention are required when designing building fabric, particularly at interfaces, to ensure robust solutions are achieved that will perform in the final construction. In particular there should be a focus on minimising thermal bridging, thermal bypasses, air leakage and condensation; air barrier and insulation continuity should be indicated on all drawings. Once robust design solutions have been determined, they should be rendered into drawings accurately and with sufficient detail, so that contractors on site can understand and deliver what is required. [redacted]

[redacted]

## 7.7: Findings about Project Management and Responsibilities

Through analysis of data from multiple methods it became apparent that project management and the allocation of responsibilities may have been a reason for some of the weaknesses in fabric thermal performance.

[redacted] acted as a sub-contractor, deferring many responsibilities to the principal contractor, including: airtightness and thermal performance of the whole building, interfacing with non-modular components, cladding design, and all work carried out on site, among others. The [redacted] generic design documents focus on the modular construction, they do not cover in any detail the construction of whole buildings, or how modular components interface with non-modular components. There were no generic solutions, and they would have to be redesigned on each project, which was the responsibility of the principal contractor or architect.

The findings with regard to fabric thermal performance actually pertain to many of the factors that were not the responsibility of [redacted] Very few weaknesses were found in the design and manufacture of the modules (except for the interfacing with modular windows and the failure to seal behind sockets), the majority of weaknesses were in how whole buildings perform.

It is understandable that [redacted] should not have been responsible for achieving certain levels of performance in the completed building. However, while interfacing between modular and non-modular components varies between projects, the same types of interfaces are needed in each building, and it is questionable whether these should be completely redesigned for each project. [redacted] were well placed to devise generic designs for the air barrier, masonry supports, lintels and fenestration interfaces, and to advise the principal contractor on how to achieve good fabric thermal performance. Developing standard solutions does not mean [redacted] would have been responsible for ensuring they performed in the final construction, just as it was not their responsibility to ensure fabric U-Values complied with regulations; but they were well placed to develop standard solutions and act as an advisor.

[redacted]

Ultimately, it is difficult to see how [redacted] could have claimed to provide low energy modules with this means of operation, because they would not be responsible for (or involved in the design and construction of) so many of the features required to achieve low energy performance. To achieve good thermal and energy performance, whole building performance has to be considered, it is not sufficient that only individual elements (such as modules) perform well, the whole design has to perform. Changes in project management and responsibilities would likely have been necessary if [redacted] were to transition to providing low energy buildings, which is discussed further in Section 7.9 Recommendations.

## 7.8 Discussion of Findings

This chapter focused on building design and fabric thermal performance; it identified specific weaknesses that could cause reduced energy and thermal performance including: air leakage due to a lack of air barrier, avoidable thermal bridging, a poorly designed breather membrane, a failure to install insulation properly on site, [redacted] and a project management structure that could hinder performance and consistency.

This chapter focused on data from the Loughborough case study and the findings primarily pertain to it. However, design documentation was reviewed for many other [redacted] projects and the conclusion is that some findings likely apply to all [redacted] buildings (such as thermal bridging from module frame to window frame and the ill-fitting breather membrane), and the others could apply to many (if not all) [redacted] buildings (such as the lack of air barrier and poorly fit insulation). The thermal bridging due to masonry supports and lintels is likely only relevant to buildings with masonry facades, and not to those with lightweight cladding and rigid insulation, which do not need to be supported by steel angles (although it is possible that these claddings systems contain other avoidable bridges or thermal weaknesses).

There were some interesting aspects to the findings: they primarily pertained to how whole buildings performed and not individual modules; and they often concerned factors that were not the responsibility of [redacted] With the exceptions of breather membrane design, air leakage through sockets and thermal bridging between module frames and window frames, there were no other findings that indicated any weaknesses with the design and manufacture of the modules. The majority of weaknesses relate to how modules were combined into one structure and completed on site; it is not the individual modular elements that are the problem, it is how they perform as whole buildings. The weaknesses identified were at interfaces (both between modular components, and between modular and non-modular components), and with the fitting of the envelope of site; which were not the responsibility of [redacted] but of the principal contractor on each project. However, to achieve good fabric thermal performance the whole building design and the work done on site are fundamental, they determine: the airtightness of the structure, the presence of thermal bridges and thermal bypasses, and the moisture control properties of the fabric. There is no way to guarantee good airtightness, low fabric heat losses and no interstitial condensation through the design and manufacture of individual modules in a factory alone, they will always be partly dependent on whole building design and on the work done on site, and this is something that needs to be recognised, and systems put in place to ensure quality in all stages of work.

Ultimately, it is a positive finding that there is no need for major changes to the module design or manufacturing procedure, because this could be very costly. Also, many of the weaknesses identified would be relatively straightforward to resolve if time were spent redesigning interfaces with a focus on achieving good thermal performance, and ensuring the quality of work done on site. This chapter has specifically looked for the weaknesses in design and fabric performance and tried to identify what could be improved to achieve a low energy building with good thermal performance. However, there is no evidence that these buildings perform worse than other residential buildings or fail to comply with the regulations in any way. There are no weaknesses that cannot be resolved, they are all pertain to relatively small details, [redacted] but it is in the details where performance is made or lost. There are numerous resources available, both generic [British Standards Institution, 2011; BRE, 2016a; BRE, 2016b, DTLR and DEFRA, 2016; CIBSE, 2016, DCLG, 2007b, Energy Saving Trust, 2009] and specifically for steel construction [DCLG, 2007; SCI, 2016a; SCI, 2016b] that provide guidance about good and best practice that can be used to help optimise design.

## 7.9 Recommendations

There are many recommendations that can be made about how to improve the fabric design in buildings constructed using [redacted] modules. It is not possible to prescribe exact solutions as this would have required input from [redacted] (regarding which solutions were most suitable for the design), but they entered administration before this collaborative stage could happen. However, the intellectual property (the modular design) was sold on and the design could be used again in the future. Furthermore, some of the findings may be relevant to other manufacturers of steel modular construction; unfortunately there was no research into other manufacturers because the need to have a wider focus was not foreseen.

### 7.9.1 Air Barrier

The design ought to feature an air barrier, which could be achieved in a number of ways. This is a job that would need to be completed on site; there is no way to complete it in the factory. The accredited details for hybrid steel framed buildings indicate how the air barrier can be provided by dry lining, rigid insulation or sheathing boards [DCLG, 2007]. Another option is to use a whole building wrap applied after the modules have been installed, however puncturing the layer during construction may be impossible to avoid, and therefore this is perhaps not the best option. The simplest solution would be to use the dry lining in the modules as an air barrier and then on site join together the air barriers in individual modules to form one continuous air barrier. This would involve covering the junctions between modules with a membrane or a gasket, they could even be manufactured in the factory and partially fitted to modules prior to transportation to facilitate installation on site. Whatever the solution, the air barrier needs to be properly sealed around and bridges and openings in the external wall, such as around windows and ventilation ducting.

### 7.9.2 Thermal Bridges

There is scope to improve the fabric thermal performance by minimising thermal bridging. Lintels, fenestration, and masonry supports should be thermally separated from the modular structure, and not directly fixed to it. There are thermal break components available for this purpose in steel construction [Way and Kendrick, 2008]. Perhaps it is best to avoid the need for masonry supports and lintels altogether through the choice of non-masonry cladding solutions. A secondary benefit of avoiding lintels and masonry supports is that by reducing the number of bridges and obstructions in the external wall, it is easier to correctly fit the rigid insulation and ensure airtightness.

These areas of thermal bridging would benefit from the creation of standard robust designs, detailing how thermal separation of lintels, masonry supports and fenestration from the masonry structure should be achieved. The design drawings should also detail how continuity of the air barrier and external insulation should be achieved. Ideally standard solutions would also be devised for interfaces between the modular structure and cladding, particularly around complex interfaces, such as fenestration.

### 7.9.3 Breather Membrane

To optimise the fabric performance of the design the breather membrane would need to be redesigned, [redacted]. The membrane must be tight fitting so that the insulation can be correctly fitted on site. [redacted] the membrane should be cut around the windows and sealed appropriately in the factory, and then the windows should be recovered with a different material if there is a need to protect them during transit and construction. In reality, it would be difficult to design a perfect membrane because components have to be connected to the modules on site, and this means puncturing the membrane; [redacted].

### 7.9.4 Rigid Insulation

The rigid insulation fitted on site is fundamental to the thermal performance of [redacted] buildings and this cannot be avoided. [redacted] Insulation must be fitted correctly if building fabric is to perform as intended; this is particularly important in steel construction due to the increased risk of condensation. To improve the performance of the fabric, better quality work is required on site. This could be achieved in a number of ways, such as: by actively educating contractors on correct installation and why it is important, through the employment of specialists who already understand the importance of quality installation, and through the creation of systems designed to oversee, check and ensure the quality of installation.

There could be the possibility of fitting insulation and cladding in the factory, to control the quality of work done and further minimise the work required on site. Whether this is something that is practicable is not known, and would depend on many factors (based on the ability to make it in the factory, to transport it to site and to install it). Even if certain tasks done on site could be moved to the factory, they would still need to be finalised at junctions on site, and the performance of the fabric would still be influenced by the work done on site.

### 7.9.5 Design Responsibility

For [redacted] to have been able to move into the low energy domestic market, they would have needed to change the way they operated, to shift their focus from individual modules to whole buildings. With [redacted] operating as a sub-contractor with no responsibility for the design of non-modular components or the performance of the completed building, it is hard to see how [redacted] could market themselves as a low energy housing provider, or guarantee any sort of energy or thermal performance. [redacted] would have needed to be able to demonstrate that they could construct low energy buildings, and this is not possible acting solely as a sub-contractor; it would have required a shift in focus to looking at whole building design and performance, and to thinking about design aspects that they had previously left to the principal contractor. Ideally, they would have needed to be able to provide information to clients about how modular and non-modular components could be combined to achieve a low energy building. This could have included specifying (or even supplying) specific products that could be used with the modules to achieve the desired performance, or it could have involved collaboration with other parties, such as cladding specialists and roof manufacturers, to develop robust solutions. It could even have included the development of particular designs to meet different standards, and the creation of a portfolio of designs based on performance, from which the client could choose based on their requirements

### 7.9.6 Provision of Robust Design Details

As previously discussed it is necessary to provide accurate and sufficiently detailed drawings of complex interfaces to contractors on site so that they can properly construct the features that have been designed. It is also important that the designs represented in drawings are robust, that they represent good thermal design by minimising thermal bridging, avoiding thermal bypasses and ensuring the continuity of insulation and the air barrier across the envelope. This is not a minor point, it is vital step that is needed to optimise building design and to ensure what is constructed on site actually matches the design. [redacted] This is a further reason why the advice to [redacted] would have been to extend their practices, to ensure the development of robust details of standard interfaces that could be used directly or used as a reference for checking the suitability of other drawings. It would perhaps have been beneficial to also have quality checks in place, where somebody is specifically tasked with checking and ensuring that design drawings are created for all complex details and are of suitable quality (in terms of fabric thermal performance).

## 7.10 Summary

This chapter aimed to identify weaknesses in fabric thermal performance, that if rectified would lead to improved energy and thermal performance of [redacted] buildings. It detailed the various sources of data used to identify these weaknesses, namely: blower door tests, IR thermal imaging, inspections, and reviews of design documentation and photographs from site. It then detailed the specific weaknesses that were identified: poor airtightness, thermal bridging, breather membrane design, the installation of insulation on site, [redacted]. It also explained why these particular weaknesses existed, which largely related to design and construction quality, and the allocation of responsibilities within the design teams. The chapter finished by making recommendations about how to resolve the various weaknesses in order to achieve better fabric thermal performance. Recommendations for future research are discussed in Chapter 10.

# Chapter 8 – Energy Use

This chapter presents the energy use findings from the case studies using the data collected from building monitoring (Table 8.1). The radiator temperature data collected in the London case study cannot be used to directly calculate energy use, but provides information about space heating usage patterns. The purpose of monitoring energy use was to gain insight into: how energy may be wasted, the suitability of building services, if building layout affects energy use, and if any aspects of occupant behaviour could have implications for the design of buildings and services. There was a focus on space heating because fabric thermal performance influences the space heating requirement of buildings; the intention was to use space heating use, internal temperature and window opening data to analyse fabric thermal performance and use it to calibrate building models, but due to data reception problems and the delays installing equipment, the dataset was not suitable for these purposes. Therefore the energy use data was primarily used to assess the performance of building services and appliances, and identify ways that energy use could be reduced.

**Table 8.1: Data collection summary for both case studies**

| **Case study** | Loughborough | London |
|---|---|---|
| **Dates of study** | 05-Mar-2013 – 28-Jun-2013 | 09-Mar-2013 – 31-Aug-2013 |
| **Study duration** | 115 days | 176 days |
| **Data collected** | Electrical power use (W)<br>Electrical energy use – meter totals (kWh)<br>Internal temperature (°C)<br>External air temperature (°C) | Radiator surface temperature (°C)<br>Internal temperature (°C)<br>Internal relative humidity (%)<br>External air temperature (°C) |
| **Monitored zones** | 3 whole flats | 16 individual bedrooms |
| **Participants** | 12 | 16 |

The building monitoring required sensors to be fitted within bedrooms, and for data to be collected over a period of months. This required occupants' to agree to participate in the studies. Securing participants involved numerous stages including planning an ethical study, highlighting target participants, making contact with occupants, data protection, and obtaining signed consent forms, all of which are discussed in Appendix B. On a technical level, many decisions had to be made before monitoring could begin including: selecting suitable equipment, testing equipment, conducting a pilot study, planning the installation, arranging permission, and sourcing an electrician. Safety was of the upmost importance, and required special attention for the electricity monitoring because it involved modifications to the electrical services, which required the employment of an electrician; electricity monitoring is discussed in Appendix C.

## 8.1 Energy Use - Loughborough

### 8.1.1 Monitoring Details – Loughborough

Three whole flats were monitored in the North building in the Loughborough study, including one studio flat, one five-bed flat and one six-bed flat, with twelve participants in total (Table 8.2). It is not possible to show a drawing with the locations of the flats or detail which storeys they are on, as to do so could make the participants identifiable, breaching anonymity and data protection. Whole flats were monitored because it allowed data to be collected from communal kitchens and corridors. The monitored flats included bedrooms that face all orientations, providing the opportunity to investigate the impact that orientation had on performance.

A total of 25 electricity meters were installed (Table 8.2), thirteen were fitted into the main distribution boards in the flats (Figure 8.1), and twelve were fitted within four isolation boxes (three meters per box), to sub-meter the electricity use in four bedrooms (1Eb, 1Ec, 1W and 2Sc) (Figures 8.2 and 8.3). The isolation boxes were fitted in the module risers of the four bedrooms that were sub-metered; the electricity supply from the bedroom distribution board was routed into the isolation box to meter consumption. Initially, no repeaters were installed because they were thought unnecessary, however after problems with network range three were installed. Electricity meters were installed and removed by the electrician, upon removal the electrical services were returned to their original state. No equipment was lost and all was returned at the end of the study. Electricity monitoring is further discussed in Appendix C.



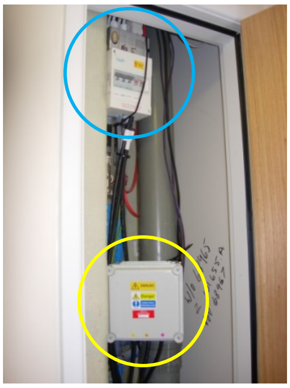

**Figure 8.1: Electricity meters installed in Flat 1 DB, the front of the meters are visible (highlighted red)**

**Figure 8.2: Meters installed in isolation box (yellow) and routed through bedroom DB (blue): Open**

**Figure 8.3 Meters installed in isolation box (yellow) and routed through bedroom DB (blue): Closed**

The electricity data were collected in varying degrees of detail for different rooms, (Table 8.2); this was partly due to resource restrictions limiting the number of meters that could be purchased, and partly due to space limitations within distribution boards limiting where meters could be installed. It was also impossible to monitor total electricity in any of the flats because they had circuit ratings of 100A, but the meters were only rated at 65A.

**Table 8.2: Data collected in each flat and room and meter installation location**

| **Room code**[1] | **Flat** | **Room type** | **Orientation** | **Electricity data collected** | **Meter installation location** | **Circuit rating (A)** |
|---|---|---|---|---|---|---|
| 1Ea | 1 | Bedroom | East | Room total | Flat 1 main DB | 40 |
| 1Eb | 1 | Bedroom | East | Space heating<br>Lighting<br>Sockets | In isolation box connected to room 1Eb DB in module riser | 6<br>6<br>20 |
| 1Ec | 1 | Bedroom | East | Space heating<br>Lighting<br>Sockets | In isolation box connected to room 1Ec DB in module riser | 6<br>6<br>20 |
| 1Sa | 1 | Bedroom | South | Room total | Flat 1 main DB | 40 |
| 1Sb | 1 | Bedroom | South | Room total | Flat 1 main DB | 40 |
| 1W | 1 | Bedroom | West | Space heating<br>Lighting<br>Sockets | In isolation box connected to room 1W DB in module riser | 6<br>6<br>20 |
| K1E | 1 | Kitchen | East | Room total | Flat 1 main DB | 40 |
| C1 | 1 | Corridor | South & West | Lighting | Flat 1 main DB | 10 |
| 2Na | 2 | Bedroom | North | Room total | Flat 2 main DB | 40 |
| 2Nb | 2 | Bedroom | North | Room total | Flat 2 main DB | 40 |
| 2Sa | 2 | Bedroom | South | Room total | Flat 2 main DB | 40 |
| 2Sb | 2 | Bedroom | South | Room total | Flat 2 main DB | 40 |
| 2Sc | 2 | Bedroom | South | Space heating<br>Lighting<br>Sockets | In isolation box connected to room 2Sc DB in module riser | 6<br>6<br>20 |
| K2N | 2 | Kitchen | East | Room total | Flat 2 main DB | 40 |
| C2 | 2 | Corridor | N/A | None | N/A | N/A |
| 3W | 3 | Bedroom | West | Space heating | Flat 3 main DB | 16 |
| 3KW | 3 | Kitchen | West | Space heating<br>Ventilation system | Flat 3 main DB | 16 |

[1] *For the room code, the number represents the flat in which the room is located. For bedrooms the uppercase letter indicates room orientation, the lowercase letter is a generic describer when there is more than one room in the same flat with the same orientation. Kitchens codes also include a "K" and corridor codes a "C" to distinguish them from bedrooms.*

There were a number of problems with the equipment that impacted on the data collected. There were various data reception problems caused by poor network range resulting in lost data. Some solar powered sensors became depleted of charge during the vacation when the building was largely empty, resulting in lost data. Four electricity meters developed faults early in the study, after which they only transmitted data once every one to three days. The controller was also turned off by someone prior to the office closure for Easter; it was off for eight days resulting in lost data (fortunately the monitored flats were largely empty during this period). There were also concerns over the accuracy of the window opening data, so they were excluded from the vast majority of analyses. The loss of data limited the analyses that could be conducted for many rooms, particularly regarding the relationship between internal temperature, window opening and space heating use. The problems with the monitoring equipment and its impact on analysis are discussed in Appendix E.

### 8.1.2 Total Electricity Consumption – Loughborough

There were total electricity consumption data for all the bedrooms and kitchens in Flats 1 and 2 (Figure 8.4, plots are given in Appendix J). There was a large variation in consumption, particularly between kitchens and bedrooms, with kitchens using from five to 25 times more electricity than bedrooms.

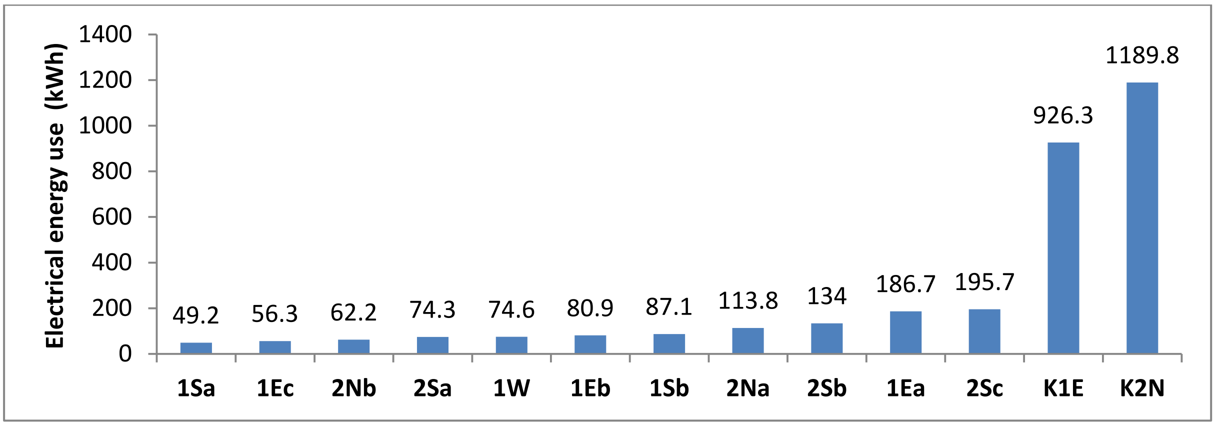


**Figure 8.4: Total electricity use in Bedrooms and kitchens: 05/03/2013 – 23/06/2013**

Flat 2 consumed 21% more electricity than Flat 1, using 1770kWh, compared to 1461kWh (excluding corridor electricity use which was not monitored fully in either flat). Kitchen K1E and K2N consumed around two thirds of total electricity in each flat at, 63% and 67% respectively (excluding corridors). Kitchen K2N consumed 28.4% more electricity than K1E, and more than all the bedrooms in Flats 1 and 2 combined (1115kWh). The five bedrooms in Flat 2 consumed more electricity (580kWh) than the six bedrooms in Flat 1 (534.8kWh). Electricity consumption per person was 354kWh in Flat 2 compared to 243.5kWh in Flat 1; therefore the occupants in Flat 2 used 45.4% more per person than the occupants in Flat 1.

In the bedrooms, the highest consumer (room 2Sb) used four times more electricity than the lowest consumer (room 1Sa). The average electricity consumption for the eleven bedrooms is 101.3kWh, however the seven lowest consumers were well below average using 87.1kWh or less, and the four highest consumers were well above average using 113.8kWh or more. The highest consumers, while fewer in number, used significantly more electricity, skewing the average above the consumption of the majority of the rooms. Three of the four highest consumers were in Flat 2, whereas the two lowest consumers were in Flat 1, which explains why the bedrooms in Flat 2 used more electricity than in Flat 1 despite being less in number.

To understand why there were such differences in consumption between different rooms, it is necessary to look at how energy was consumed in different rooms, by different end uses throughout the study.

### 8.1.3 Kitchen Electricity Use – Loughborough

The kitchens in Flats 1 and 2 used significantly more electricity than measured by any of the other electricity meters; only the lighting usage in corridor C1 was remotely close (Figure 8.5). It was not possible to meter the total consumption in the kitchen of Flat 3 (K3W), but the ventilation system was metered (so too was the heating, but this is discussed with bedroom heating in Section 8.16 because this was a studio flat and not a typical kitchen).

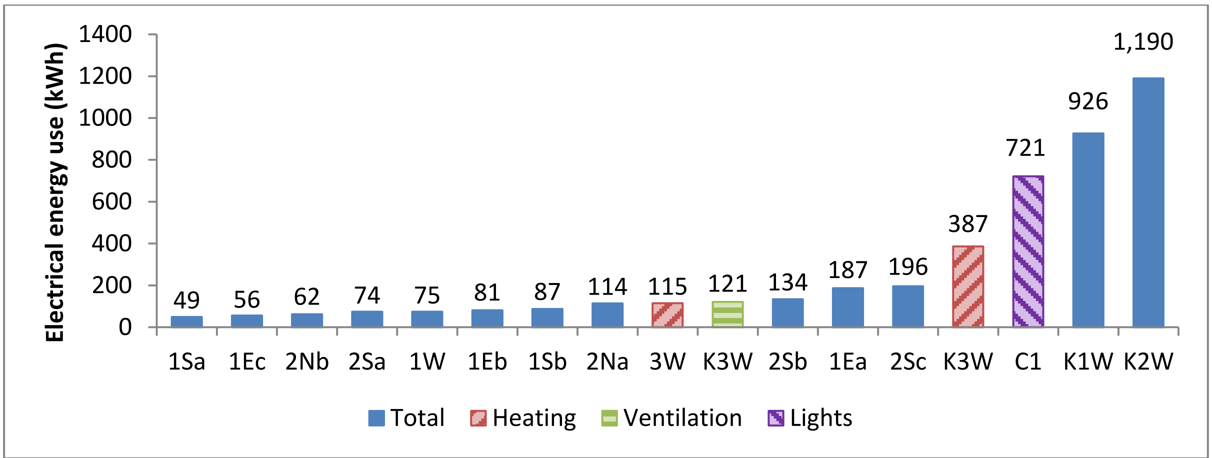


**Figure 8.5: Electricity consumption in kitchens compared to bedrooms and other meters**

The load was never zero in the kitchens because certain equipment was constantly operational (Figures 8.6 and 8.7). In kitchens K1E and K2N loads of up to 3000W occurred repeatedly during each occupied day and were generally short lasting. Loads of between 3000W and 7000W occurred on nearly all occupied days, sometimes numerous times per day and were generally short lasting. Loads above 7000W occurred less than 20 times during the study in kitchens K1E and K2N, and were always short lasting. Kitchens K1E and K2N were unused by occupants during the university vacation: from 28th March to 14th April for K1E and from 18th March to 12th April for K2N.

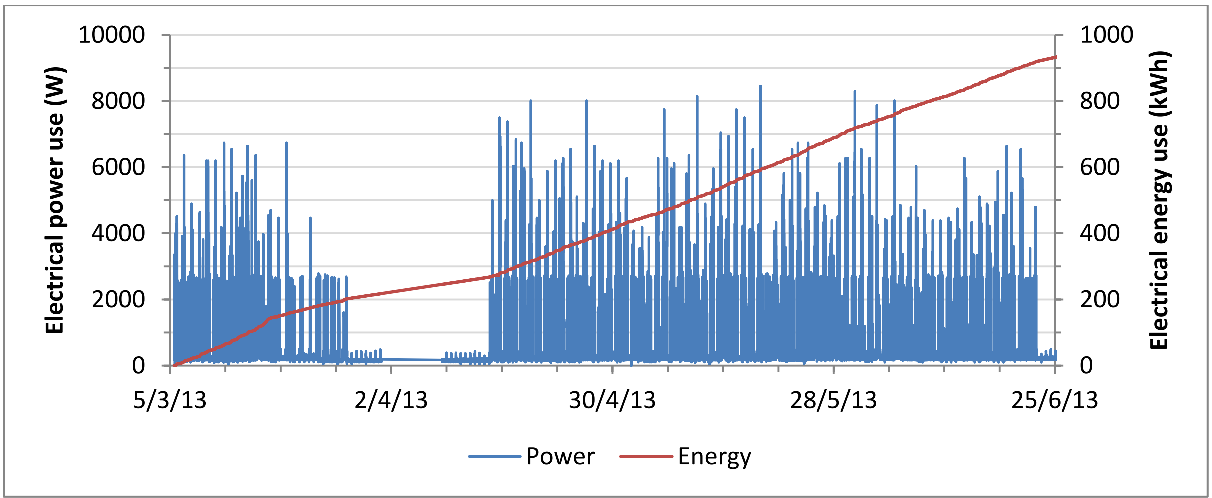


**Figure 8.6: Energy and power consumption data for kitchen K1E**

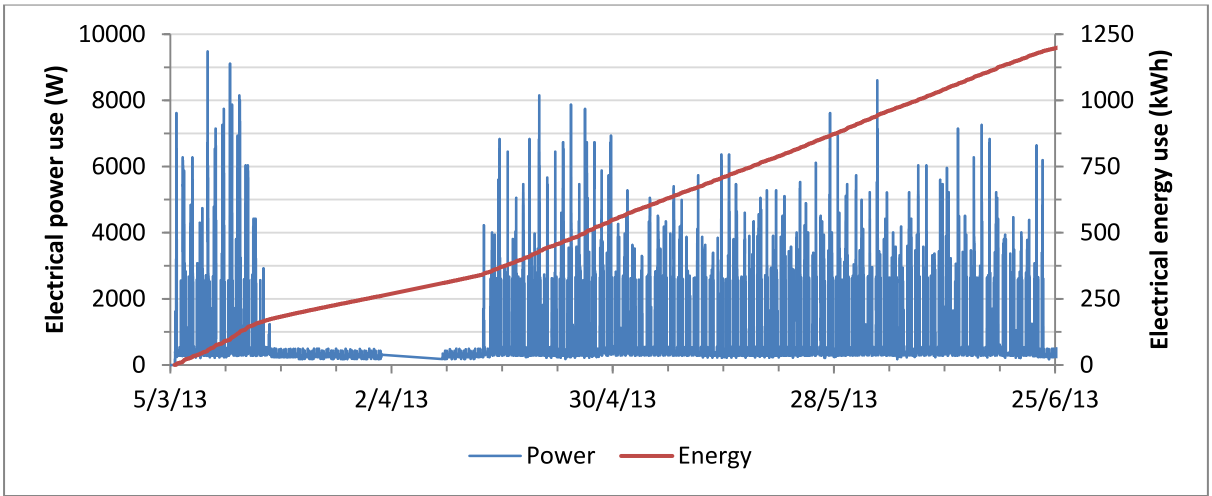


**Figure 8.7: Energy and power consumption data for kitchen K2N**

### *Electrical Devices*

The kitchens contained a variety of electrical equipment; their power consumption was determined by reading the ratings from labels and by taking measurements of some equipment using the installed electricity meters (Table 8.3).

**Table 8.3: Electricity consuming devices and their loads in kitchen K1E**

| Electricity consuming devices | Rating |
|---|---|
| Kettle | 2200-2400W |
| Toaster | 800W |
| Microwave | 900W |
| 2 x Fridge freezer (1 in studio flats) | 215W each (energy efficiency rating = A) |
| Iron | 1200W |
| Oven set at 200°C | Up to 2191W |
| Oven grill | Up to 3160W |
| Oven cooling fan | 16W |
| Hob: all four rings on | Up to 7258W |
| Hob: one large ring on | Up to 1773W |
| Hob: one small ring on | Up to 1739W |
| Radiator | 1250-1400W |
| Ventilation | 24 - 194W |
| Kitchen light | 46W |
| Living room light | 13W |

### *Base Loads*

The electricity consumption in the kitchens was never zero, there was always a base load, because the following equipment was constantly running:

- ventilation system,
- fridge freezers,
- oven to power a clock, and
- microwave to power a clock

It is assumed the power consumption for clocks was small, and therefore the majority of each base load was for fridge freezers and ventilation. The base loads fluctuated continuously throughout the day, which is to be expected due to the modulating power consumption of fridge freezers. The base load profile varied between kitchens K1E and K2N with K2N consuming more electricity than the K1E (Figure 8.8). It is not clear why there was a difference in the base loads, the kitchen may have had different appliances. Unfortunately the list of appliances and their ratings was only collected in Flat 1 and the realisation that there could be different appliances in Flat 2 was not made until too late.

The average base loads during the course of the study were estimated at 210W in K1E and 320W in K2N, and it is estimated that the base loads accounted for 60% and 71% of total electricity use in K1E and K2N respectively (Table 8.4). This shows that the majority of electricity consumed in the kitchens was for the constantly running electrical devices, and that the main reason for the difference in electricity consumption between the kitchens was the difference in base loads. Only around 29% of electricity consumed in K2N, and 40% in K1E was for the active use of electricity by the occupants for kitchen appliances, lighting, space heating and sockets. These figures include electricity consumption during the vacation when there was little occupant electricity use. If only occupied periods are considered, the base loads still accounted for 54% and 63% in K1E and K2N respectively.

It is clear that the base loads from constantly running electrical equipment played a significant role in determining total electricity consumption, indicating that the specification of base load equipment can have a major impact on electricity use and costs. Therefore, minimising the energy consumption of constantly running equipment should be a priority.

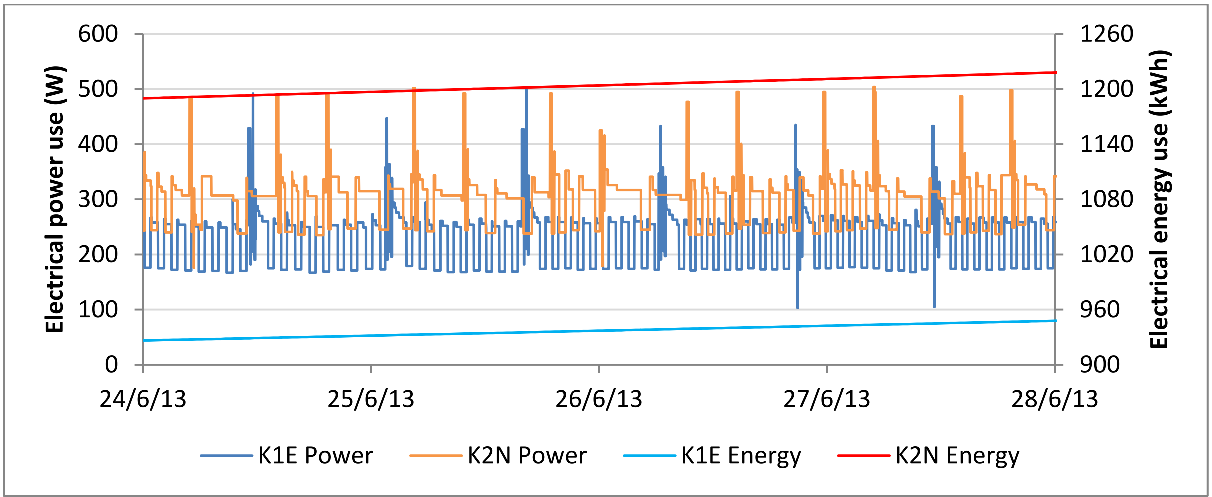


**Figure 8.8: Base loads in kitches K1E and K2N while building was vacant**

**Table 8.4: Base load data for kitchens K1E and K2N**

| Description | K1E | K2N |
|---|---|---|
| Approximated average base load (W) | 210 | 320 |
| Electricity consumed by base load in one day (kWh) | 5.04 | 7.68 |
| Total electricity consumed in kitchen: 05/03-23/06 (kWh) | 926.3 | 1189.8 |
| Electricity consumed by base load: 05/03-23/06 (kWh) | 556.4 | 847.9 |
| Active electricity use by occupants: 05/03-23/06 (kWh) | 369.9 | 341.9 |
| Active electricity use by occupants per occupant: 05/03-23/06 (kWh) | 61.6 | 68.4 |
| Electricity consumed by base load in one year (kWh) | 1839.6 | 2803.2 |
| Percentage of electricity use for base load (%) | 60.1 | 71.3 |

### *Mechanical Ventilation*

The ventilation system in Flat 3 consumed 121.4kWh during the study, using approximately 45W, 84W and 185W on the low, medium and high settings respectively (Figure 8.9). Spot measurements were also taken for Flats 1 and 2 on the lowest setting only (due to a difficulty finding the control panel); the ventilation system in K1E consumed 44W, and in K2N consumed 24W, it is not known why Flat 2 had a lower consumption.

The occupant in Flat 3 nearly always used the ventilation on the default setting, only turning it up eight times during the study and always for short periods. The ventilation systems are operational all year; they are not switched off when in summer when the building is vacant. Based on the consumption observed, it is estimated that the ventilation system in Flat 3 would consume 400kWh per annum. It cannot be known if the ventilation systems in Flats 1 and 2 were operated in a similar manner; if they were typically used on their default setting then the majority of the base loads in the kitchens must be due to the fridge freezers.

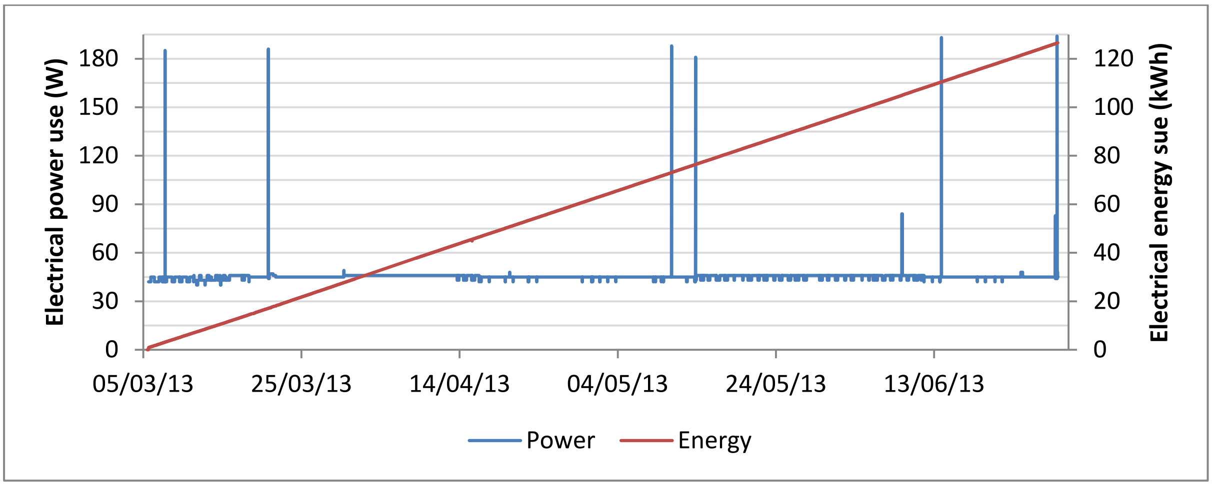


**Figure 8.9: Power and Energy use of the ventilaiton system in Flat 3**

More electricity was consumed by the ventilation system in Flat 3 than in eight of the eleven bedrooms in Flats 1 and 2, which seems excessive. However, it is better to consider the performance of the ventilation system in terms of the specific fan power (SFP), which is a measure of the flowrate achieved for the electricity consumed. Flowrate measurements were taken in Flats 1 and 2 (Table 8.5), but not in Flat 3 because access was not possible. The flowrates achieved were poor, particularly on the default setting and particularly in the bedrooms, to the extent that it seems pointless to run the ventilation systems on the default settings. The SFPs achieved are not acceptable by any available standard (CIBSE, 2005b; DCLG, 2013). It is not clear why the systems performed poorly, whether they were commissioned, to what extent they are maintained, if system specification and design were modified for each project or if standard solutions were simply used without consideration.

**Table 8.5: Ventilation system electricity use and performance data for kitchens K1E and K2N**

| Room/vent | Flow at Speed 1 (l/s) | Flow at Speed 2 (l/s) | Flow at Speed 3 (l/s) |
|---|---|---|---|
| **Flat 1** | | | |
| 1Ea | 0 | 4 – 5 | 5 – 6 |
| 1Eb | 0 | 3 – 3.5 | 5 |
| 1Ec | 0 | 3 – 3.5 | 5 |
| 1Sa | 0 | 3 – 3.5 | 5 |
| 1Sb | 0 | 3 – 3.5 | 5 |
| 1W | 2.5 | 4 | 7.5 |
| K1E cooker hood | 0 | 30 | 40 |
| K1E inlet | 7 – 8 | 13 | 24 |
| **Power consumption** | **44W** | **Assumed 84W** | **Assumed 185W** |
| **SFP ($W/l.s^{-1}$)** | **5.5** | **2.8** | **4.6** |
| **Flat 2** | | | |
| 2Na | 1 | 5 – 6 | 6 – 7 |
| 2Nb | 1.8 | 4 – 5 | 7 |
| 2Sa | 2 | 5 – 6 | 7 – 8 |
| 2Sb | 2 | 5 – 6 | 7 – 8 |
| 2Sc | 2.3 | 5 – 6 | 7 – 8 |
| K2N cooker hood | 0 | 28 | 40 |
| K2N inlet | 4 – 5 | 12 – 13 | 21 |
| **Power consumption** | **24W** | **Assumed 84W** | **Assumed 185W** |
| **SFP ($W/l.s^{-1}$)** | **4.8** | **3.0** | **4.6** |

### *Space Heating Use*

It was difficult to identify space heating electricity consumption from the total consumption in kitchens K1E and K2N; certain loads of 1250-1400W are believed to be the radiators (Figure 8.10). The data suggest that the radiators only stayed switched on for the full two hour duration ten times or less in each kitchen during the study, and that the vast majority of heating durations lasted for less than 30 minutes, and often for less than ten minutes (radiator performance is discussed in Section 8.16). The internal temperature increased rapidly in response to space heating, by 4-5°C with a two hour heating period (Figures 8.10). The internal temperature was also seen to rise in response to other high loads in the kitchens, which is not surprising because the building fabric is thermally lightweight.

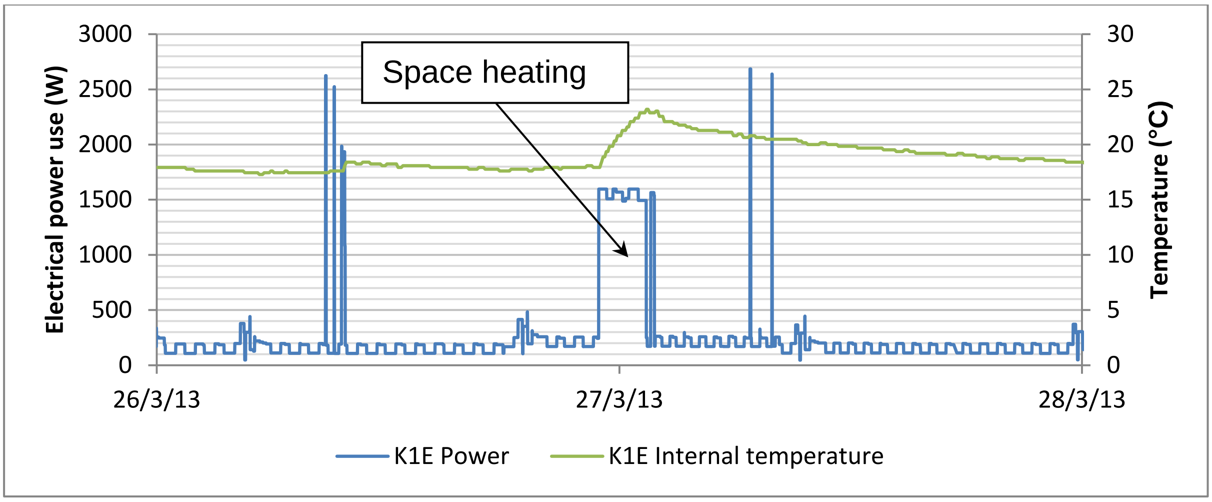


**Figure 8.10: Space heating identified in total consumption for kitchen K1E**

It was not possible to estimate space heating usage in kitchens K1E and K2N, but it was possible to look at the rate of electricity use at different times during the study, which showed that 2-3kWh more electricity was used per day during the coldest part of the study (March) compared to the warmest part of the study (June) (Table 8.6). The additional energy used in March could have been for the attainment of thermal comfort (from space heating, hot food and drinks), and/or for lighting (due to the lower natural light levels). Even if all the additional electricity was used for space heating, it would only equate to around two hours or less of heating per day, which is small and much less than would be typically assumed for a domestic building. March had the lowest average temperatures of any month in 2013, with temperatures well below average, putting it clearly within the space heating season.

**Table 8.6: Rates of total electricity consumption in kitchens K1E and K2N during different periods**

| **Room** | **Average daily electricity consumption (kWh/day)** | | | | |
|---|---|---|---|---|---|
| | **March** | **April** | **May** | **June** | **Whole study**[1] |
| K1E | 10.79 | 9.55 | 9.79 | 8.81 | 9.61 |
| K2N | 14.69 | 12.47 | 11.73 | 11.68 | 12.28 |
| [1] *Calculated for occupied dates only, and the vacant period over Easter was excluded* | | | | | |

### *Kitchen Electricity Use Summary – Loughborough*

The kitchen data revealed the dominant role that constantly running electrical equipment played in the determination of total electricity consumption. It also showed that the ventilation systems had very poor flowrates and unacceptable SFPs. Space heating use was low in kitchens K1E and K2N, and it would be better to focus attention on reducing the electricity consumption of other equipment in the kitchens, such as ventilation systems and constantly running appliances, recommendations are made in Section 8.4.

### 8.1.4 Corridor Lighting Use – Loughborough

Lighting electricity use in the corridor of Flat 1, corridor C1, was unexpectedly high at 721.3kWh; which is 16-30 times greater than the four bedrooms with lighting data (Figure 8.11). In fact, it was the electricity meter with the third highest electricity consumption, after kitchens K1E and K2N (which used 926.3kWh and 1189.8kWh respectively), using more than the six bedrooms in Flat 1 used in total (534.8kWh). Of all the electricity monitored in Flat 1 (which included all electricity consumption in the flat except sockets in the corridor), 33.1% was used for lighting the corridor. This is a surprising finding, that the lights in a passage space were the largest individual use of electricity in the whole flat. While more electricity was used in the kitchen it was for numerous end uses (appliances, lights, ventilation, heating and sockets), none of which could individually have been more than the electricity used for lights in the corridor.

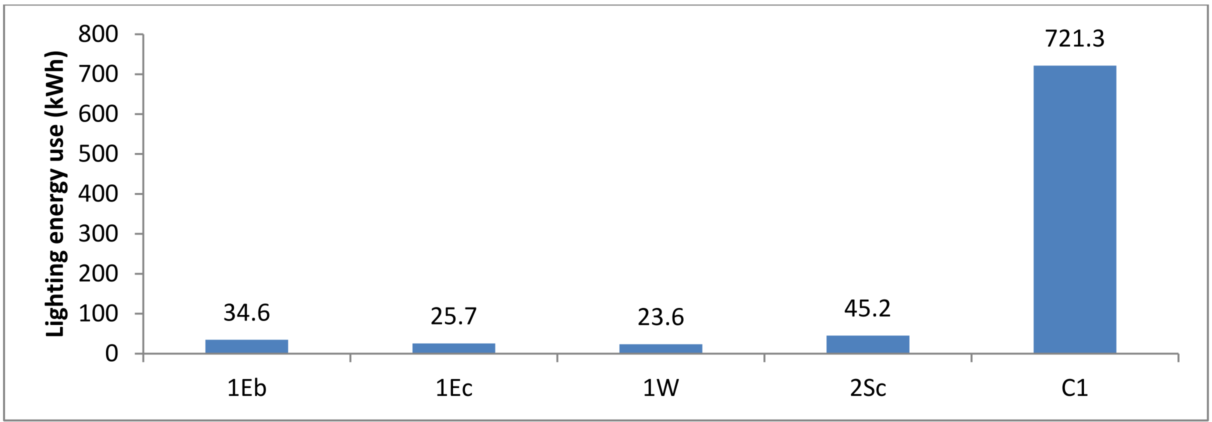


**Figure 8.11: Lighting electricity use in corridor C1 compared to in sub-metered bedrooms**

The corridor lighting consumption was high because: the lighting load was high at around 300W, the occupants rarely turned the lights off, and when the lights were turned off they were rarely off for long (Figure 8.12).

The only time when the lights were turned off with any regularity was at the end of March when the occupant in room 1W was the only occupant in the flat. When the flat was fully occupied the occupants rarely turned the lights off, it is not the case that one occupant turned lights off and another turned them straight back on again, they mostly just stayed on. It is interesting that the occupant in room 1W had different behaviour; when they were alone in the flat and when they were not, but there is no way to know why they changed their behaviour; perhaps another occupant asked that lights be kept on, or perhaps there was no verbal communication and occupants left lights switched on out of politeness for their fellow occupants or through feeling a lack of ownership for the operation of communal devices.

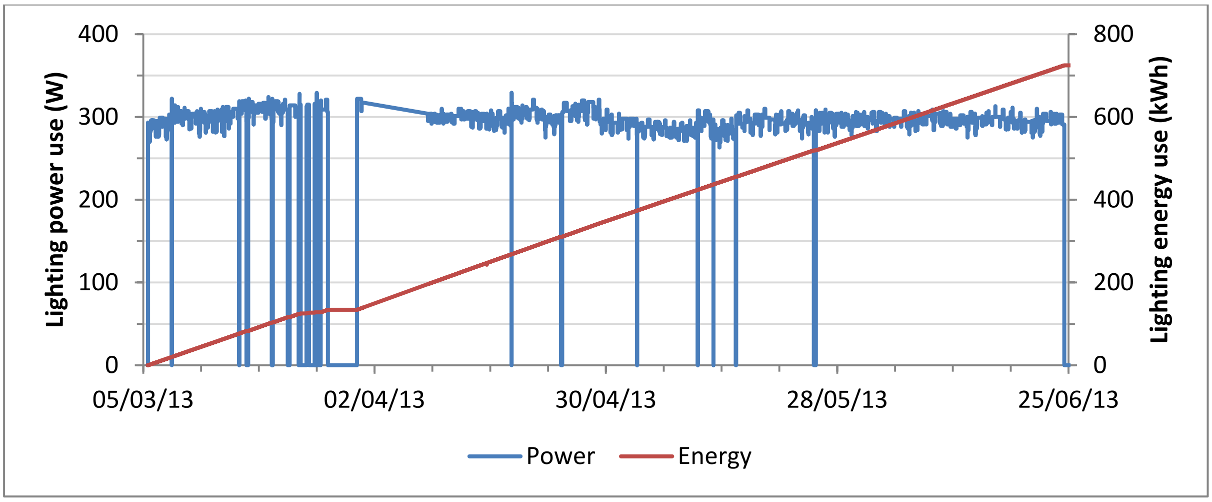


**Figure 8.12: Power and Energy use for lights in corridor C1 during the whole study**

The flat corridors had numerous 2D bulkhead light fittings each with 38W lamps (Figure 8.13). The number of lights varied based on the size of flat, Flat 1 had eight and Flat 2 had six. Firstly, the number of lights seems excessive, they are not emergency exit lights, and there is no need to have so many in each corridor. Secondly, the lamp ratings were high, and lower powered options (around 10-18W) are readily available at comparable prices.

**Figure 8.13: Corridor lighting**

There are 29 flats between the north and south buildings, with an average of around seven lights in each corridor. If the behaviour in corridor 1 is typical, and the lights are always on, then the lights in the flat corridors in the north and south buildings would consume approximately 179kWh per day and 18300kWh over the course of the study. There are also four stair cores and communal corridors connecting flats to stair cores, which have the same lighting and were observed to be always switched on during visits to the site. [redacted] ensured all lights were turned off when the building was vacated in June.

There is clearly scope to reduce lighting usage in passage spaces through better design and control, and the use of lower rated lamps. Passage spaces only need to provide illumination when they are in use, they do not need to be turned on constantly, and tackling this seems like an easy way to reduce energy use, without the need to offer a diminished service, recommendations are made in Section 8.4.

### 8.1.5 Bedroom Electricity Consumption by End Use – Loughborough

Four bedrooms were sub-metered (Appendix K), and in a further five bedrooms total consumption could be separated into space heating consumption and lights and sockets consumption (Appendices L and M).

Space heating accounted for between 20.6% and 35.5% of total consumption (25.5% average), with the remaining electricity used for lights and sockets (Figure 8.14). As with the total electricity consumption, the highest consumers used approximately four times more than the lowest consumers, for space heating and for lights and sockets combined. It is interesting that there was not one end use that determined the difference in consumption between bedrooms, and higher consumers used more for space heating, lights and sockets. The sub-metered data from the four bedrooms reveal a large variation in electricity consumption between the three end uses. Rooms 1Eb and 1Ec used most of their electricity for lighting (42.8% and 45.6% respectively), whereas rooms 1W and 2Sc used most of their electricity for sockets (46.6% and 56.3% respectively). Room 2Sc used nearly as much electricity for lights (45.2kWh), as room 1Sa used in total (49.2kWh), and used more electricity for sockets (110.2kWh) than seven of the bedrooms in Flats 1 and 2 used in total.

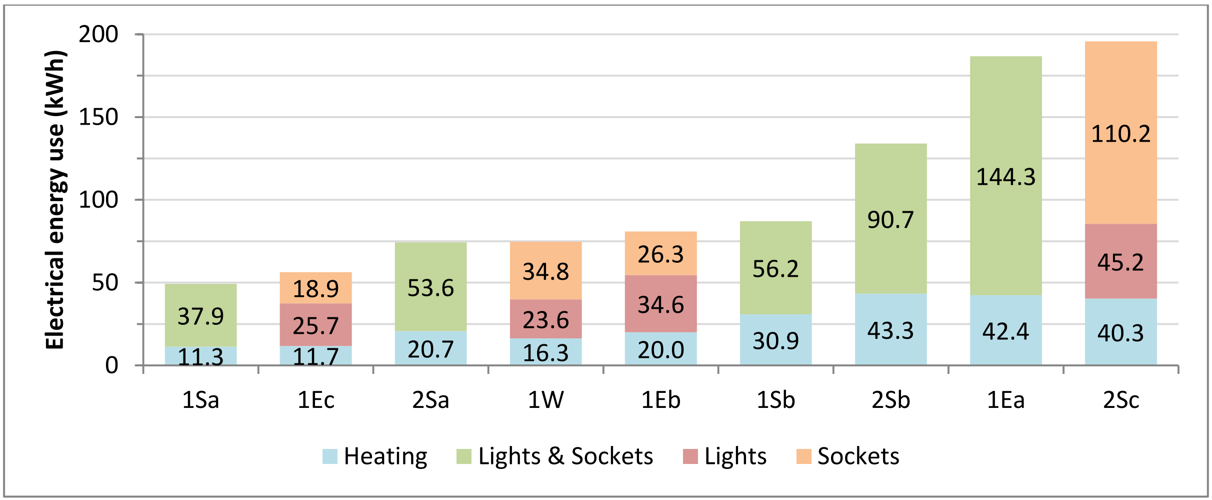


**Figure 8.14: Electricity use by end use in nine rooms in Flats 1 and 2**

Since data were collected for less than a year, and missed most of the heating season, the ratio of space heating use to lights and sockets use in each room is unlikely to be representative of annual consumption. However, it was possible to split the data to analyse how electricity consumption varied during different periods in the study (Table 8.7).

**Table 8.7: Average daily electricity use by end use for each room during different periods of the study**

| Room | Average use (kWh/day) | March | April | May | June | April-June | Whole study[1] |
|---|---|---|---|---|---|---|---|
| 1Ea | Heating | 1.61 | 0.82 | 0.28 | 0.10 | 0.37 | /[2] |
| | Lights and Sockets | 2.49 | 1.27 | 2.01 | 2.48 | 1.94 | 2.01 |
| 1Eb | Heating | 1.43 | 0.07 | 0.06 | 0.01 | 0.04 | / |
| | Lights | 0.62 | 0.27 | 0.41 | 0.50 | 0.40 | 0.43 |
| | Sockets | 0.19 | 0.25 | 0.37 | 0.43 | 0.35 | 0.33 |
| 1Ec | Heating | 1.07 | 0 | 0 | 0 | 0 | / |
| | Lights | 0.26 | 0.30 | 0.38 | 0.41 | 0.34 | 0.33 |
| | Sockets | 0.24 | 0.25 | 0.27 | 0.25 | 0.24 | 0.24 |
| 1Sa | Heating | 1.04 | 0 | 0 | 0 | 0 | / |
| | Lights and Sockets | 0.47 | 0.43 | 0.48 | 0.53 | 0.48 | 0.48 |
| 1Sb | Heating | 2.61 | 0 | 0.07 | 0 | 0.03 | / |
| | Lights and Sockets | 0.64 | 0.57 | 0.69 | 0.88 | 0.71 | 0.70 |
| 1W[3] | Heating | 0.73 | 0.03 | 0 | 0.02 | 0.01 | / |
| | Lights | 0.38 | 0.35 | 0.32 | 0.47 | 0.35 | 0.36 |
| | Sockets | 0.59 | 0.44 | 0.48 | 0.76 | 0.50 | 0.53 |
| 2Sa | Heating | 1.32 | 0 | 0.09 | 0.04 | 0.05 | / |
| | Lights and Sockets | 0.62 | 0.56 | 0.74 | 0.65 | 0.66 | 0.66 |
| 2Sb | Heating | 1.78 | 0.81 | 0.18 | 0 | 0.27 | / |
| | Lights and Sockets | 0.75 | 1.09 | 1.11 | 1.23 | 1.14 | 1.08 |
| 2Sc | Heating | 2.15 | 0.42 | 0.37 | 0.02 | 0.27 | / |
| | Lights | 0.53 | 0.47 | 0.61 | 0.59 | 0.57 | 0.57 |
| | Sockets | 1.43 | 1.45 | 1.43 | 1.26 | 1.37 | 1.38 |

[1] *Only occupied periods were considered, including habitual vacancies (e.g. regular weekends away), any irregular vacancies were excluded (e.g. the month long vacancy between terms)*
[2] *With little space heating use during many months, averaging over the whole period is illogical*
[3] *Room 1W was vacant from 25th May to 17th June, the daily averages are for occupied periods only*

In terms of lights and sockets electricity consumption, some bedrooms used consistent quantities of electricity during each month (such as 1Ec and 1Sa), whereas in other rooms it varied (such as 1Ea and 1Eb). Further analysis of the lights and sockets data for bedrooms (Appendices K and M) were not particularly useful because they did not reveal any significant ways that the design or construction of the buildings could be improved to reduce energy use. The only findings were that energy could be saved if lower powered lamps were used, if each light in the bedrooms had individual controls (instead of only one switch to operate two lights), and if the bathroom lights were on timers (as in some other student halls).

In terms of space heating use, electricity consumption differed markedly in March compared to the whole study because space heating accounted for a far higher proportion of the total, between 43.2% and 80.4% (with seven of the nine rooms using more than half their electricity for heating). March had the lowest average temperatures of any month in 2013, and was far colder than average, putting it clearly within the space heating season. Space heating use dropped after March, with two rooms (1Ec and 1Sa) using no heating from April to June, and four (1Eb, 1Sb, 1W and 2Sa) using very little (at 3.2kWh or less). Whereas, the three highest consumers (1Ea, 2Sb and 2Sc) used approximately half their space heating energy in March and the other half from April to June, with usage gradually diminishing as the studied progressed. However, the average daily space heating use in March was not particularly large in any of the bedrooms in Flats 1 and 2, representing only around 2-4 hours of heating per day, which is less than would be assumed for a typical domestic building. The radiators in the Loughborough study had quite restrictive controls which kept heating use low and made it difficult to use excessive heating; the space heating use and radiator controls are discussed further in the following section.

### 8.1.6 Space Heating Electricity Consumption - Loughborough

So far space heating use has only been discussed for the bedrooms of Flats 1 and 2, but it was also sub-metered in Flat 3. Flat 3 used significantly more heating than the bedrooms of Flats 1 and 2 (Figure 8.15 and Appendix O), particularly kitchen K3W which used more than all the other radiators combined (357.1kWh), and 34 times more than the lowest consumer, room 1Sa. Flat 3 is a studio flat comprising one kitchen module and one bedroom module connected by an arch, the studio modules have the same size, fabric, radiators and fenestration as bedroom modules, but different internal layouts. Observations suggest the occupant in Flat 3 may have used the kitchen radiator more than the bedroom radiator simply because it was more practical, because of where they had placed their belongings.

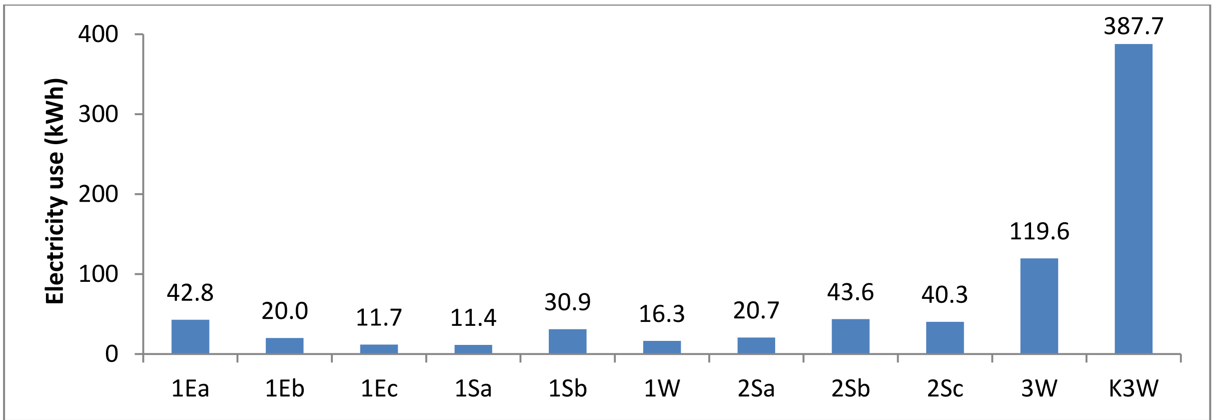


**Figure 8.15 Space heating electricity consumption in all rooms with heating data**

There were five days in March when the electricity consumption for radiator K3W was more than radiators 1Ec and 1Sa used during the whole study (Figure 8.16). The reasons for the variation in consumption between different rooms are partly due to the way the radiators operated and partly due to the behaviour of the occupants.

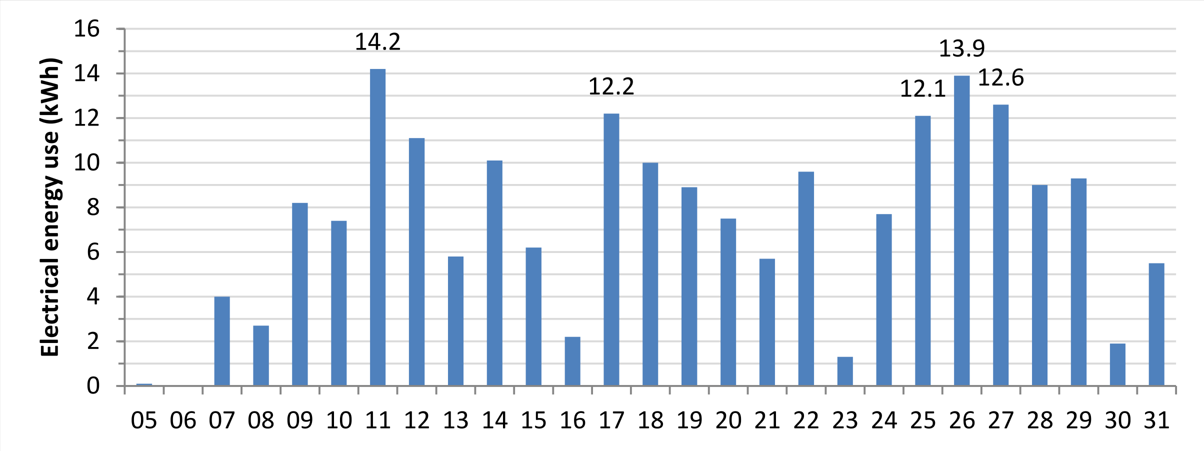


**Figure 8.16: Electricity consumption for the radiator in kitchen K3W for each day in March**

### *Radiator Operation*

The radiators should stay switched on for a maximum duration of two hours, and switch off earlier if the thermostat setpoint is reached, however, they did not always operate accordingly.

In Flats 1 and 2, the radiators normally worked correctly, but there were some occasions when radiators stayed on for longer than two hours and there were many occasions when the radiators turned off after less than two hours at temperatures below any reasonable thermostat setpoint. Obtaining extra heating is unlikely to be problematic for the occupant, but the inability to turn the heating on for sufficient durations may be. The radiator in room 1Ec exhibited both of these irregularities on the 11th March when the occupant returned after a weekend away to an internal temperature of around 14°C (Figure 8.17). The first heating instance lasted for eight hours, raising the temperature to around 18°C. Despite the long heating duration the internal temperature was still low, and the occupant activated the heating again, but it stayed on for only thirty minutes. The heating switched off prematurely a further two times before finally remaining on for two hours from 19:20 to 21:20. Out of the five heating instances on the 11th March, only the last followed the correct operation.

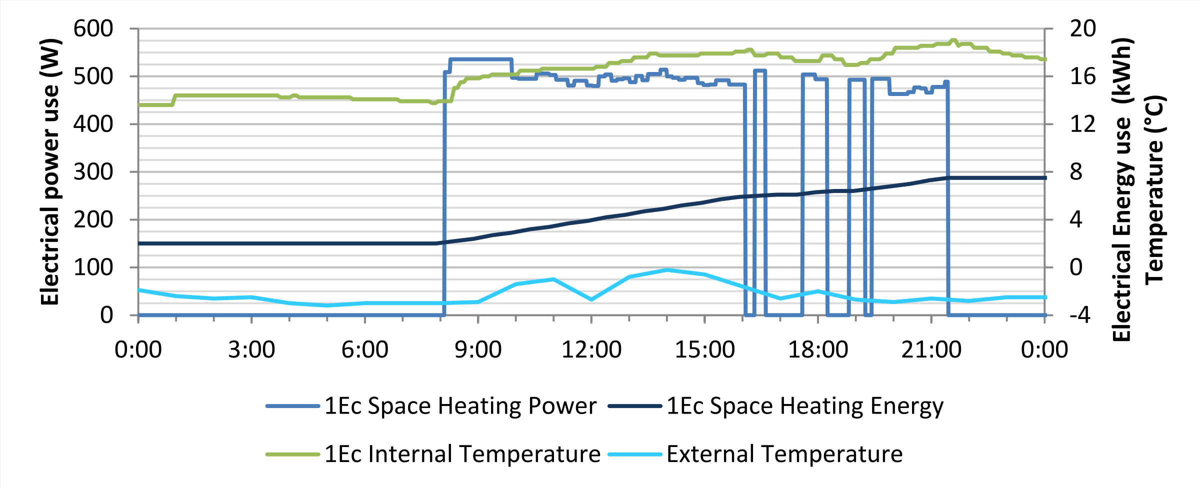


**Figure 8.17: Graph showing heating durations in room 1Ec both longer and shorter than they should be**

There were some instances that were particularly concerning, when internal temperatures were at uncomfortably low levels but radiators would not stay on, this was observed in every room with temperature data, (in all the bedrooms and kitchens of Flats 1, 2 and 3). It occurred in room 1Ea on 21st March when the occupant returned after being away for four days to an internal temperature of around 16°C (Figure 8.18). They activated their heating sixteen times between 9am and 11pm, but each time the heating stayed on for only 10-22 minutes despite internal temperatures of only 16-17°C. The cause is not clear (perhaps the thermostat or the controls), but it raises concerns that the radiators did not always provide adequate thermal comfort.

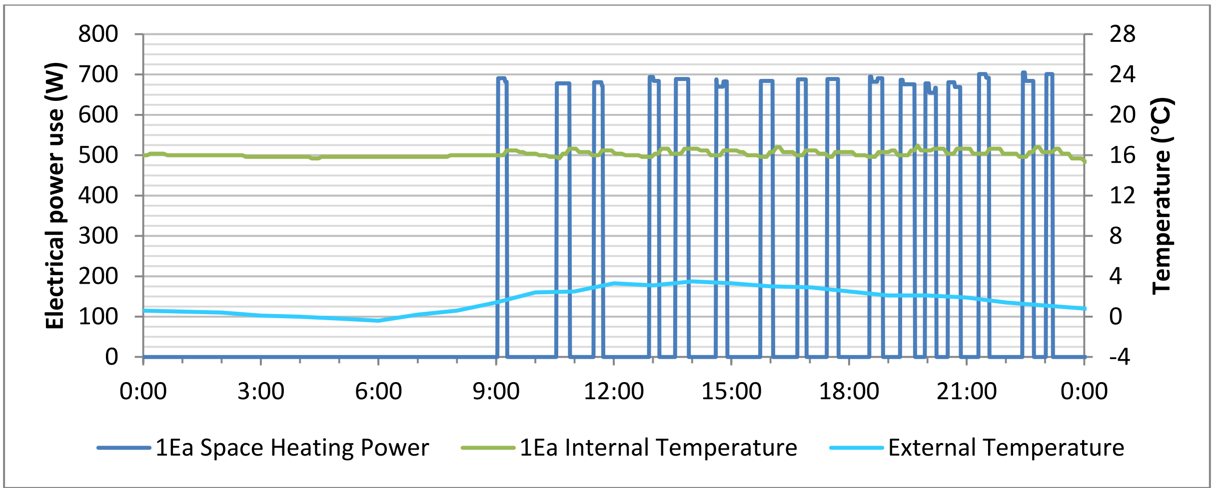


**Figure 8.18: Graph showing incorrect functioning of the radiator in room 1Ea leading to low temperatures**

The radiators in Flat 3 operated differently, typically providing heating for up to eight hours although there were instances when the heating was on for longer and shorter periods (Figure 8.19). There was also no evidence that the radiators in Flat 3 had a thermostat setpoint, and on occasions they stayed on above 26°C. Occupants in [redacted] buildings had been known to tamper with this type of radiator to obtain more heating; and it seems certain that this had happened Flat 3, but it is not clear what was done to them to change their operation, whether they had been reset with the controller (which is a remote possibility) or if they had been physically tampered with in some way. Whatever was done to the radiators, they still turned off automatically, and therefore were not completely under the control of the occupant and could not be used continuously for days or weeks at a time.

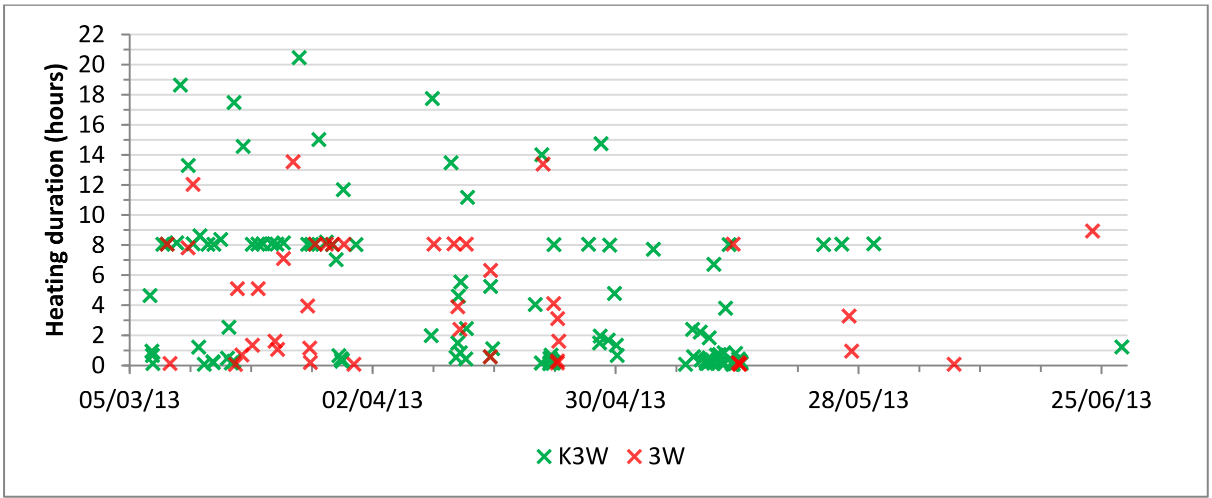


**Figure 8.19: Scatter plot showing heating durations throughout the study: Rooms K3W and 3W**

The difference in radiator operation between Flat 3 and Flats 1 and 2 was one of the reasons that heating use was so much higher in Flat 3. The radiators in Flat 3 made it easy for the occupant to obtain more heating, and therefore consume more electricity. However, occupant behaviour also played a role, because the occupant still had to turn the heating on repeatedly to consume as much as they did, space heating usage is discussed below.

### *Space Heating Behaviour and Patterns*

The way occupants used space heating differed greatly, including the quantity of electricity used, the number of times the heating was activated and the length of the heating season (Table 8.8). In general higher consumers activated their heating more times and later into the year than the lower consumers. However, there was variation in this pattern, such as in room 1Ea where the heating was activated 117 times, nearly twice as many as in room 2Sb, but the total electricity used for heating was similar (Figure 8.20, and Appendix O for all rooms). Many of the heating instances in room 1Ea were very short, 48 lasted ten minutes or less and only thirteen lasted two hours or more, this is because the internal temperature was often too high for heating to remain on for long. In contrast, room 2Sb only had three heating instances last ten minutes or less, but 28 instances last two hours or longer, because the internal temperature was lower which allowed heating to stay on for longer.

The radiator in K3W was turned on more times than any other radiator, and since each heating instance typically lasted eight hours, this explains why this radiator used so much more electricity than others.

**Table 8.8: Space heating data for rooms in Flats 1, 2 and 3**

| Room | Number of times heating activated | Last heating occurrence | Last two hour heating occurrence | Heating electricity use (kWh) | Total heating duration (hours) |
|---|---|---|---|---|---|
| 1Ea | 117 | 14th June | 13th May | 42.8 | 62.7 |
| 1Eb | 30 | 17th June | 22nd April | 20.0 | 39.6 |
| 1Ec | 14 | 15th March | 14th March | 11.7 | 23.9 |
| 1Sa | 20 | 13th March | 13th March | 11.4 | 21.1 |
| 1Sb | 36 | 8th June | 25th May | 30.9 | 44.3 |
| 1W | 18 | 21st April | 26th March | 16.3 | 23.7 |
| 2Sa | 21 | 5th June | 13th May | 20.7 | 40.2 |
| 2Sb | 61 | 21st June | 16th May | 43.6 | 79.6 |
| 2Sc | Unknown[1] | Approx. 9th June[1] | Unknown[1] | 40.3 | 73.1 |
| 3W | 43 | 24th June | 24th June (9 hours heating) | 119.6 | 219.5 |
| K3W | 133 | 27th June | 30th May (8 hours heating) | 387.7 | 564.0 |

[1]*The heating meter in 2Sc was faulty so accurately determining dates was not possible*

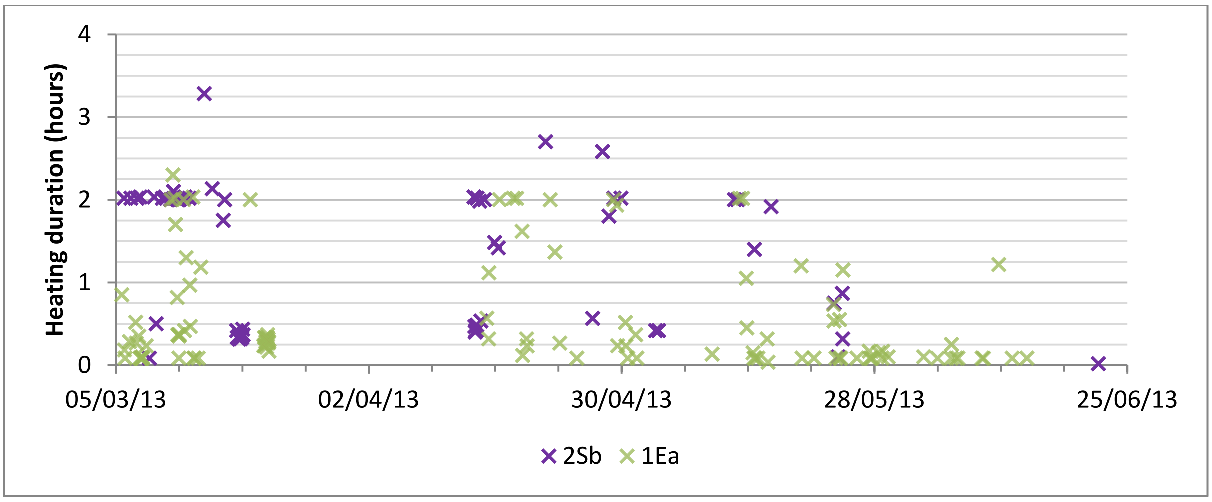


**Figure 8.20: Scatter plot showing heating durations throughout the study: Rooms 1Ea and 2Sb**

An occupants' desire for space heating was not the only factor that determined heating electricity consumption; the way the radiators operated clearly played a role. The repeated attempts to use heating in room 1Ea indicate that the occupant would have used more heating if they could, but the radiators would not allow it. This was seen in all rooms during the study, where occupants would turn heating on but it would not stay on, showing that there were occasions when occupants wanted more heating but could not obtain it, which is a clear indication that the radiators were restricting space heating usage.

The data were analysed further to try to determine any other factors that may have influenced space heating consumption, revealing a number of findings. No heating routine was observed in any room, such as turning the radiator on upon waking or before sleeping, and occupants used heating during all hours of the day. No strong relationship was observed between external temperature and space heating use, and it was not possible to predict heating use from the external temperature data. Nor were any patterns observed between space heating use and room orientation, internal layout or fabric properties. However, this does not mean that these factors do not influence heating use, just that they were not evident in the data. It may be that the studies were too small and covered too little or the heating season, to identify patterns. The large variation in occupant behaviour could also have overshadowed and masked any other relationships.

Only one clear pattern did emerge in Flats 1 and 2, a link between space heating use and internal temperature. Problems with the reception of temperature data (particularly early in the study when most space heating occurred) mean that there is only useable temperature data for some rooms. In these rooms occupants were seen to activate their space heating when the internal temperature dropped to a certain level, indicating that internal temperature was a driver for space heating use. Different occupants appear to have been comfortable at different internal temperatures, because they activated the heating at different temperatures. The occupant in room 1W tended to turn on the radiator when the internal temperature dropped to 18-20°C (Figure 8.21), similar patterns were observed in rooms 1Eb and 2Sb. Whereas, the occupant in room 1Ec only activated their radiator when internal temperature dropped to 16-17°C, less heating is required to maintain lower temperatures, which may explain why this room used so little space heating (11.7kWh). In contrast, the occupant in room 1Ea turned their heating on at higher internal temperatures, typically at around 22°C, but on occasions space heating was activated at internal temperatures of 23-24°C, and even 25-26.5°C in late May and June (but the heating would not stay on). The data suggest that different occupants favoured different thermal conditions, and this may be a reason why space heating use differed between occupants.

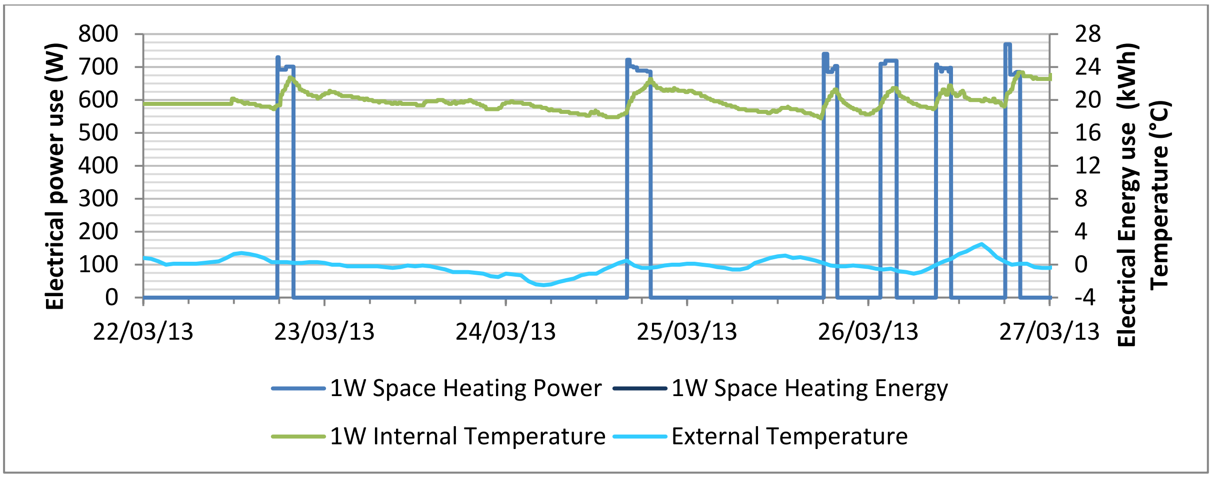


**Figure 8.21: Graph showing apparent thermostat setpoint range in room 1Wc at 18-19°C**

The space heating patterns observed in Flat 3 were different, because the occupant used significant quantities of heating over a range of temperatures. Space heating was on for 58.5% of the time between 7$^{th}$ and 31$^{st}$ March. (Figure 8.22), and it appears that if this occupant could have left the heating on constantly during the colder months they may have. The high heating use in Flat 3 compared to other rooms was clearly due to the combination of occupant behaviour and radiator operation. The heating usage in Flat 3 shows that space heating use is not simply a function of internal temperature, and that some occupants will use large quantities of heating if given the opportunity. There were actually data to suggest that this occupant was regularly opening the window while using the heating, and by doing so avoided overheating the room despite the large use of heating. This is exactly why these restrictive radiators were used, to stop the wasteful use of heating. The internal temperatures within Flats 1 and 2 were normally within comfortable ranges despite the much reduced heating usage, and the data indicate that the heating use in Flat 3 was wasteful and that comfortable conditions could have been achieved with less heating.

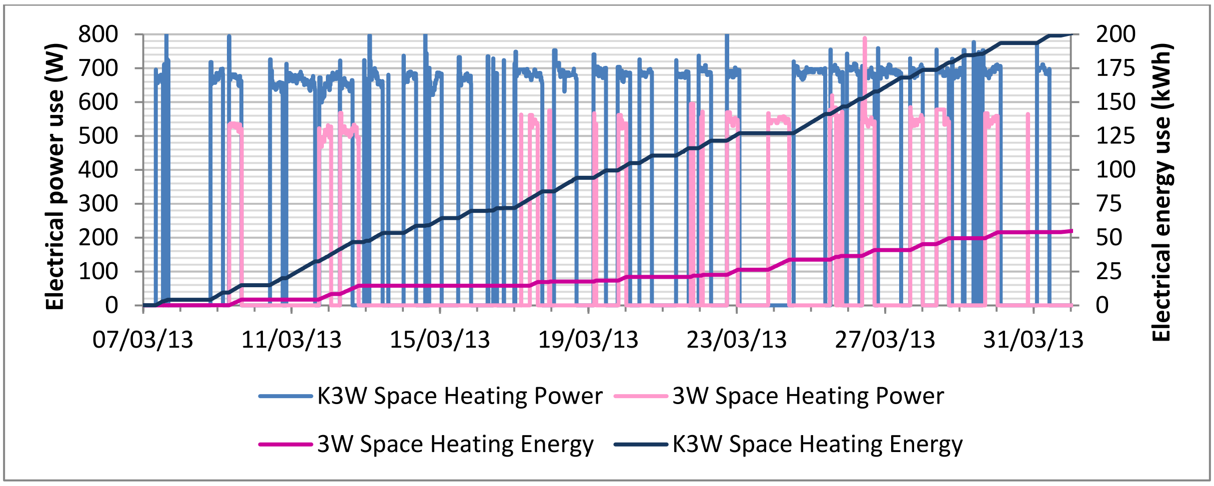


**Figure 8.22: Space heating electricity consumption in Flat 3 during March**

As previously discussed space heating use diminished as the study progressed. In Flats 1 and 2 the radiators would turn off after shorter and shorter periods because internal temperatures were higher: therefore it cannot be known if the reduction in space heating was entirely at the wish of the occupants or if some occupants still wanted to use space heating but simply gave up trying to obtain it. Whereas, in Flat 3, the occupant could still obtain long heating periods even in June and the reduction in heating demand appears to be occupant driven, because they no longer wanted heating, not because they had given up trying to obtain heat from unresponsive radiators, which may have been the case in Flats 1 and 2.

It is clear that the radiators often restricted the occupant's ability to use heating, and therefore it cannot be known how occupants wanted to use their heating versus how they were able to use their heating.

### *Space Heating Use Discussion – Loughborough*

There were large differences in space heating use, particularly in Flat 3 compared to Flats 1 and 2. The radiators in Flats 1 and 2 typically provided heating instances of up to two hours and responded to thermostat setpoints. Whereas, in Flat 3 the radiators typically provided heating for up to eight hours and did not appear to have thermostat setpoints; indicating that these radiators had been tampered with. The difference in radiator operation is the main reason for the large differences in space heating use between Flat 3 and Flats 1 and 2, although occupant behaviour also played a role.

Many occupants were seen to use heating based on the internal temperature and did not have a routine based on the time of day. This shows that if the thermal performance of the building fabric can be improved, so that internal temperatures are higher without the need for space heating, then heating use can be reduced for these types of occupants. However, the occupant in Flat 3 did not exhibit such clear patterns of space heating behaviour, and tended to use heating regularly with no clear link to internal temperature. Therefore, it may be difficult to predict how much space energy could be saved by raising ambient temperatures through fabric improvements, because there is variation in occupant behaviour, and not all behaviour can be predicted based on environmental conditions alone.

The differences in heating use between Flat 3 and Flats 1 and 2 indicate that restricting the radiators in the manner they were helps to limit space heating electricity use. While heating use was much higher in Flat 3, the radiators were still restricted just to a lesser extent. The data indicate that if restrictions had been lifted then space heating would likely have been much higher, particularly in some rooms, such as 1Ea, 1Eb, 2Sb, and Flat 3.

Restricting heating clearly keeps energy use low, however, the data also revealed instances when radiators would not stay turned on at low temperatures, raising concerns for thermal comfort. It is not certain why this is the case, but care is needed in the control of restrictive radiators, so that they limit energy use but can be relied upon to meet comfort requirements.

This research included two case studies with entirely different heating systems and heating controls, which provided the opportunity to further analyse the impact that heating system designs and controls have on space heating use and occupant behaviour. The findings from the London study are discussed in the following section (8.2) and the two studies are compared in Section 8.3.

## 8.2 Energy Use – London

### 8.2.1 Monitoring Details – London

Monitoring equipment was installed in sixteen bedrooms in Block B; therefore sixteen participants were involved in the study (Table 8.9). Room 9S was excluded because the sensor became unstuck from the radiator early in the study, and room 10Wa was excluded because the sensor was lost. It is not possible to show a drawing with the locations of the bedrooms as to do so could make the participants identifiable, breaching anonymity and data protection. Participant selection and recruitment are detailed in Appendix B. The rooms were spread throughout the building on different floors and with different orientations, to capture data about the range of conditions within the building. Equipment was installed on 8th March 2013, and removed in September, occupants moved out on or before 31st August 2013. Prior to installation various tasks had to be completed such as: equipment testing and building inspections, which are discussed in Appendix C.

The performance of the radiator temperature sensors was good and they all operated correctly. There were however major problems with the wireless sensor network, the range was very low resulting in the loss of nearly all wireless data. Multiple attempts were made to resolve this by installing additional repeaters and moving repeaters and controllers, but to no avail. The only room with internal temperature and humidity data is the one room with the missing radiator temperature sensor, room 10Wa. The loss of wireless data limited the analyses that could be conducted, particularly regarding the relationship between internal temperature, space heating and window opening. The problems with the monitoring equipment and its impact on analysis are discussed in Appendix E.

**Table 8.9: Monitored bedrooms and their location within Block B**

| Room Code[1] | Floor Number | Orientation |
|---|---|---|
| 1Ea | 1 | East |
| 1Eb | 1 | East |
| 1Ec | 1 | East |
| 2E | 2 | East |
| 7Wa | 7 | West |
| 7Wb | 7 | West |
| 7Wc | 7 | West |
| 8S | 8 | South |
| 9W | 9 | West |
| 9Ea | 9 | East |
| 9Eb | 9 | East |
| 9S[2] | 9 | South |
| 10Wa[3] | 10 | West |
| 10Wb | 10 | West |
| 10Wc | 10 | West |
| 11W | 11 | West |

[1] *Room code: number indicates storey uppercase letter indicates room orientation, and lowercase letter is a generic describer when there are multiple rooms with the same storey orientation*
[2] *Sensor became unstuck early in the study and room 9S was excluded from the analysis*
[3] *Radiator sensor lost so room 10Wa excluded from space heating analysis*

### 8.2.2 Space Heating Results – London

The data from the temperature sensors fixed to bedroom radiators yielded interesting results about space heating behaviour and about the performance of the space heating system.

#### *Space Heating System Performance*

Two unexpected findings were made about the heating system: heating was unavailable nightly between approximately midnight and 3:15am, and heating was available during each month of the study because it was never turned off.

The temperature of any radiator that was on at midnight suddenly dropped indicating that it was no longer providing heat, the temperature would continue to drop until around 3:15am, after which it would rapidly spike indicating that the radiator had switched on again. This pattern was observed every night in every monitored room where the heating was on prior to midnight, (Figures 8.23 and 8.24). This greatly affected the radiator temperature data with sharp drops in temperature at midnight and sharp peaks at 3:15am. Enquiries were made with [redacted] about this behaviour, but no explanation was obtained for it.

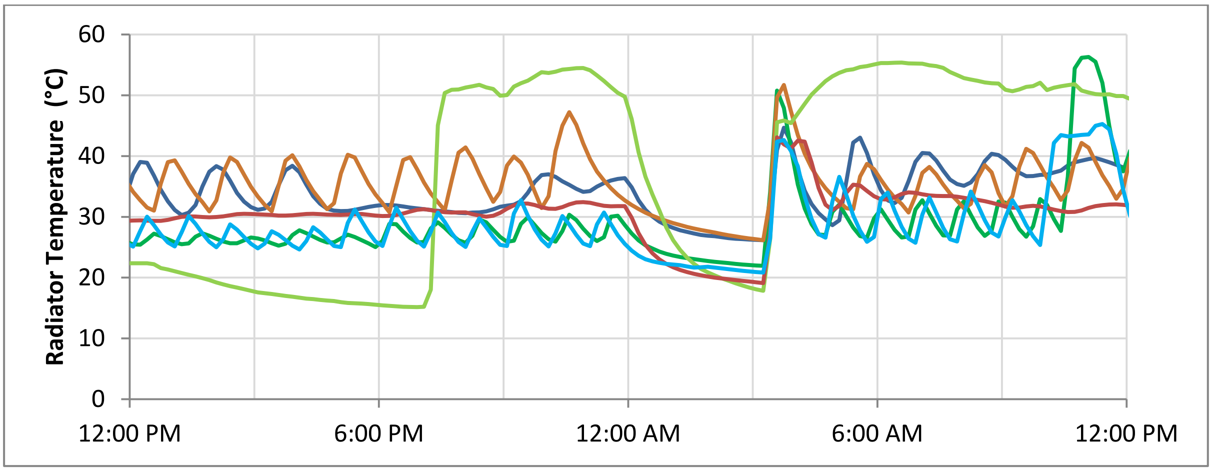


**Figure 8.23: Heating system shutdown on 11th Match 2013**

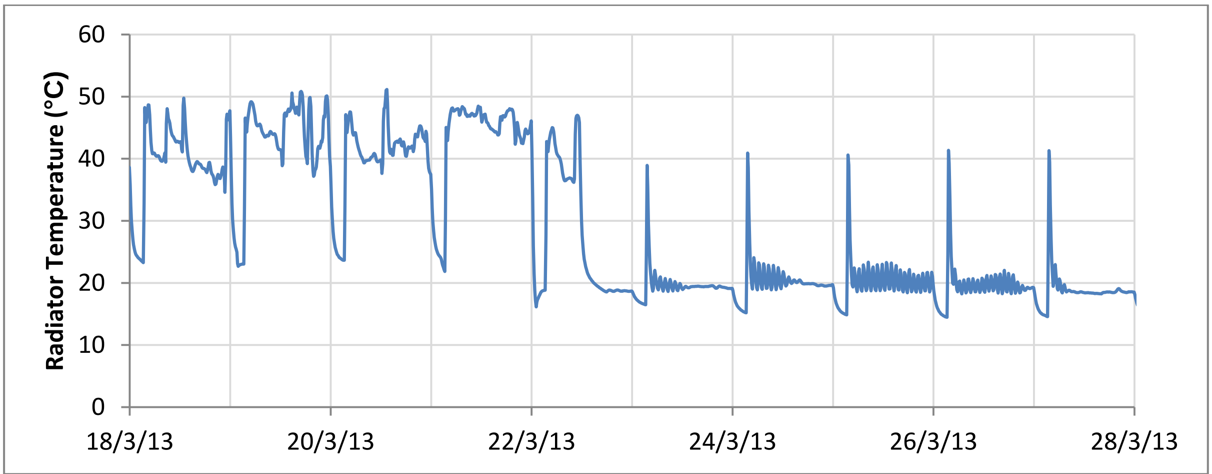


**Figure 8.24: Room 1Ea heating system shutdown patterns with variable TRV settings**

Space heating was available whenever external temperature dropped to 15°C or less, and it was not deactivated in summer. External temperature regularly dropped below 15°C, including throughout the summer (particularly at night), therefore heating was available during each month of the study, even in July and August (Figure 8.25 and Table 8.10). The study lasted 4224 hours in total; the temperature data from St James's Park weather station [UK Met Office, 2014d] show that external temperature was at or below 15°C for 2301 hours of the study (54.5%), factoring in the unavailability of heating between midnight and 3:15am this becomes 1909 hours (45.2%). There is no need to heat the building during summer, doing so wastes energy (and with it money), and it increases the likelihood that overheating will occur.

It is clear with the nightly unavailability of heating and its continued availability throughout the summer that that the operation of the heating was not ideal.

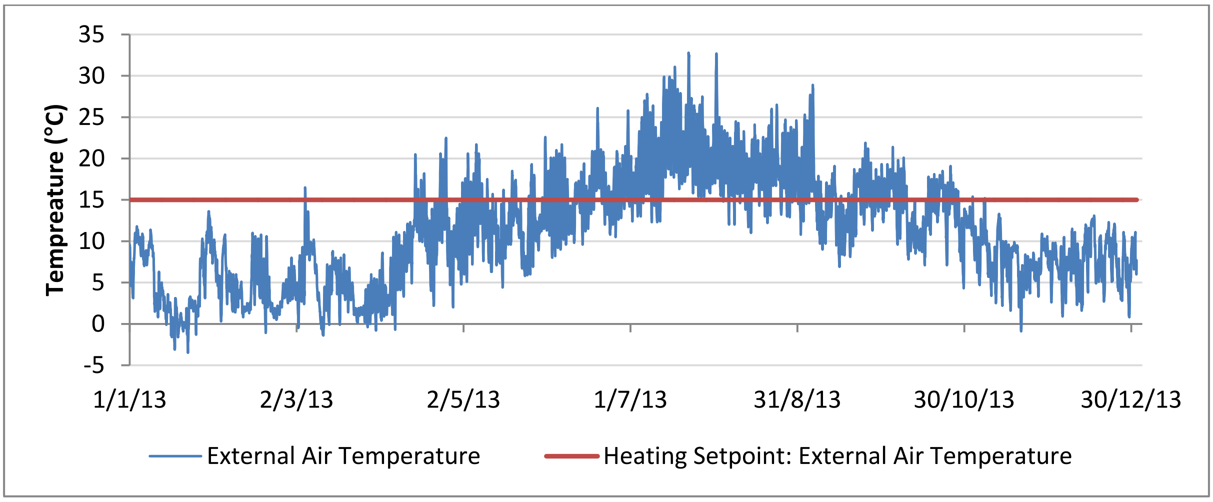


**Figure 8.25: External Temperature – St James's Park weather station London 2013**

**Table 8.10: Space heating availability in London case study building during 2013**

| **Period** | **Average Temperature** | **External Temperature ≤15°C** | | **Space Heating Available** | |
|---|---|---|---|---|---|
| | **°C** | **Hours** | **% of Period** | **Hours** | **% of Period** |
| January | 4.9 | 744 | 100 | 643.25 | 86.5 |
| February | 4.2 | 672 | 100 | 581 | 86.5 |
| March | 4.3 | 740 | 99.5 | 639.25 | 85.9 |
| April | 9.1 | 656 | 91.1 | 558.5 | 77.6 |
| May | 12 | 599 | 80.5 | 500.25 | 67.2 |
| June | 15.5 | 327 | 45.4 | 252 | 35.0 |
| July | 20.5 | 70 | 9.4 | 49.5 | 6.7 |
| August | 18.8 | 97 | 13 | 71.75 | 9.6 |
| September | 15.1 | 375 | 52.1 | 306 | 42.5 |
| October | 13.6 | 486 | 65.3 | 406.25 | 54.6 |
| November | 7.9 | 714 | 99.2 | 616.5 | 85.6 |
| December | 7.5 | 744 | 100 | 643.25 | 86.5 |
| Whole study | 13.7 | 2301 | 54.5 | 1909.25 | 45.2 |
| Whole year | 11.2 | 6224 | 71.1 | 5267.5 | 60.1 |

### *Space Heating Use*

Space heating use varied widely between occupants over the course of the study, including how much heating was used (Figure 8.26), when it was used, and how it was used. On average, the 14 occupants obtained heat from their radiator for 550 hours (22.9 days) during the study, but the variation between occupants was significant. The highest user was in room 9W, where the radiator provided heat for 1393 hours, which accounted for 33% of the whole study, and 73% of the time that space heating was available. This is 63 times longer than the smallest consumer, room 7Wa, which obtained only 22 hours of heating (0.5% of the study). It should be noted that the hours of heating used cannot be used to infer energy use, because although the radiator rating is known (800W), the radiators were not always used on maximum. Nothing is known about how much energy radiators used on each TRV setting, nor is it possible to identify the five TRV settings from the data, although the differences between high and low settings are apparent.

There was no clear pattern based on orientation, storey or external cladding that could predict which rooms would use more heating and which less. The second highest consumer (10Wb) and the second lowest consumer (10Wc) were in the same flat but had vastly different heating use. Similarly, rooms 1Ea, 1Eb and 1Ec were all in the same flat, but room 1Ea obtained heating for nearly as long as rooms 1Eb and 1Ec combined. The three rooms on the seventh storey were among the four lowest consumers, but there is still a significant variation between them with the heating duration in room 7Wb 8.7 times greater than in 7Wa. The participants on the first and second storeys were not the lowest of consumers; and it may be that because the lowest storeys were cooler they had a greater base need for heating, but there were not enough rooms in the study to be certain of any link.

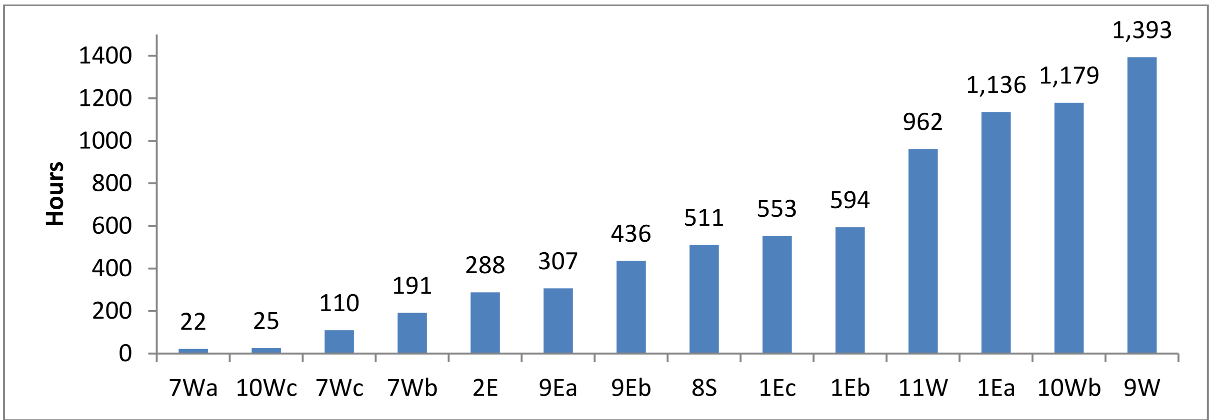


**Figure 8.26: Hours of space heating used in London case study: 9th March – 31st August 2013**

The data suggest that it was the variation in occupant behaviour that was the main reason for the differences in space heating use. The highest consumers regularly left their radiators on for weeks at a time, which meant they obtained space heating whenever it was available (all space heating graphs are given in Appendix P). The radiator in room 10Wb was turned on continuously for 57 days between 27th March and 21st May, at which point it was only switched off for ten hours before it was turned back on again until 2nd June (Figure 8.27). The radiator in room 10Wb was only turned on six times during the study, for an estimated total of at least 84 days (47.7% of the study); meaning that on average each time the radiator was turned on it was for 14 days (Table 8.11).

There is an important distinction to be made between the duration that a radiator was turned on and the duration of heating that was obtained, as they are not the same. Room 10Wb only obtained heating for 49.1 days, or 58.5% of the time that the radiator was on (Table 8.11) because heating was not available between midnight and 3:15am, and anytime the external temperature exceeded 15°C, but the radiator could remain turned on even if heating was not available. Identifying radiators that were left on for long periods was straightforward because they would immediately heat up whenever heating became available.

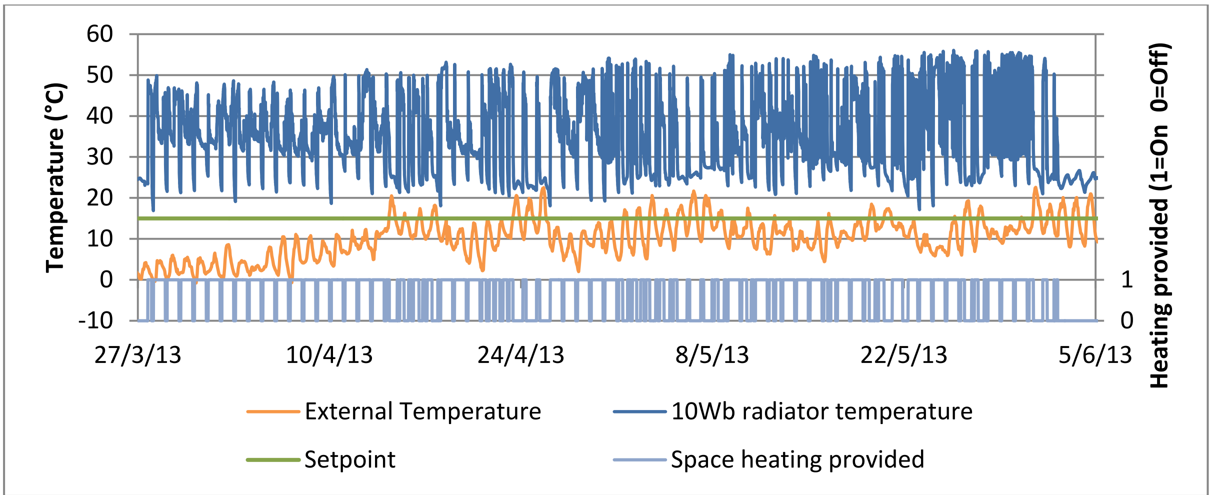


**Figure 8.27: Radiator in 10Wb was only turned off once for 10 hours between 27th March and 2nd June**

The data clearly show that the highest consumers habitually left their radiators switched on for weeks at a time. In fact even the average users and some of the low users left their heating on for days to weeks at a time, but just to a lesser extent than the high users. The fact that radiators could be left turned on continuously is seen as a major factor in the large space heating use compared to the Loughborough study.

Table 8.11: Durations that radiators were turned on in each room

| Room | No. of times radiator turned on | Total duration radiator on (hours) | Total duration heating obtained (hours) | How often heating obtained when radiator on (%) |
|---|---|---|---|---|
| 1Ea | 9 | 1638.5 | 1135.7 | 69.3 |
| 1Eb | 5 | 702.5 | 593.7 | 84.5 |
| 1Ec | 4 | 877 | 553.2 | 63.1 |
| 2E | 27 | 359.5 | 287.8 | 80.1 |
| 7Wa | 4 | 25.33 | 21.8 | 86.2 |
| 7Wb | 5 | 221.2 | 191.2 | 86.4 |
| 7Wc | 7 | 132.8 | 109.5 | 82.4 |
| 8S | 26 | 594.5 | 510.8 | 85.9 |
| 9Ea | 25 | 359.7 | 306.5 | 85.2 |
| 9Eb | 16 | 557.2 | 435.8 | 78.2 |
| 9W | 16 | 2203.7 | 1393.2 | 63.2 |
| 10Wb | 6 | 2015.3 | 1179.3 | 58.5 |
| 10Wc | 6 | 57.33 | 25.3 | 44.2 |
| 11W | 3 | 1160.3 | 961.8 | 82.9 |

However, just because radiators could be left on does not mean they all were or that they always were. The lowest users rarely used their heating, and when they did it was typically for shorter periods, such as room 7Wa where heating was used on only four occasions, averaging 6.3 hours each, and room 7Wc where the radiator was turned on only seven times, once for 2.8 days, but typically for less than ten hours each (Figure 8.28).

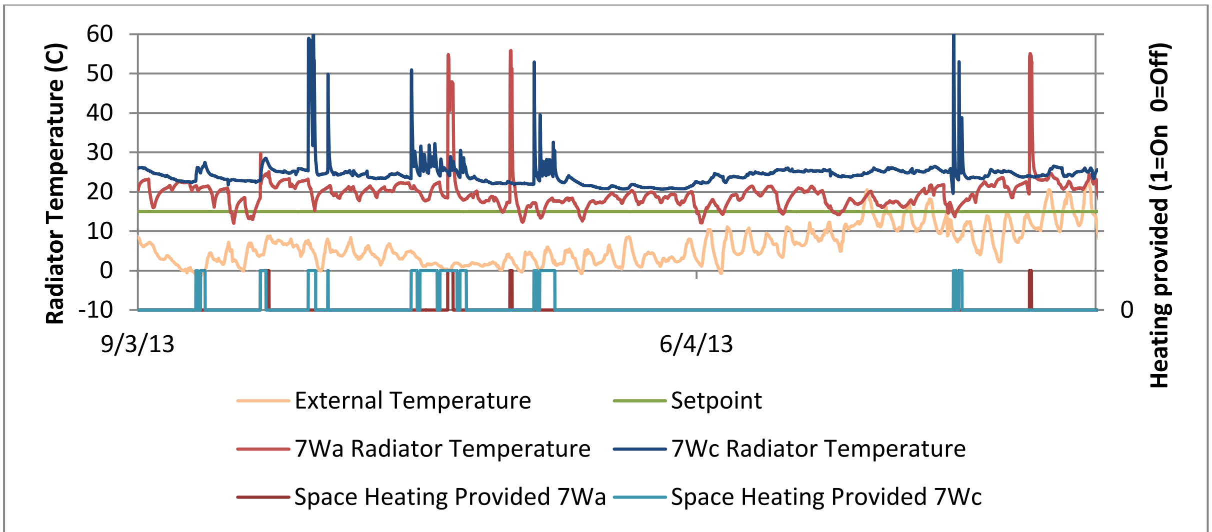


Figure 8.28: All space heating use in room 7Wa between 9th March and 31st August 2013

The medium users were between the two extremes, sometimes radiators were turned on for days at a time and other times they were turned on for short durations. The occupant in room 8S was an average user, obtaining 510 hours of heating, the radiator was turned on 27 times, far more than the highest consumers, because although the occupant regularly used heating, they also turned it off regularly (Figure 8.29).

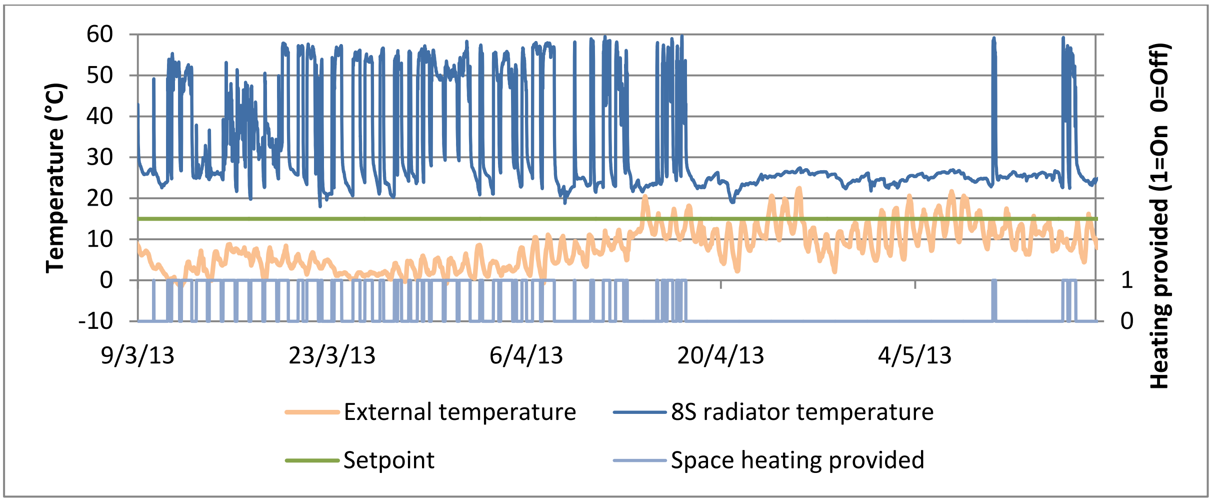


**Figure 8.29: All space heating use in room 8S between 9th March and 31st August 2013**

The length of the space heating season varied for different participants, as too did the quantity of space heating used during each month of the study (Table 8.12 and Appendix P for data plots). Some occupants used large quantities of heating during the coldest months and then completely stopped, whereas usage for others tapered off as the external temperature rose, and then there were other occupants who used very little heating at all. The highest space heating users tended to use large quantities of heating and have the longest heating seasons, and the lowest users tended to use small quantities and have shorter heating seasons, and all other users fell somewhere between the two extremes.

There was little evidence of a daily or weekly heating routine based on the time of day, and most participants turned their radiators on at different times of day throughout the study. Unfortunately due to the loss of wireless data, it is not possible to determine if internal temperature was a driver for space heating use for any of the occupants, as observed in the Loughborough study.

**Table 8.12: Hours of space heating used in the London study during different periods**

| Room | March (hours) | April (hours) | May (hours) | June (hours) | July (hours) | August (hours) | Total (hours) |
|---|---|---|---|---|---|---|---|
| 7Wa | 19.5 | 2.3 | 0 | 0 | 0 | 0 | 21.8 |
| 10Wc | 4.8 | 0 | 0 | 16.7 | 3.8 | 0 | 25.3 |
| 7Wc | 102.5 | 7 | 0 | 0 | 0 | 0 | 109.5 |
| 7Wb | 190.5 | 0 | 0.7 | 0 | 0 | 0 | 191.2 |
| 2E | 128 | 106.5 | 53.3 | 0 | 0 | 0 | 287.8 |
| 9Ea | 254.3 | 37.3 | 13.8 | 1 | 0 | 0 | 306.5 |
| 9Eb | 255.3 | 170.5 | 10 | 0 | 0 | 0 | 435.8 |
| 8S | 324 | 162.8 | 24 | 0 | 0 | 0 | 510.8 |
| 1Ec | 0.2 | 50.7 | 475.3 | 27 | 0 | 0 | 553.2 |
| 1Eb | 381.3 | 208.3 | 0 | 4 | 0 | 0 | 593.7 |
| 11W | 475.5 | 486.3 | 0 | 0 | 0 | 0 | 961.8 |
| 1Ea | 464.8 | 419 | 131 | 100.8 | 20 | 0 | 1135.7 |
| 10Wb | 98.3 | 527 | 469 | 80.5 | 3.8 | 0.7 | 1179.3 |
| 9W | 404.7 | 440.7 | 445.2 | 99.2 | 0 | 3.5 | 1393.2 |
| *Heating available* | *477.25* | *558.5* | *500.25* | *252* | *49.5* | *71.75* | *1909.25* |

### *Summertime Space Heating*

One surprising finding was the use of space heating in June, July and August when external temperatures were high. June is not typically considered part of the space heating season but heating was available for 35% of the month (factoring in the nightly unavailability of heating), and was used in seven of the fourteen rooms. Of these, rooms 1Ea, 9W and 10Wb used heating repeatedly in June, whereas rooms 1Eb, 1Ec, 9Ea and 10Wc used it only once or twice and for short periods. Only three rooms used space heating in July: room 1Ea used it on three occasions and rooms 10Wb and 10Wc used it once. The space heating was theoretically available for 71.75 hours in August; however it was only used twice by Room 9W (totalling 3.5 hours) and once by Room 10Wb (totalling 0.7 hours).

During June, July and August the external temperature often rose above 15°C during the day, and space heating was mostly available for short periods at night, (although there were also some days in June with heating). Due to the external temperature and the nightly shutdown of the heating system at midnight, most of the space heating in June occurred between 3:15am and 6am-10am. Therefore, it is possible that many of the occupants were not intentionally heating their room. An occupant could have opened the TRV on their radiator at a prior point in the hope of obtaining space heating, but when no heating was provided the TRV was left open, meaning that radiator would later provide heat when space heating became available, but not necessarily when the occupant wanted. Some occupants may not even have been immediately aware they were obtaining intermittent heating in June because they were likely sleeping during the hours that heating was available.

Providing heating during July and August was completely unnecessary, and was more likely to be detrimental to thermal comfort than beneficial, by increasing the risk of overheating (see Chapter 9).

### *Space Heating Use Discussion – London*

There was a large variation in occupant behaviour, in the quantity of heating used, the way radiators were operated, the length of the heating season, and in how heating use changed as the study progressed. There was no evidence of a heating routine based on time of day, nor were there any clear patterns linking heating use with building fabric, storey or orientation; however the study was too small to determine that there are not links, and the variation in occupant behaviour could have overshadowed other influencing factors.

The heating system design is not ideal because the only means of occupant control is via TRVs on radiators, there was no way to turn heating on for a fixed duration or to have it turn off automatically. There was nothing to stop occupants from leaving radiators turned on for days or weeks at a time, and this is exactly what was observed for many rooms in the study. On at least one occasion twelve out of the fourteen rooms with heating data had radiators turned on constantly for more than one day, eight had their radiator turned on for more than a week, four had them turned on for more than 33 days, and one had their radiator on for 57 days. This would be impossible in the Loughborough study; it was only possible in the London study because the system allowed it. However, not all occupants just left their radiators turned on for days or weeks at a time, some rarely used their heating, and others used it often but tended to turn it off.

The heating was also controlled centrally by a BMS, managed by a third party specialist. However, the control was not ideal because heating was unavailable every night between midnight and 3:15am, and because the system was not turned off at the end of the heating season. The summertime availability of heating gives cause for concern, because it increases the risk of overheating in a building that is theoretically already at risk. The decision to provide heating based on a spot measurement of external temperature is also questionable; the heat requirement of a large, thermally lightweight, highly insulated building in a large urban heat island is not best determined by a spot measurement of external temperature, because it takes no account of the inherent lags in the system. The decision to control the heating in this way is strange; with a new BMS controlled by a specialist it should have been more sophisticated, or at least more logical. There is no evidence that any changes were made to the operation of the heating system during the study. It is important to give attention to the performance of controls and building services during a building's first year of operation, because problems are likely and settings may need to be tweaked.

The combination of BMS control and TRV control may have been confusing to occupants because it was not explained to them that heating was only available at certain temperatures; sometimes occupants turn the radiators on and they work and other times they do not. If an occupant opens the TRV on their radiator when heating is unavailable they would obtain no heat when they wanted it. If the TRV was then left open (because why close it if the heating is not available), the occupant will obtain heat whenever the space heating next becomes available whether they want it or not. This is not an effective system for meeting the comfort requirements of the occupants; it may lead to thermal discomfort and wasted energy.

The heating system would probably have been better controlled if it were just turned on in October and turned off in April: it would provide consistency for the occupants, remove the risk of overheating the building in summer, and it would likely consume less energy (by not providing heating for significant parts of May, June and September).

The data clearly show that the design of the space heating system and the way it was controlled influenced energy use. Occupants were able to leave their radiator TRVs open continuously and use heating whenever it was available, and as a result heating use was high in many rooms, particularly compared to the Loughborough study. The findings from the two studies are discussed in the following section (8.3).

### 8.2.3 Ventilation Systems – London

It was not possible to take flowrate measurements of the ventilation systems in the London study due to the near constant occupancy, but there were some limited findings. During an inspection of the building it was noted that the ventilation systems were very loud in the flat corridors. The facilities supervisor on site informed that some occupants had complained about the noise and had requested that systems be turned off, and they were turned off. Given the level of noise it is not surprising that occupants wanted to turn systems off. The systems may have had low specific fan powers, providing good flowrates for the electricity they consumed, but this is irrelevant if they are so loud that they end up being turned off. System design and commissioning are important if ventilation systems are to perform optimally, and this is discussed further in Section 8.4.

## 8.3. Comparison of Space Heating Findings: London and Loughborough

There were similarities and differences in the findings from each case study, which highlights the importance of using multiple studies, because it demonstrated the variation possible within the same construction type and that the findings from one building are not necessarily applicable to all buildings.

The main similarities were that there was no evidence of a heating routine based on time of day or day of the week, or any evidence that storey and orientation impacted on heating use. The former is thought to be due to the type of heating controls and the latter possibly due to the size of the studies or because the differences were overshadowed by the large differences in occupant behaviour.

The main difference between the studies was the quantity of heating used. In 2013, the external temperature was an average of 1.8°C higher in London than in Loughborough, and during the study the temperature in London was only lower than in Loughborough briefly on two occasions. However, the occupants in the London study used significantly more heating than in Loughborough (Figures 8.30 and 8.31). The Loughborough study was shorter in duration however it was deemed acceptable to compare the two studies because even although heating was available in London in July and August, very little was actually used.

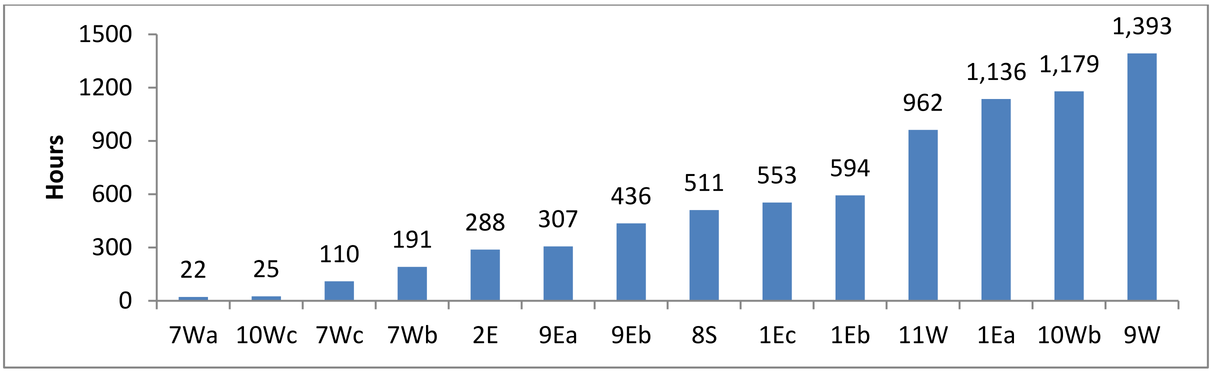


**Figure 8.30: Space heating use in London case study: 9th March – 31st August 2013**

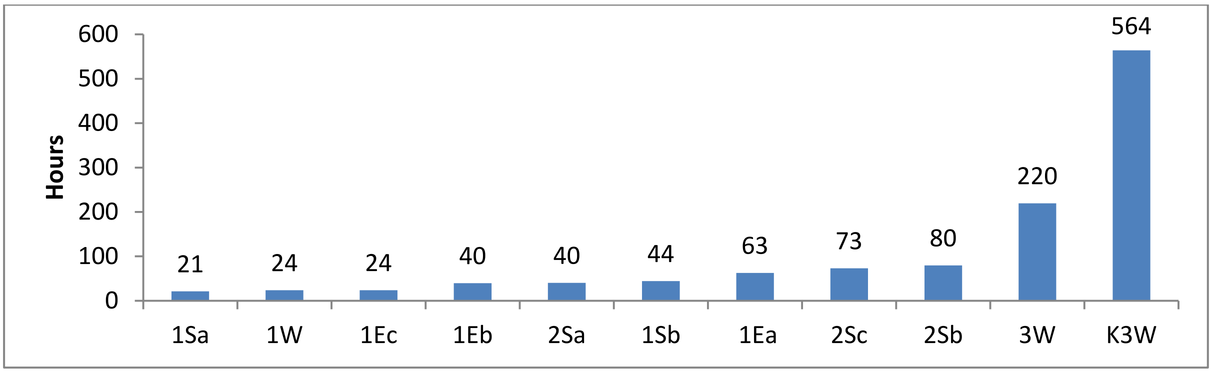


**Figure 8.31: Space heating use in rooms in Loughborough case study – 5th March – 23rd June 2013**

The variation in heating use reveals the significant role that space heating control has on energy use and thermal comfort. The strict controls on the radiators in Flats 1 and 2 in Loughborough limited the space heating that could be obtained, keeping energy use low. The controls were less strict in Flat 3, and the jump in heating use is significant, but the radiators were still restrictive; had this not been the case then it is believed the occupant would have used more heating. The controls in London were overly lax, allowing heating to be used continuously for large parts of the year, which made it easy for occupants to use significantly more heating than in Loughborough. The heating controls in both studies also created problems with thermal comfort: there were times in Loughborough when rooms were too cold but radiators would not stay on, and times when the London building was too hot but heating was available (see Chapter 9 for the overheating analysis). Neither of these situations is desirable, and both could be rectified with better control.

The data also revealed the significant role of the occupant in determining energy use. There were large differences in energy use in comparable rooms in the individual studies, and the only reason found for this is the difference in occupant behaviour.

During the research there was a focus on space heating because it is typically the main use of energy in domestic buildings and because it can be reduced through good building design (which is not necessarily the case for other end uses of electricity). However, the results have challenged the onus that is placed on the role of fabric thermal performance in determining energy use. While good fabric thermal performance is essential for well performing buildings, it is not the only factor, and the heating systems, heating controls and occupant behaviour also play a significant role. These factors are completely separate from fabric performance, and also require specific attention in addition to fabric improvements, this is discussed further in the following section.

## 8.4 Recommendations

It is important to remember that it is not the fabric that consumes energy in a building, it is the appliances and building services, and if they perform badly and waste energy then it does not matter how well the fabric performs; good fabric does not ensure the heating is turned off in summer or that lights are turned off when they are not in use. Fabric performance is vitally important, but it should not be the only consideration. The findings revealed ways that the design, specification and operation of energy consuming devices could be improved to reduce energy consumption and improve thermal comfort.

### *Space Heating*

The space heating systems and their means of control directly influenced energy use and thermal comfort in both studies.  While both systems were different, neither was ideal.

The restrictive radiators in the Loughborough study kept energy use low, however at times they did not operate correctly failing to increase internal temperatures to comfortable levels. These radiator controls are used in many [redacted] buildings, and further measurements should be taken to determine why the radiators were switching off early at low temperatures and whether this is also occurring in other buildings.  If this is found to be a common problem then these controls should no longer be used, and should be replaced in existing buildings, if not immediately then certainly when they come to the end of their lives.

In contrast to the Loughborough study, excessive space heating was provided in the London study, both during the heating season and during the summer.  The BMS controls should be altered to limit heating use and to ensure heating is turned off during the warmest months.  It is not possible to prescribe exactly how the heating controls should be altered, it may require a number of iterations to achieve optimisation.  Various options exist, such as using daily average external temperatures or running mean temperature as well as utilising internal temperature sensors that are located in the stair cores on each storey.  While changes to the BMS controls would be straightforward to elicit, changes to occupant controls are not really practical in the existing building without considerable cost and work.  Therefore, the controls can be improved in the London building but only by so much.  This type of simplistic occupant control, via TRVs only, is not ideal for minimising energy use and should be avoided in new buildings or when heating systems are replaced.

The Loughborough study revealed that space heating had a rapid impact on internal temperature, (with two hours of heating increasing temperatures by 2-5°C), and that after heating ceased the internal temperatures remained elevated for hours (if windows were closed).  This shows how thermally responsive the fabric is and that small quantities of heat can have a significant impact on the internal environment.  Therefore, the concept behind the restrictive radiators is not necessarily bad for this type of construction, but only if the radiators work as they are supposed to and are setup optimally.  It is questionable however, if occupants want such restrictions imposed upon them, this research did not investigate occupant views, but it may be useful to conduct further research aimed at tailoring the heating systems to the needs to occupants while still restricting excessive usage.  Admittedly this is a difficult balance, to determine the optimal control strategy that ensures comfort and limits energy use, and more research is needed in this area.

If the fabric thermal performance of the [redacted] design were to be improved, then the heating requirement of the building would reduce, and the optimal heating system and control would differ from the requirements of existing [redacted] buildings. If this were to happen then further research would be required to determine the heating needs to the new design.

Whether for existing buildings, or any future low energy buildings, the heating specification should be based on the heat requirements of the structure, which could be informed by testing modules or existing buildings, or by undertaking thermal modelling. Testing could reveal how quickly the internal temperature rises and falls in response to internal gains, which could inform on radiators sizing and controls.

From the findings it is clear that optimising space heating systems and controls need to be regarded as fundamentally important during the design stage, in order to minimise energy use and ensure thermal comfort.

***Ventilation Systems***

Ventilation systems were found to perform poorly, with high electricity use, negligible flowrates and excessive noise. Therefore, there is significant scope for improvement in the ventilation systems, so that they consume less energy, provide better flowrates and are less bothersome to occupants. Low energy ventilation systems with heat recovery are preferable to the systems used in both case studies; they could save energy and improve thermal comfort. However, simply specifying a ventilation system and installing it is not sufficient; they must be correctly designed, commissioned and maintained to ensure optimal performance. The data clearly show that a greater focus on ventilation system performance is required during design and construction, to ensure actual performance meets expectations. This will become increasingly important as fabric performance improves, because ventilation systems will be necessary for the provision of fresh air and for maintaining thermal comfort.

***Lighting***

Electricity use for lights was wasteful in the Loughborough study and should be improved through better design and control. The two lights in the bedroom modules should be individually controllable so that occupants can choose to use individual lights rather than be forced to always use both. The number of light fittings in the corridors was excessive and far fewer, lower powered lamps would suffice. The lights in passage spaces should be controlled by a timer so that they cannot be left switched on when not in use, the savings over the buildings life far outweigh the additional cost of installing timer switches.

### *Kitchen Appliances*

Another area where energy savings could be made is with the specification of kitchen appliances, especially those that are constantly running. Specifying better performing equipment does not have to cost more at the outset because the power consumption of appliances, ventilation systems, and lighting can vary significantly between similarly priced devices. Some products may cost more at the outset, but when the whole life costs are considered the higher initial outset may be worthwhile, it makes particular sense to specify more efficient devices if the owner pays the energy bills, as is the case with [redacted].

### *Recommendations Summary*

The performance of heating, lighting, ventilation and appliances may not be important to all building constructors, but for fully-fitted modular construction, the module manufacturer typically installs appliances and services within modules. Therefore modular manufacturers could play a role in encouraging the client to choose better performing equipment.

Reducing space heating use is complicated because it is influenced by many factors including climate, building fabric, thermal comfort, system efficiency and controls; and to make significant improvements all must be considered. The same is not true for other energy consuming devices where significant savings can be made through different specification without a need to consider building fabric, occupant behaviour or the climate, or to provide diminished performance. This is low-hanging fruit that should not be ignored or considered insignificant in comparison to space heating energy use or fabric performance.

This research focused on the technical performance of fabric and services; however the data show that occupants play a major role in determining energy use, and further research into occupant behaviour may be required to ensure energy use can be reduced in all buildings irrespective of occupants.

## 8.5 Chapter Summary

This chapter presented the energy use findings from the case studies. It detailed how data were collected, which parameters were measured, and the problems encountered. Findings were presented which revealed ways to reduce energy use and improve thermal comfort. The chapter showed that there is scope to reduce all forms of energy use, including for heating, lighting, ventilation and appliances. It explained that reductions can be achieved through better design, specification, commissioning, control and maintenance, and warned against focusing too heavily on only space heating use and fabric performance, because energy use can be reduced for all end uses.

# Chapter 9 – Overheating

This chapter presents the findings from the case studies regarding overheating; using the data collected from the building monitoring (Table 9.1). It details the two overheating metrics used, and then presents the results from the Loughborough and London studies separately, before comparing the findings for each study, and finally making recommendations.

**Table 9.1: Data collection summary for both case studies**

| **Case study** | Loughborough | London |
|---|---|---|
| **Dates of study** | 05-Mar-2013 – 28-Jun-2013 | 09-Mar-2013 – 06-Sep-2013 |
| **Study duration** | 115 days | 182 days |
| **Data collected** | Internal temperature<br>External air temperature | Radiator surface temperature<br>Internal temperature<br>Internal relative humidity<br>External air temperature |
| **Monitored zones** | 3 whole flats | 16 individual bedrooms |
| **Participants** | 12 | 16 |

The building monitoring involved many stages such as testing equipment, arranging participants, employing an electrician, undertaking a pilot study, etc. These topics were already discussed in Chapter 8 and in Appendices B and C, and will not be repeated here.

## 9.1 Overheating Metrics

Two overheating metrics were used: one static and one adaptive.

### 9.1.1 Static Overheating Metric

The static metric determines if overheating has occurred based on whether internal temperature exceeds a static threshold for a given length of time in a year. The data were assessed using the static overheating criteria in the 7$^{th}$ Edition of *Environment Design: CIBSE Guide A* for dwellings [CIBSE, 2006], where overheating is deemed to occur if:

- **In bedrooms: 1% of occupied hours per year are greater than 26°C**
- **In living areas: 1% of occupied hours per year are greater than 28°C**

This is a simple analysis which has been criticised in recent times for its failure to take into account the extremity or duration of overheating, or people's ability to adapt to a changing climate [CIBSE, 2013]. For these reasons, the static metric is no longer advised in the most recent, 8$^{th}$ Edition of *Environment Design: CIBSE Guide A* for dwellings [CIBSE, 2015], However, it was considered important to use more than one metric, and the static approach has been the standard approach until relatively recently [CIBSE, 2013, CIBSE 2015].

Since the student bedrooms could be used as living areas as well as bedrooms, two analyses were done for bedrooms, splitting each day into daytime and night time periods. The temperature threshold was 26°C during night time hours, assumed to be 10pm to 8am, and 28°C during daytime hours, assumed to be 8am to 10pm. The decision of when to split the day into daytime and night time hours was not critical to the results, using different splits made no significant difference to the overall results in either study.

### 9.1.2 Adaptive Overheating Metric

The adaptive overheating metric used is that outlined in *CIBSE TM52 Limits of thermal comfort: avoiding overheating in European building* [CIBSE, 2013].

There are three criteria, failure of two during occupied hours and the zone is deemed to overheat. The criteria are based on the adaptive approach to overheating, which means that the range of acceptable indoor temperatures changes each day as a function of the exponentially weighted running mean of the daily mean temperature, $T_{rm}$. CIBSE TM52 recommends that new buildings should achieve Category II performance, which is classed as "normal expectation", setting a range on acceptable temperature as the comfort temperature ±3°C. The adaptive comfort temperatures were calculated using temperature data from weather stations near the case study sites (Chapter 6.4).

The overheating criteria are all assessed in terms of ΔT, where:

$$\Delta T = T_{op} - T_{max} \qquad \textbf{Equation 9.1}$$

#### *Criterion 1: Hour of Exceedance ($H_e$)*

Criterion 1 calculates the number of hours during the free-running period of May to September that the operative temperature is above the upper band for thermal comfort by 1°C or more (i.e. the number of hours that $\Delta T \geq T_{max}+1$). If this is more than 3% of time then the zone is deemed to fail the criterion. If temperature data are not available for the whole of May to September then 3% of available hours should be used.

#### *Criterion 2: Daily Weighted Exceedance ($W_e$)*

Criterion 2 allows for a measure of the severity of overheating during any given day. To pass, the weighted exceedance must equal six or less on every day during the free-running period.

$$W_e = (\sum h_e) * WF = (h_{e1} * 1) + (h_{e2} * 2) + (h_{e3} * 3) \ldots \qquad \textbf{Equation 9.2}$$

Where:

WF=0 if $\Delta T \leq 0$, otherwise WF=ΔT rounded to whole numbers

$h_{eX}$ is the number of hours during the day in question when WF = X.

For example, if on one day ΔT=2 for 3 hours and ΔT=1 for 2 hours, and ΔT=0 for the remainder of the day, then:

$$W_e = (\sum h_e) * WF = (2 * 1) + (3 * 2) = 8$$ **Equation 9.3**

With a value of eight this room would fail criterion 2.

***Criterion 3: Upper Limit Temperature ($T_{upp}$)***

Criterion 3 sets a maximum allowable temperature, $T_{upp}$, and a room should not exceed this value at any time during the free-running period, if it does then it fails the criterion. The upper allowable temperature is defined as 4°C above maximum comfort temperature ($T_{max}$):

$$T_{upp} = T_{max} + 4$$ **Equation 9.4**

Or, specifically for a category II building:

$$T_{upp} = T_{comf} + 7$$ **Equation 9.5**

$$T_{upp} = 0.33T_{rm} + 25.8$$

### 9.1.3 Operative Temperature

The overheating criteria require the use of room operative temperature, $T_{op}$, rather than room air temperature, $T_a$:

$$T_{op} = HT_a + (1 - H)T_r$$ **Equation 9.6**

Where:

$$H = h_c/(h_c + h_r)$$ **Equation 9.7**

$$(1 - H) = h_r/(h_c + h_r)$$ **Equation 9.8**

Due to varying opinions as to the value of H, another value is often used for the ratio of $h_c$ to $h_r$, namely √(10v), where v is the air speed (m/s). This results in the following equation for operative temperature:

$$T_{op} = \frac{T_a\sqrt{(10v)} + T_r}{1 + \sqrt{(10v)}}$$ **Equation 9.9**

At indoor air speeds of below 0.1m/s, the heat transfer by natural convection is assumed to equal that of an air speed of 0.1m/s, thus equation can be reduced to:

$$T_{op} = \frac{1}{2}T_a + \frac{1}{2}T_r \qquad \textbf{Equation 9.10}$$

In well insulated modern buildings, the difference between air temperature and radiative temperature is small.

For the case studies it is assumed the difference between air and radiative temperatures is low, and that air speed is 0.1m/s or less, and therefore air temperature approximates radiative temperature approximates operative temperature.

EnergyPlus simulations of a calibrated model of the Loughborough case study building predicted small differences between operative, air and radiative temperatures, typically 0.5°C or less (less than the accuracy of the sensors). Based on a comparison of the temperature trends recorded on site and the temperature output by the simulations it is believed that the temperature measured on site was not a true measurement of air temperature, but also contained a radiative component. This is a common occurrence in temperature measurement, particularly with small, cheap sensors. The sensor is contained within a housing which is fixed to a surface; which is not ideal for measuring air temperature, which would be to suspend a sensor (with no housing) in the centre of the room. It may be the case that the temperature measurements by the sensors more closely approximate operative temperature than air temperature.

Therefore, it is assumed that the internal temperature measured on site is approximately equal to the operative temperature

$$T_i \approx T_{op} \qquad \textbf{Equation 9.11}$$

### 9.1.4 Occupancy

A requirement of most overheating metrics is that they assess only occupied hours, because temperatures only have to be comfortable when a building is occupied. Student halls of residences could theoretically be occupied at any time of the day or night. Therefore, it was concluded that the buildings should be considered constantly occupied, and overheating should be avoided at all times of day.

## 9.2 Overheating Results – Loughborough

Internal temperature and relative humidity was monitored in three flats, which included twelve bedrooms, three kitchens and two corridors (Table 9.2). It is not possible to show a drawing with the locations of the flats or detail which storey they are on, as to do so could make the participants identifiable, breaching anonymity and data protection.

Data were collected from 5th March until the 28th June 2013; occupants moved out around 23rd June. Due to signal reception problems data were lost in June for room 1Sb and all rooms in Flat 2 except room 2Sc, (Appendix E). Therefore, overheating analyses could not be done for many rooms in June, the most likely month in the study for overheating to occur.

**Table 9.2: Details of rooms and flats with temperature and relative humididty data: Loughborough**

| Room code[1] | Flat | Room type | Orientation |
|---|---|---|---|
| 1Ea | 1 | Bedroom | East |
| 1Eb | 1 | Bedroom | East |
| 1Ec | 1 | Bedroom | East |
| 1Sa | 1 | Bedroom | South |
| 1Sb | 1 | Bedroom | South |
| 1W | 1 | Bedroom | West |
| K1E | 1 | Kitchen | East |
| C1 | 1 | Corridor | South & West |
| 2Na | 2 | Bedroom | North |
| 2Nb | 2 | Bedroom | North |
| 2Sa | 2 | Bedroom | South |
| 2Sb | 2 | Bedroom | South |
| 2Sc | 2 | Bedroom | South |
| K2N | 2 | Kitchen | East |
| C2 | 2 | Corridor | N/A |
| 3W | 3 | Studio Bedroom | West |
| 3KW | 3 | Studio Kitchen | West |

[1] *For the room code, the number represents the flat in which the room is located. For bedrooms the uppercase letter indicates room orientation, the lowercase letter is a generic describer when there is more than one room in the same flat with the same orientation. Kitchens codes also include a "K" and corridor codes a "C" to distinguish them from bedrooms.*

Space heating was used in many bedrooms during May and even June (Chapter 8), which is not ideal because overheating analyses should really only be conducted in free-running buildings. However, since space heating use was low in most rooms, and there were insufficient data to conduct an analysis during free-running periods alone, it was decided that an overheating analysis would still be conducted for May and June.

### 9.2.1 Static Overheating Results – Loughborough

No room in the Loughborough study failed the static overheating criteria. However, some rooms did exceed the static thresholds.

#### *Exceedance of the Static Threshold during Daytime Hours*

Kitchen K1E is the only room that exceeded 28°C during the study (Figure 9.1 and Appendix Q for all rooms). This occurred for 1.1 hours on 18th June and 4.3 hours on 19th June, totalling 0.11% of annual daytime hours. Kitchen K2N reached a maximum temperature of 27.84°C on 7th May, (compared to 27.04°C in K1E on the same day). Temperature data for K2N were lost for June, but it can be seen that the temperature in K2N was comparable and often warmer than K1E, therefore it is possible that kitchen K2N also exceeded 28°C in June.

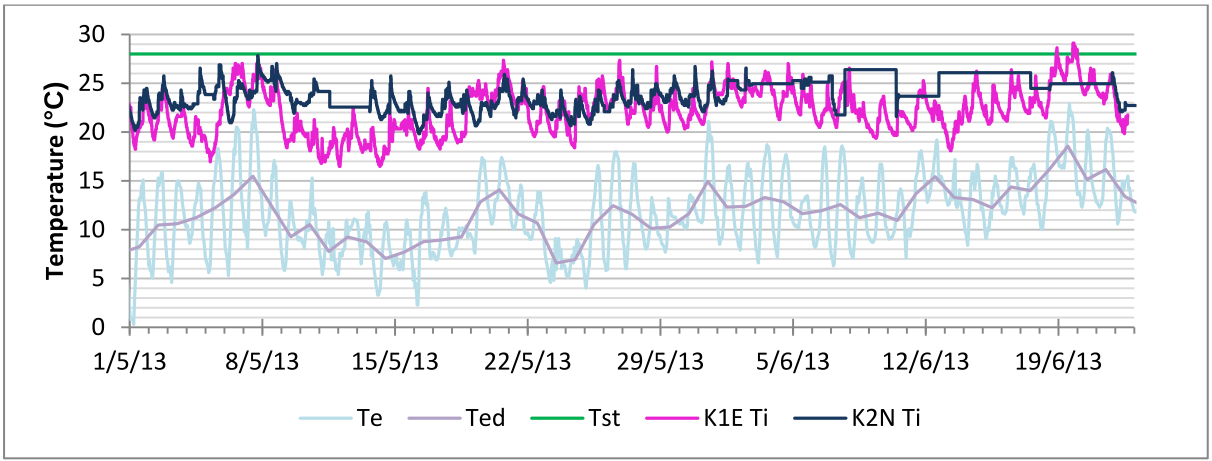


**Figure 9.1: Internal temperatures in kitchens K1E and K2N: 1st May – 22nd June 2013**

#### *Exceedance of the Static Threshold in Bedrooms during Night Time Hours*

Only bedrooms 1Ea and 1W exceeded 26°C during the night in May and June. Room 1Ea exceeded 26°C on twelve days (Figure 9.2), totalling 47.5 hours, with 17.3 hours between 10pm and 8am. However, given the repeated attempts to use space heating during May and June, even when the internal temperature was above 25°C, it can only be assumed that the occupant wanted to maintain their room at these temperatures. The room was regularly vacant at the weekend, and whenever it was the internal temperature dropped markedly, indicating that the occupant was the determining factor in the internal temperature. Due to the use of space heating, room 1Ea cannot be included in the analysis, but it is interesting because it demonstrates that some people choose to live at temperatures that others may consider uncomfortable.

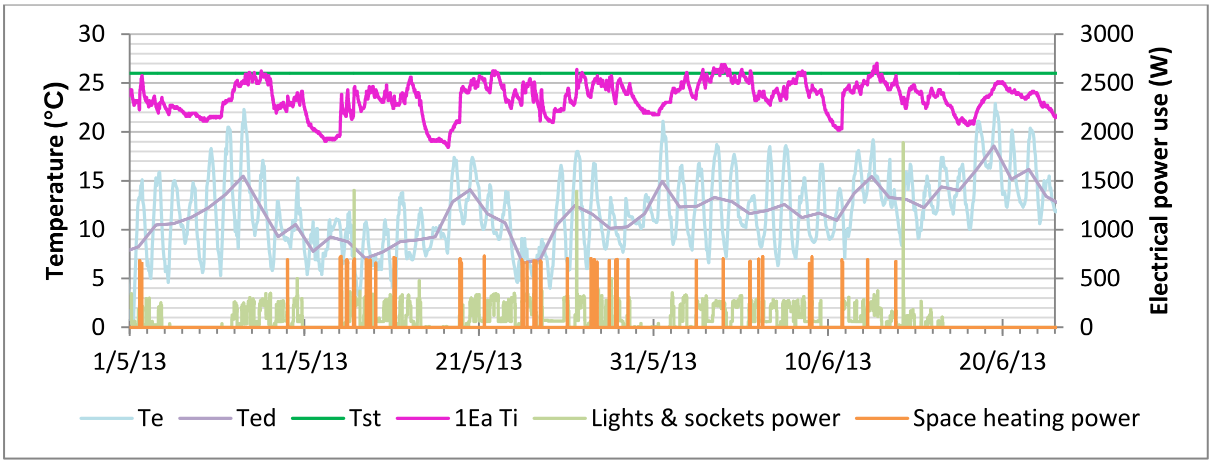


**Figure 9.2: Internal temperature in room 1Ea exceeded 26°C numerous times in May and June**

Room 1W exceeded 26°C nearly continuously from 8pm on 18th June until 3am on 22nd June (Figure 9.3), totalling 74.2 hours, of which 33.6 hours occurred during night time hours (0.92% of annual night time hours and 5.5% of night time hours in May and June). During this period the temperature dropped to 26°C or less for only 4.8 hours, with a minimum of 25.6°C. This room came close to failing the annual criterion due to internal temperatures experienced over a 79 hour period. Given that external temperatures were significantly higher in July and August, it is likely that this room would have failed if it were occupied throughout summer.

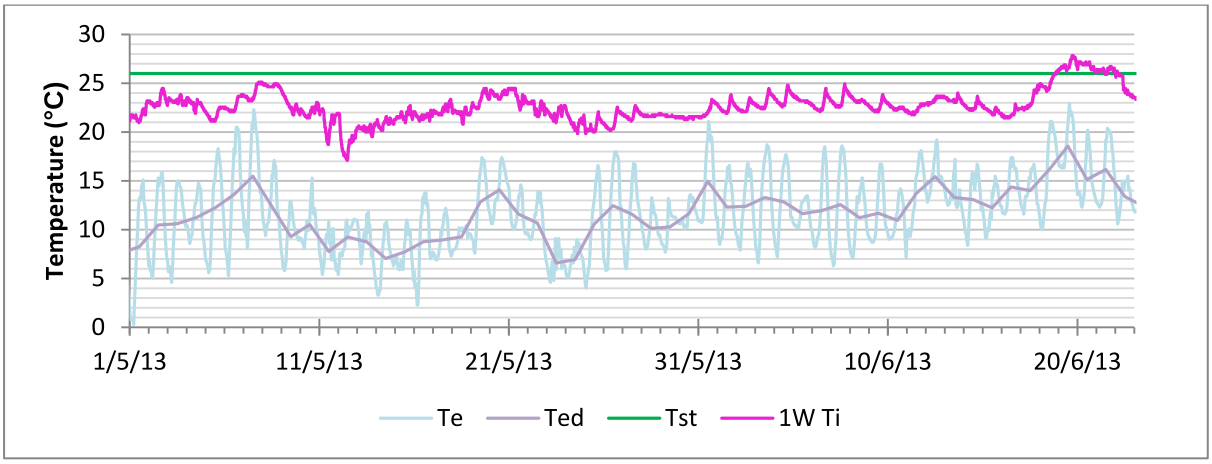


**Figure 9.3: Internal temperature in room 1W exceeded 26°C between 18th and 22nd June**

Room 1Eb was the only other bedroom to exceed 26°C at any point during May and June, but this was during daytime hours. Temperature data were lost for five of the thirteen bedrooms for most of June, it is possible that some of these rooms also exceeded 26°C during June.

### 9.2.2 Adaptive Overheating Results – Loughborough

The adaptive thermal comfort temperatures were calculated for a category II building for Loughborough during 2013 using the Nottingham Watnall weather station data [UK Met Office, 2014c] (Chapter 6 and Figure 9.4). It can be seen that at times there is a significant difference between the conditions that the adaptive and static metrics class as overheating.

Room 1Ea was excluded from the analysis due to the use of space heating (Figure 9.2 above). However, irrespective of heating use, room 1Ea was not warm enough to fail the adaptive overheating metric.

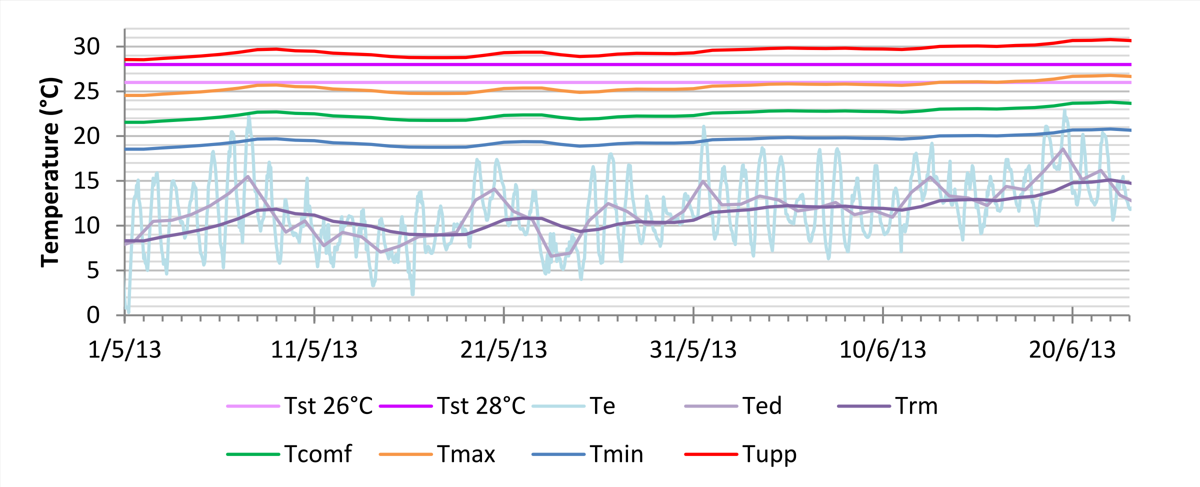


**Figure 9.4: Adaptive thermal comfort temperatures for a category II building: Loughborough 2013**

#### *Criterion 1: Hour of Exceedance ($H_e$)*

During the study only four of the seventeen rooms exceeded the upper limit for thermal comfort, $T_{max}$, but none did so sufficiently to fail the criterion (Table 9.3)

**Table 9.3: Adaptive overheating metric: Criterion 1 results Loughborough study**

| Room | Hours of exceedance ($H_e$): 1st May-23rd June | Percentage of time: 1st May-23rd June | Percentage of time: 1st May-30th September | Result |
|---|---|---|---|---|
| 1W | 5.6 | 0.38 | 0.15 | Pass |
| C1 | 1.1 | 0.08 | 0.03 | Pass |
| K1E | 33.0 | 2.25 | 0.90 | Pass |
| K2N[1] | 10.6 | 1.42 | 0.29 | Pass |
| [1]*No temperature data from 1st June to 23rd June* | | | | |

As with the static overheating metric, kitchen K1E was the worst performing room. It exceeded the upper threshold many times in May and June (Figure 9.5), totalling 88.7 hours, of which 33 hours were sufficient to count towards the metric ($\Delta T \geq 1°C$). Kitchen K2N exceeded the upper limit for thermal comfort many times in May, totalling 37.8 hours, of which 10.6 hours counted toward the metric. Based on the temperature profile for May and its comparison with K1E data, it is believed that K2N would have continued to exceed the upper limit for June (but the data were lost).

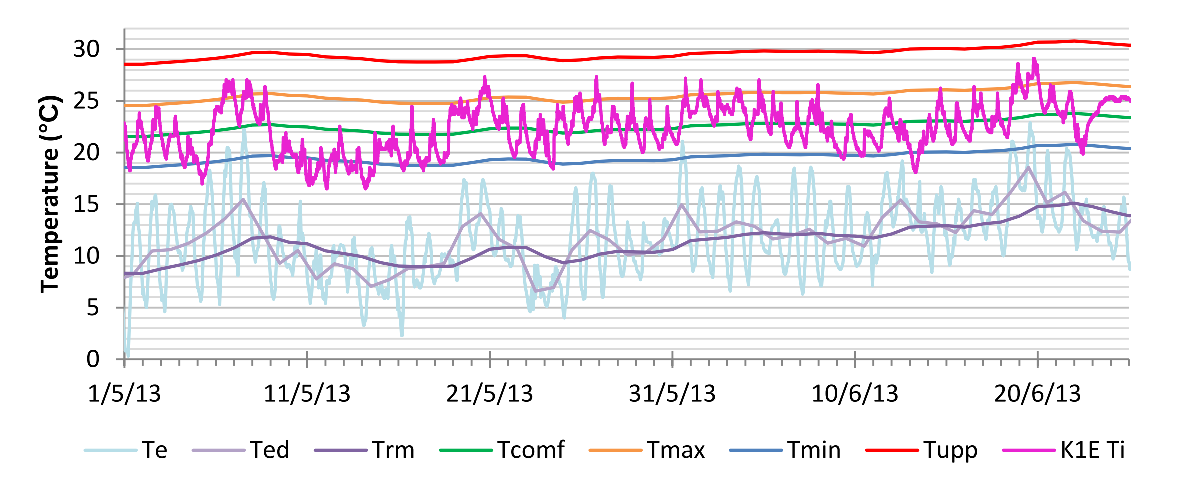


**Figure 9.5: Kitchen K1E in Loughborough repeatedly exceeded the upper comfort band in May and June**

### *Criterion 2: Daily Weighted Exceedance ($w_e$)*

Only the rooms that exceeded the upper limit for thermal comfort could fail Criterion 2, and of the four rooms that did, all did so sufficiently to fail the criterion (Table 9.4 and Appendix R). Rooms 1W, C1 and K2N failed on one day only, whereas K1E failed on four days. The kitchens exceeded the upper limit for thermal comfort by a greater amount and for longer than rooms 1W and C1, when comparing the same day (Figure 9.6 and Table 9.4).

**Table 9.4: Adaptive overheating metric: Criterion 2 results Loughborough study**

| Room | No. of fails | Date | $W_e$ | Hours at WF=1 (hh:mm) | Hours at WF=2 (hh:mm) | Hours at WF=3 (hh:mm) | Total exceedance (hh:mm) | Average ΔT (°C) | Max ΔT (°C) |
|---|---|---|---|---|---|---|---|---|---|
| 1W | 1 | 19/06 | 11.28 | 11:17 | 0 | 0 | 11:17 | 0.98 | 1.47 |
| C1 | 1 | 19/06 | 9.62 | 09:37 | 0 | 0 | 09:37 | 0.87 | 1.15 |
| K1E | 4 | 06/05 | 14.73 | 09:42 | 02:31 | 0 | 12.22 | 1.19 | 1.92 |
| | | 07/05 | 6.37 | 04:22 | 01:00 | 0 | 05.22 | 1.09 | 1.68 |
| | | 20/05 | 13.08 | 09:23 | 01:51 | 0 | 11.14 | 1.11 | 2.33 |
| | | 19/06 | 21.07 | 09:12 | 03:56 | 01:20 | 14.28 | 1.37 | 2.75 |
| K2N[1] | 1 | 07/05 | 7.38 | 04:11 | 01:36 | 0 | 05.47 | 1.19 | 2.48 |
| [1]*No temperature data from 1st June to 23rd June* | | | | | | | | | |

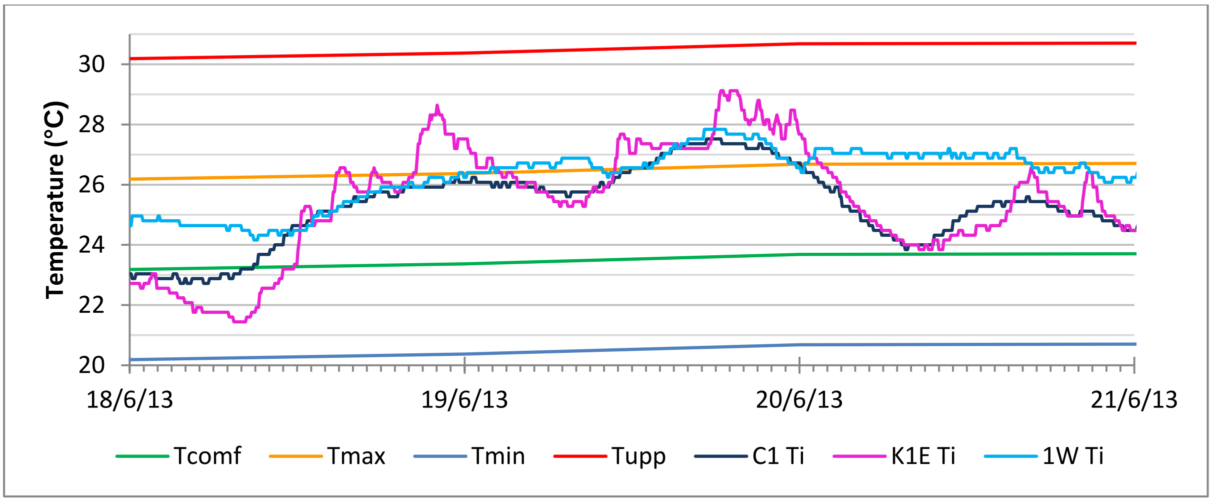


**Figure 9.6: K1E exceeded the upper limit for thermal comfort by more than the 1W and C1**

### *Criterion 3: Upper Limit Temperature*

No rooms failed the third criterion because no room exceeded the maximum allowable temperature ($T_{upp}$). Kitchens K1E and K2N exceeded the upper limit for thermal comfort by more than bedrooms 1Ea and 1W and corridor C1, but none sufficiently to fail (Table 9.5).

**Table 9.5: Adaptive overheating metric: Criterion 3 results Loughborough study**

| Room | Max ∆T May-June (°C) | Corresponding temperature (°C) | Date |
|---|---|---|---|
| 1Ea | 1.43 | 26.4 | 26/05 |
| 1W | 1.47 | 27.84 | 19/06 |
| C1 | 1.15 | 27.52 | 19/06 |
| K1E | 2.75 | 29.12 | 19/06 |
| K2N (No June data) | 2.48 | 27.84 | 07/05 |

### *Adaptive Overheating Results*

No rooms failed criteria 1 and 3, and four failed criterion 2 (Table 9.6), therefore no room failed the CIBSE TM52 adaptive overheating metric. The June data were lost for five bedrooms, kitchen K2N and corridor C2, had it been available then perhaps there would have been further fails, but it is unlikely any room would have failed two or more criteria.

**Table 9.6: Adaptive overheating results: Loughborough study**

| Room | Criterion 1 (more than 3% of occupied time) | Criterion 2 | Criterion 3 | Overall result |
|---|---|---|---|---|
| 1Ea | Pass | Fail | Pass | N/A[1] |
| 1Eb | Pass | Pass | Pass | Pass |
| 1Ec | Pass | Pass | Pass | Pass |
| 1Sa | Pass | Pass | Pass | Pass |
| 1Sb | Pass | Pass | Pass | Pass |
| 1W | Pass | Fail | Pass | Pass |
| C1 | Pass | Fail | Pass | Pass |
| K1E | Pass | Fail | Pass | Pass |
| 2Na | Pass | Pass | Pass | Pass |
| 2Nb | Pass | Pass | Pass | Pass |
| 2Sa | Pass | Pass | Pass | Pass |
| 2Sb | Pass | Pass | Pass | Pass |
| 2Sc | Pass | Pass | Pass | Pass |
| C2 | Pass | Pass | Pass | Pass |
| K2N | Pass | Fail | Pass | Pass |
| 3W | Pass | Pass | Pass | Pass |
| K3W | Pass | Pass | Pass | Pass |

[1]*Room 1Ea used heating throughout the study so should not be included in the analysis, but irrespective of heating use the room did not fail*

## 9.2.3 Discussion of Findings – Loughborough

None of the rooms in the Loughborough study failed the CIBSE static or adaptive overheating assessment methods. During the study the internal temperatures were generally within the adaptive comfort range and below the static overheating thresholds (Figures 9.7 and 9.8). All rooms except 2Sc experienced temperatures below the lower limit for adaptive comfort ($T_{min}$), whereas only four rooms exceeded the upper limit for adaptive thermal comfort ($T_{max}$), and three exceeded the static overheating threshold. The multi-occupancy kitchens (K1E and K2N) experienced greater diurnal temperature fluctuations than the other rooms and often exceeded the upper and lower limits for adaptive comfort for short periods, but temperatures mostly fell within the adaptive comfort range. While it is positive that internal temperatures were typically within the comfort range during the study, the temperature trends indicate that overheating could be a problem if the building were occupied throughout the summer.

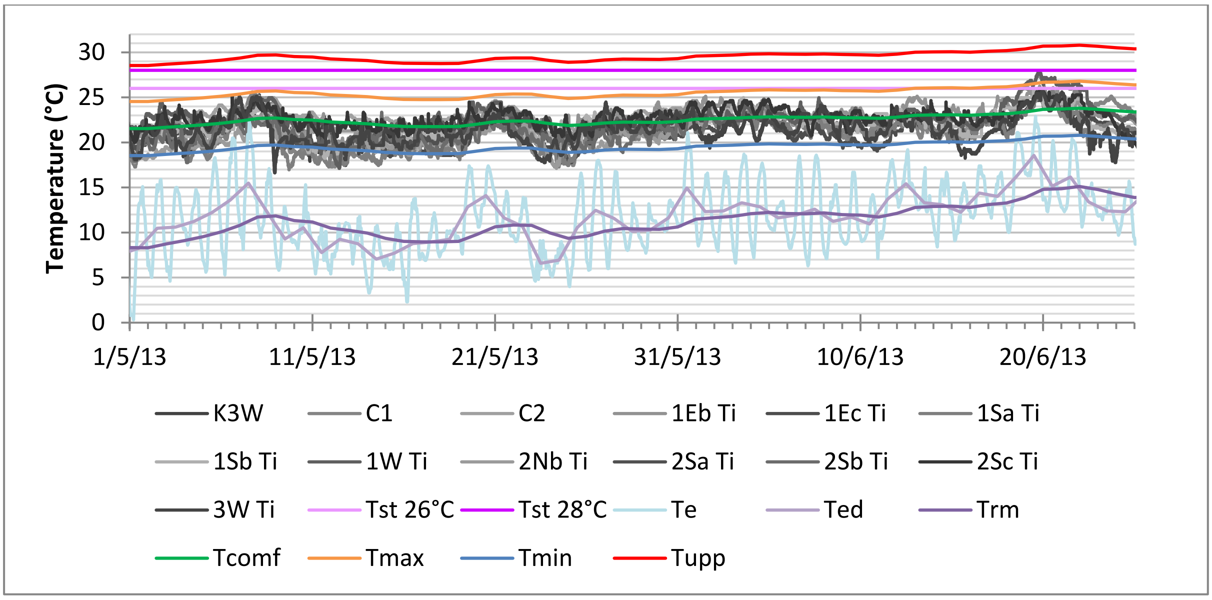


**Figure 9.7: Temperatures in bedrooms, studio and corridors were normally within comfort ranges**

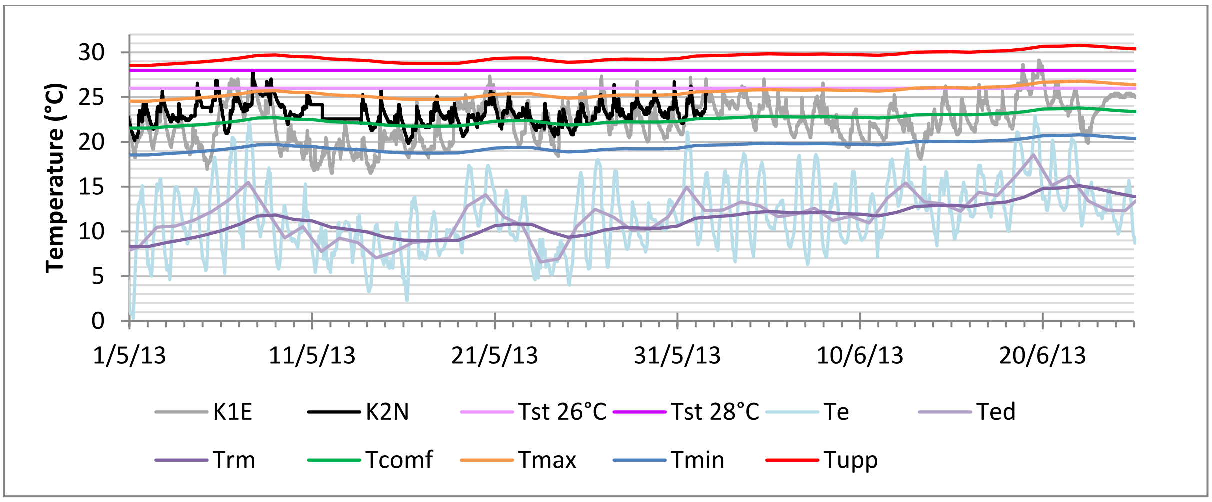


**Figure 9.8: Temperatures in communal kitchens fluctuated but were normally within comfort ranges**

When the external temperature spiked around 19th June, the internal temperature within many rooms came close to exceeding, or did exceed, the adaptive and static comfort thresholds. This is concerning because there were 24 days in July, August and September that were warmer than 19th June, seventeen of which measured 25°C or more, with a maximum of 30.6°C on 1st August.

In May and June the external temperature was typically below the lower limit for thermal comfort ($T_{min}$), only exceeding it during the spikes in external temperature around 7th May, 31st May, and 19th June, and never exceeding the comfort temperature ($T_{comf}$) (Figure 9.9). Whereas, in July, the external temperature was regularly above the lower limit for thermal comfort and the comfort temperature, and on three days (13th July, 22nd July and 1st August) it actually exceeded the upper limit for thermal comfort ($T_{max}$). The situation is similar for the static overheating thresholds, with external temperatures well below the thresholds in May and June but exceeding them in July and August.

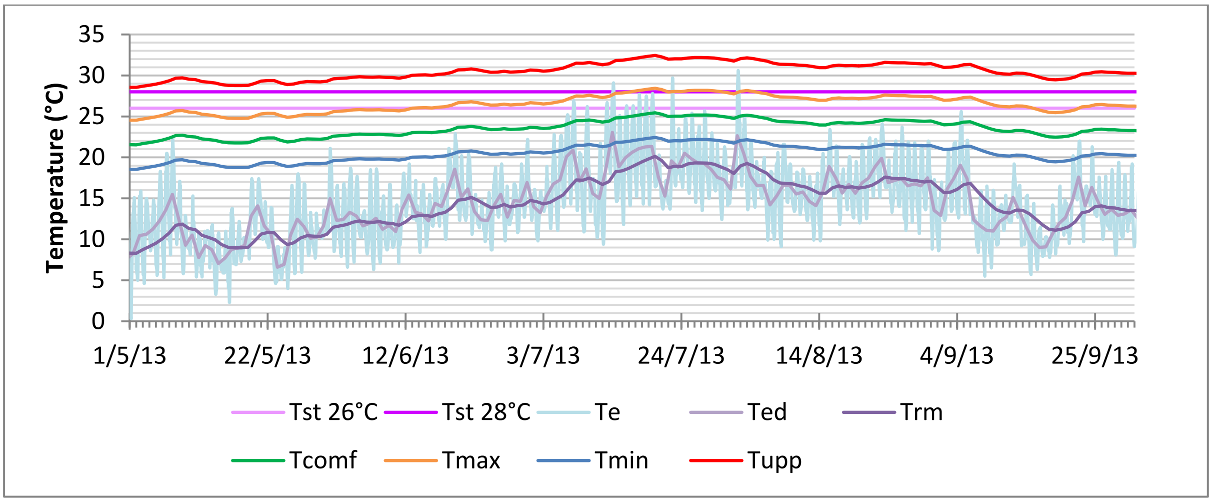


**Figure 9.9: The difference between external temperature and overheating thresholds varies**

The way the external temperature approached or exceeded the static and adaptive comfort thresholds during the hottest weeks of the year is concerning because the internal temperatures are linked to the external temperature. During the study, the internal temperatures within sixteen of the seventeen monitored rooms were always greater than the external temperature (Figure 9.10). Only room 2Nb measured internal temperatures below the external temperature, and only for short periods on 6th and 7th May.

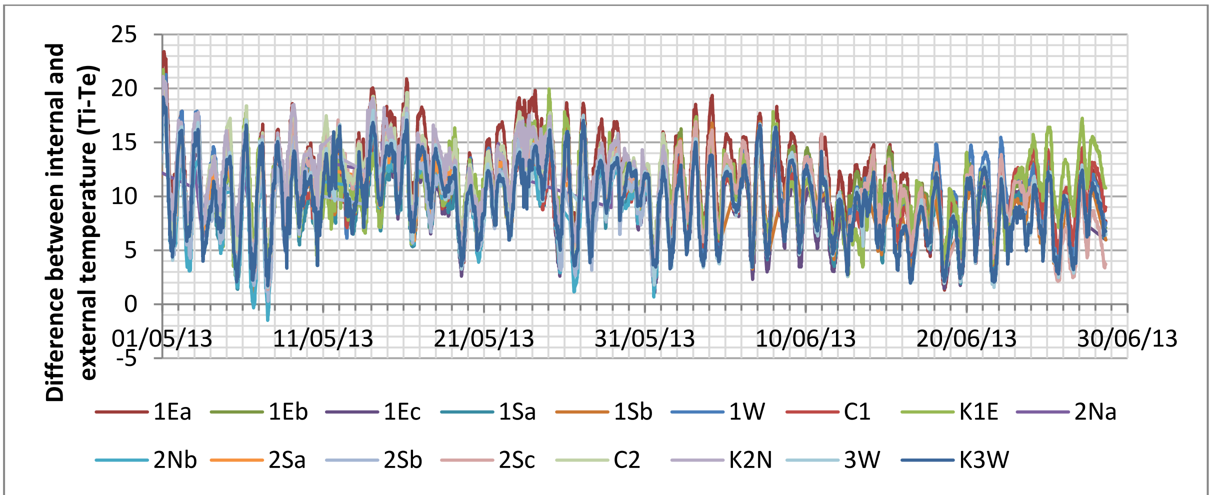


**Figure 9.10: Difference between internal and external temperatures: Loughborough**

It is difficult to predict how the internal temperatures trends would vary if the building were to be occupied throughout the summer. It is not clear if they would continue to exceed external temperatures in July and August, or if on the hottest days of the year external temperature would have exceeded internal temperatures. However, if the observed trends were to continue, it is likely that the internal temperature would have exceeded the static and adaptive thresholds for thermal comfort on many occasions during summer.

Ultimately, the Loughborough study was not best suited to investigating the risk or occurrence of overheating due to its occupancy; which is largely why the London case study was selected.

## 9.3 Overheating Results – London

As discussed in Chapter 8, sensors were installed in sixteen bedrooms (Table 9.7). It is not possible to show a drawing with the exact locations of the rooms, as to do so could make the participants identifiable, breaching anonymity and data protection.

Data were collected from 9th March until the 6th September 2013; occupants moved of their accommodation on or before 31st August. Unfortunately, due to the loss of wireless data and the physical loss of some sensors, there is no full set of data for any room (Appendix E). The one missing radiator temperature sensor was for the only room with wireless temperature sensor data, Room 10Wa.

The loss of internal temperature data from the wireless sensors presented a problem for the intended overheating analysis because the plan was to use these data. However, it was determined that the radiator temperature data could be used to approximate internal room temperature during free-running periods (Appendix S).

Space heating was available whenever external temperature dropped to 15°C or less, which happened during every month of the year. The longest continuous free-running period was 23 days from 12th July to 4th August (Figure 9.11); the second longest period was only 3.6 days, from 21st to 25th August. There were also numerous occasions when the external temperature was above 15°C for two to three days at a time.

**Table 9.7: Details of the data that were collected for each room in the study**

| Room Code[1] | Storey | Orientation | Data obtained (Yes/No) | | |
|---|---|---|---|---|---|
| | | | **Radiator temperature** | **Internal temperature and relative humidity** | **Window opening** |
| 1Ea | 1 | East | Yes | No | No |
| 1Eb | 1 | East | Yes | No | No |
| 1Ec | 1 | East | Yes | No | No |
| 2E | 2 | East | Yes | No | No |
| 7Wa | 7 | West | Yes | No | No |
| 7Wb | 7 | West | Yes | No | No |
| 7Wc | 7 | West | Yes | No | No |
| 8S | 8 | South | Yes | No | No |
| 9W | 9 | West | Yes | No | No |
| 9Ea | 9 | East | Yes | No | No |
| 9Eb | 9 | East | Yes | No | No |
| 9S | 9 | South | Yes[2] | No | No |
| 10Wa | 10 | West | No | Yes | Yes – poor |
| 10Wb | 10 | West | Yes | No | Yes – poor |
| 10Wc | 10 | West | Yes | No | No |
| 11W | 11 | West | Yes | No | Yes – poor |

[1] *Room code: the number indicates the storey, the uppercase letter indicates room orientation, the lowercase letter is a generic describer when there are multiple rooms with the same storey orientation*
[2] *Sensor became unstuck early in the study and room 9S was excluded from the analysis*

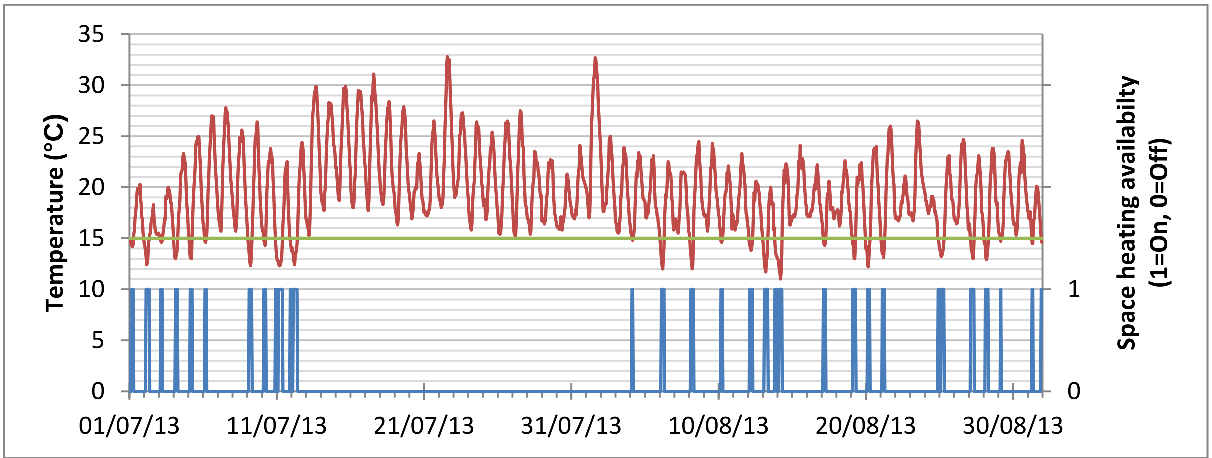


**Figure 9.11: Space heating availability limited free-running periods in the London study**

Different rooms were free-running for different lengths of time (Table 9.8), many from the beginning of May until the occupant moved out, but other rooms had shorter free-running periods, and four rooms used limited heating in July and/or August. The availability of space heating is not ideal, because even if individual rooms were free-running there could still be heating use in adjacent zones, and therefore the overheating analyses are not simply a test of the free-running, passive performance of the building. The availability of space heating was smallest in July and August, few monitored rooms used it and none used it to its full availability. It was decided that an overheating analysis would still be conducted, focusing on July and August. From the occupants' perspective, it is not important if overheating is the result of building fabric, layout or services, because they cannot change or control these factors and they will experience discomfort at high temperatures irrespective of the cause.

The four rooms that used space heating in July and August were not excluded from the analysis, instead the data were edited to remove space heating and its impacts (Appendix T).

**Table 9.8: Free-running dates for monitored rooms in the London case study – 2013**

| Room | Free-running start | Free-running end | Exclusions – days with space heating |
|---|---|---|---|
| 1Ea | 29th June | 31st August | 9th, 11th and 12th July |
| 1Eb | 21 April | 31st August | 14th June |
| 1Ec | 6th June | 31st August | |
| 2E | 31 May | 31st August | |
| 7Wa | 22 April | 31st August | |
| 7Wb | 28th March | 31st August | 12th May |
| 7Wc | 18th April | 31st August | |
| 8S | 15th May | 31st August | |
| 9Ea | 17th May | 31st August | 13th June |
| 9Eb | 25th May | 31st August | |
| 9W | 29th June | 31st August | 13th and 28th August |
| 10Wa | 29th June | 31st August | |
| 10Wb | 29th June | 31st August | 9th July, 28th August |
| 10Wc | 13th March | 31st August | 23rd 28th and 29th June, 9th July |
| 11W | 30th April | 31st August | |

### 9.3.1 Static Overheating Results – London

#### *Night Time Overheating*

All bedrooms failed the static night time overheating criterion for one year using the July and August data alone, (Figure 9.12 and Table 9.9). Therefore, it does not matter if the night time temperatures for the remaining ten months of the year were always below 26°C because all rooms had already failed. The extent to which rooms exceeded 26°C during night time was greater in July than August. The rooms on the first and second floors performed better than the upper floors. Rooms 7Wc and 9Ea were above 26°C for 97.8% and 98.3% of July respectively, compared to 25.9% for the "best" performing room, room 2E.

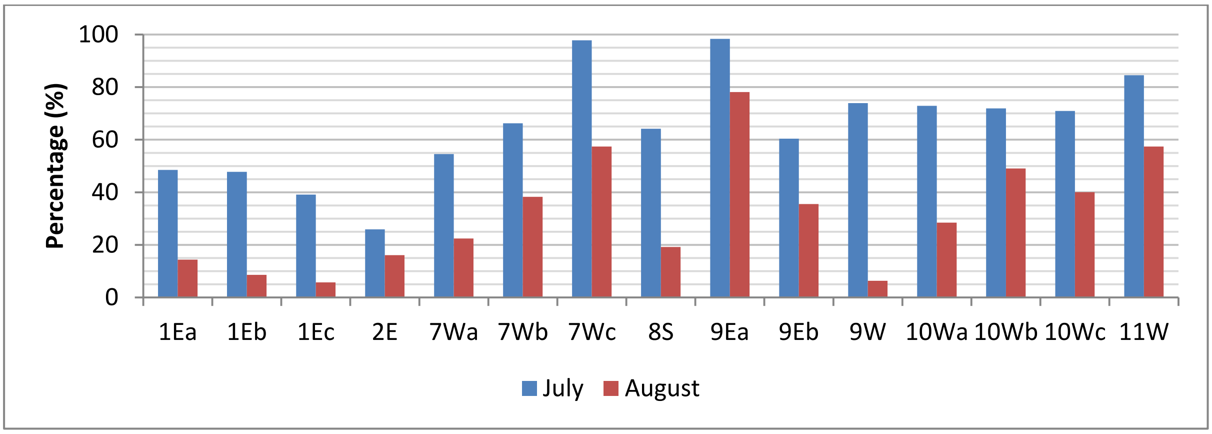


**Figure 9.12: Percentage of night time hours above 26°C in July and August [10pm to 8am]: London**

**Table 9.9: Percentage of night time hours above 26°C during July and August [10pm to 8am]: London**

| **Percentage of Night Time Hours[1] >26°C** | | | | | |
|---|---|---|---|---|---|
| **Room** | **% of July** | **% of August** | **% of July & August** | **July & August data as a % of May to September[2]** | **July & August data as a % of the whole year[3]** |
| 1Ea | 48.5 | 14.4 | 31.5 | 12.7 | 5.3 |
| 1Eb | 47.8 | 8.6 | 28.2 | 11.4 | 4.8 |
| 1Ec | 39.1 | 5.8 | 22.4 | 9.1 | 3.8 |
| 2E | 25.9 | 16.1 | 21.0 | 8.5 | 3.6 |
| 7Wa | 54.5 | 22.4 | 38.5 | 15.6 | 6.5 |
| 7Wb | 66.2 | 38.3 | 52.3 | 21.2 | 8.9 |
| 7Wc | 97.8 | 57.4 | 77.6 | 31.4 | 13.2 |
| 8S | 64.2 | 19.2 | 41.7 | 16.9 | 7.1 |
| 9W | 73.9 | 6.3 | 40.1 | 16.3 | 6.8 |
| 9Ea | 98.3 | 78.1 | 88.2 | 35.8 | 15.0 |
| 9Eb | 60.4 | 35.5 | 48.0 | 19.4 | 8.1 |
| 10Wa | 72.9 | 28.4 | 50.7 | 20.5 | 8.6 |
| 10Wb | 71.9 | 49.1 | 60.5 | 24.5 | 10.3 |
| 10Wc | 70.9 | 40.1 | 55.5 | 22.5 | 9.4 |
| 11W | 84.5 | 57.4 | 71.0 | 28.8 | 12.1 |

[1] *Night time hours are 10pm-8am, which totals 310 hours each in July and August*
[2] *July & August (620 hours) as a percentage of May to September night time hours (1530 hours), means the maximum value possible is 100*(620/1530)=40.52%*
[3] *July & August night time hours (620 hours) as a percentage of night time hours in one year (3650 hours), means the maximum value possible is 100*(620/3650)=16.99%*

### *Daytime Overheating*

Rooms 1Ea, 1Ec and 2E passed the annual static daytime overheating criterion using the July and August data, (Figure 9.13 and Table 9.10), the remaining eleven rooms failed using the July and August data alone. Many rooms exceeded the 28°C threshold during the daytime for significant portions of July; seven rooms were over 28°C during daytime hours for at least 50% of the month. The threshold temperature was exceeded far less in August, but for many rooms the extent was still unacceptable such as rooms 9Ea and 11W which were above 28°C during daytime hours for 73.3% and 21.8% of August respectively.

**Table 9.10: Percentage of daytime hours above 28°C in July and August [8am to 10pm]: London**

| **Percentage of Daytime Hours[1] >28°C** | | | | | |
|---|---|---|---|---|---|
| **Room** | **% of July** | **% of August** | **% of July & August** | **July & Augus data as a % of May to September[2]** | **July & August data as a % of the whole year[3]** |
| **1Ea** | 6.0 | 2.1 | 4.1 | 1.6 | 0.7 |
| **1Eb** | 11.9 | 1.6 | 6.8 | 2.7 | 1.1 |
| **1Ec** | 1.7 | 0.6 | 1.2 | 0.5 | 0.2 |
| **2E** | 4.3 | 1.0 | 2.7 | 1.1 | 0.5 |
| **7Wa** | 32.8 | 4.8 | 18.8 | 7.6 | 3.2 |
| **7Wb** | 38.5 | 6.3 | 22.4 | 9.1 | 3.8 |
| **7Wc** | 69.9 | 13.9 | 41.9 | 17.0 | 7.1 |
| **8S** | 18.9 | 0.0 | 9.5 | 3.8 | 1.6 |
| **9W** | 67.4 | 1.6 | 34.5 | 14.0 | 5.9 |
| **9Ea** | 82.0 | 64.6 | 73.3 | 29.7 | 12.4 |
| **9Eb** | 37.8 | 17.3 | 27.6 | 11.2 | 4.7 |
| **10Wa** | 61.4 | 9.1 | 35.3 | 14.3 | 6.0 |
| **10Wb** | 61.1 | 5.3 | 33.2 | 13.5 | 5.6 |
| **10Wc** | 55.2 | 13.7 | 34.4 | 14.0 | 5.8 |
| **11W** | 72.5 | 21.8 | 47.1 | 19.1 | 8.0 |

[1] *Daytime hours are 8am-10pm, which totals 434 hours each in July and August*

[2] *July & August (868 hours) as a percentage of May to September daytime hours (2142 hours), means the maximum value possible is 100*(868/2142)=40.52%*

[3] *July & August night time hours (868 hours) as a percentage of daytime hours in one year (5110 hours), means the maximum value possible is 100*(868/5110)=16.99%*

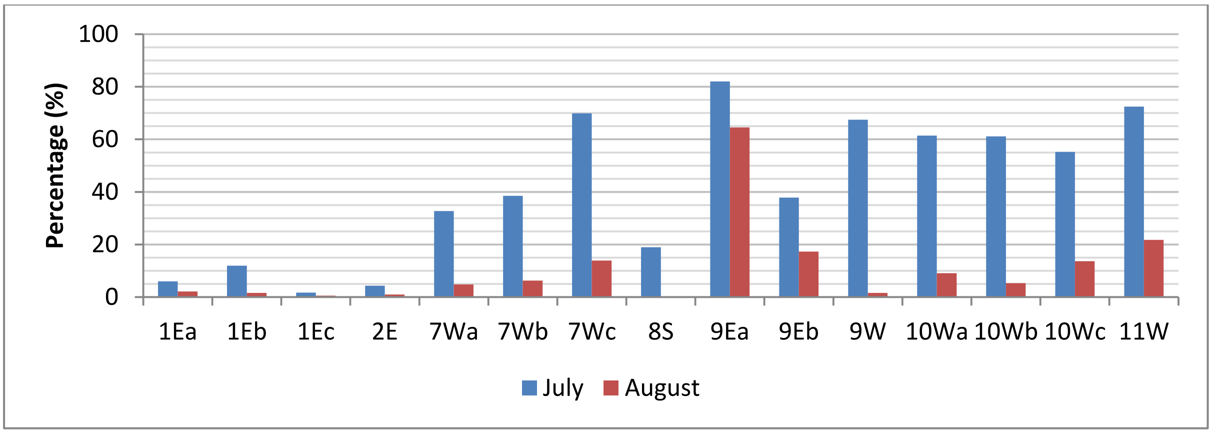


**Figure 9.13: Percentage of daytime hours above 28°C in July and August [8am to 10pm]: London**

### *Exceedance of Static Temperatures during all Hours of the Day*

Splitting the day into night time and daytime hours with different thresholds for each obscures an understanding of the actual temperatures experienced within the rooms. Therefore an additional analysis was done to look at temperatures at all times of day. All rooms were greater than 26°C for more than 30% of July and August. Eleven rooms exceeded 30°C, with room 11W exceeding it for 30% of July and August. Five rooms exceeded 33°C and two exceeded 34°C (Figure 9.14 and Appendix U).

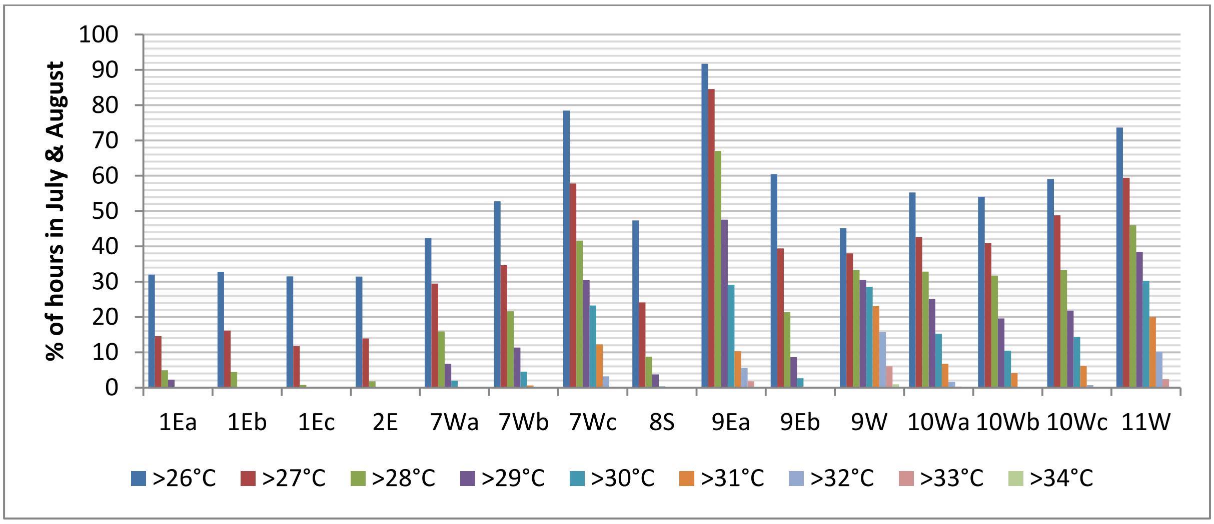


**Figure 9.14: Percentage of July and August that rooms spent above various temperatures: London**

The worst performing rooms (such as room 11W and 7Wc) exceeded 28°C for prolonged periods, sometimes lasting weeks; and even the best performing rooms (such as room 1Ea) were constantly above 26°C for up to eight days at a time (Figure 9.15 and Appendix V). The worst performing rooms also experienced elevated temperatures during May and June (if they were free-running), such as room 11W which exceeded 28°C for 3.4% of May and

30.4% of June; or in rooms 7Wc and 10Wc which exceeded 28°C for 6.3% and 10.8% of June respectively. This demonstrates that overheating was occurring throughout the study, and is not only a concern during the warmest months of the year (July and August) and was not caused solely by the heatwave in July.

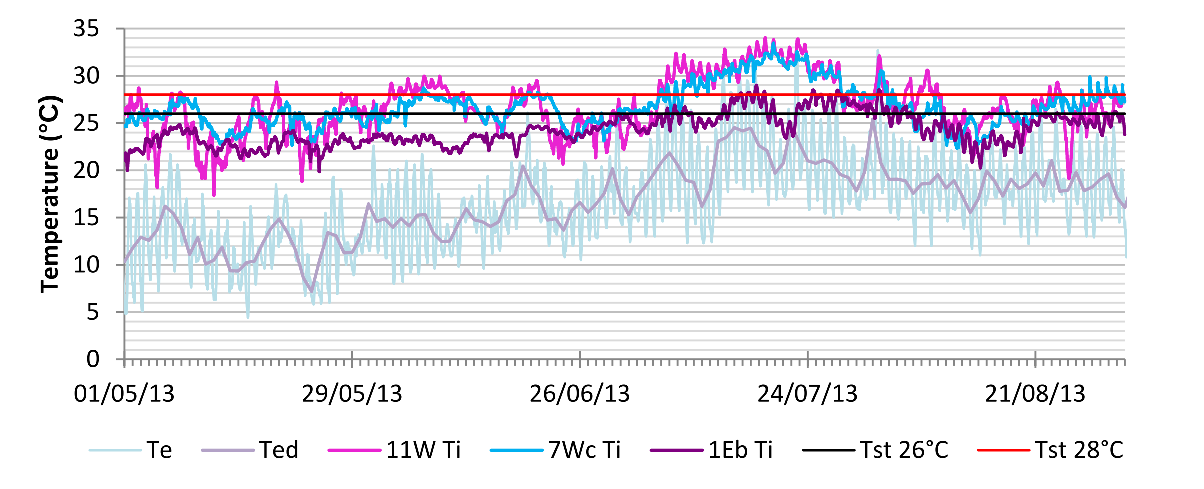


**Figure 9.15: Rooms exceeded the static threshold(s) for days to weeks at a time: London**

### 9.3.2 Adaptive Overheating Results – London

The adaptive thermal comfort temperatures for a category II building in London during 2013 were calculated using the St James's Park weather station data (Chapter 6 and Figure 9.16) [UK Met Office, 2014d]. It can be seen that at times there is a significant difference between the conditions that the adaptive and static metrics class as overheating.

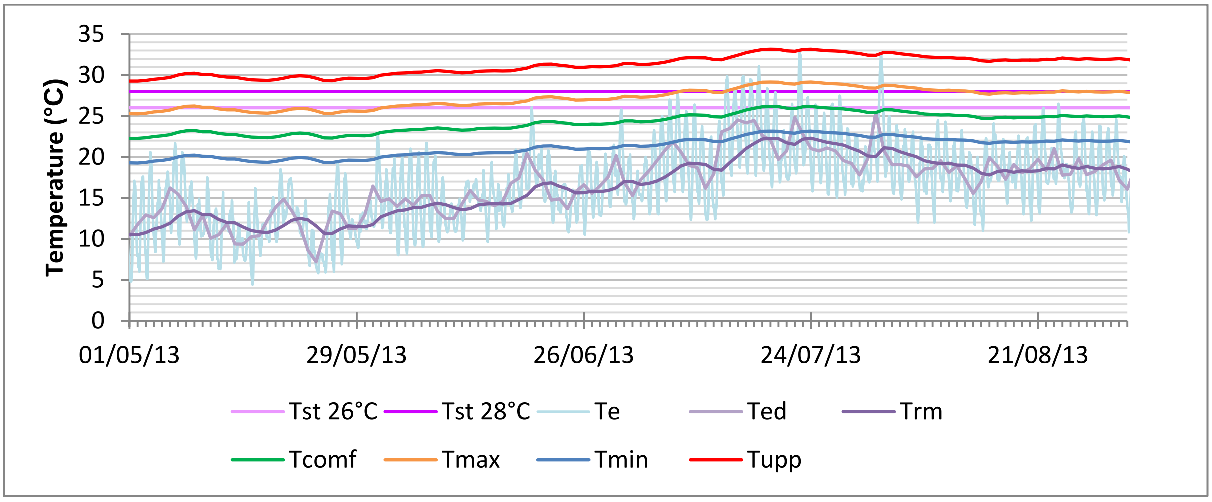


**Figure 9.16: Adaptive comfort temperatures: category II building in London from May to September 2013**

***Criterion 1: Hours of Exceedance ($H_e$)***

Thirteen rooms exceeded the upper limit for thermal comfort ($T_{max}$), eleven did so sufficiently to count towards the metric ($\Delta T \geq 1°C$), of which nine did so for long enough to fail Criterion 1 (Figure 9.17 and Table 9.11). Seven rooms failed for the whole period of May to September using just the July and August data, because the extent of the failures was so great. Rooms 1Ec and 2E were the only rooms where internal temperatures never exceeded the upper limit for thermal comfort.

The most extreme overheating occurred in July, rooms exceeded the threshold temperature much less in August, with the exception of Room 9Ea, which continued to experience elevated temperatures. Despite the reduction in internal and external temperatures during August, the majority of rooms still exceeded the upper limit for thermal comfort for significant lengths of time.

Ten of the bedrooms were free-running during other months, revealing further periods of overheating. In fact there was overheating in all rooms during all free-running months with the exception of those on the first and second floors. Room 11W which used no space heating from 1st May until 31st August, was above the upper threshold for thermal comfort for a category II building for 45.2% of this time, of which 34.1% counted towards the overheating criterion ($\Delta T \geq 1°C$).

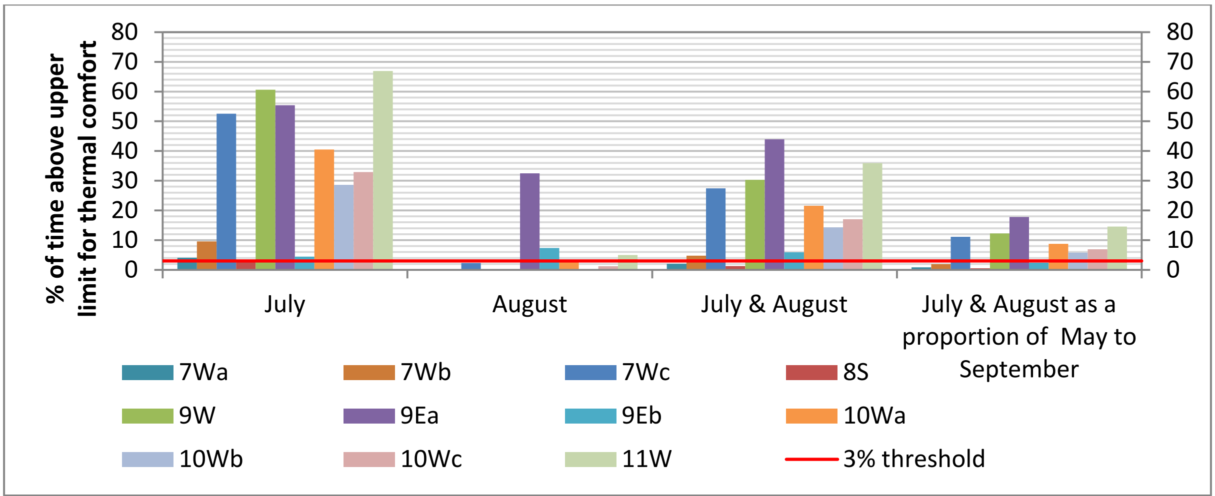


**Figure 9.17: Adaptive overheating metric: Criterion 1 results London study**

**Table 9.11: Percentage of time during free running in which ΔT⩾1°C: Adaptive overheating London**

| Room | May | Jun | Jul | Aug | Free running period | Jul-Aug | Free running as % of May-Sep | Jul-Aug as % of May-Sep | Result |
|---|---|---|---|---|---|---|---|---|---|
| 1Ea | N/A | N/A | 0 | 0 | 0[1] | 0 | 0 | 0 | Pass |
| 1Eb | 0 | 0 | 0 | 0 | 0[3] | 0 | 0 | 0 | Pass |
| 1Ec | N/A | N/A | 0 | 0 | 0[1] | 0 | 0 | 0 | Pass |
| 2E | N/A | 0 | 0 | 0 | 0[2] | 0 | 0 | 0 | Pass |
| 7Wa | 0.1 | 1.2 | 4.1 | 0 | 1.3[3] | 2.0 | 1.1 | 0.8 | Pass |
| 7Wb | 5.0 | 0.0 | 9.6 | 0 | 3.7[3] | 4.8 | 3.0 | 1.9 | Fail |
| 7Wc | 8.2 | 19.3 | 52.6 | 2.3 | 20.6[3] | 27.4 | 16.6 | 11.1 | Fail |
| 8S | N/A | 2.3 | 2.6 | 0 | 1.6[2] | 1.3 | 1.0 | 0.5 | Pass |
| 9Ea | N/A | 3.2 | 55.4 | 32.5 | 30.7[2] | 44.0 | 18.4 | 17.8 | Fail |
| 9Eb | N/A | 0.7 | 4.4 | 7.4 | 4.2[2] | 5.9 | 2.5 | 2.4 | Fail |
| 9W | N/A | N/A | 60.6 | 0 | 30.3[1] | 30.3 | 12.3 | 12.3 | Fail |
| 10Wa | N/A | N/A | 40.5 | 2.6 | 21.6[1] | 21.6 | 8.7 | 8.7 | Fail |
| 10Wb | N/A | N/A | 28.6 | 0 | 14.3[1] | 14.3 | 5.8 | 5.8 | Fail |
| 10Wc | 7.1 | 12.6 | 32.9 | 1.2 | 13.5[3] | 17.1 | 10.8 | 6.9 | Fail |
| 11W | 24.6 | 40.0 | 66.9 | 5.0 | 34.1[3] | 35.9 | 27.4 | 14.6 | Fail |

*Note: N/A signifies room was not free-running*
[1] *Free-running period runs from 1st July to 31st August*
[2] *Free-running period runs from 1st June to 31st August*
[3] *Free-running period runs from 1st May to 31st August*

***Criterion 2: Daily Weighted Exceedance ($w_e$)***

Eleven rooms failed Criterion 2, the nine rooms that failed Criterion 1, plus rooms 7Wa and 8S; only the rooms on the first and second floors passed. Failures occurred in free-running rooms from May to August, the most severe and most frequent were in July (Figure 9.18).

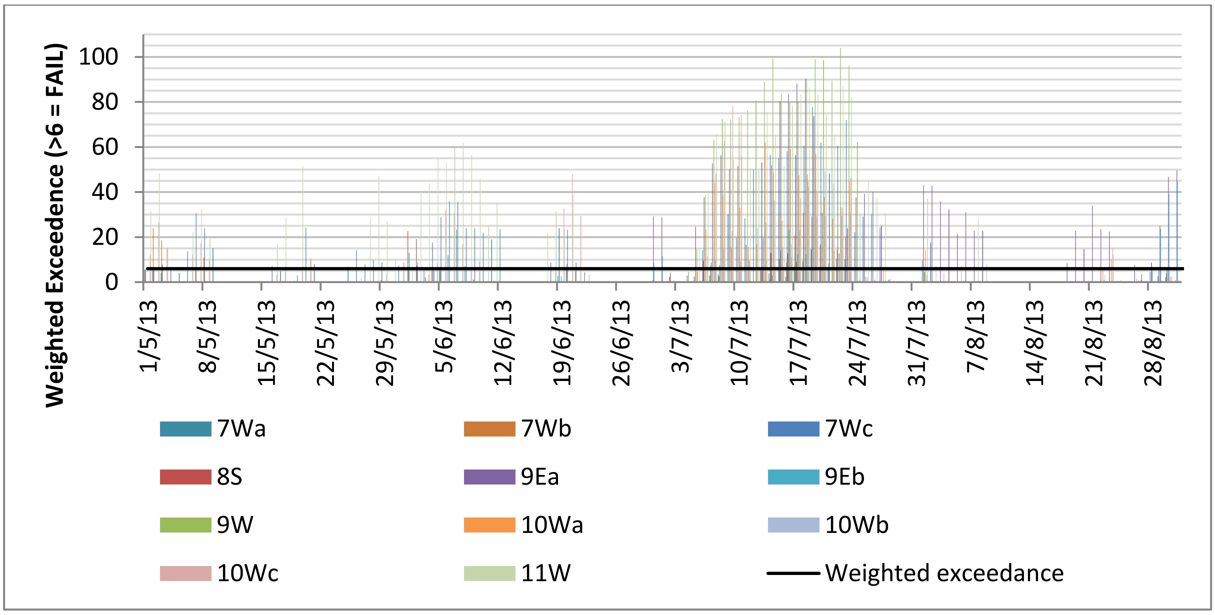


**Figure 9.18: Weighted exceedance: category II building in London May to September – failing rooms only**

The greatest number of failures occurred between 16th and 23rd July (Figure 9.19), during this period space heating was unavailable and the whole building was free-running. All eleven failing rooms failed on 17th July.

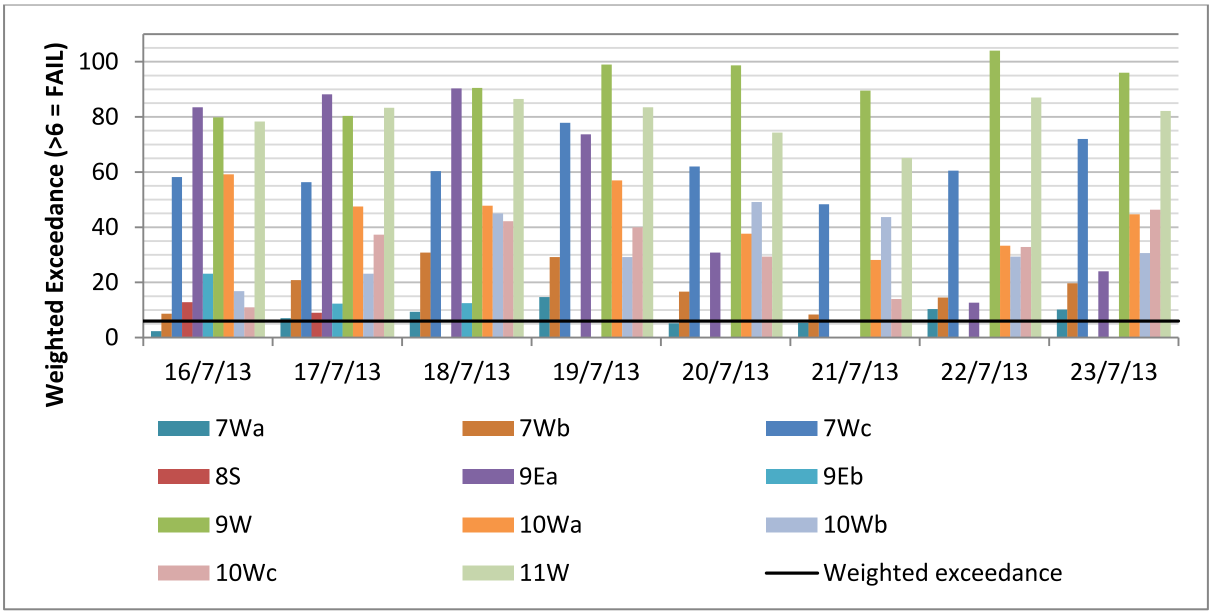


**Figure 9.19: Weighted Exceedance in the London study 16th-23rd July 2013**

Room 9W failed the criterion most severely (Table 9.12), with a maximum value of 104 on 22nd July; to achieve this value means the room had to be 4-5°C above the upper limit for thermal comfort for the whole day. Many rooms failed the criterion significantly and repeatedly, because many rooms were above the upper limit for thermal comfort continuously for days to weeks at a time (Figure 9.20 and Appendix V). Criterion 2 is designed to indicate the severity of overheating, and with such high weighted exceedances there can be no doubt that these rooms suffered extreme overheating.

**Table 9.12: Maximum weighted exceedances: Adaptive overheating criterion 2: London**

| Room | Maximum $W_e$ | Date Max $W_e$ occurred | Result |
|---|---|---|---|
| 1Ea | 5 | 1st August | Pass |
| 1Eb | 0 | N/A | Pass |
| 1Ec | 0 | N/A | Pass |
| 2E | 0 | N/A | Pass |
| 7Wa | 23.33 | 7th June | Fail |
| 7Wb | 30.83 | 1th July | Fail |
| 7Wc | 77.83 | 19th July | Fail |
| 8S | 22.67 | 1st June | Fail |
| 9Ea | 90.33 | 18th July | Fail |
| 9Eb | 44.83 | 31st August | Fail |
| 9W | 104 | 22nd July | Fail |
| 10Wa | 62 | 13th July | Fail |
| 10Wb | 49.17 | 20th July | Fail |
| 10Wc | 78.33 | 9th July | Fail |
| 11W | 87 | 22nd July | Fail |

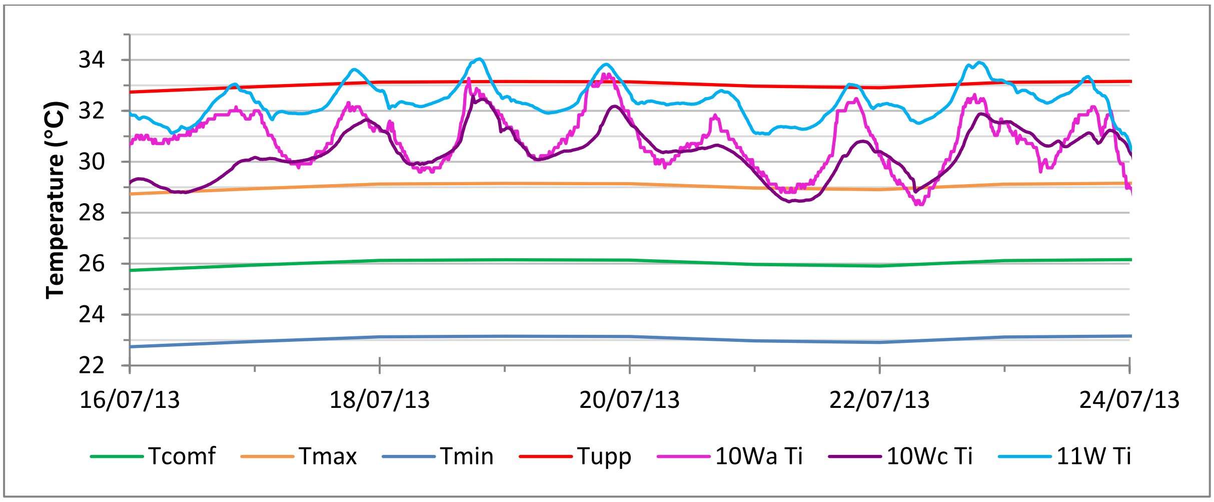


**Figure 9.20: Weighted exceedances were large as temperature exceeded threshold for days: London**

### *Criterion 3: Upper Limit Temperature*

The third criterion had the least failures, with only six fails out of fifteen. All failures occurred between 7th and 23rd of July when the whole building was free-running, (Figure 9.21). Rooms 10Wc and 7Wc failed on one day only, 10Wa on two days, and 9Ea on three days. Room 9W again performed the worst, failing on sixteen of the seventeen days; 11W performed slightly better, failing on ten of the seventeen days. Many rooms came close to failing on other days, including rooms that passed the criterion. Room 9W exceeded the upper threshold by 1.6°C on 19th July, 11W exceeded it by 1°C on 23rd July, and the remaining rooms exceeded it by 0.15°C to 0.58°C. When failures occurred, they lasted from two to twelve hours.

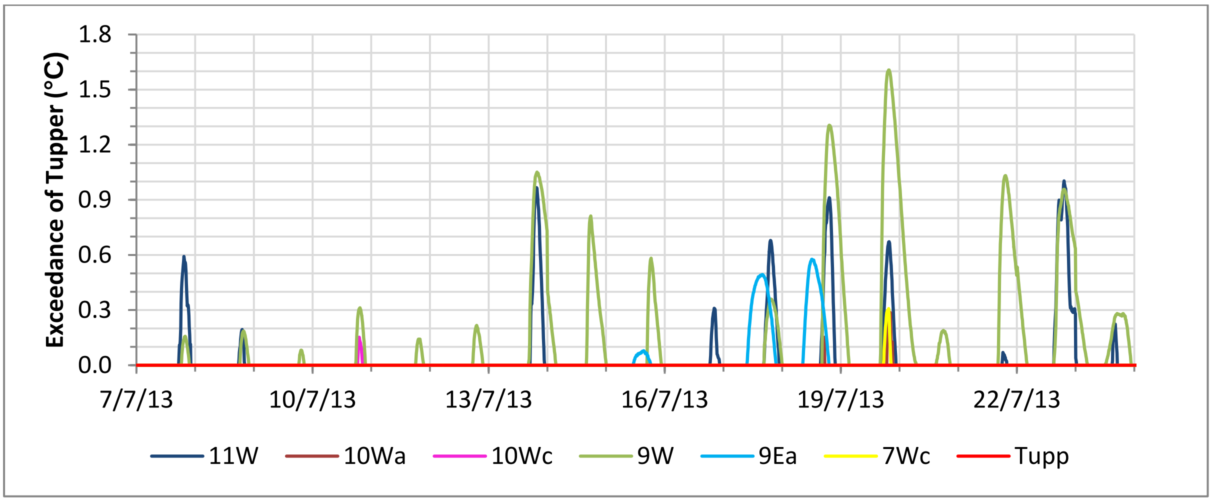


**Figure 9.21: Adaptive thermal comfort - Criterion 3: Extent and duration of failures: London**

These numbers show the extent to which rooms failed Criterion 3, but they do not convey just how hot the rooms were during this period, for this it is necessary to look at the absolute temperatures (Figure 9.22). During this period the internal temperatures were very high, all rooms that failed Criterion 3 exceeded 32°C at some point and they were above the upper limit for thermal comfort for all or nearly all of the time. The temperatures tended to stay between the upper limit for thermal comfort ($T_{max}$) and the upper allowable temperature ($T_{upp}$), which is outside the range considered comfortable by this metric. Only 10Wa and 10Wc were cool enough during this period to equal the comfort temperature.

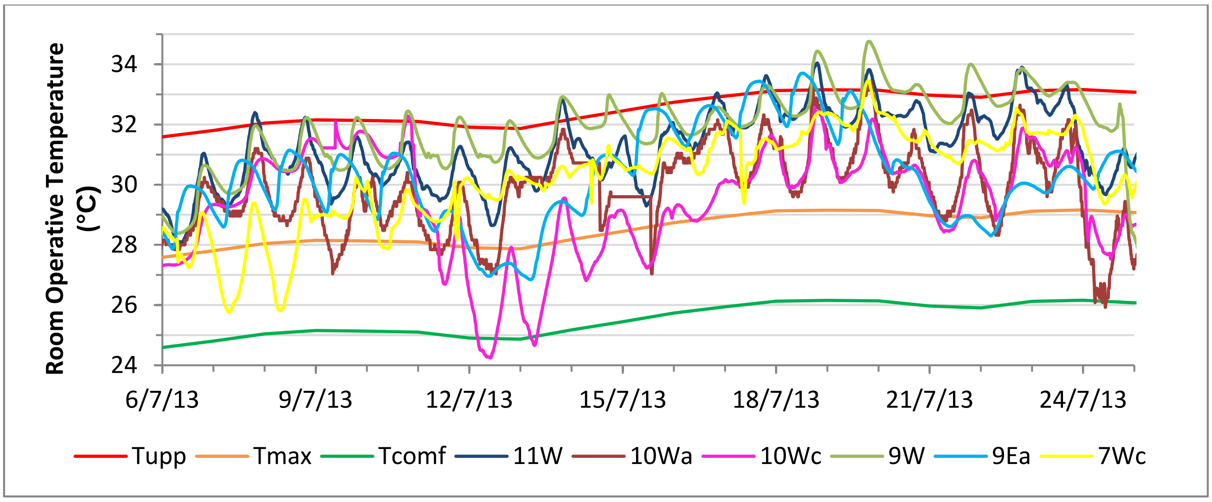


**Figure 9.22: Adaptive thermal comfort Criterion 3: Absolute temperatures for failing rooms: London**

### *Adaptive Overheating Results*

In total six rooms failed three criteria, and three rooms failed two criteria, therefore nine rooms failed the CIBSE TM52 adaptive overheating metric (Table 9.13).

**Table 9.13: Results of CIBSE TM52 adaptive overheating analysis: London**

| Room | Criterion 1 result | Criterion 2 result | Criterion 3 result | Overall result |
|---|---|---|---|---|
| 1Ea | Pass | Pass | Pass | Pass |
| 1Eb | Pass | Pass | Pass | Pass |
| 1Ec | Pass | Pass | Pass | Pass |
| 2E | Pass | Pass | Pass | Pass |
| 7Wa | Pass | Fail | Pass | Pass |
| 7Wb | Fail | Fail | Pass | Fail |
| 7Wc | Fail | Fail | Fail | Fail |
| 8S | Pass | Fail | Pass | Pass |
| 9Ea | Fail | Fail | Fail | Fail |
| 9Eb | Fail | Fail | Pass | Fail |
| 9W | Fail | Fail | Fail | Fail |
| 10Wa | Fail | Fail | Fail | Fail |
| 10Wb | Fail | Fail | Pass | Fail |
| 10Wc | Fail | Fail | Fail | Fail |
| 11W | Fail | Fail | Fail | Fail |

Since space heating was available whenever external temperature dropped to 15°C or less, the overheating analysis was not ideal. Therefore, a second analysis was conducted for the only prolonged free-running period, 12th July to 4th August. Of the nine rooms that failed the metric using the July and August data, eight clearly failed using only the data from 12th July to 4th August (Figure 9.23 and Table 9.14). There was no change in the results from Criteria 2 and 3, only in Criterion 1. The fact that the eight of the nine rooms still failed with only 22.7 days of temperature data indicates just how extreme the overheating was during this period.

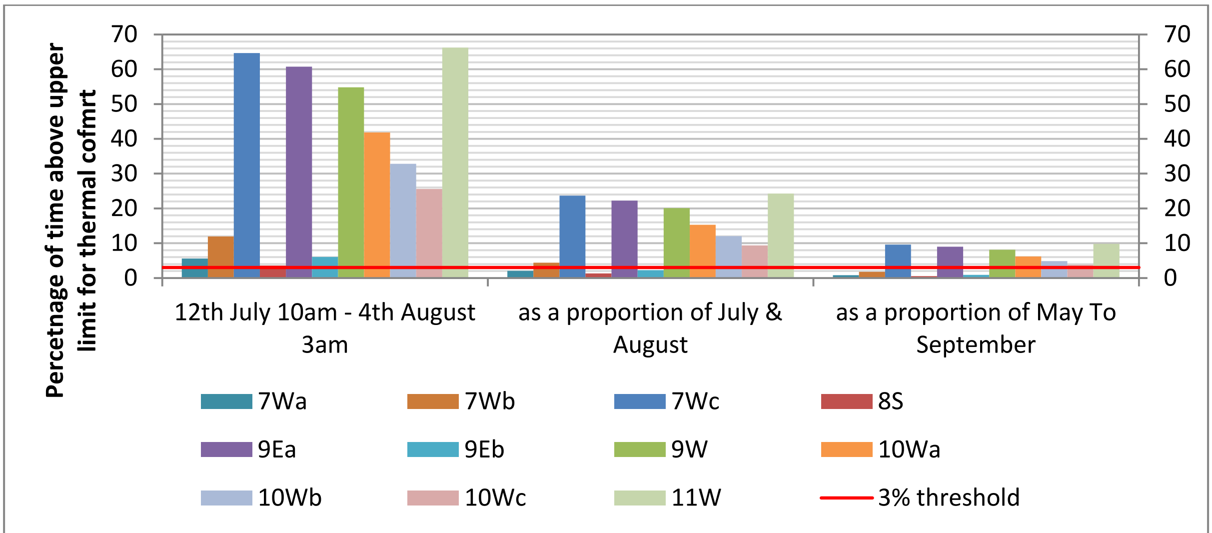


**Figure 9.23: Adaptive overheating criterion 1 results using 12th July to 4th August data only: London**

**Table 9.14: Results of CIBSE TM52 adaptive overheating analysis: 12th July to 4th August data: London**

| Room | Criterion 1 result | Criterion 2 result | Criterion 3 result | Overall result |
|---|---|---|---|---|
| 1Ea | Pass | Pass | Pass | Pass |
| 1Eb | Pass | Pass | Pass | Pass |
| 1Ec | Pass | Pass | Pass | Pass |
| 2E | Pass | Pass | Pass | Pass |
| 7Wa | Pass | Fail | Pass | Pass |
| 7Wb | Fail | Fail | Pass | Fail |
| 7Wc | Fail | Fail | Fail | Fail |
| 8S | Pass | Fail | Pass | Pass |
| 9Ea | Fail | Fail | Fail | Fail |
| 9Eb | Pass or Fail[1] | Fail | Pass | Pass or Fail[1] |
| 9W | Fail | Fail | Fail | Fail |
| 10Wa | Fail | Fail | Fail | Fail |
| 10Wb | Fail | Fail | Pass | Fail |
| 10Wc | Fail | Fail | Fail | Fail |
| 11W | Fail | Fail | Fail | Fail |

[1]*The room could be deemed to pass or fail depending on the averaging period*

### 9.3.4 Heat Stress – London

Because of the extent of overheating, the risk of heat stress was also considered. Whether the thermal environment could cause heat stress can be determined from the wet bulb globe temperature (WBGT) [British Standards Institution,1994], which is derived from wet bulb temperature and globe temperature (for internal calculations). These measurements were not taken within the rooms and therefore it is difficult to accurately predict WBGT, however it can be estimated from temperature and humidity measurements [WBGT calculator, 2015], there are also simpler metrics that use temperature and humidity data directly, the Heat Index [Heat Index 2015; heat Index calculator, 2015] and Humidex [Humidex, 2015; Humidex calculator, 2015]. These metrics are typically used in weather warnings or so employers can ensure safe working environments. Room 10Wa was the only room with humidity data (Figure 9.24), so the risk of heat stress could be estimated for this room only. It was impractical to calculate these values for the whole dataset; therefore some extreme conditions were selected to determine the extent of the risk. The results show there were many times when the internal conditions could cause heat stress although the risk was at the lower end of the scales (Table 9.15); implying heat stress is only likely when undertaking moderate levels of activity or in the case of prolonged exposure. This is not ideal in a residential building where prolonged exposure is the norm (where "prolonged exposure" is considered in terms of hours because the metric is commonly used in the workplace). The conditions may also be prohibitive, limiting occupants from undertaking moderate levels of activity within their rooms, because they may raise metabolic rate to the point where heat stress is likely. It should be noted that the only reason the results were at the lower end of the heat stress scales is because relative humidity was very low (uncomfortably and unacceptably low at times [CIBSE, 2015]), had humidity been as little as 20 percentage points higher (values common in the UK), then the risk of heat stress would have been higher.

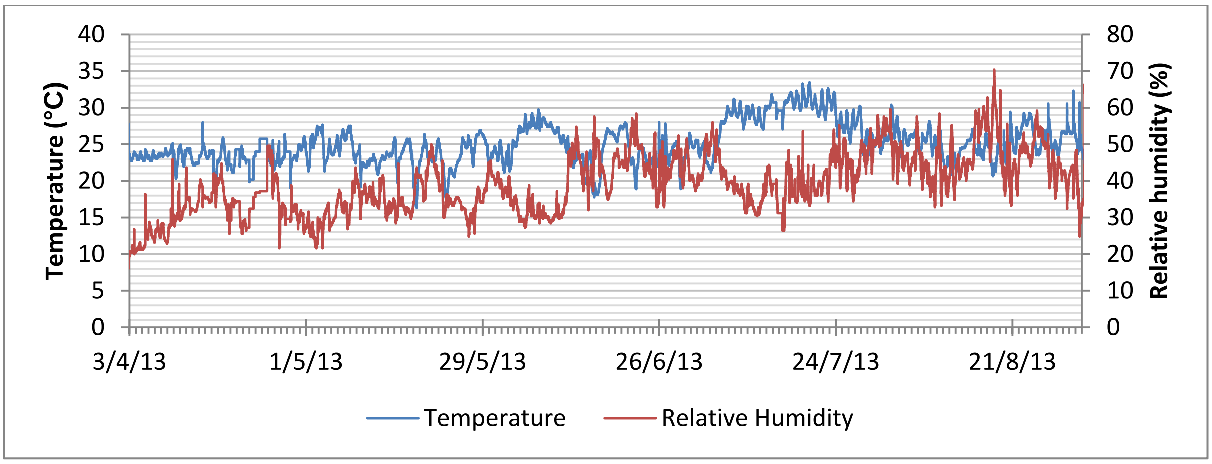


**Figure 9.24: Internal temperature and relative humidity data for room 10Wa: July and August: London**

**Table 9.15: Heat stress results for room 10Wa during extreme internal temperatures: London**

| Date time | Temperature (°C) | Temperature (°F) | Relative humidity (%) | Estimated indoor WBGT (°C) | Humidex | Heat index |
|---|---|---|---|---|---|---|
| 13/07/13 09:15 | 30.2 | 86.4 | 44.4 | 24.1 | 95°F / 35°C "Some discomfort" | 87°F / 31°C "Caution" |
| 13/07/13 18:58 | 31.5 | 88.7 | 37.6 | 24.9 | 97°F / 36°C "Some discomfort" | 88°F / 31°C "Caution" |
| 16/07/13 20:38 | 32.2 | 89.9 | 41.6 | 25.9 | 100°F / 38°C "Some discomfort" | 91°F / 33°C "Extreme caution" |
| 17/07/13 18:01 | 32.3 | 90.2 | 34.4 | 24.6 | 97°F / 36°C "Some discomfort" | 89°F / 32°C "Caution" |
| 18/07/13 17:10 | 33.3 | 91.9 | 44.8 | 26.9 | 104°F / 40°C "Great discomfort - avoid exertion" | 96°F / 35°C "Extreme caution" |
| 18/07/13 18:35 | 32.8 | 91.0 | 53.6 | 27.6 | 108°F / 42°C "Great discomfort - avoid exertion" | 98°F / 37°C "Extreme caution" |
| 19/07/13 16:23 | 33.1 | 91.6 | 34.0 | 25.2 | 99°F / 37°C "Some discomfort" | 91°F / 33°C "Extreme caution" |
| 19/07/13 18:59 | 33.4 | 92.2 | 33.6 | 25.3 | 99°F / 37°C "Some discomfort" | 92°F / 33°C "Extreme caution" |
| 21/07/13 19:50 | 32.5 | 90.5 | 36.4 | 24.9 | 99°F / 37°C "Some discomfort" | 90°F / 32°C "Extreme Caution" |
| 21/07/13 19:55 | 32.3 | 90.2 | 37.2 | 25 | 99°F / 37°C "Some discomfort" | 90°F / 32°C "Extreme caution" |
| 23/07/13 16:10 | 32.0 | 89.6 | 54.0 | 26.9 | 106°F / 41°C "Great discomfort - avoid exertion" | 96°F / 35°C "Extreme caution" |
| 01/08/13 18:49 | 30.4 | 86.7 | 52.8 | 25.4 | 99°F / 37°C "Some discomfort" | 90°F / 32°C "Extreme caution" |
| 01/08/13 18:54 | 30.2 | 86.4 | 53.2 | 25.2 | 99°F / 37°C "Some discomfort" | 90°F / 32°C "Extreme caution" |

### 9.3.4 Discussion of Findings – London

The overheating results for the London case study show there was extreme overheating on floors seven to eleven in the study, and zero to little overheating on floors one and two.

All rooms failed the annual static night time overheating criterion using the July and August data alone. Rooms 1Ea, 1Eb and 2E passed the annual static daytime overheating criterion, the remaining twelve rooms failed using the July and August data alone.

Nine rooms failed the adaptive overheating metric, six failed all three criteria, and three failed two criteria. Rooms 7Wa and 8S only failed criterion 2, and rooms 1Ea, 1Eb, 1Ec and 2E passed all three criteria.

The temperatures recorded within some rooms were extremely high (Table 9.16) and often long lasting. The data show a large variation in maximum internal temperature, the largest difference was between rooms 1Ec and 9W, at 6.6°C. The results indicate that there was little risk of overheating on the lowest floors, and a high risk of extreme overheating on the highest floors, with variable performance on the intermediate floors where rooms may overheat a little or a lot.

**Table 9.16: Simple statistics about internal temperature during July& August 2013: London**

| Room | Maximum (°C) | Minimum (°C) | Mean (°C) | Standard Deviation (°C) |
|---|---|---|---|---|
| 1Ea | 29.7 | 19.8 | 25.3 | 1.7 |
| 1Eb | 29.0 | 20.2 | 25.4 | 1.5 |
| 1Ec | 28.2 | 20.4 | 25.3 | 1.5 |
| 2E | 28.7 | 20.5 | 25.2 | 1.5 |
| 7Wa | 31.1 | 17.9 | 24.9 | 2.9 |
| 7Wb | 31.4 | 19.3 | 25.9 | 2.6 |
| 7Wc | 33.5 | 22.4 | 27.8 | 2.4 |
| 8S | 30.2 | 20.9 | 25.7 | 1.8 |
| 9W | 34.8 | 17.9 | 26.3 | 4.3 |
| 9Ea | 33.7 | 22.0 | 28.8 | 2.0 |
| 9Eb | 30.8 | 21.8 | 26.6 | 1.7 |
| 10Wa | 33.4 | 20.6 | 26.7 | 2.8 |
| 10Wb | 31.9 | 22.5 | 26.9 | 2.1 |
| 10Wc | 32.6 | 19.3 | 26.8 | 2.7 |
| 11W | 34.0 | 19.1 | 28.0 | 2.9 |

Many factors have been identified that could increase the likelihood of overheating in the building, particularly on the upper floors.

The building is thermally lightweight and highly insulated, with 200mm thick rigid insulation on some walls. It was densely occupied, and the more occupants in a given space the higher the internal gains are likely to be. Many walls and windows experience direct solar insolation, especially on the upper floors where there is no shading from adjacent buildings. Space heating was available during the summer when it was completely unnecessary.

The ventilation systems may have been ineffective (as in the Loughborough study) or turned off due to noise (which had been done in some flats in the London study). The windows within bedrooms and kitchens have restricted opening, limiting the ability for natural ventilation. The bedroom and flat entrance doors are fire doors that must be kept closed, limiting natural ventilation between rooms. The flat corridors have no windows, and therefore relied upon the ventilation system extract ducting. There is no means of ventilating the stair core, because it has no mechanical ventilation and no openable windows or vents.

The lack of ventilation in the stair core and flat corridors is a problem because they may experience high internal gains from the constantly operational lighting and building services. The stair cores contained communications equipment, back up boilers, and flow and return pipework for hot water and space heating; the corridors also contained flow and return pipework. Heat losses from the hot water ductwork cannot be avoided during warmer months, but could have been avoided from the space heating system if it were turned off.

Heat within the stairs cores could rise easily to the upper storeys via the stairs, because the stairs were essentially one open space spanning the full height of the building. The BMS system had temperature sensors in the stair cores, problems meant the data could not be logged, but spot readings from 1st November 2012 (when external temperature measured 12°C) showed that the internal temperatures increased with storey number (Table 9.17). There are not thought to be any seals or air barriers between storeys, which means warm air could also rise up through the structure via the party wall cavity between modules and at the junctions between modules and corridors.

It is believed that if louvered fenestration had been included in the stair core, as per the original design, then less heat would have been able to accumulate on the upper floors of the stair core, which would have a beneficial impact on conditions within flats.

**Table 9.17: Temperatures within stair cores on each storey: London BMS system data**

| **Storey** | **Temperature in stair cores (°C)** | |
|---|---|---|
| | **Block A** | **Block B** |
| Ground | 10.4 | 14.7 |
| 1st | 14.3 | 15.4 |
| 2nd | 15.6 | 16.7 |
| 3rd | 19.2 | 18.1 |
| 4th | 17.3 | 21.2 |
| 5th | 21.1 | 20.2 |
| 6th | 21.9 | 22.1 |
| 7th | | 21.3 |
| 8th | | 23.2 |
| 9th | | 24.4 |
| 10th | | 25.0 |
| 11th | | 27.0 |

Temperature data collected while the building was completely vacant show that internal temperatures were higher on the uppermost floors compared to the lowermost floors (Figure 9.25). It cannot be known if these differences are purely a result of differences in location within the building, because ventilation flowrates and solar shading (from window blind position) could have varied between rooms. Had the study been larger then it may have been possible to identify trends based on location within the building, but the dataset is too small to confidently explain how it impacted on internal temperature.

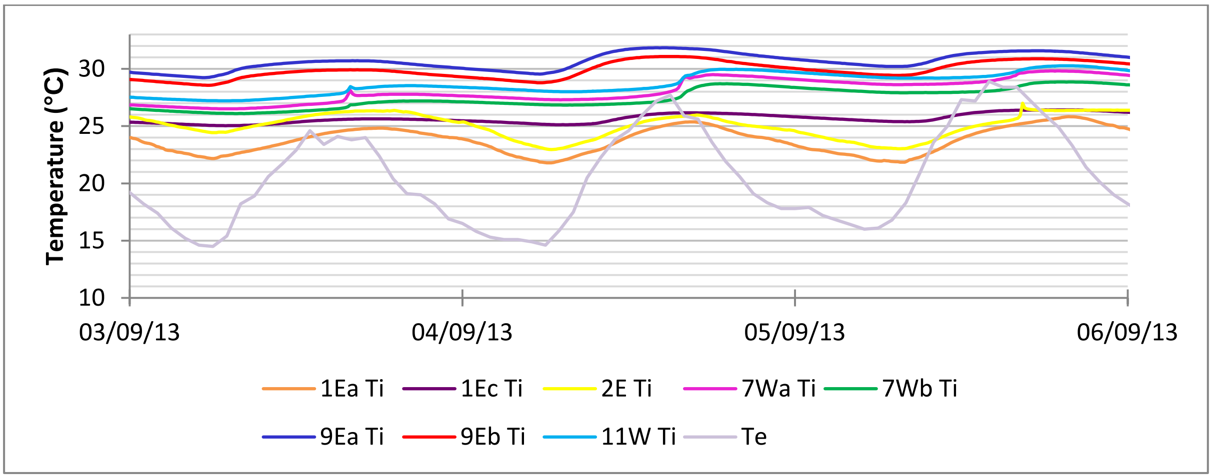


**Figure 9.25: Variations in diurnal temperatures fluctuations in rooms in the vacant building: London**

While the building design and operation appears to make overheating more likely on the uppermost floors compared to the lowermost floors; this is not the only factor influencing internal temperature. Differences in occupant behaviour (which impact upon occupancy, internal gains, solar gains and ventilation rates) also play a role in determining internal temperatures. This is evident for rooms 7Wa and 7Wc which were located next door to each other in the same flat, where 7Wc was warmer than 7Wa for 99% of July and August (Figure 9.26 and Table 9.18). However, whenever rooms 7Wa and 7Wc were vacant (such as at the end of August and start of September) the room temperatures converged indicating that the difference was due to the occupants. Unfortunately no data were collected about the other factors that influence internal temperatures, (occupancy, heat gains and ventilation rates). Therefore it is not possible to normalise the data, to separate occupant related factors from building performance factors, or to quantify the role that location within the building plays in determining internal temperature.

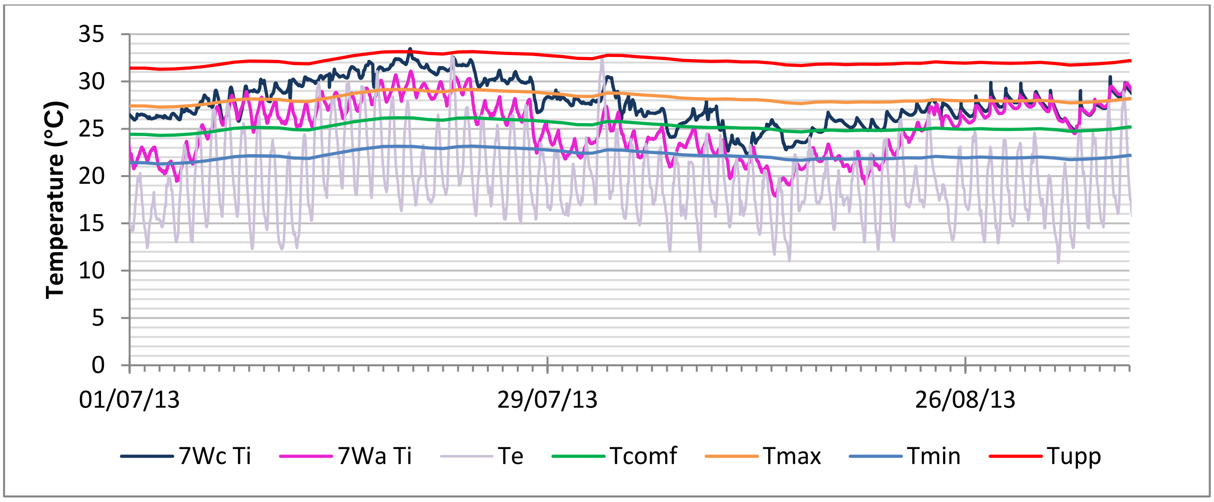


**Figure 9.26: Internal temperatures in rooms 7Wa and 7Wc: July and August: London**

**Table 9.18: Comparison of internal temperatures within rooms during July and August: London**

| | Percentage of July and August 2013 that room x was warmer than room y | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| y \ N | 1Ea | 1Eb | 1Ec | 2E | 7Wa | 7Wb | 7Wc | 8S | 9Ea | 9Eb | 9W | 10Wa | 10Wb | 10Wc | 11W |
| 1Ea | | 52 | 47 | 52 | 41 | 60 | 90 | 62 | 98 | 79 | 50 | 69 | 80 | 71 | 85 |
| 1Eb | 47 | | 45 | 36 | 42 | 62 | 94 | 59 | 98 | 82 | 48 | 66 | 79 | 74 | 88 |
| 1Ec | 53 | 55 | | 51 | 50 | 66 | 89 | 59 | 98 | 83 | 55 | 74 | 83 | 75 | 85 |
| 2E | 48 | 64 | 49 | | 48 | 67 | 86 | 60 | 97 | 87 | 50 | 65 | 78 | 73 | 82 |
| 7Wa | 59 | 58 | 50 | 52 | | 76 | 99 | 59 | 98 | 79 | 79 | 89 | 94 | 88 | 90 |
| 7Wb | 40 | 38 | 34 | 33 | 24 | | 86 | 46 | 91 | 62 | 64 | 70 | 68 | 69 | 81 |
| 7Wc | 10 | 6 | 11 | 14 | 1 | 14 | | 21 | 76 | 29 | 35 | 24 | 30 | 26 | 60 |
| 8S | 38 | 41 | 41 | 40 | 40 | 54 | 79 | | 95 | 70 | 54 | 66 | 76 | 69 | 77 |
| 9Ea | 2 | 2 | 2 | 3 | 2 | 9 | 24 | 5 | | 4 | 25 | 17 | 18 | 18 | 36 |
| 9Eb | 21 | 18 | 17 | 13 | 21 | 38 | 71 | 30 | 96 | | 43 | 50 | 54 | 51 | 69 |
| 9W | 50 | 52 | 45 | 50 | 21 | 36 | 65 | 46 | 75 | 57 | | 58 | 60 | 60 | 68 |
| 10Wa | 31 | 34 | 26 | 35 | 11 | 30 | 76 | 34 | 83 | 50 | 42 | | 52 | 50 | 82 |
| 10Wb | 20 | 21 | 17 | 22 | 6 | 32 | 70 | 24 | 82 | 46 | 40 | 48 | | 51 | 77 |
| 10Wc | 29 | 26 | 25 | 27 | 12 | 31 | 74 | 31 | 82 | 49 | 39 | 50 | 49 | | 75 |
| 11W | 15 | 12 | 15 | 18 | 10 | 19 | 40 | 23 | 64 | 30 | 32 | 18 | 22 | 25 | |

In choosing this case study building the hope had been to observe some overheating, there was no deliberate attempt to choose a badly performing building, just a typical medium-rise [redacted] building in London that was occupied during the summer. The building was in its first year of operation, so there was no prior knowledge of its operational performance. If this building had not overheated, then it would have given confidence that other [redacted] buildings would not overheat. However, it did overheat, extremely, and this raises concerns for other [redacted] buildings, this matter is discussed further is section 9.4.

## 9.4 Recommendations

The overheating analysis concluded that [redacted] buildings are at risk overheating. Many rooms on the upper floors in London overheated substantially, and the temperature trends in the kitchens and corridors in Loughborough were also concerning. If the climate were to warm then the likelihood of overheating would increase. The data suggest that avoiding overheating would be significantly easier in low rise buildings than in the tallest buildings (twelve storeys as in the London study).

Further work is required to better understand the risk and causes of overheating in [redacted] buildings. Ideally, further temperature data should be collected from more buildings to determine the extent of overheating in different types of rooms, on different storeys, in different sized buildings, in different locations, and whether the overheating in the London study is typical of a large [redacted] building. Many buildings have building management systems from which it may be possible to obtain some temperature data with minimal effort.

Ideally, efforts should also be made to minimise overheating in existing [redacted] buildings, this could involve further case studies in buildings known to overheat aimed at examining interventions. For example, there are various changes that could be made to the operation of the London case study building that could have a beneficial impact on internal conditions, including running/opening the AOV (automatic opening vent for smoke control) to ventilate the stair core, better controlling the space heating, and ensuring the ventilation systems are operating correctly and with minimal noise. It would also be beneficial (if possible) for the window opening restrictions to be modified to represent the design drawings (150mm open from the face of the facade, rather than 150mm open from the window frame), to improve natural ventilation within rooms. These measures would provide much needed feedback; to determine if optimising operation can have a significant impact on overheating, or whether it makes little difference. It could have the added benefits of improving thermal comfort for occupants and reducing energy use by limiting space heating.

While [redacted] are no longer in operation, and there will be no new [redacted] buildings, it is important to comment on how design and operational changes could help minimise the risk of overheating. Many of these issues are not unique to [redacted] construction, and could be relevant to other forms of modular construction, to other forms of thermally lightweight construction, or more generally to all construction.

Like many forms of construction, [redacted] construction is thermally lightweight, and this cannot be avoided, therefore designs ought to be optimised in view of this. There is very little thermal mass to damp temperature fluctuations, and therefore limiting solar gains should be a priority. This can be achieved by optimising orientation, internal layout, and fenestration, and by using solar shading both externally on the facades and internally with blinds.

Ventilation is also extremely important and it will become increasingly important as thermal performance improves into the future. Simply specifying a ventilation system is not enough, it needs to function properly and it cannot be used to counter poor building design. The design of student halls requires the use of fire doors, and this hinders natural ventilation options, but in a domestic setting there is not the same requirement, and there is more freedom to consider natural ventilation strategies and to optimise the layout of buildings for good thermal performance. Night cooling strategies should be considered, and may be necessary in taller buildings to extract the heat that has accumulated during the day and stop the incremental rise in internal temperatures during prolonged periods of warm weather. Stair cores could be designed to provide stack ventilation, and corridors should be ventilated.

The performance of passage spaces can impact on the performance of occupied rooms, and their design should not be neglected.

Controlling internal gains is also particularly important. Space heating should not be available during the warmest months of the year. Low energy appliances and lighting systems would help to reduce internal gains and the risk of overheating, particularly in kitchens and corridors. Limiting the rise of heat through a building should also be considered, for [redacted] construction (and perhaps other modular construction) there are particular concerns about how heat rises between modules, and there are more general concerns about how heat rises via stair cores.

There are numerous measures that could be adopted to reduce the risk of overheating in new buildings, but it is not possible to specify exactly which combination of measures would be required, as they are likely to be project dependent. An holistic approach to design is likely required to limit overheating, because no one passive measure would be effective on its own. Dynamic thermal building simulations are likely necessary to help optimise building designs. Ongoing feedback about the performance of new and existing buildings would also be very helpful for quantifying the extent of overheating and the effectiveness of current approaches, and for identifying future changes.

## 9.5 Discussion of Overheating Metrics

Two distinct overheating metrics were used for the overheating analyses, interestingly they yielded similar results, however this could have been coincidental. From a practical perspective, the static metric is not best suited to a dataset that only covers part of the free-running period, due to the requirement to average over a whole year. The adaptive overheating metric is better because it allows calculations to be made over the dates for which there are actually data. Only Criterion 1 in the adaptive metric requires averaging over the whole dataset, the remaining two criteria consider spot measurements and data for individual days. This means that a room could fail with only one day of data, if on that day the weighted exceedance is greater than six (Criterion 2), and the absolute maximum allowable temperature ($T_{upp}$) is exceeded (Criterion 3). Therefore the metric is more useable, because the hottest days and weeks can be targeted for data collection rather than requiring the whole free-running period. If data are collected for only the hottest weeks, and rooms fail Criteria 2 and 3, then it does not matter the status of Criterion 1, because two failures results in an overall failure.

## 9.6 Chapter Summary

This chapter concerned overheating in the case study buildings. It began by presenting the static and adaptive overheating metrics used, before giving the results for each study separately. It discussed the occurrence and risk of overheating, the temperature trends within different rooms, and how design and operation could have impacted on overheating. It showed that no overheating was determined in Loughborough but the temperature trends suggest some overheating would have occurred if the building was occupied throughout summer. It showed that there was extreme overheating on the upper floors in the London study, but very little to no overheating on the lower floors. The chapter concluded by making recommendations for further research focussed on better determining the extent of overheating in existing [redacted] buildings, and identifying and testing possible operational interventions that could alleviate overheating. It also discussed the various design and operational issues that are important in limiting the risk of overheating in new thermally lightweight construction, ultimately suggesting that a holistic approach with dynamic thermal simulations is likely required.

# Chapter 10 – Conclusions

## 10.1 Research Summary

The aim of this research was to investigate ways to reduce the in-use energy consumption of light-gauge steel modular construction used for residential purposes, while ensuring thermal comfort. It involved collaboration with an industrial sponsor, [redacted] and the research focused on their modular design and buildings; unfortunately they entered administration before the research concluded. The involvement with [redacted] provided access to their factory, construction sites, and a wealth of design and construction documentation; which allowed in-depth understanding to be gained of the construction. The research aims and objectives were formulated based on findings from the literature review, the ontological and epistemological views on reality, and the requirements of the sponsor (which was to focus on factors that they could influence, namely technical and operational factors). A case study approach was chosen for data collection which included two studies, a low-rise building with masonry cladding in Loughborough and a medium-rise building with lightweight cladding in London. Various data collection methods were used including: building monitoring, IR thermographic imaging, blower door tests, inspections of factory and sites, and a review of design documentation and photographs. The data were used to identify weaknesses in fabric thermal performance, scope for reducing energy use, and the occurrence of overheating; the specific findings and recommendations are discussed in detail Chapters 7, 8 and 9 respectively, and are summarised in Table 10.1 below.

In terms of fabric thermal performance the main findings were that greater attention needs to be given to the design of whole buildings, particularly at the interfaces between modular components and between modular and non-modular components; and that better quality control is required on site, particularly regarding the installation of insulation. There is significant scope to reduce thermal bridging, thermal bypasses and air leakage at interfaces, particularly at masonry supports, lintels, fenestration, and party wall junctions between modules. There is also scope to improve fabric thermal performance by redesigning the breather membrane and ensuring that installation is properly fitted on site.

In terms of energy use, the main findings were that energy can be saved by better specification and control of heating systems, ventilation systems, lights and appliances. Improvements in performance can likely also be achieved by better design, commissioning and maintenance of ventilation systems. In many instances an equal level of service could be achieved while also reducing energy use, such as by specifying more efficient appliances and ventilation systems, or by using timer controlled switches for passage space lighting.

In terms of overheating, the main finding was that extreme overheating occurred in the London study. Overheating did not occur in the Loughborough study, but it cannot be known if this was simply because the building was unoccupied in July and August. Various factors were identified that could exacerbate overheating in the London study, such as summertime space heating, minimal scope for natural ventilation, and high levels of insulation. However, it is not clear to what extent these were actually exacerbating factors, and whether the overheating in London represents a typical or extreme case.

Many of the factors that lead to poor fabric thermal performance or wasteful energy consumption would be relatively straightforward to rectify, if sufficient attention were given to the design of interfaces, construction quality on site, specification of energy consuming devices, control of heating and lighting, and commissioning of services. Based on the findings, there is a strong belief that the thermal and energy performance of [redacted] buildings could be significantly improved without the need for significant changes to the modular design, and this is discussed in the following section.

However, determining how to ensure the avoidance of overheating could be more challenging, especially if the fabric performance were to be improved. The extent of overheating in [redacted] buildings needs to be better understood, and limiting overheating may require the whole design to be optimised through building modelling (as any one measure is unlikely to be sufficient, at least in particular buildings). The avoidance of overheating ideally requires further research, which is discussed in section 10.3.

**Table 10.1: Summary of research findings: problems and causes**

| Problem | Cause |
|---|---|
| Air leakage | Poorly designed interfaces, allowing air leakage via the party wall junctions between modules and at interfaces between corridors and the envelope |
| Thermal bridging | Poorly designed interfaces, such as the failure to thermally separate fenestration, masonry supports and lintels from the modular structure |
| Thermal bypasses | Poorly designed interfaces, allowing air to bypass insulation around curtain walling.<br>Poorly installed insulation on site, allowing air to bypass the insulation layer through gaps and unsealed joints in the insulation |
| Poor building services | Poor radiator operation in Loughborough with the regular inability to turn heating on at low internal temperatures<br>Failure to turn space heating off in summer in London<br>Unacceptable noise from ventilation systems<br>Unacceptable flow rates through ventilation systems |
| Inefficient energy use | Excessive lighting electricity use in passage spaces due to poor lighting design and control<br>High electricity use in kitchens from inefficient base load equipment (appliances and ventilation systems)<br>Wasted energy due to failure to turn space heating off in London |
| Thermal comfort - Extreme overheating in bedrooms on upper floors in London | Poorly performing ventilation systems<br>Limited scope for natural ventilation strategies<br>Availability of space heating during warmest months<br>High occupant density<br>High insulation levels<br>High solar gains and minimal solar shading<br>Low thermal mass |
| Thermal comfort - uncomfortably cool | Radiators failing to stay switched on in the Loughborough study resulted in uncomfortably low internal temperatures (~16°C in March) |

## 10.2 The Performance of Modular Construction

As discussed in Chapter 2, offsite construction methods are often viewed as offering a solution to many of the quality and performance related problems that exist within the construction industry. This research provided the opportunity to investigate this view; and while it only focused on one manufacturer of one type of modular construction, the conclusions may be more widely applicable to all modular construction.

Observations from the factory and from construction site photographs agree with the general consensus about offsite construction, that moving construction indoors onto a production line in a factory results in a product of consistent and repeatable quality. All the data and observations indicate that the modules fabricated in the factory were consistent, that they were essentially identical, with no chance that they would have missing or incorrect materials. However, the assumption that the consistency and quality achieved from fabrication in a factory automatically translates into good energy and thermal performance is questionable [redacted]. The modules were of a consistent and repeatable quality but at the same time there were weaknesses in the thermal and energy performance of the buildings. A product can be simultaneously good in some respects and poor others, and it should not be assumed that quality in one area (repeatability) translates into quality in other areas (energy and thermal performance). While production in a factory enables consistency, it cannot ensure the fabric design contains no thermal weaknesses, that the construction on site is of a suitable quality, or that the energy consuming devices are optimally specified and controlled; and all of these factors are important in determining the fabric thermal performance and/or energy consumption of operational buildings.

However, there was one significant finding that could have important implications: there was consistency in the way the buildings underperformed (based on data from the Loughborough study and design documents from other buildings). The underperformance was not random but due to specific weaknesses occurring at specific features and interfaces, such as the thermal bridging around windows and at masonry supports, and air leakage at party wall junctions between modules. Most weaknesses pertained to the performance of whole buildings, to the way that modules were combined and not to individual modules or how they were manufactured in the factory (with the exception of window-module interfacing and the breather membrane). The fabric weaknesses identified can be eliminated or significantly improved with greater attention to the thermal design of interfaces and better quality control on site. The data strongly suggest that if these design and construction problems were resolved, that the new design could be used to construct buildings that consistently provide good energy and thermal performance.

Based on the findings, the conclusion is that modular construction can be used to consistently construct low energy, comfortable buildings; but that performance is not guaranteed and depends upon the fabric design (particularly at interfaces) and adequate quality control in the factory and on site. To consistently construct comfortable, low energy buildings is not easy, it takes dedicated effort and attention to details; however once the design is optimised it may be easier to achieve consistent performance using modular construction than using traditional construction.

## 10.3 Recommendations for Future Research

Recommendations about how to improve thermal fabric performance, energy use and thermal comfort have already been made in chapters 7, 8 and 9 respectively. These are steps that [redacted] could have taken to improve performance if they were still in operation, or that [redacted] could take to optimise operational performance. This section makes recommendations for future research that could also be undertaken.

### Air Leakage and Thermal Performance at Interfaces

The research focused primarily on the Loughborough study and to a lesser extent on the London study; it also analysed design documentation for other buildings. [redacted] This could be achieved through a combination of blower door test, IR thermal imaging, building inspection and document review. Ideally numerous [redacted] buildings could be studied to investigate how different buildings (in terms of size, age, cladding etc.) perform.

The blower door tests would ideally be of whole blocks to gain accurate measurements of air leakage through external envelopes, and to determine if the air leakage paths identified in Loughborough remained the same and are present in other buildings. During the literature review, no data were found about envelope airtightness in steel modular construction, so conducting tests on multiple buildings under ideal conditions would help to provide information that is currently lacking.

IR thermography would ideally be used to identify thermal bridging and air leakage (such as in the form of plumes), as was done in the Loughborough study. The images would support findings from the blower door tests, inspections and document reviews and could identify fabric weaknesses that are not visible in the final construction (such as missing insulation).

By undertaking this further research the aim would be to identify whether the weaknesses identified in the Loughborough study occur in other buildings. It would be useful:

- to compare similar cladding systems, to determine if they perform in a consistent or variable manner
- to compare different cladding systems, to determine if any are better or worse, and if certain systems should be favoured (such as lightweight cladding systems over masonry cladding) in order to optimise fabric thermal performance,

- to determine if masonry supports and lintels are used in all masonry clad walls, and if they all perform similarly to the Loughborough study or if there is variation,
- to determine if plumes of heat are evident in IR thermal images at the party wall junctions between modules in all buildings
- to determine if there is any evidence that other buildings have an air barrier
- to investigate the performance at curtain walling interfaces, to compare how different designs perform in different buildings, with an aim to identifying the best design
- to identify the best and the worst performing interfaces and the reasons for them, so that lessons can be learned about which designs perform well and which do not.

**Overheating**

The extent of overheating in the London study is concerning and further research is needed to determine the occurrence of overheating in [redacted] buildings, to determine whether the London study is a typical or extreme case, and to identify factors that influence the occurrence of overheating (such as building size, location, services and cladding type). This could include monitoring the internal environment and/or undertaking occupant comfort questionnaires in a number of [redacted] buildings. As well as determining the occurrence of overheating, the research could also be aimed at minimising overheating, by improving the design of any future buildings and/or by making modifications to existing buildings (modifications could be to ventilation systems, heating controls, window opening, solar shading etc.). If overheating were found to be a common problem in [redacted] buildings, it would have implications for the future design and could dictate certain design aspects (such as building size, ventilation strategy, envelope design, etc.), and would likely require the use of dynamic thermal building simulations because a combination of measures would be required to minimise the risk of overheating.

**Building Modelling**

Initially, this research aimed to include dynamic thermal building simulations as a tool to help optimise the design of [redacted] buildings, but for various reasons, it was not seen to completion. It would still be beneficial if modelling were undertaken as future research. Modelling could be used to help optimise building layout, solar shading, facade design, thermal comfort, space heating energy use, heating control strategies and ventilation strategies. As discussed above, building modelling may be particularly important for minimising the risk of overheating.

## 10.4 Research Limitations

The research was limited in various ways, most significantly by [redacted] entering administration. The research was undertaken partly because it offered the potential to be involved in making improvements to real buildings, but when [redacted] ceased trading this was no longer a possibility. The collaboration would have also allowed for the development of exact solutions to the weaknesses identified, but this was not possible because it required input from [redacted] about which solutions were suitable and preferable for the construction method. The loss of collaboration with [redacted] also limited access to information, and made data analysis harder and more time consuming. It also led to uncertainty, because questions that could easily and quickly have been answered by [redacted] were impossible to answer without them, ([redacted]).

Another limiting factor was the poor performance of the wireless monitoring equipment and the loss of data that it caused. All of the window data were lost which meant it was not possible to study window opening behaviour or to investigate the relationship between window opening and internal temperature or the simultaneous use of windows and space heating. The loss of temperature data early in the Loughborough study and entirely in the London study also meant it was difficult to investigate any relationship between space heating use and internal conditions. The loss of data was a significant reason why building modelling was not completed, as there was insufficient data for model calibration.

The research was also limited by the size of the studies, they were ultimately too small and covered too short a duration to separate the roles that occupant behaviour, building design and building services operation played in the determination of energy use.

Despite the limitations, the research highlighted many ways that improved energy and fabric thermal performance could be achieved, and confirmed that overheating is a significant concern, in at least some [redacted] buildings.

## 10.5 Reflections on Data Collection Methods

Various data collection methods were used during the research, some more successfully than others, which impacted on the data collected.

The blower door tests were not ideal as whole blocks could not be tested, resulting in the test being a measure of air leakage through internal and external envelope and therefore not comparable with results from other tests; and the tests were only really useful for the identification of air leakage paths.

The largest problems were with the EnOcean enabled wireless sensor networks, which is a relatively new technology. Poor network range resulted in lost temperature, humidity and window opening data. This impacted on the data collected and the analyses possible (Appendix E). However there were various factors that meant using different monitoring equipment may not have been much more beneficial. Firstly, there was no safe option for monitoring window opening using standalone sensors as all would have had trailing wires, therefore a wireless solution was the only option. There are other wireless solutions, but they may have experienced the same problems, and most of the equipment from other manufacturers was prohibitively expensive, so may not have been affordable. The loss of temperature data could have been avoided in the Loughborough study by using standalone sensors. However, in the London study this would not have resolved the problem because cleaners threw away or broke most of the sensors after the occupants moved out, and this would have happened to the standalone sensors also.

The performance of the network range could have been better in the Loughborough study from the start, had the pilot study been better or the handheld diagnostic tool purchased, which was advised against (Appendix E). However, it is possible that the problems in London could not have been fixed, and a different building may have been preferable. There were major delays receiving the equipment, and then in understanding how to use the Can2Go controller once it was received (because no documentation was available). This meant there was no time to conduct more pilot studies, which would have helped identify range problems. The first pilot study used an Eltako controller and temperature sensor, and did not go far enough to test the equipment's capabilities, (including testing the new equipment specified for the main studies), and this led to an overconfidence with the performance of equipment. Inexperience of conducting monitoring studies also played a role. It is believed that if further studies were done that the EnOcean networks could be made to perform better in some buildings (such as the Loughborough study), through the use of more extensive pilot studies and the fact that documentation and Can2Go specific Lua syntax is now publicly available; but perhaps not in all buildings (such as the London study)

The data from energy harvesting EnOcean enabled sensors was poor, but ultimately it is not certain that other methods would have been much more successful.

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# Appendix A: EnOcean Wireless Sensor Networks

A wireless sensor network (WSN) is a network of sensors that measure parameters at regular intervals, and transmit the measurement data wirelessly to a central location, typically to a controller or receiver. The data may be logged or used for decision making purposes; for example, a room temperature measurement may be used to determine whether windows should be opened or if space heating should be turned on. WSNs may also have additional components such as repeaters, actuators and gateways. The specific features of, and components in, a WSN depend upon the technology selected, its intended use, and the installation location. The use of WSNs in building monitoring, control and automation is becoming increasingly common.

EnOcean WSNs were selected for this project. The decision to use them was based on a host of constraining factors (see Table A.1), which ruled out many other options. The restricted access to the rooms was the biggest constraint as many standalone sensors within budget did not have sufficient logging capacity or battery life for a project to run for months. Other WSN options were considered, but were also ruled out due to a range of issues including the battery life of sensors, the cost of software licenses, restrictions on the number of sensors in a network, the cost of equipment, the type of sensors available, and data logging capacities. There were also difficulties finding suitable window opening sensors and electricity metering equipment, and the best solutions found used EnOcean WSNs.

**Table A.1: Project constraints regarding the selection of monitoring equipment**

| Constraint | Implication |
|---|---|
| No access to rooms during study other than to install and remove equipment | Sensors had to have sufficient power and logging capacity (if standalone) to last the duration of the case studies |
| No damage could be caused | Wired sensor network not suitable as they normally pass through walls and ceilings<br>Sensor had to be fixed in a way to avoid damage paint or finishes |
| Equipment and installation had to be safe | No trailing wires that could be tripped over or caught, so wired sensor networks not suitable |
| Equipment and installation could not interfere with occupants, or affect their use of the space | Installation had to be quick<br>Equipment had to be unobtrusive |
| Equipment had to be within budget | Restricted options, many sensors and WSNs were too expensive |
| An increased risk damage or loss of equipment expected in a student hall | Favoured a solution where data can be stored centrally as soon as it is collected |

EnOcean is the originator of low powered, energy harvesting wireless sensor technology. EnOcean sell modules (see Figure A.1) to Original Equipment Manufacturers (OEMs) who then program, package, brand, and market them to suit their needs, creating unique WSN solutions. These products are termed “Enabled by EnOcean”, there are currently more than 100 OEMs providing EnOcean Enabled equipment, and the number is growing. In theory the equipment should be interoperable; however this is not always the case, as some OEMs restrict this ability.

### Range

The range of wireless data telegrams in EnOcean WSNs varies based on how and where it is installed. In open air the range of EnOcean telegrams is quoted at 300m. Within buildings this is reduced to 10m to 30m, and is influenced by the type of construction. The actual range of a network can be much larger through the use of range boosting equipment such as repeaters, gateways, and multiple controllers.

A range of 10m indoors is considered the worst case scenario and failure to achieve this indicates a problem. Wireless telegrams can be subject to shielding and interference. Shielding may completely or partially block data transmissions, and interference may be constant or intermittent. Diagnostic equipment is available that can be used to optimise the placement of equipment to minimise shielding and interference. There is little that can be done about signal shielding as it is often cause by materials within a building, the only option is to identify sources and place equipment in locations that avoid or minimise shielding. Interference can be caused by other electrical equipment, and again there is often little that can be done to reduce the problem other than to place equipment away from sources of interference. Avoiding shielding and interference may not always be possible, and the strategic use of range boosting equipment may be required to work around problem areas in a building. This may not always be effective, and in some situations it will be difficult or impossible to obtain data from certain locations despite every effort to do so.

### Energy Harvesting

The energy harvesting ability of EnOcean enabled sensors sets them apart from other WSNs that are currently available. The majority of sensors harvest light energy through miniature photovoltaic panels located on the front of sensors; other sensors harvest kinetic energy (in various forms) or thermal energy, (see Figure A.1). Controllers, repeaters and some sensors use mains electricity, because the energy requirements of this equipment cannot currently be met through energy harvesting. Some sensors also use batteries, either alone or in addition to energy harvesting capabilities.

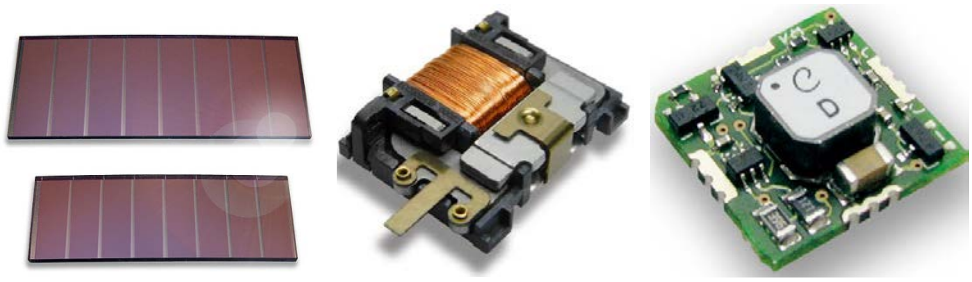


**Figure A.1: EnOcean energy harvesting modules: Solar energy (left), kinetic energy (centre), and thermal energy (right) [EnOcean, 2014]**

### Ultra Low Power Consumption

The energy harvested from sensors and switches is very small (13µW for a small solar cell at 200lux [EnOcean, 2014b], therefore it is essential that they use energy efficiently to maintain sufficient power to operate. This is achieved in two ways: through the bi-stable operation of sensors, and through the wireless communication protocol.

Most sensors operate in a bi-stable manner, where they will only transmit data if there has been a change in state above a threshold value, or significant time has passed without change. This saves energy by minimising repeated transmissions of parameters that have not changed state, such as repeatedly transmitting data to say a window is closed. Energy harvesting sensors spend most of their time in sleep mode, which saves energy. Most sensors count to 100 seconds while in sleep mode, and then awake to check whether there has been a significant change in sensor state to warrant the transmission of data. If the state has changed significantly since the last data transmission then the sensor will transmit a telegram with the new state, and then return to sleep more and start counting to 100 again. If there has been no significant change in state then the sensor transmits no data and returns to sleep more and begins counting to 100 again. If there continues to be no change in state then most energy harvesting sensors will count to 100 ten times before automatically sending a wireless data telegram irrespective of state. This means that most sensors transmit data approximately every 17 minutes unless there has been a significant change in state to warrant more frequent transmissions. Some sensor operate differently, such as electricity meters, which still operate in a bi-stable manner but transmit data more frequently because they are powered from the mains electricity supply and do not have need to conserve energy. The bi-stable settings cannot be changed.

Wireless data is transmitted at ultra-high frequency (868MHz in Europe) using the EnOcean Radio Protocol (ERP), which has been optimised for ultra-low power operation. The data is transmitted in short packets using hexadecimal numbers. The transmissions have a very short duration, (<1ms), and use very little energy (50µWs), this ensures that enough power can be generated through energy harvesting alone.

## Interoperability

Interoperability of equipment between OEMs is achieved by: limiting the number of types of sensors, controlling sensor functionality and dictating the format of data telegrams. This is all achieved and outlined by the EnOcean Equipment Profiles (EEP). The EEP details the types of sensors, and the format of the wireless data transmissions for each type of sensor.

There are only a limited number of types of sensors, the number is restricted because too many types of sensors would make interoperability difficult to achieve. OEMs have to try to fit new sensors to existing sensor types; if this is not possible then a new type of sensor may be created by the EnOcean Alliance, but only if deemed appropriate.

The functionality of each type of sensor is controlled and restricted, and each type of sensor has fixed specifications that OEMs cannot change. This means that the same type of sensors from different OEMs have exactly the same technical specifications in terms of:

- The type of data they collect
- The accuracy of the data
- The content of the wireless data transmissions
- The timing of the wireless data transmissions
- The consumption of energy for data transmissions
- The frequency of wireless data transmissions (based on geographic region)

Features that may vary between OEMs of the same sensors include:

- The equipment housing
- The size of the solar cell
- The presence of backup batteries
- The ability to connect to the mains electricity supply

The key difference between EnOcean enabled WSNs offered by different OEMs is the operation of the system, achieved through software or servers. Each manufacturer that sells controllers or receivers also provides or sells a software or server to operate the network, and it is here that the variation lies between the various options. Some manufacturers provide simple solutions that do not utilise the full capabilities of the equipment, whereas others provide access to the full functionality.

## Appendix B: Participants

The monitoring of occupied zones required that occupants living in those zones agreed to participate in the studies. Potential participants had to be identified, contacted, and agreement sought from them; and how these steps were to be approached and achieved had to be decided. Additionally, the involvement of participants necessarily required due consideration of ethics, data protection, health and safety, and selection bias.

### Ethics

The involvement of participants required the ethics of the monitoring plan to be considered, and for it to be structured in a way that ensured the interests and privacy of the participants throughout. Monitoring involved entering occupants' bedrooms and installing monitoring devices in their bedrooms', which is understandably a sensitive area, and it was important that the fair and ethical treatment of the occupants was a priority.

The monitoring studies did not present any major ethical concerns due to the nature of the data collected and the manner in which it was collected. The studies involved participants over the age of 18 who were fully informed of the nature and scope of the studies; no vulnerable groups were involved. The data collected and the methods adopted did not pose any health or safety risks to the occupants, since it collected data about the building and services using equipment that is approved for general sale and already used commercially in other buildings. To some extent the data collected was of a personal nature, the names and addresses of the participants were known and so were their habits in terms of electricity use and to some extent when the rooms were occupied and unoccupied. The participants had to provide consent, and this required knowledge of names and addresses, however no other personal data was collected about participants. While electricity usage data and occupation patterns are personal, the purpose of collecting this data was not to make personal or value judgements about the occupants, and this was made clear to participants.

The managers of the case study buildings were rightly protective of their clients, and were involved in finalising the monitoring plans and arranging the volunteers, to ensure that these stages were implemented in a way that they saw fit and fair to the occupants and the company as a whole. [redacted] dictated how occupants could be contacted and the scope of access to occupied zones, which had an impact on the time required to secure participants and the type of equipment that was suitable (sensors were unsuitable if they had unsufficient battery life or logging capacity to last the duration of the monitoring study, or if they posed a health and safety risk from trailing wires for example).

### Informed Consent

All occupants were provided with information prior and given the opportunity to ask any questions, before they agreed to participate. There were two sets paperwork, one for each case study. The information included details of the researcher and the project, and how the data would be used, the limitations on its use, and how it would be stored and destroyed. It also informed that they could withdraw from the study at any time if they wished, without the need for explanation, and provided details of where any complaints should be made. The occupants involved in the studies signed and dated a consent form to agree to participate.

### Data Protection

Data protection is extremely important, and care was taken to avoid the release of data that could lead to participants being identified. It is not possible to indicate exactly which flats and rooms were included in the studies, because with the right knowledge it is possible for participants to be identified from this. Instead, flats and rooms were allocated new names unrelated to their actual names, to ensure anonymity. Occupants names and room numbers were obtained on the consent forms, they were not input into any electronic device, this information has remained in paper form only, filed securely.

### Selection Bias

Volunteers were informed that the monitoring was part of a wider study into the performance of their accommodation, to determine how well the building performed when it was in use. Overheating was not mentioned prior to volunteer agreement so as not to bias the sample group, because the aim was not to specifically seek out any occupants that felt their rooms were too hot (or too cold). When discussing the project with occupants, the focus was placed on the performance of the building rather than the behaviour of the occupant, so as to minimise the risk that occupants become self-conscious of their behaviour, which could risk altering their behaviour. Occupants were targeted to participate in the studies based on technical criteria (discussed below), and not on any personal attribute. In targeting occupants, the focus was on which locations within the buildings could yield the best results, and not which occupants and their personal characteristics.

### Participant Selection

The buildings in the case studies housed hundreds of occupants, and it was decided best to target specific occupants based on certain criteria, rather than to approach all potential candidates in the search for volunteers. The criteria were technical in nature with a focus on the characteristics of the building rather than the occupants, and are discussed below.

***Criterion 1: Wireless equipment must be placed within range of the controller***

The expected range of EnOcean WSNs is 10m-30m within buildings, which can be increased with repeaters and additional controllers. From the Loughborough pilot study in the range was found to be around 15m without repeaters. The controllers and repeaters were the most costly equipment, and the budget did not allow for their extensive use; instead it was necessary to target occupants that were close to the controller to minimise the size of the network and thus the need for additional equipment.

Within each case study there were limited options for where the controller could be sited as it requires a power supply and ideally an Ethernet connection for remote access. Therefore, the controller locations were chosen first in each study, and the range determined from this. Only the occupants that lived within range of the controller could participate in the studies.

***Criterion 2: Data must include a range of conditions within the building***

The orientation of glazing and the relative position of a zone within a building can affect the thermal conditions of that zone. It was deemed important to try to capture data about the range of conditions within the case study buildings; therefore it was considered important to target diverse locations with the aim of capturing data for a variety of conditions.

***Criterion 3: Volunteers targeted must suit the monitoring method***

The data collected in each case study differed, with electricity data in the Loughborough study, and radiator temperature data in the London study. This influenced how the monitoring studies were designed and conducted, and which occupants were best to target, this is discussed separately below for each study.

***Criterion 4: Volunteers targeted must be attainable***

It was important to select target volunteers that could be attained, to realise that the occupants targeted may not want to participate, and therefore to create a monitoring plan that was flexible.

## Target Participants Loughborough

***Criterion 1: Wireless equipment must be placed within range of the controller***

In the Loughborough study, the only logical placement of the controller was in the staff office in the reception/common area, where it was safe and could be powered and connected to the internet. From this location there were a number of flats in the North building that were within wireless range, whose occupants could be targeted to participate in the study. Parts of the North building and all of the South building were out of range and not suitable.

***Criterion 2: Data must include a range of conditions within the building***

The north building is relatively small and with only three storeys it was deemed unlikely that there would be significant variation in thermal conditions between the ground floor and the second floor, and therefore it was concluded that there was no need to aim to monitor conditions on each floor. It was however considered important to aim to capture data about a range of orientations, as the variation in solar gains due to variations in orientation can have a significant impact on internal temperature, and with it space heating demand and overheating risk. Each flat (excluding studio flats) has rooms that face two or three orientations, and two flats could be selected so that all orientations could be monitored.

***Criterion 3: Volunteers targeted must suit the monitoring method***

Occupants use electricity in their bedrooms, kitchens and corridors, however kitchens and corridors are communal spaces; therefore to monitor these spaces required that all occupants within a flat agreed to participate in the study. It seemed an unsuitable approach to monitor electricity consumption in bedrooms alone, because this would give no indication of the total electricity consumed by occupants. Therefore, it was decided best to target whole flats of occupants to participate in the monitoring study.

***Criterion 4: Volunteers targeted must be attainable***

It was considered achievable to obtain participants from whole flats in the Loughborough study because the flats only contained up to six occupants.

***Conclusion***

The four criteria lead to the conclusion that it was best to target whole flats of occupants to participate in the study. This was considered achievable because flats were relatively small, and advantageous because it would allow data to be collected for all orientations and in communal rooms.

## Securing Participants Loughborough

Three suitable flats in the North building were initially selected and only their occupants were approached to volunteer. If volunteers could not be obtained from these flats, then new target flats would be selected that met the criteria above. With target locations selected, occupants were approached to volunteer. [redacted] requested that occupants be contacted by email, however, despite numerous attempts this approach was unsuccessful. Ultimately, occupants were secured through a combination of letters and knocking on flat doors. In total, twelve participants were secured, from a five bedroom flat, a six bedroom flat, and a studio flat. The flats secured were those initially selected and targeted, no occupants refused to be involved and therefore there was no need to target new flats.

### Target Participants London

#### *Criterion 1: Wireless equipment must be placed within range of the controller*

There were a number of communications rooms where the controller could be fitted; providing security, power and internet connection. Only the building in which the controller was placed would be within wireless range. Since the London study was selected to investigate overheating, it was logical that Block B was included in the study because its size means it is more likely it more likely to overheat than Block A. Due to the size of the building, it was clear that repeaters would be required for this study.

#### *Criterion 2: Data must include a range of conditions within the building*

Block B has 413 occupants and twelve storeys, with up to ten occupants per flat. Due to its size, it was considered likely that there would be different thermal conditions between the top and bottom floors. Based on the size of Block B, and the fact that each flat only faces one orientation, it was decided that studying individual flats would not be the best use of resources. The monitoring study was small and only two whole flats could have been studied, which would not capture the range of conditions within the building. Instead it was considered better to study individual rooms spread throughout the building, to investigate conditions in rooms on different floors and with different orientations.

#### *Criterion 3: Volunteers targeted must suit the monitoring method*

In London no electricity monitoring was to be conducted due to difficulties with approved contractors, access, electrical safety, permission, time and budget, and perhaps most important because monitoring electricity use would not capture any space heating data. This meant that there was no strong driver to obtaining whole flats of participants, and that the resources required to achieve it were not worth the data that would be gained.

#### *Criterion 4: Volunteers targeted must be attainable*

Given the size of flats in the Block B, it was considered unrealistic to attempt to obtain volunteers from whole flats. It was time consuming to obtain flats of five or six volunteers in the Loughborough study, and the effort to obtain whole flats in the London study would likely have been more challenging (especially since occupants were from a range of institutions and may not know each other, making them less likely to agree as a group to participate), and this could have wasted significant time that simply was not available.

#### *Conclusion*

The four criteria lead to the conclusion that it was best to target individual occupants to participate in the study, rather than whole flats. The occupants should be spread throughout the building to capture data from a range of storeys and orientations. It was considered unrealistic to aim to obtain volunteers from a whole flat, and there was little benefit to doing so because it would not include the range of conditions within the building and there was no electricity monitoring in the study so less impact from the inability to study communal rooms.

### Securing Participants London

A number of suitable flats and orientations were selected in Block B, the aim was to secure a total of 20 volunteers, with two to four volunteers on every second floor (e.g. two to four volunteers each on the 1$^{st}$, 3$^{rd}$, 5$^{th}$, 7$^{th}$, 9$^{th}$ and 11$^{th}$ storeys). Volunteers on the same floor would have rooms with different orientations.

After failure to secure volunteers by email and by approaching people in the entrance hall, arrangements were made to approach occupants directly by knocking on doors with the help of a [redacted] employee. Unfortunately upon arriving on site the [redacted] employee refused to help and the manager was not there to insist upon the arrangement. Therefore, doors were knocked on alone with little success, with few occupants answering their doors. This made it difficult to obtain volunteers from the planned locations; instead volunteers had to be obtained where they could be. The majority of people who answered their door agreed to participate in the study. Most volunteers were from the upper floors, which are the most likely to overheat, the remainder were from the lowest modular floors which are least likely to overheat. There were no volunteers from storey 3 to 6, or the ground floor which is not modular. In hindsight, more effort should have been made to secure volunteers from the middle floors, but the last minute changes to plans meant the process of approaching occupants was not ideal.

## Appendix C: Building Monitoring Preparations

Building monitoring was the most challenging data collection method, not only did it require participants; it also required significant planning, testing, and specialist expertise.

### Equipment Selection

The equipment selected had to be suitable, and not all equipment was suitable. There was to be no access to occupied rooms during the study, so monitoring equipment had to be able to operate for the duration of the study without intervention (such as to change batteries or download data) and this ruled out many options. Of vital importance was the safety of the installation, there could be no trailing wires between sensors and loggers within rooms, and electricity meters had to be installed safely, which required specialist expertise.

### Electrical Expertise

Help from a laboratory electrical technician was necessary for the following reasons:

- To provide expertise regarding the feasibility, requirements and implications of the electricity monitoring
- To attend the inspection to ensure that the equipment specified could be installed safely
- To assist in the specification of additional equipment to ensure a safe installation (isolation boxes, cables etc.)
- To create a test rig so that the inline meters could be tested in the laboratory prior to installation on site
- To assist with the formulation of the risk assessment and method statement with regards to the electricity monitoring

Without this support and expertise provided by the technician it would not have been possible to monitor electricity use, because that input was required to ensure safe procedures and requirements were understood and followed.

An electrician was required for any electrical work conducted in the Loughborough case study. The electrician had to be approved by [redacted] and the university; although the laboratory technician was competent to carry out the work, he had no approval to work on the [redacted] site, and no means of obtaining it. The electrician employed was the existing electrician for the [redacted] site, which meant they were already approved by [redacted] and had prior experience of the case study building. The electrician was employed a number of times, for inspections and the installation and removal of equipment for the main and pilot studies. The electrician worked according to the method statement and risk assessment provided.

## Inspection

Inspections were also done with the electrician to understand the layout of electrical services in the Loughborough study, to determine which monitoring equipment was suitable for installation and how it could be installed. Prior to the inspections steps had already been taken to specify equipment, but until the inspections were done it was not possible to know if it was truly suitable.

## Layout of Electrical Services

The design of the electrical services in [redacted] modular buildings is different from traditional buildings, owing to the plug and play design utilised to achieve a fully factory fitted module and rapid installation on site. Each module (or pair of modules in a studio flat) has its own distribution board (DBs), and therefore each module has its own electrical circuitry separate from the other modules and non-modular zones (Figures C.1 to C.4). This setup lends itself very well to electricity sub-metering because it means it is possible to measure electricity by end use individually for each room.


**Figure C.1 (far left): Studio flat distribution board**

**Figure C.2 (centre left): Bedroom distribution board in bedroom riser**

**Figure C.3 (centre right): Kitchen distribution board in kitchen K1E**

**Figure C.4 (far right): Flat main distribution board with electricity meters installed (visible – blue)**

Electricity is routed from the main DB in the plant room to DBs in the service risers in each building, where it branches off to power each flat individually (Figure C.5). Electricity enters each flat at the flat's main distribution board, where it is split further based on the type of flat. Studio flats have only one DB (the main flat DB) which splits the power directly to its end uses. In flats of five or six occupants the electricity is routed from the flat's main DB to the kitchen and bedrooms DBs before being split for the end use in each module. The flat corridors have circuits for lighting and sockets routed directly from the flat DB. A five bed flat has seven DBs and 32 meters would be required to meter all electrical circuits (including module and flat totals).

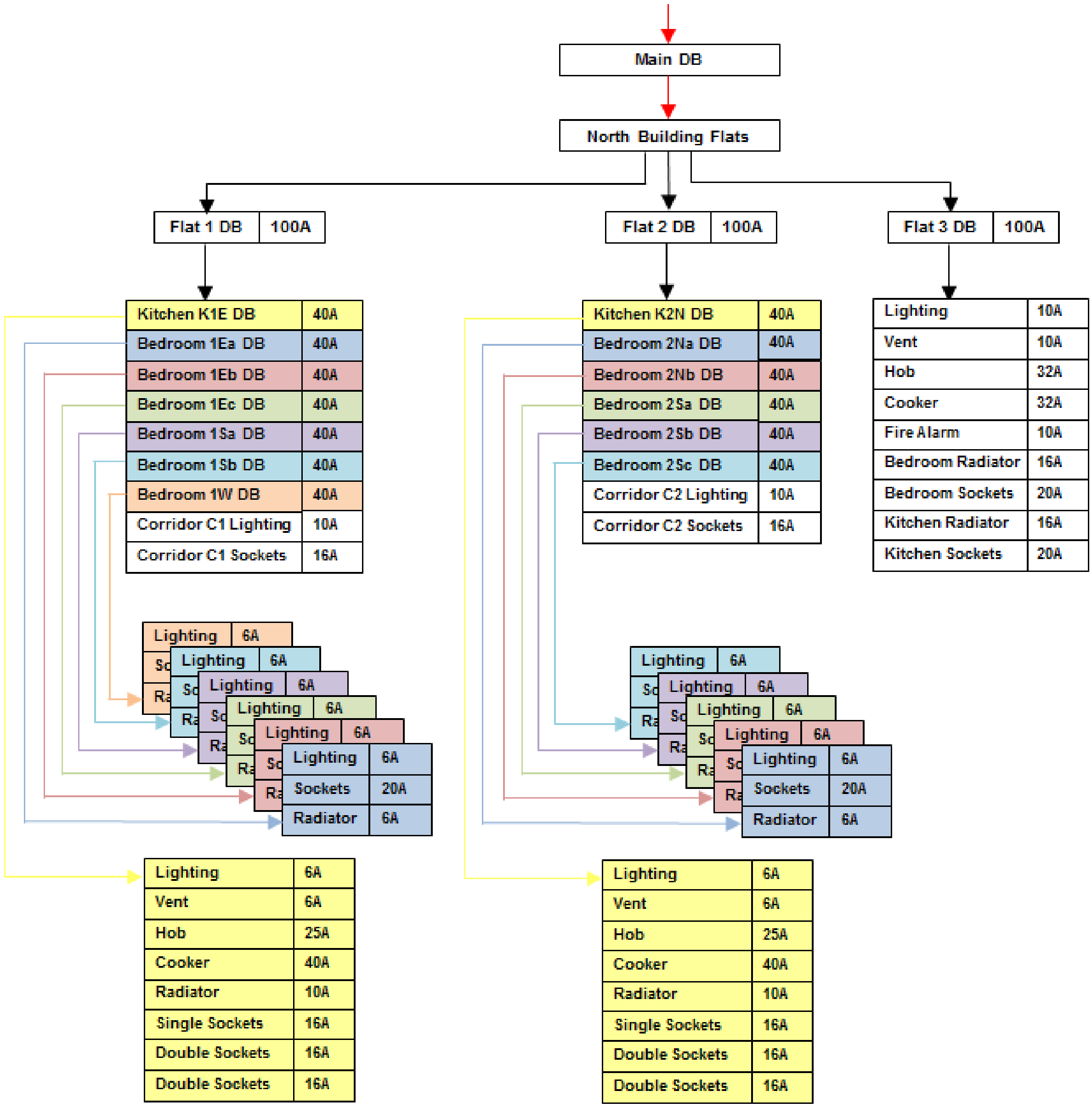



**Figure C.5: Schematic layout of electrical services in the three monitored flats in Loughborough**

## Testing

The monitoring equipment had to be tested to ensure its accuracy and safety. In the case of the EnOcean equipment, testing was also necessary to understand how it worked because the information provided by EnOcean and the various OEMs was crude at best. Testing helped to decipher the wireless telegrams sent by sensors, and to understand the bi-stable nature of their operation.

The technician created a test rig so that the electricity meters could be tested in the laboratory. A range of household appliances were used to test the meters, including a desk lamp, a fan, a hairdryer, a laptop, and a mobile phone, which provided the added benefit of allowing the load profiles of domestic appliances to be observed.

During testing, three meters were found to be faulty, while they were physically safe to install, they did not transmit wireless data correctly, and only sent data sporadically. The faulty meters were removed and not used in the study. The remaining meters functioned correctly at the time of testing and were found to operate within their stated accuracy.

The energy harvesting EnOcean sensors (temperature and humidity sensors and window contacts) were tested in various ways. They were installed in a domestic property (non-modular) to test their operation over a period of weeks. Their charge was also tested by fully charging sensors and then placing them in a box to determine how long they would operate. Sensors remained charged for over one week, but the test could not be completed due to a problem with the Eltako controller.

Initially an Eltako controller was specified, and understanding its operation was difficult due to poorly translated documentation, therefore the testing allowed for its operation to be better understood. The pilot study found the Eltako controller was unsuitable (discussed below), leading to the specification of the Can2Go controller. The documentation for the Can2Go controller was really poor and the supplier was unwilling to provide much support without additional costs. Much time was needed testing the controller simply to understand its most basic functions.

The MadgeTech temperature sensors were tested firstly in a liquid calibration bath to ensure their accuracy, they were found to operate well within their stated accuracy. It was not possible to test the EnOcean sensors in the ice bath because the test equipment shielded the wireless telegrams. Therefore, the accuracy of the EnOcean temperature data was tested by comparing them with the MadgeTech sensors. EnOcean temperature sensors data was found to compare well with the MadgeTech data, therefore the EnOcean sensors were assumed to be operating within their stated accuracy.

Once accuracy was ensured, the MadgeTech sensors were tested by fitting them to radiators in a domestic property (non-modular). Testing determined that the fixing method was the main difficulty as many adhesives lost their bonding strength at high temperatures, so after hours or days the sensors would become unstuck. A further issue was that many adhesive tapes (preferred over adhesives due to speed of installation) contained foam that would act as an insulant. A thermally conductive double sided adhesive tape was sourced that would typically be used on a computer heat sink, which was designed to operate at high temperatures. Testing found this new adhesive tape performed well, and the bond improved after being heated. Testing found it was better to place the sensor at the bottom of the radiator because it heated up more quickly than the top of the radiators: sensors responded rapidly to the initiation to space heating, beginning to heat up in a matter of minutes.

***Monitoring Plan***

The most complex aspect of the monitoring was the electricity monitoring due to the safety issues involved and the need to employ an electrician. By comparison, planning the installation of the window contact sensors and temperature and humidity sensors was straightforward.

There was little option about where to fix window contact sensors, which had to be fixed to the bottom of window frames where they opened. In this position sensors should receive sufficient light energy to remain charged. Window frames were powder coated aluminium, and the sensors would be fixed to them without causing damage.

Optimal siting of the temperature and humidity sensors was less straightforward, because they needed to be kept away from heat sources but at the same time receive sufficient light energy to maintain their charge, so they need to receive solar energy but not direct solar gain. The optimal location was tested during the pilot study and the decision was made to fix sensors to the cupboard in each bedroom. There were fewer difficulties in the kitchens and corridors where the rooms were larger and easier to find a location to site the sensors that avoided solar gains and internal gains but still had sufficient light levels. In all rooms the sensors were to be fixed to cupboards or doors, because the sensors could be removed from these surfaces without causing damage.

The electricity meters had to be safely fitted and enclosed to avoid risk of injury or damage. Meters are DIN rail mountable, and would require available DIN rail space within the DBs to be correctly and safely fitted. Only the main distribution boards in the flats had available space on the DIN rails, whereas the kitchen and bedroom DBs had no free space. This meant that a limited number of meters could be fitted within the main flat DBs but that none could be fitted within the kitchen or bedroom DBs. The space within the main flat DBs was not sufficient to monitor all rooms in a flat, and therefore the monitoring plan (which was to monitor electricity use in each module in a flat) could not be fulfilled through this means alone. Therefore, isolation boxes were purchased for use with some bedroom DBs, which allowed all rooms in a flat to be monitored (Figure C.6). The isolation boxes could contain numerous meters, which were fitted to DIN rails within the boxes (Figure C.7), and the electricity circuits to be monitored would be routed through the meters in the box (Figure C.8). The bedroom DBs are all located within riser cupboards in each module, which are locked and inaccessible to occupants, which meant occupants could not come into contact with the isolation boxes which increases safety. The main flat and kitchen DBs were not hidden behind a locked door and were accessible to occupants, therefore any isolation boxes would also be accessible which meant there was a chance the boxes could be touched, tampered with or damaged, and although their design made damage or injury highly unlikely, this posed too much of a safety concern to consider. The budget only allowed for the purchase of four isolation boxes, which was sufficient to allow for all modules to be monitored (in varying degrees of detail). The boxes were specified and fitted out by a university electrical technician, as the work had to be done by a competent person.


**Figure C.6 (left): Isolation box used to sub-meter bedrooms in Loughborough**
**Figure C.7 (centre): Isolation box used in Loughborough study – opened to reveal meters and wiring**
**Figure C.8 (right): Isolation box installed in bedroom riser in Loughborough study**

Other aspects of planning involved:

- Arranging installation and removal dates with [redacted] management, participants and the electrician
- Gaining approval of the method statements and risk assessments from the university and [redacted]
- Arranging network access for the controllers so they could be accessed remotely via the internet

## Pilot Study

A pilot study was conducted in the north building of the Loughborough case study from June to August 2012. It was used to test the performance of the EnOcean equipment on a small scale to ensure its suitability prior to the purchase of equipment for the full scale studies.

Sensors were installed to monitor one bedroom, and the receiving equipment was installed in the staff office (Table C.1 and Figures C.9 to C.13). The participant was secured with the help of the site manager and they were provided with the same information as the participants of the main study. The equipment was installed while the room was still occupied and it remained in the room during summer after the occupant had moved out.

This allowed the pilot study to capture data while the building was in use and also for testing to be conducted while the building was vacant.

**Table C.1: Monitoring equipment used in the pilot study**

| Equipment type | Model used |
|---|---|
| Receiver/controller | 1 Eltako FAM-USB receiver |
| Computer | 1 Zotac box mini PC running Eltako FVS-Home software |
| Temperature sensor | 1 Eltako FTF55 (0°C – 40°C) |
| Window contact sensor | 1 Eltako FTK-an |
| Electricity meters | 2 Eltako FWZ12 16A and 1 Eltako FWZ12 65A |
| Isolation box | Isolation box, DIN rail, wiring etc. for safe installation |

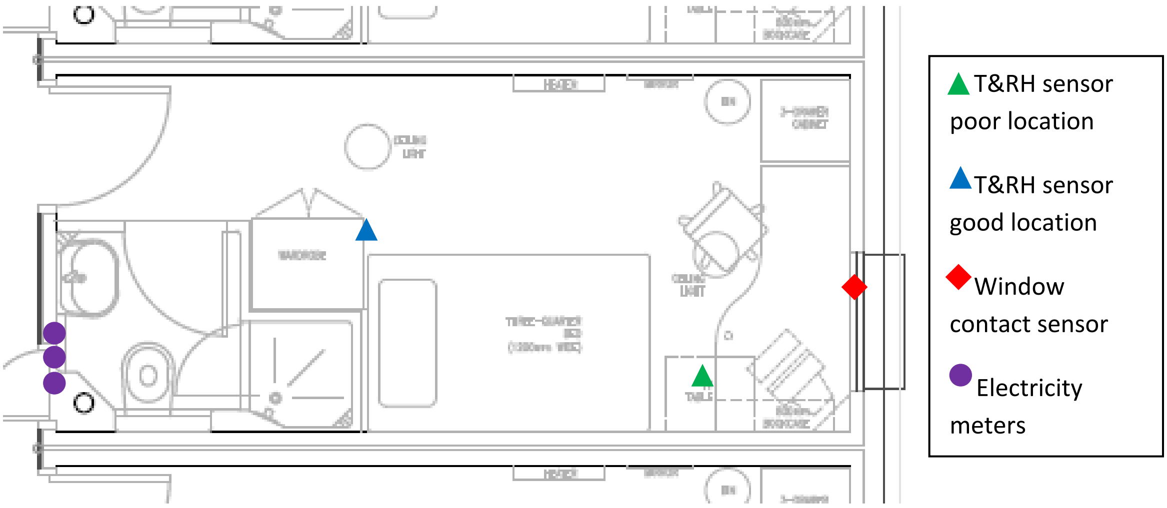
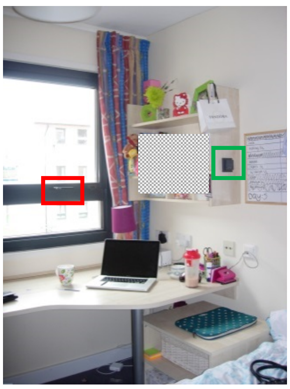



**Figure C.9: Floor plan marked to indicate location of sensors in pilot study [[redacted] 2012]**



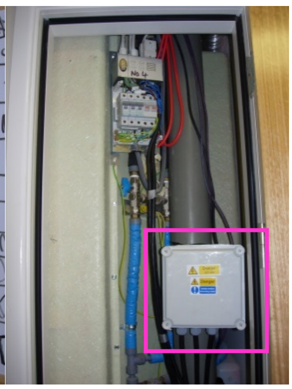



**Figure C.10 (far left): Temperature sensor and window contact installed for pilot study**

**Figure C.11: (centre left): Window contact sensor fitted installed for pilot study**

**Figure C.12: (centre right): Temperature sensor installed for pilot study**

**Figure C.13: (far right): Isolation box for sub-metered electricity use in one bedroom for pilot study**

The pilot study highlighted a number of issues. There were problems with the Eltako receiver, with both the software and the hardware, that lead to it being deemed unsuitable;

this meant a better and more advanced controller/receiver to be sourced. The sensors seemed to perform well and the main problem appeared to be with the receiver. There was a problem with the initial placement of the temperature sensor (either signal shielding, insufficient light energy, or both) which meant it collected little data during the initial part of the pilot study (while it was occupied). Once the room was vacant, the temperature sensor was moved to a new location (Figure C.9 above), after which it performed well.

The poor range that was experienced in the main Loughborough and London studies show that the pilot study was unsuccessful at highlighting this. The problems with the Eltako receiver overshadowed and masked many of the other problems with the equipment, and while the receiver problem was identified and resolved, others were not. A second failing of the pilot study was in the room selected for monitoring; in hindsight it was too close to the controller and lead to overconfidence with the performance of the equipment. It would have been better to monitor a room further from the controller to better test the range of the equipment, or at least determine the maximum range of the equipment while the building was empty, bus since there were no apparent problems it did not seem necessary.

There were significant delays obtaining the new equipment (the Can2Go controller), and further delays deciphering its use and writing code to log data. Therefore, there was no time to run another pilot study, and at this stage no belief that it was necessary. No pilot study was conducted in the London study, due to time delays, difficulties with access to the rooms, and because it was not thought necessary because both buildings were modular. In hindsight it would have been better if further pilot studies had been conducted.

***Equipment Installation Preparations***

The equipment was prepared in advance to minimise time on site and time in participants' bedrooms. All equipment was labelled, with an identification number and with a message indicating ownership. The EnOcean sensors were charged in bright light for one week before use, and had double sided adhesive tape stuck to their backs. The controller was setup with sensor IDs and code to log data from them. Permission was arranged for the controller to have internet access through the Local Area Network in the building, and the controller was setup with the relevant network addresses to allow connection for remote access. The MadgeTech temperature sensors were set to launch at midnight on the day of installation, and double sided heat conducting adhesive tape was fixed to the backs in preparation.

## Appendix D: Can2Go Lua Scripts

Sensor IDs were written in decimal form into the controller as AVs (analogue variables). Data from temperature and humidity sensors and electricity meters were written to AVs, and data from contact sensors were written to BVs (binary variables). The Lua scripts looped constantly during operation, loop duration varied, but was typically around six seconds. The scripts are essentially checking if each newly received telegram matches any of the saved sensor IDs, and if it does then the data payload within the telegram is decoded and written to the correct location where it can be logged.

### *Lua Script for two EnOcean temperature and relative humidity sensors*

```
if sensor_init == nil then -- *** Variables and Functions ***
    sensor_init = true -- This section is only executed once
  -- Map sensors to BACnet points:

    --Sensor 1
    sensor1_eid = ME.AV101_Present_Value -- EnOcean ID
    sensor1_prh = ME.AV1_Present_Value -- Relative Humidity
    sensor1_deg = ME.AV2_Present_Value -- Temperature Reading

    --Sensor 2
    sensor2_eid = ME.AV102_Present_Value -- EnOcean ID
    sensor2_prh = ME.AV3_Present_Value -- Relative Humidity
    sensor2_deg = ME.AV4_Present_Value -- Temperature Reading

            -- This routine prints with a date/time prefix:
    function display(...) print(os.date(), ...) end

else -- *** Program Execution ***
    -- Sensor1
    -- Packet processing: read and analyze telegrams.
    eo_packet = vm.eo_read(sensor1_eid.value) -- Read just this device.
    -- Check if a valid packet was received:
    if eo_packet ~= nil then
        -- Check if packet ID matches kept ID:
        if eo_packet.enocean_id == sensor1_eid.value then
            sensor1_deg.value = eo_packet.bytes[7] * 40 / 250
            sensor1_prh.value = eo_packet.bytes[8] * 100 / 250
        end
     end
    -- Sensor2
    -- Packet processing: read and analyze telegrams.
    eo_packet = vm.eo_read(sensor2_eid.value) -- Read just this device.
    -- Check if a valid packet was received:
    if eo_packet ~= nil then
        -- Check if packet ID matches kept ID:
        if eo_packet.enocean_id == sensor2_eid.value then
            sensor2_deg.value = eo_packet.bytes[7] * 40 / 250
            sensor2_prh.value = eo_packet.bytes[8] * 100 / 250
        end
     end
 end --***End of Script **
```

***Lua Script for two EnOcean enabled window contact sensors***

```
if contact_init == nil then -- *** Variables and Functions ***
    contact_init = true -- This section is only executed once
    -- Map contacts to BACnet points:

    --Contact 1
    contact1_eid = ME.AV121_Present_Value -- EnOcean ID
    contact1_st = ME.BV1_Present_Value -- Contact State

    --Contact 2
    contact2_eid = ME.AV122_Present_Value -- EnOcean ID
    contact2_st = ME.BV2_Present_Value -- Contact State

            -- This routine prints with a date/time prefix:
    function display(...) print(os.date(), ...) end

else -- *** Program Execution ***
    -- Contact1
    -- Packet processing: read and analyze telegrams.
    eo_packet = vm.eo_read(contact1_eid.value) -- Read just this device.
    -- Check if a valid packet was received:
    if eo_packet ~= nil then
        -- Check if packet ID matches kept ID:
        if eo_packet.enocean_id == contact1_eid.value then
            contact1_st.value = eo_packet.bytes[9] - 8
        end
     end

    -- Contact2
    -- Packet processing: read and analyze telegrams.
    eo_packet = vm.eo_read(contact2_eid.value) -- Read just this device.
    -- Check if a valid packet was received:
    if eo_packet ~= nil then
        -- Check if packet ID matches kept ID:
        if eo_packet.enocean_id == contact2_eid.value then
            contact2_st.value = eo_packet.bytes[9] - 8
        end
     end
end -- *** End of Script ***
```

### *Lua Script for two EnOcean enabled Eltako FWZ12 electricity meters*

```
if meter_init == nil then -- *** Variables and Functions ***
meter_init = true -- This section is only executed once
   -- Map meter to BACnet points:

meter1_eid = ME.AV151_Present_Value -- EnOcean ID (received by teach-in)
meter1_inst = ME.AV35_Present_Value --Instantaneous Power Consumption (W)
meter1_tot = ME.AV36_Present_Value  --Total Power Consumption (kWh)

meter2_eid = ME.AV152_Present_Value -- EnOcean ID (received by teach-in)
meter2_inst = ME.AV37_Present_Value --Instantaneous Power Consumption (W)
meter2_tot = ME.AV38_Present_Value  --Total Power Consumption (kWh)

-- This routine prints with a date/time prefix:
  function display(...) print(os.date(), ...) end

else -- *** Program Execution ***
-- Meter1
   -- Packet processing: read and analyze telegrams.
   eo_packet51 = vm.eo_read(meter1_eid.value) -- Read just this device.

   -- Check if a valid packet was received:
   if eo_packet51 ~= nil then
      -- Check if packet ID matches kept ID:
     if eo_packet51.enocean_id == meter1_eid.value then
     if eo_packet51.bytes[6] == 12 then -- If DB6 = 12(in decimal) then data telegram gives instantaneous power
consumption (W)
        meter1_inst.value = eo_packet51.bytes[7]*16^0 + eo_packet51.bytes[8]*16^2 +
eo_packet51.bytes[9]*16^4 -- See content of Eltako Telegrams: DB9 is MSB, DB7 is LSB
      elseif eo_packet51.bytes[6] == 9 then -- If DB6 = 9(in decimal) then data telegram gives total power
consumption (W)
        meter1_tot.value = (eo_packet51.bytes[7]*16^0 + eo_packet51.bytes[8]*16^2 +
eo_packet51.bytes[9]*16^4)/10 --See content of Eltako Telegrams DB9 is MSB, DB7 is LSB
      end
     end
   end

-- Meter2
   -- Packet processing: read and analyze telegrams.
   eo_packet52 = vm.eo_read(meter2_eid.value) -- Read just this device.

   -- Check if a valid packet was received:
   if eo_packet51 ~= nil then
      -- Check if packet ID matches kept ID:
     if eo_packet52.enocean_id == meter2_eid.value then
     if eo_packet52.bytes[6] == 12 then
        meter2_inst.value = eo_packet52.bytes[7]*16^0 + eo_packet52.bytes[8]*16^2 +
eo_packet52.bytes[9]*16^4
      elseif eo_packet52.bytes[6] == 9 then
        meter2_tot.value = (eo_packet52.bytes[7]*16^0 + eo_packet52.bytes[8]*16^2 +
eo_packet52.bytes[9]*16^4)/10
      end
     end
   end
end --***End of Script **
```

## Appendix E: Monitoring Equipment Performance and its Impact on Analysis

There were problems with the EnOcean enabled equipment during the pilot and main studies, which impacted on the quality of data collected. There were no problems with the MadgeTech sensors fixed to radiators in the London study.

### Pilot Study

The problems experienced in the pilot study were discussed already (Appendix C). Essentially, the pilot study only identified the problem with the Eltako controller and helped determine some places not to site temperature-humidity sensors (but not where best to place them). It did not highlight any of the other problems experienced in the main studies, which meant time had to be spent identifying and trying to resolve them during the main studies, impacting on data quality. There would still haven been problems in the main study, but some could have been avoided with had better pilot studies been conducted. At the time of the pilot study there was overconfidence with the performance of the equipment.

### Loughborough

#### *Temperature and Humidity Sensors*

Upon installation the wireless range was particularly poor, and there were significant problems receiving data from twelve of the seventeen temperature-humidity sensors (Figure E.1). Data was only received for the five sensors closest to the controller, and there were even small gaps for some of these rooms. The electricity meters did not suffer the same loss of data because they were closer to the controller and transmitted wireless telegrams at a higher power because they were powered by the mains supply. Three repeaters were installed on 22nd March to boost the range, and this initially resolved the problem.

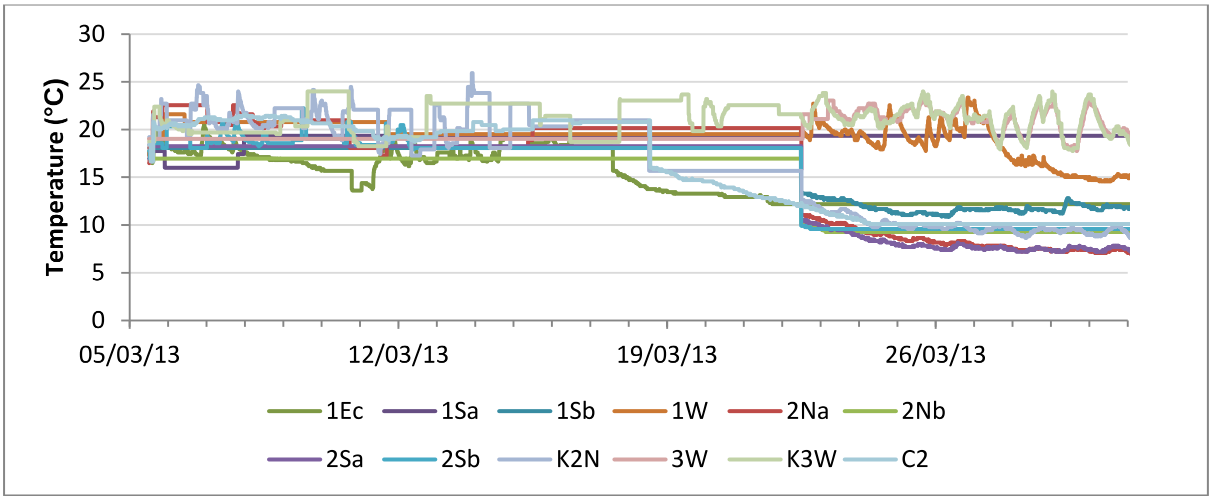



**Figure E.1: Poor network range lead to loss of temperature data at start of the Loughborough study**

Around mid-May further reception problems arose with some temperature-humidity sensors, particularly in Flat 2. A visit to the site found the repeater was damaged, it was replaced and data reception improved again. Problems arose again at the start of June but the cause could not be identified, and temperature-humidity data was lost for the whole of June for all rooms in Flat 2 except 2Sc (Figure E.2). There were also some problems with the reception of temperature and humidity data in rooms 1Sb and 3W in June. Data reception improved for some rooms when the occupants moved out, suggesting that interference from electrical equipment belonging to one or more occupant could have caused some of the data loss.

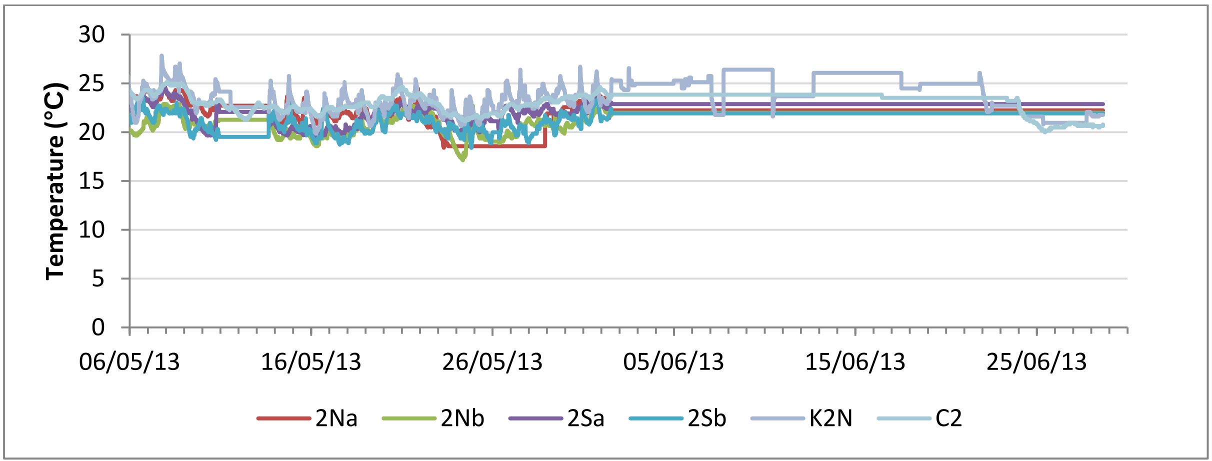



**Figure E.2: Temperature data lost for all rooms in Flat 2 during most of June except room 2Sc**

During the vacation between terms some temperature-humidity sensors appeared to become depleted (Figure E.3). Not all sensors were affected, suggesting that curtains may have been closed in the rooms with depleted sensors. When occupants returned after the vacation, sensors quickly began to operate again.

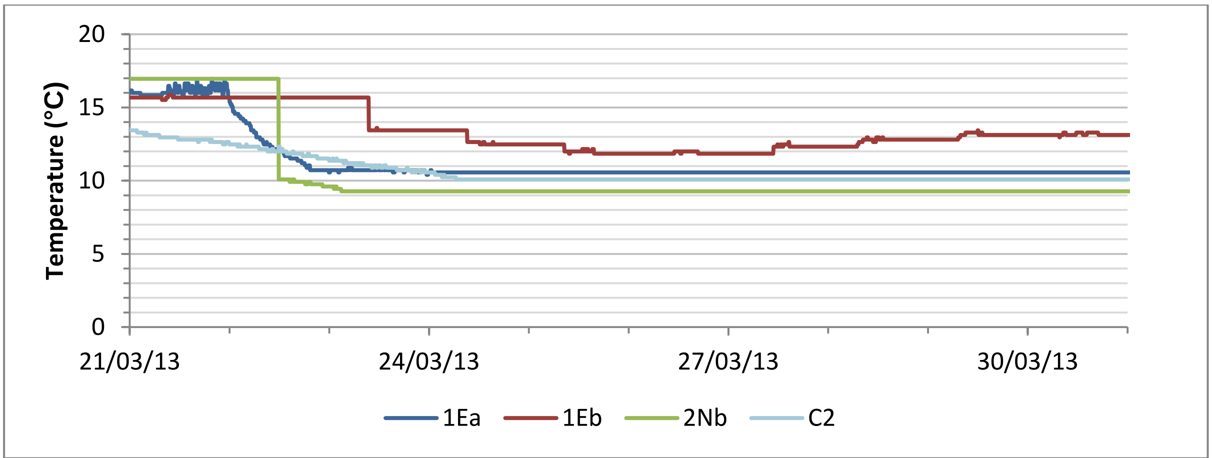



**Figure E.3: The power source of many energy harvesting sensors became depleted during the vacation**

The loss of internal temperature data for many rooms at different points in the study was unfortunate because the intention had been to use temperature data for various analyses, which were no longer possible. It was during the first fortnight of the study that the majority of space heating was used; the loss of temperature data at this time meant it was not possible to analyse the relationship between space heating use and internal temperature for most rooms. The loss of temperature data in June for many rooms impacted the overheating analysis, because overheating was most likely to occur in June. The loss of data during the vacation meant it was difficult to analyse how temperature fell within the building when it was vacant during the heating season, or to determine how cold the rooms would get in the absence of (most) internal gains.

***Electricity Meters***

There were also some problems with the reception of electricity data from three meters: 1Ec Sockets, 1Ec Lighting and 2Sa DB Total (Figure E.4). The problems were intermittent in nature and would typically last for one to two days at a time. The gaps in the data occurred at the same time for the lighting and sockets in room 1Ec, but at different times for the 2Sa meter. The patterns suggest that there was intermittent shielding or interference blocking the transmission of data from the meters in room 1Ec, but the cause was never identified or resolved. The cause of the data loss for room 2Sa meter is not clear, because none of the other meters in the main DB of Flat 2 were affected, which would be expected in the case of signal shielding.

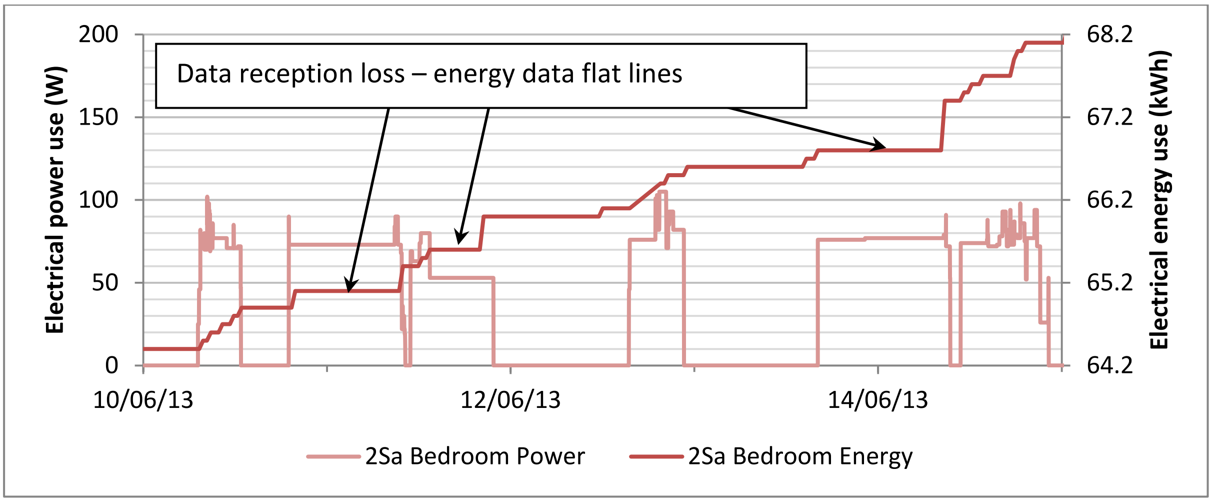



**Figure E.4: Data loss from the room 2Sa meter tended to last for one to two days at a time**

Four of the electricity meters installed also developed faults; two were faulty from the start of the study, and two developed faults within the first month. This was the same fault found in other meters during testing, although these four meters had functioned correctly during testing. The fault affected the frequency of data transmissions, sending telegrams only once every one to three days (Figure E.5).

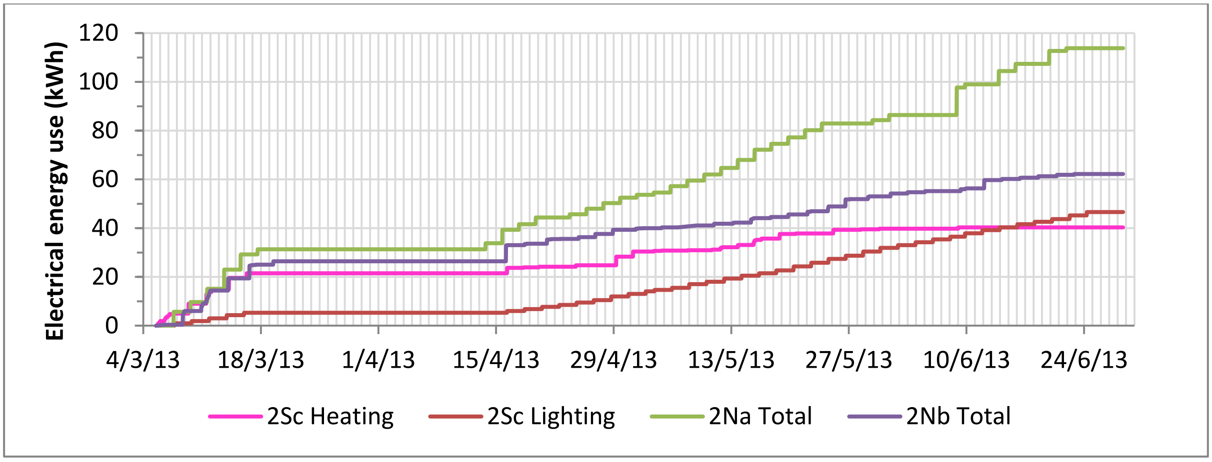



**Figure E.5: Graph showing all energy consumption data received for the faulty meters during the study**

The meter data lost due to data reception problems did not have a significant impact because it occurred infrequently and the meter still counted total energy use, so it was known how much energy was used while there were signal reception problems. The loss of data from the four faulty meters had a larger impact, because there was no useable instantaneous power data from these meters, only intermittent meter readings. The meter readings were still useful for the simplest analyses, but did not provide the same level of detail as the correctly functioning meters.

***Window Contact Sensors***

The window contact sensor experienced reception problems similar to the temperature-humidity sensors and all contact data was removed from the study. It was removed because the code was not sophisticated enough to identify when there were reception problems and when there were not. If the code had been better some window data would have been useable, however if the WSN range had been good then there would not be the need for better code and the window data could have been used.

Losing window opening data meant it was not possible to analyse the relationship between internal temperature, electricity use (including heating) and window opening, and made calibration of a building model very uncertain because the impact of window opening on ventilation rate is significant and needs to be accurately quantified for calibration of models

## London

There were major problems with the range of the EnOcean enabled WSN in the London study; it was very low resulting in the loss of nearly all wireless data. Multiple attempts were made to resolve the problem by installing additional repeaters and controllers, and altering their locations, but to no avail. The network only achieved a range of approximately two to four metres, far less than the ten metres expected in the worst case scenario. However, not all data was received even within a four meter range, and most were unreliable due to intermittent reception. The only reliable data came from the temperature-humidity sensor in room 10Wa, less than two metres from the controller and separated by one wall. Despite the close proximity data was not initially received from this sensor, and only became useable from 21st March 2013 after repeaters and controllers were moved. Room 10Wa was the only room with wireless temperature data, but also the only room with a missing radiator temperature sensor.

The range achieved was well below the expected worse case performance. All of the controllers and repeaters had to be placed within secure communications rooms and service risers for security. Placing the equipment in such small rooms may have been part of the problem; but it is believed that this could not have been the only issue and that there must also have been signal shielding or interference. The structure of the stair core and the foil backed plasterboard in the modules could have shielded the data telegrams. Perhaps performance would have been better if controllers and repeaters could have been placed within bedrooms or flats instead of in the stair core; however access to the bedrooms during the study was not possible and this would need to have been planned prior to installation.

The loss of data from the EnOcean sensors limited the analyses that could be done. It was not possible to analyse the relationship between internal temperature, window opening and space heating use, and the overheating analysis was not ideal because it had to use the radiator temperature sensors to measure room temperature.

### Summary of Problems

In summary, the problem is that the equipment simply did not perform as it should have, often failing to achieve the worst case performance in terms of wireless range. It is difficult to ascertain why the performance was so poor; it could be due to the construction type causing shielding. Diagnostic tools are available but every manufacturer and supplier contacted (at least five) advised against their purchase despite raising specific concerns about shielding in steel framed buildings. The simplest diagnostic tool is a relatively cheap (≈£100), handheld device that can ping a telegram to the controller to optimise sensor placement and identify problems with signal shielding and interference (which are invisible). It is strongly believed this tool would have been a significant benefit in the monitoring studies. It would have allowed problems to be identified before the equipment was installed, which would have highlighted the need for extra repeaters, and would likely have changed the whole monitoring plan in London or resulted in selection of a different case study building. It can only be assumed that the manufacturers and suppliers genuinely believed that the tool was not needed, because it was not prohibitively expensive.

## Appendix F: Structural Integrity

The [redacted] modules and corridor cassettes form the structure of a building; they could be used alone to construct fully modular buildings, or in conjunction with other construction methods. Some [redacted] buildings were fully modular, but many used structural steel; typically on the ground floor for large open plan spaces that could not be created with the modules. Structural steel was often used for stair cores and shear walls for structural purposes.

The modules and corridor components were installed on site and bolted together and to adjacent components: foundations, structural steel, and the roof (Figures F.1 and F.2).

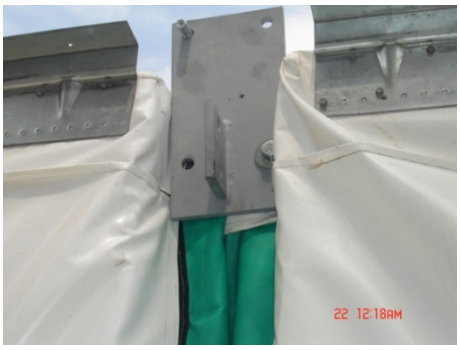



**Figure F.1 (left): Two adjacent modules fitted to the foundations [[redacted] 2012]**

**Figure F.2 (right): Two modules connected with corridor floor panel supports fitted to each [[redacted] 2012]**

Module walls carry the gravity load, to achieve this modules usually had to be stacked on top of each other so the walls of the upper module sat directly on top of the walls of the module below, (Figure F.3). The module floor and ceiling panels, corridor cassettes, external cladding and roof either hang from or sit on top of the modules, and transfer gravity loads through the modules walls (Figure F.4). In buildings below eight storeys, lateral loads are resisted by the racking strength of the plasterboard modular walls. In buildings eight storeys and above, additional steel was required in the modules and as structural steel in stair cores and shear walls to resist the increased lateral loads. The tallest [redacted] buildings possible were 12 storeys, featuring 11 storeys of modular construction and a ground floor of structural steel.

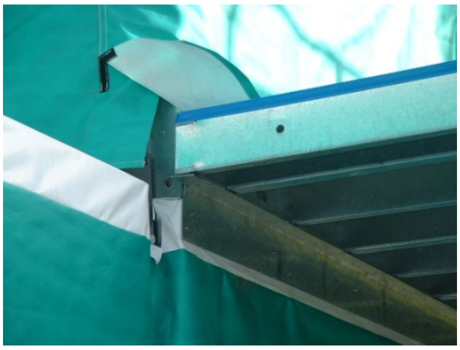


**Figure F.3 (left): Module installation on site, showing modules stacked on top of each other [[redacted] 2012]**

**Figure F.4 (right): Corridor floor cassette fitted to and supported by adjacent module [[redacted] 2012]**

## Appendix G: Material Thermal Properties

The assumed thermal properties of the materials used for the U-Value calculations are given in Table G.1

**Table G.1: Assumed material thermal properties used in [redacted] modules**

| Description | Use | Layer Thickness, x (mm) | Thermal Conductivity, k (W/m·K) | Thermal Resistance, R ($m^2K/W$) |
|---|---|---|---|---|
| Steel | Walls, Ceilings, Floors | 75 and 150 | 16 | |
| Rockwool RW3 steel stud insulation | Walls, Ceilings | 60 | 0.036 | 1.65 |
| Rockwool Rockfloor Rigid insulation | Floors | 30 | 0.038 | 0.750 |
| Lafarge Megadeco plasterboard | Walls, Ceilings | 15 | 0.25 | 0.060 |
| Verspanel CPB | Walls | 10 | 0.26 | 0.038 |
| Celotex tuff-R CW3000 rigid insulation | Walls | 35 | 0.067 | 1.5 |
| Krono OSB | Ceilings | 15 | 0.13 | |
| Norbord Sterling OSB3 (Tongue & Groove Chipboard) | Floors | 18 | 0.143 | 0.126 |
| Knauf glass fibre cavity insulation | Floors | 150 | | 4.650 |
| Brick Facade | Walls | 102 | 0.752 | 0.136 |

# Appendix H: Module Fabrication

## Steel Frame Fabrication

Each module was created from four wall panels, one ceiling panel and one floor panel; the first step in creating a module was to construct the panels. The light gauge steel was purchased in flat rolls (Figure H.1) and cold-formed in the factory into C-sections of various sizes (Figure H.2) before being riveted together into frames for the panels (Figure H.3).


**Figure H.1 (left): Rolls of light gauge galvanised steel ready for cold-forming in the factory**
**Figure H.2 (centre): Cold-formed steel C-section exiting forming machine**
**Figure H.3 (right): Steel C-sections riveted together to form a frame, photo shows wall panel frame**

## Wall Panel Fabrication

The steel frames for the walls had two layers of board fixed to one side, to form the internal surface. The first layer was nailed into place and the joints between the boards taped and sealed, (Figure H.4). The second layer was then glued or nailed to the first layer, and the joints were covered in plasterboard scrim tape. Panels with doors or windows would have voids in the boarding for their later installation. The panels then proceeded to the paint line

**Figure H.4: Wall panel with first layer of board fitted, prior to taping the board joints**

## Ceiling Panel Fabrication

Two layers of board were attached to ceiling frames in the same way as wall frames (Figure H.5). Additional steps were taken with ceiling panels at this stage.

- Holes were cut to allow mechanical and electrical services through the ceiling, and wires were fitted for electrical lighting (Figure H.6).
- Fire insulation was then placed between the steel joists (Figure H.7).

The panels then proceeded to the paint line.



**Figure H.5 (left): Ceiling panels with first layer of board fitted, taped and sealed**

**Figure H.6 (centre): Ceiling panel with holes cut for services**

**Figure H.7 (right): Ceiling panel with fire insulation between joists, hanging ready to enter the paint line**

## Paint Line

The wall and ceiling panels were hung vertically on an automated track, (Figure H.8). The joints between boards on the panels were covered with plaster to create a smooth surface, (Figure H.9). The panels were given two layers of paint; the first applied and dried by machine, and the second applied by hand.


**Figure H.8 (left): Wall and ceiling panels hanging at the end of the paint line, already painted**

**Figure H.9 (right): Wall panel showing both layers of boarding, with top layer joints covered with plaster**

## Floor Panel Fabrication

The steel frames for the floor panels had rigid insulation nailed to the underside (Figure H.10). If a wet heating system was to be used, pipework was also fitted within the floor panel at this stage (Figure H.10). The floor panels were then flipped and a layer of tongue and groove chipboard was fitted to the upper side, (Figure H.11). Holes were then cut in the chipboard for the soil and vent pipes.

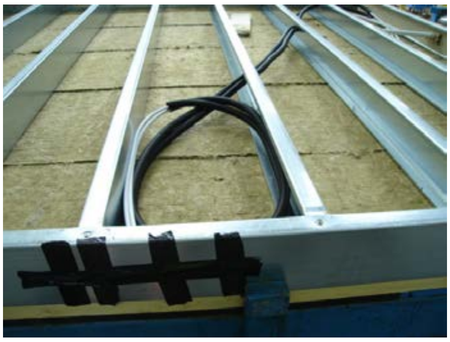



**Figure H.10 (left): Floor panel with rigid insulation fitted to underside, and space heating pipework fitted**
**Figure H.11 (right): Floor panel with floor boards fitted on top, and rigid insulation fitted on bottom**

## Shower Pod Installation

The shower pod was then lifted onto the floor panel and fixed in place (Figures H.12 to H.14).



**Figure H.12 (left): Shower pod ready to be lifted onto floor panel**
**Figure H.13 (centre): Shower pod fitted to floor panel**
**Figure H.14 (right): Shower pod fitted to floor panel, showing M&E services to back of pod**

## Volumetric Construction

Four wall panels were fitted to the floor panel with self-tapping screws (Figures H.15 and H.16). Wall panels were bolted together at their junction using cold-formed corner sections (Figure H.17), and the ceiling panel was fitted on top of the walls using self tapping screws. The non-volumetric panels had now been joined to form a volumetric unit, or module.



**Figure H.15 (left): Wall panel being lifted to be fitted to the floor panel**
**Figure H.16 (centre): Floor panel with shower pod and two wall panels already fitted**
**Figure H.17 (right): Wall panels joined together at junction with cold-formed steel corner section**

## Fitting Out

The next stage was to fit out the module. The mechanical and electrical services were fitted, including radiators, plumbing, lights, sockets, data cables, and ventilation ducting. The wires, pipes and ducts were routed to the service riser located behind the shower pod (Figures H.18 to H.20), the module would be connected to the main building services on site at the riser. Once installed the services would be tested.



**Figure H.18 (left): Bottom of service riser showing shower pod plumbing connected to soil and vent pipe**
**Figure H.19 (centre): Electrical cables & heating pipework passing through wall panel to service riser**
**Figure H.20 (right): Top of service riser showing module electricity cabling connecting to junction box**

The module was then fitted with flooring and furniture (Figures H.21 to H.23).

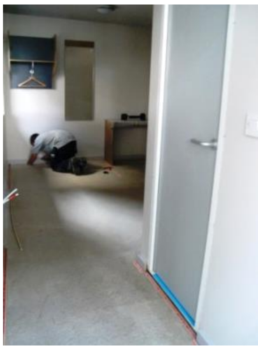


**Figure H.21 (left): Factory worker fitting module flooring in factory**
**Figure H.22 (centre): Factory photo showing bed and mattress fitted into module**
**Figure H.23 (right): Factory photo shows furniture, lighting and curtains fitted, but no window [[redacted] 2012]**

## Finish / Cover / Lift

After the internal fit out, the module was finished externally by fitting: fire insulation between wall studs (Figure H.24), windows and doors (Figure H.25), external racking boards for the medium-rise design (Figure H.25), waterproof breather membrane (Figure H.26)

Module fabrication was now complete and modules were ready to be loaded onto lorries to be transported to site.



**Figure H.24 (left): Factory photo showing fire insulation fitted between wall studs [[redacted] 2012]**

**Figure H.25 (centre): Factory photo showing windows and racking boards fitted**

**Figure H.26 (right): Factory photo showing waterproof breather membrane fitted**

## Corridor Fabrication

Corridor panels and cassettes were manufactured in the same way as the module panels. However, less work was required for corridor components as the majority of boards and insulation were fitted on site. The corridor components were completed in their own production area in the factory.

## Appendix I: [redacted] Building Construction

Preliminary work had to be completed on site before modules could be installed. This included laying foundations, and constructing cores and non-modular ground floors, if present (Figures I.1 to I.3).



**Figure I.1 (left): Site photo: Foundation being prepared on site for module installation [[redacted] 2012]**
**Figure I.2 (centre): Site photo: Modules being installed after construction of steel cores [[redacted] 2012]**
**Figure I.3 (right): Site photo: Showing lift shaft prior to module installation [[redacted] 2012]**

Modules and corridor components were transported to site by lorry; two modules were typically carried per lorry (Figure I.4). The delivery of modules to site and their subsequent installation had to be planned and timed meticulously to ensure continuous installation of modules, adequate space on site for the lorries, and efficient use of transport. A crane lifted modules and corridor panels from the lorries to their installation location on site (Figure I.5).



**Figure I.4 (left): Site photo: Two lorries on site, the first unloading, the second waiting [[redacted] 2012]**
**Figure I.5 (right): Site photo: Module being lifted by crane from a lorry into its installation site [[redacted] 2012]**

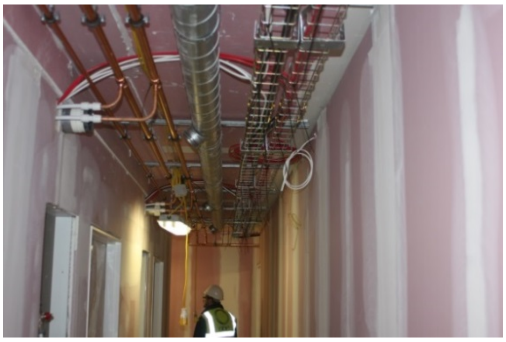
Workers would help guide the modules and corridor components into place and secure it to the foundations, structural steel or adjacent modules (Figures I.6 and I.7). In taller buildings lasers were used to ensure correct alignment of the modules.


**Figure I.6 (left): Site photo: Module suspended by crane & guided into place on foundations [redacted] 2012]**
**Figure I.7 (right): Corridor floor cassette suspended by crane & guided onto foundations [redacted] 2012]**

Once all modules and corridor panels were installed, the external walls and roof were constructed around them (Figures I.8 and I.9).

**Figure I.8 (left): Site photo: Roof on top and rigid insulation being fitted to walls [redacted] 2012]**
**Figure I.9 (right): Site photo: Brick cladding being fitted to external walls [redacted] 2012]**

In fully modular buildings, the only internal work required was in corridors and stairwells. Corridor walls and ceilings were lined with plasterboard. Mechanical and electrical services in the modules were then connected to the main building systems via the module risers. The majority of services were routed along corridor ceilings to the plant room via building risers (Figure I.10). False ceilings were fitted in corridors to conceal the services. Corridors were then painted and flooring was laid (Figure I.11). The final stage in construction was snagging, repairing any defects or damage that may have occurred during transportation or installation.



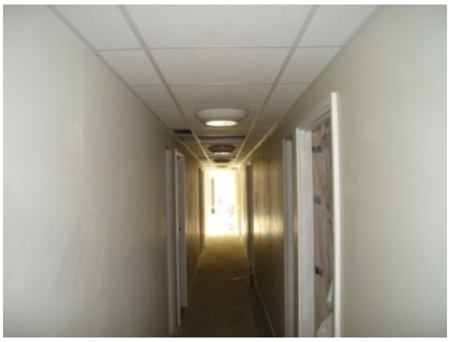
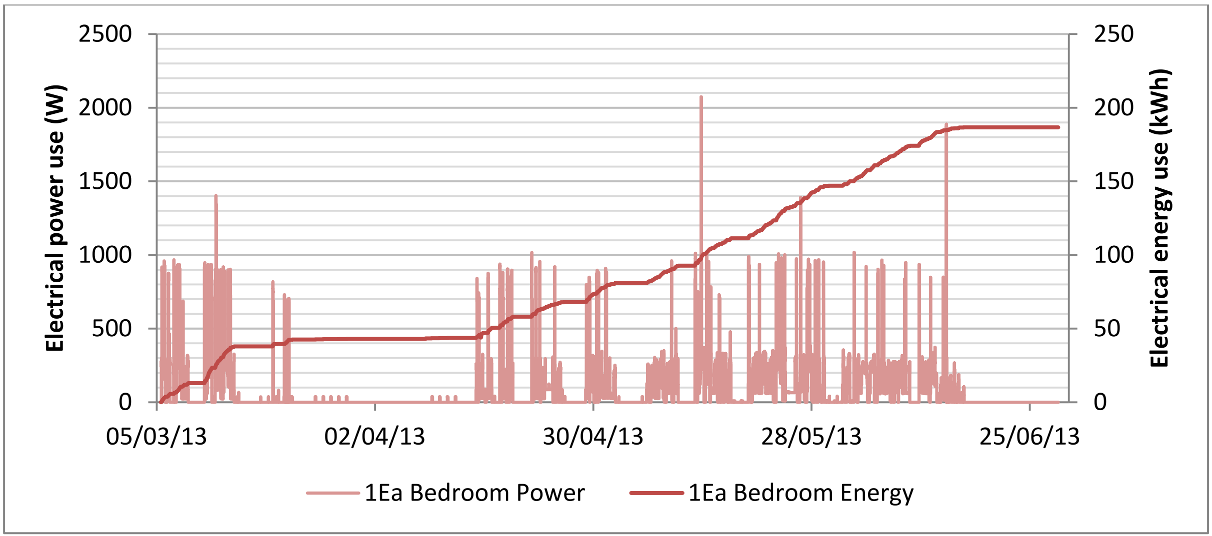
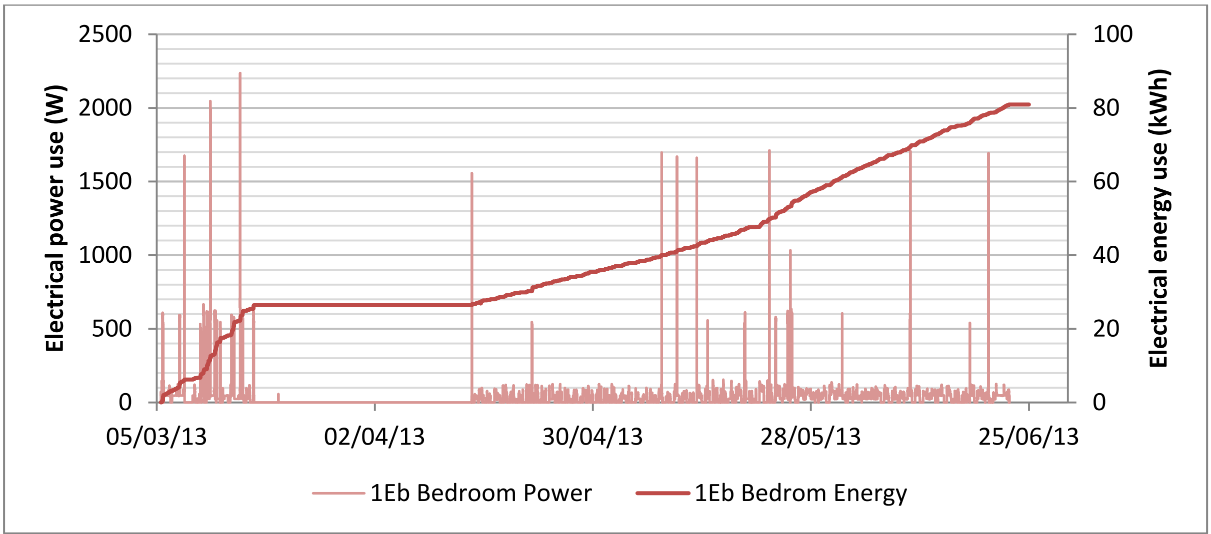
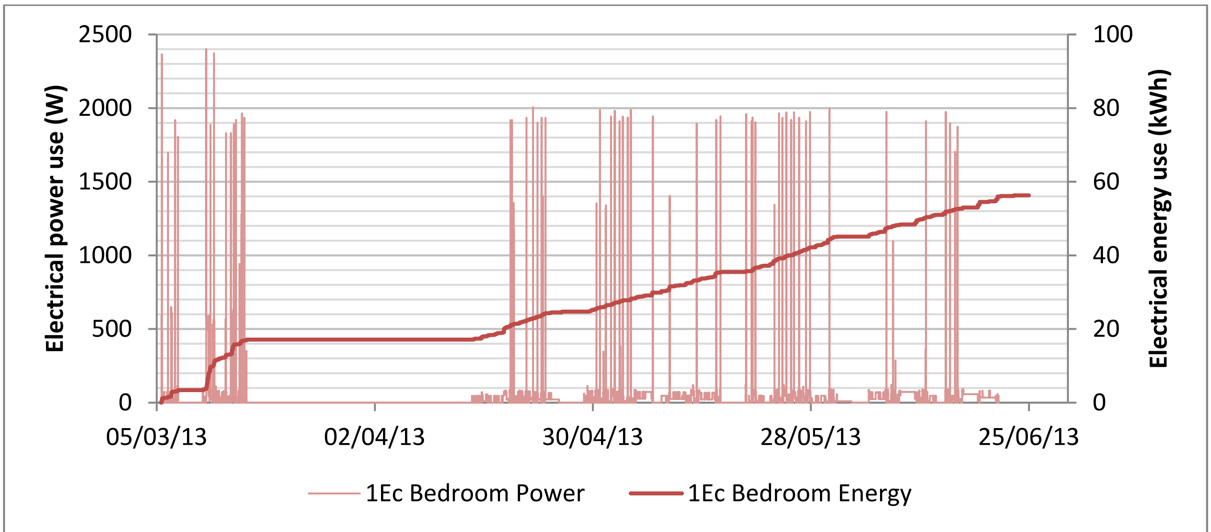


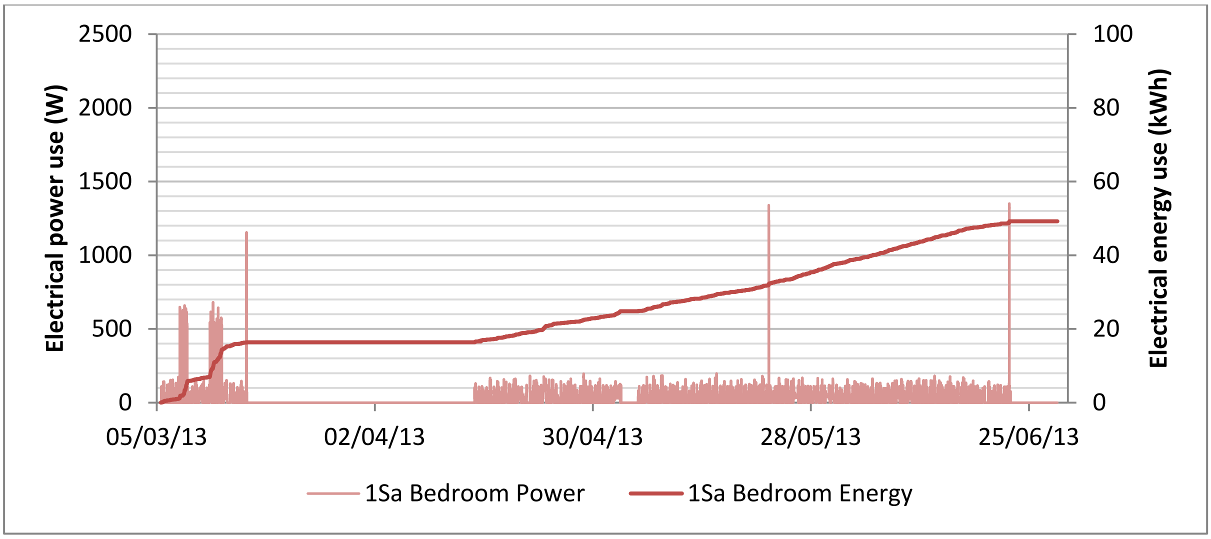
**Figure I.10 (left): Site photo: work in corridor to plasterboard walls & fit M&E services [redacted] 2012]**
**Figure I.11 (right): Site photo: corridor near completion with false ceiling & painted walls [redacted] 2012]**

# Appendix J: Total Metered Electricity Data for Flats 1 and 2 – Loughborough

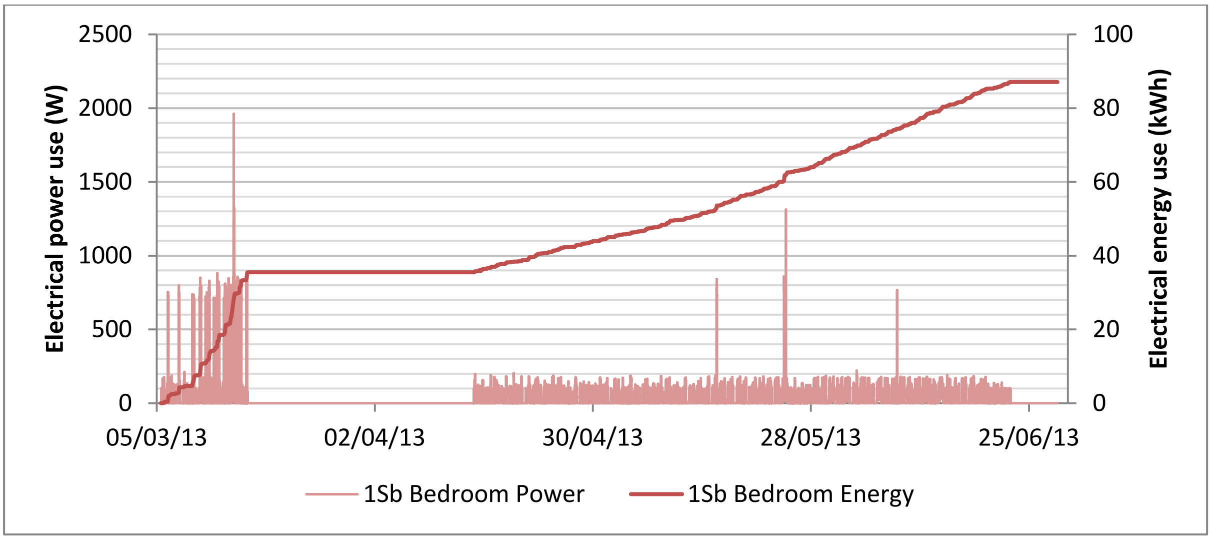


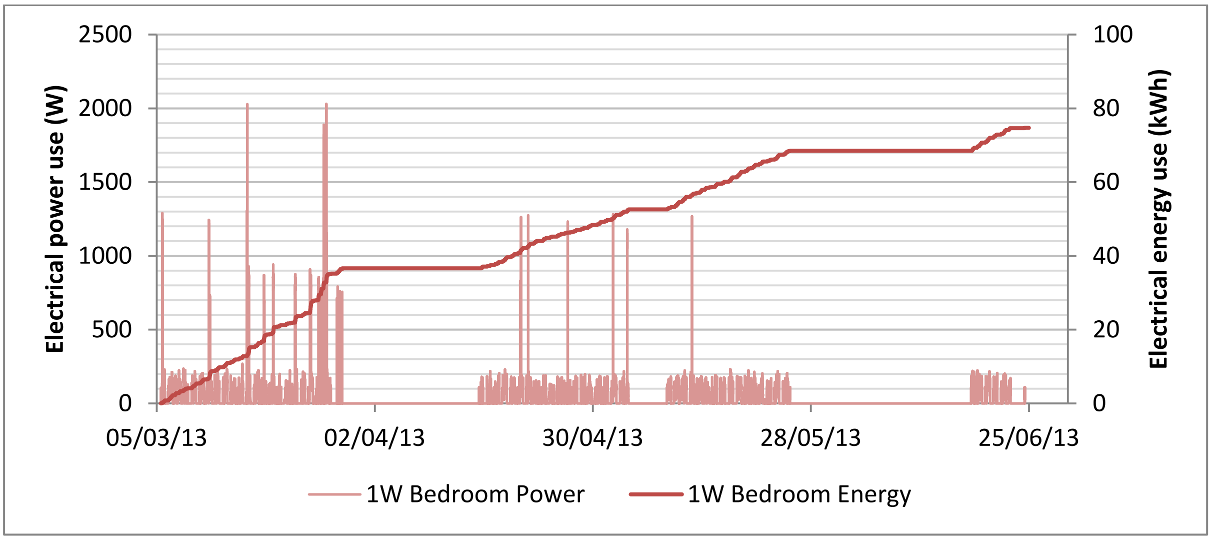





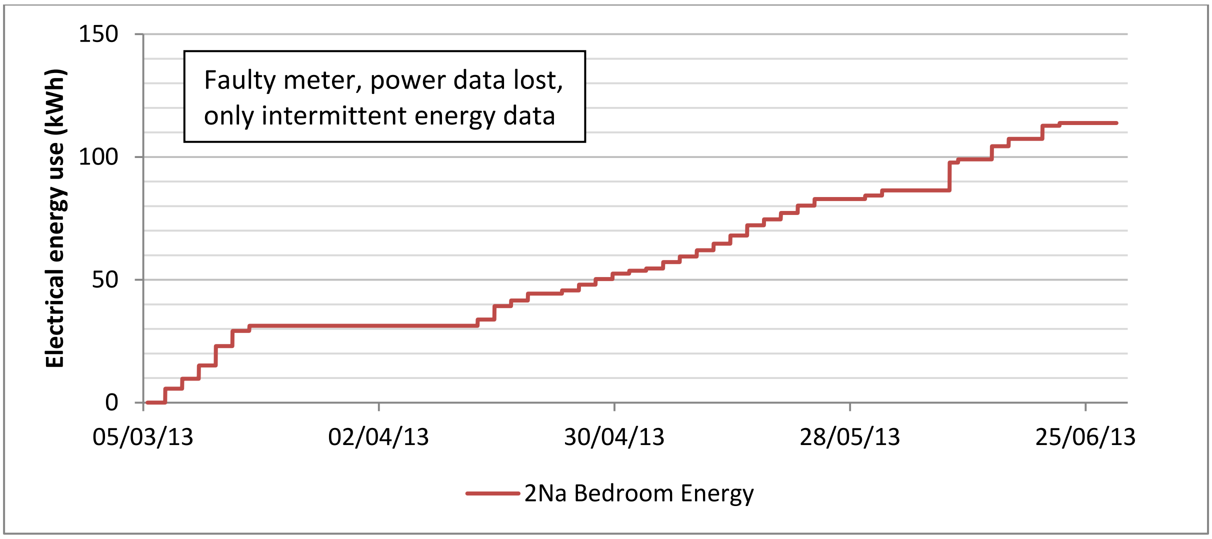
2500
2000
1500
1000
500
0
100
80
60
40
20
0
Electrical power use (W)
Electrical energy use (kWh)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Sa Bedroom Power
1Sa Bedroom Energy

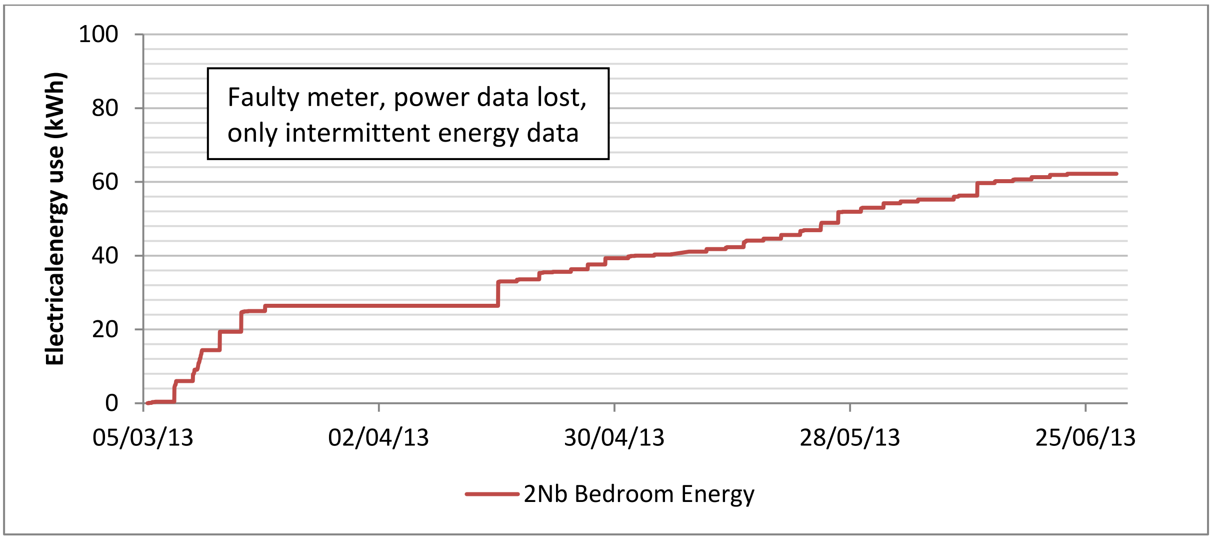



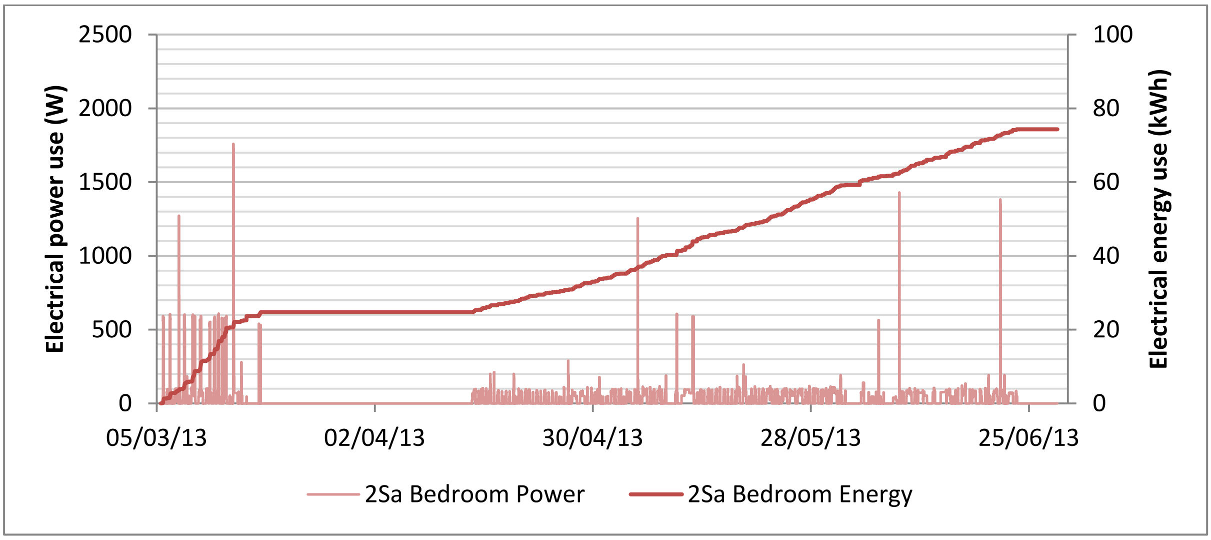
2500
2000
1500
1000
500
0
100
80
60
40
20
0
Electrical power use (W)
Electrical energy use (kWh)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Sb Bedroom Power
1Sb Bedroom Energy

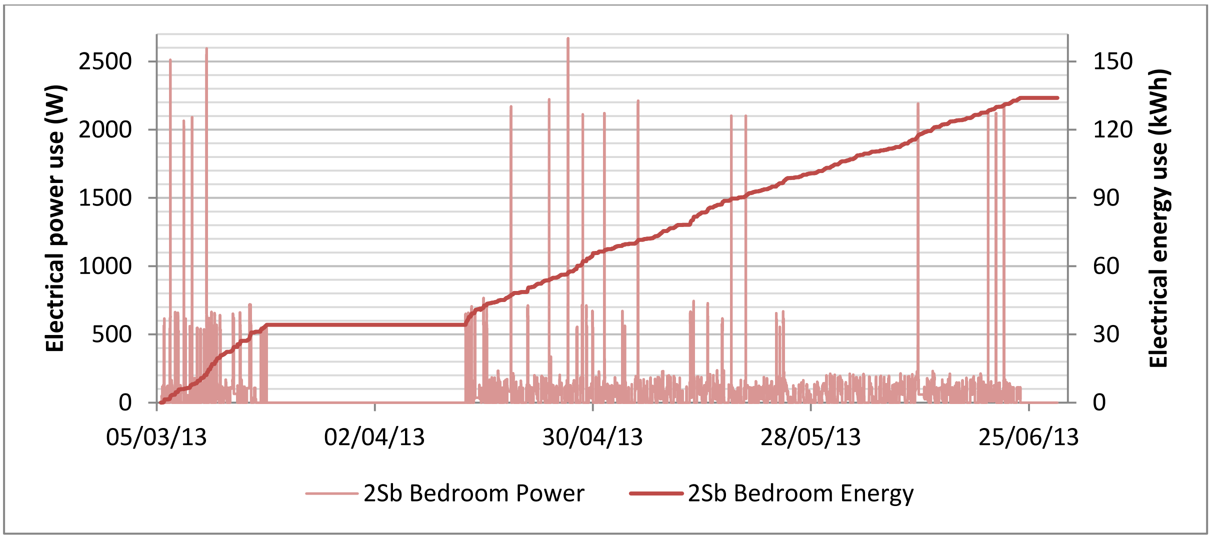



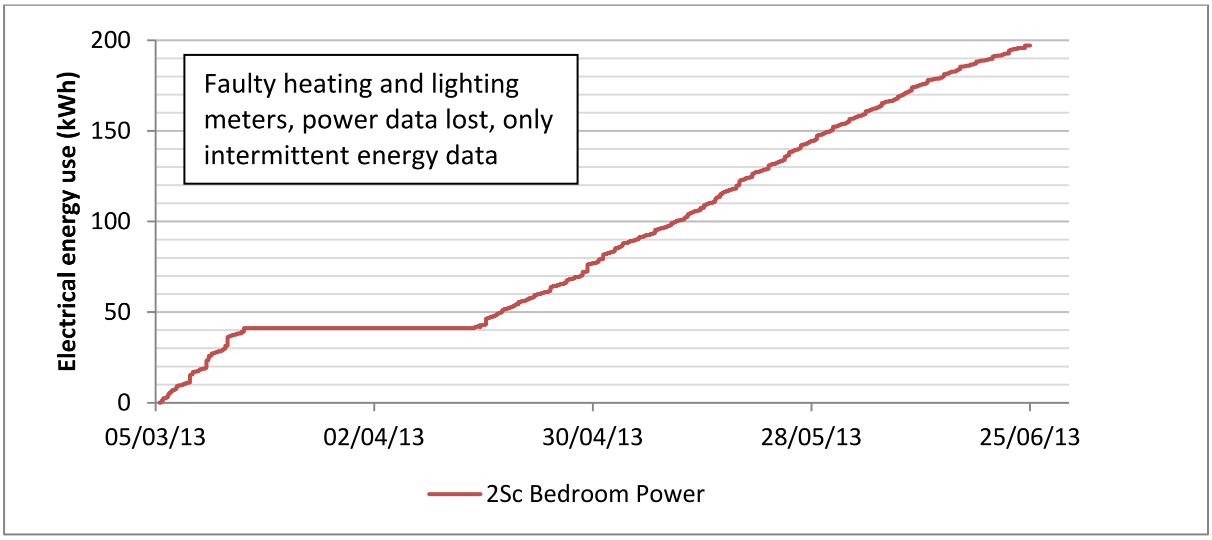
2500
2000
1500
1000
500
0
100
80
60
40
20
0
Electrical power use (W)
Electrical energy use (kWh)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1W Bedroom Power
1W Bedroom Energy

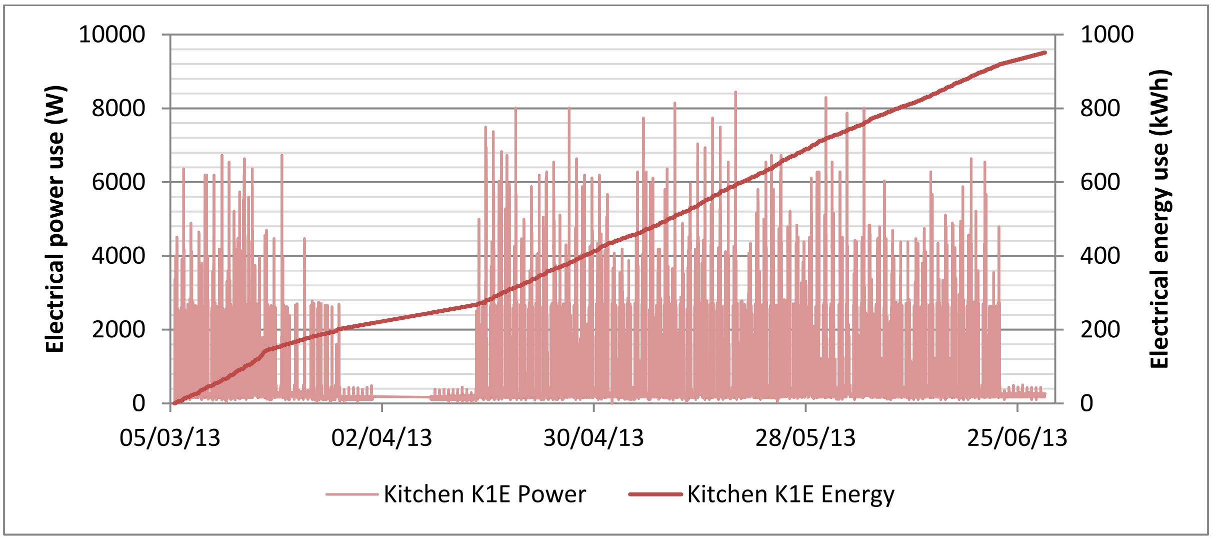

Electrical energy use (kWh)
150
100
50
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
Faulty meter, power data lost, only intermittent energy data
2Na Bedroom Energy

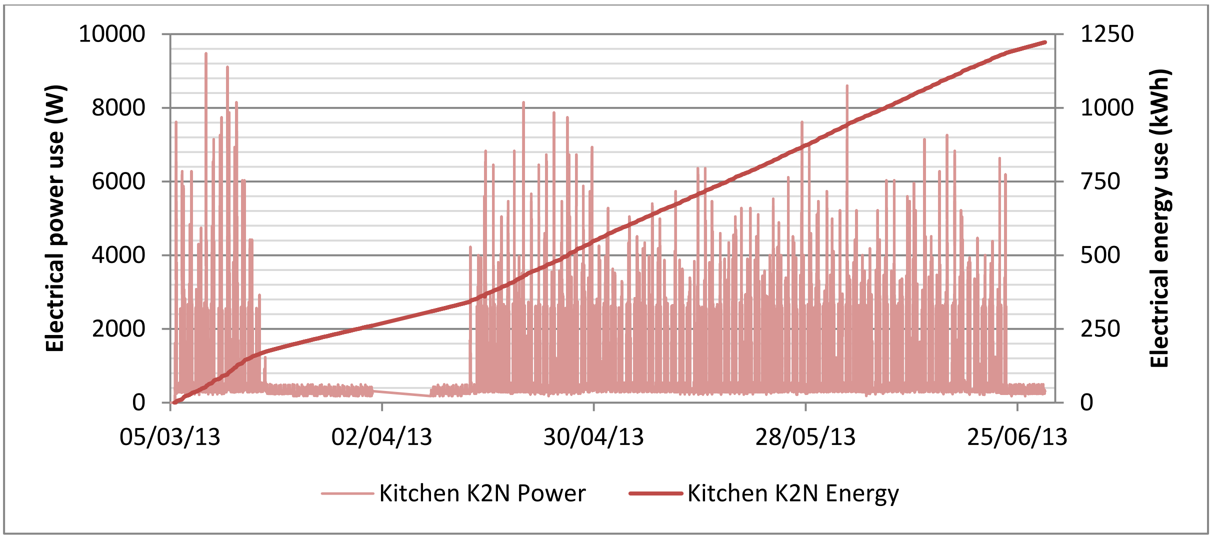

Electricalenergy use (kWh)
100
80
60
40
20
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
Faulty meter, power data lost, only intermittent energy data
2Nb Bedroom Energy


Electrical power use (W)
2500
2000
1500
1000
500
0
Electrical energy use (kWh)
100
80
60
40
20
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
2Sa Bedroom Power
2Sa Bedroom Energy


Electrical power use (W)
2500
2000
1500
1000
500
0
150
120
90
60
30
0
Electrical energy use (kWh)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
2Sb Bedroom Power
2Sb Bedroom Energy

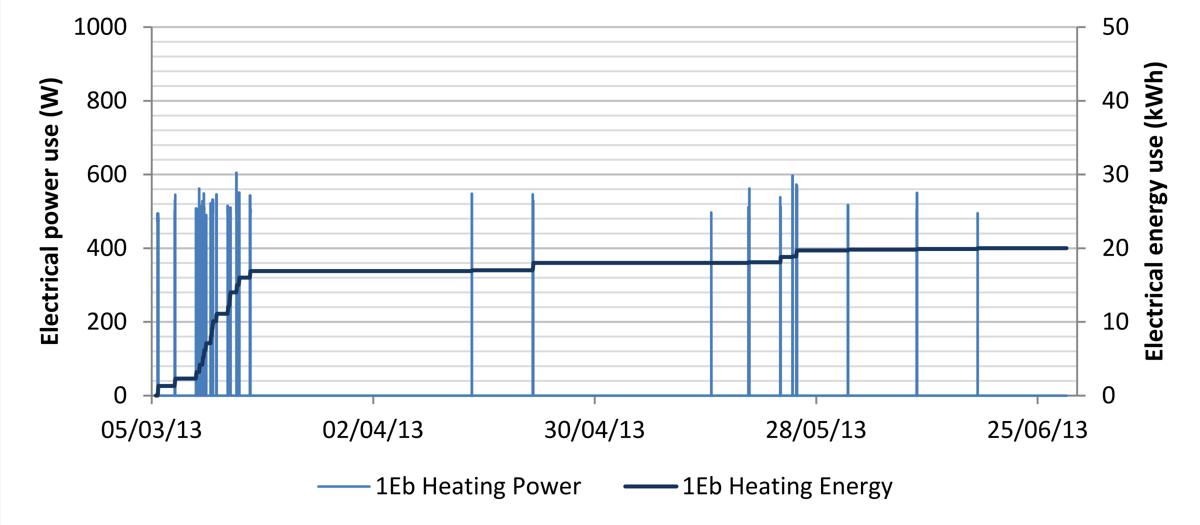

Electrical energy use (kWh)
200
150
100
50
0
Faulty heating and lighting meters, power data lost, only intermittent energy data
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
2Sc Bedroom Power

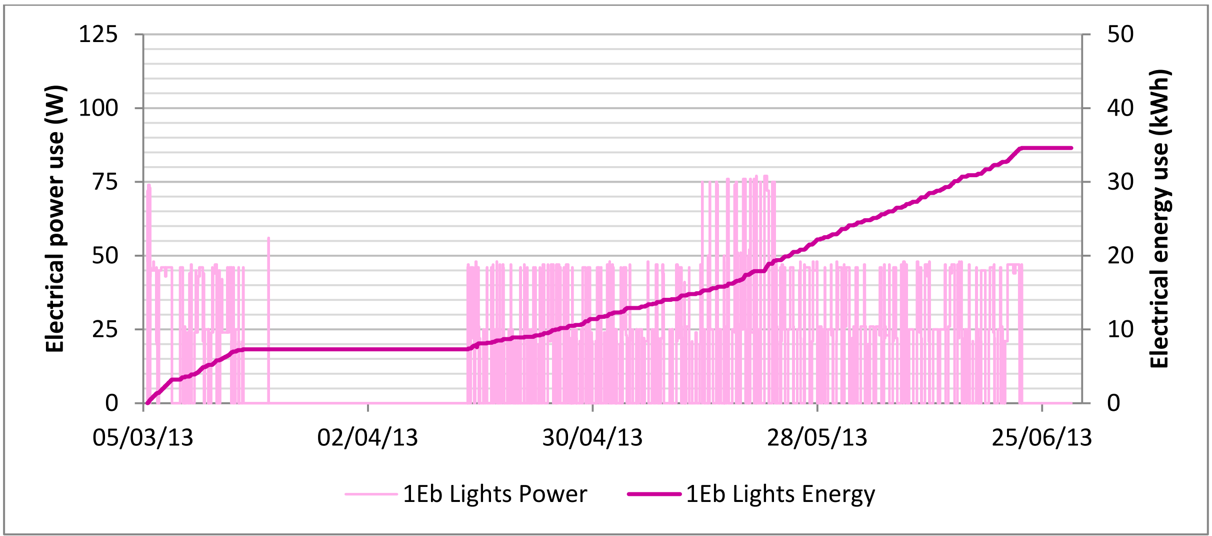

Electrical power use (W)
10000
8000
6000
4000
2000
0
1000
800
600
400
200
0
Electrical energy use (kWh)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
Kitchen K1E Power
Kitchen K1E Energy

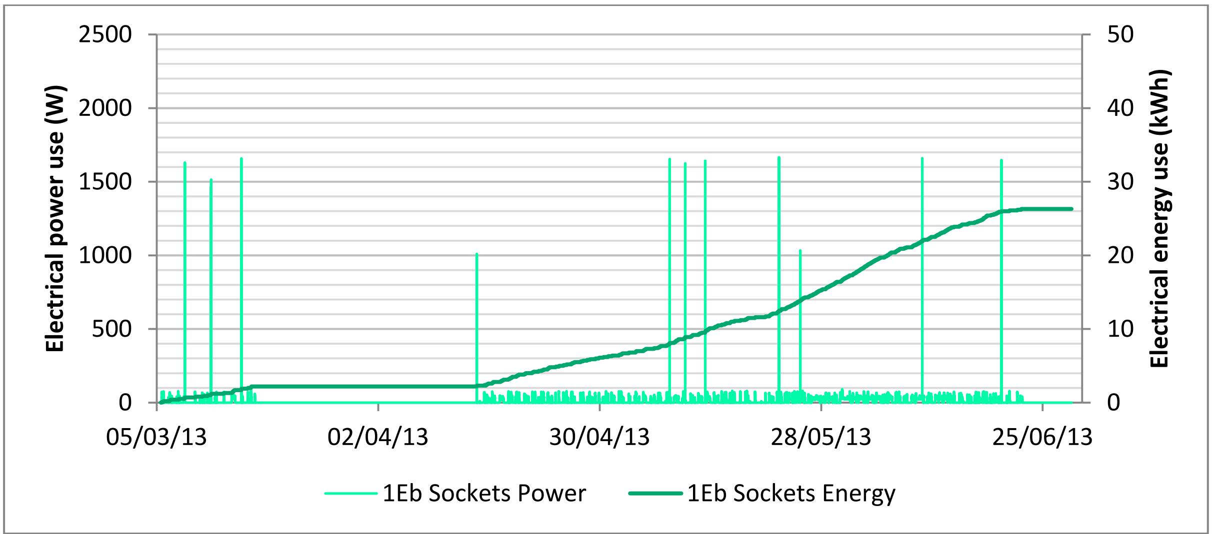


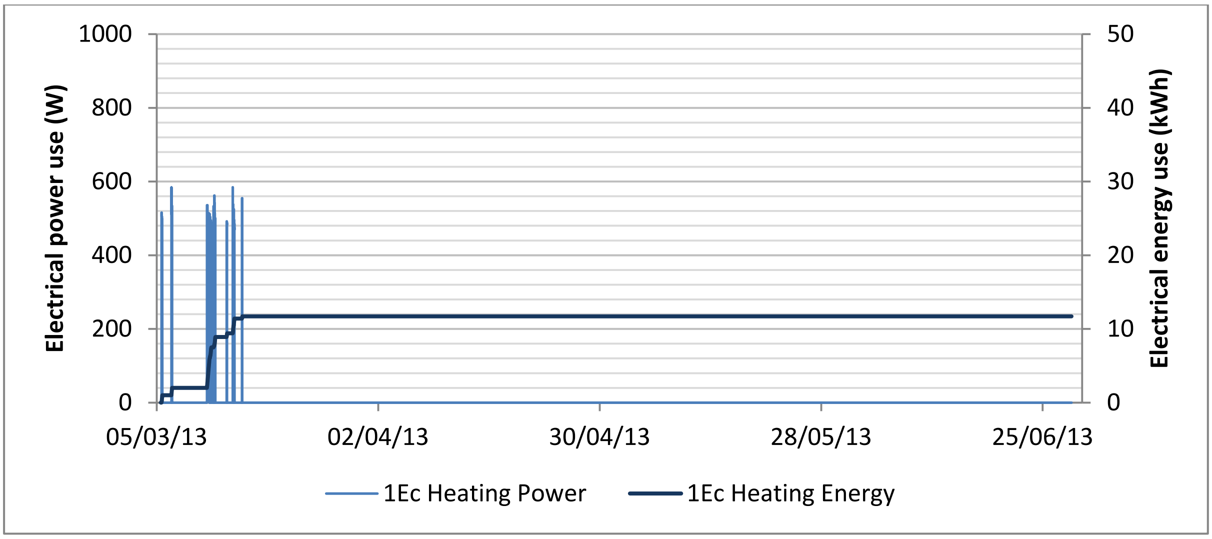
Electrical power use (W)
10000
8000
6000
4000
2000
0
Electrical energy use (kWh)
1250
1000
750
500
250
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
Kitchen K2N Power
Kitchen K2N Energy

## Appendix K: Sub-Metered Electricity Data for Flats 1 and 2 – Loughborough

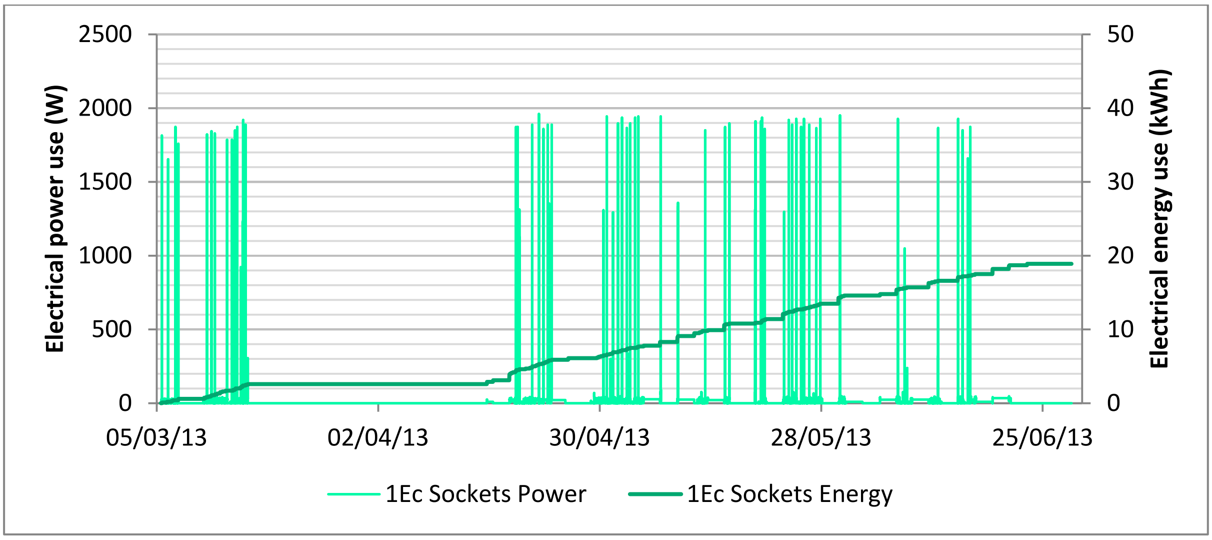


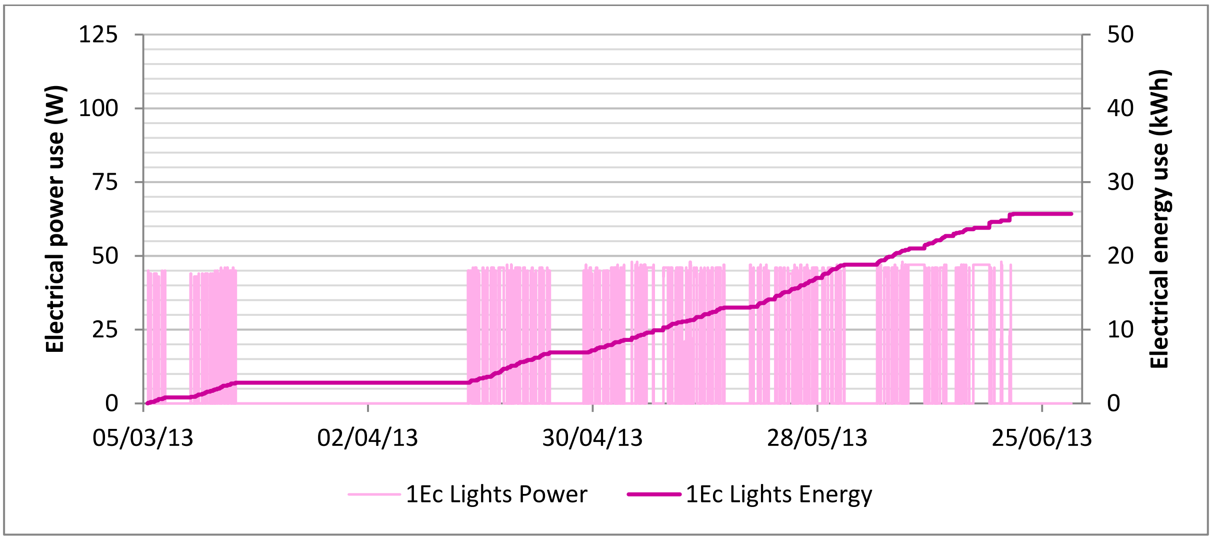





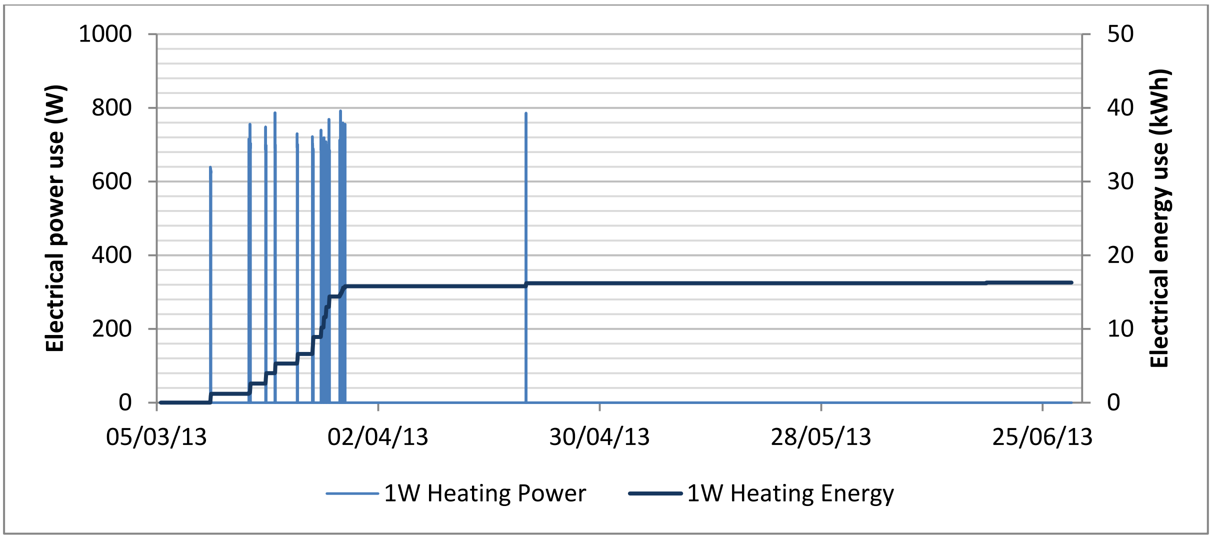
1000
800
600
400
200
0
50
40
30
20
10
0
Electrical power use (W)
Electrical energy use (kWh)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Ec Heating Power
1Ec Heating Energy

2500
2000
1500
1000
500
0
50
40
30
20
10
0
Electrical power use (W)
Electrical energy use (kWh)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Ec Sockets Power
1Ec Sockets Energy

125
100
75
50
25
0
50
40
30
20
10
0
Electrical power use (W)
Electrical energy use (kWh)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Ec Lights Power
1Ec Lights Energy



Electrical power use (W)
Electrical energy use (kWh)
1000
800
600
400
200
0
50
40
30
20
10
0
05/03/13
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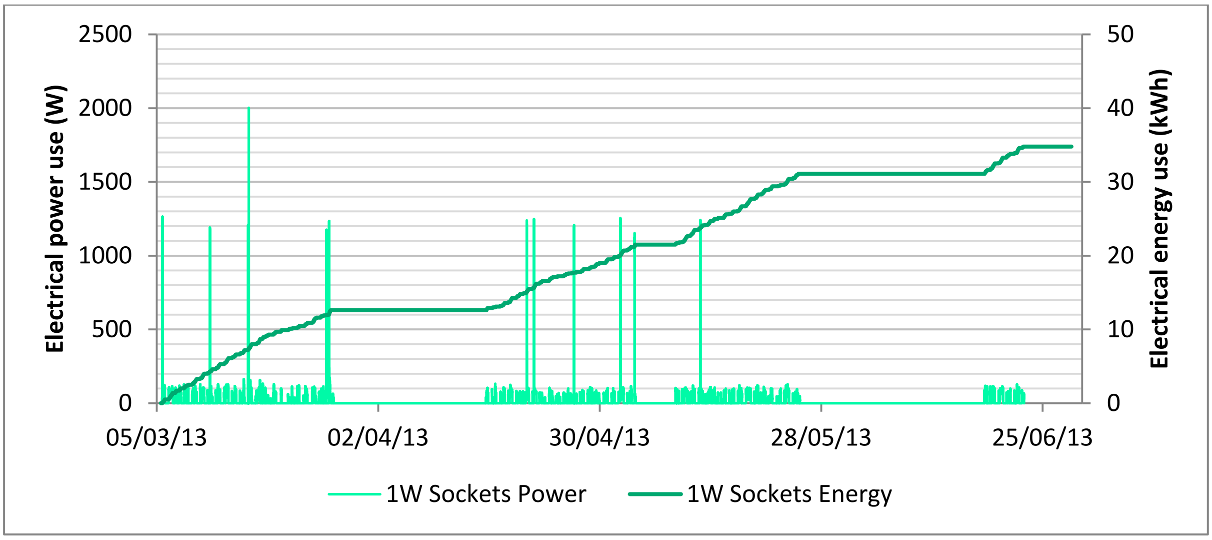
25/06/13
1W Heating Power
1W Heating Energy

Electrical power use (W)
Electrical energy use (kWh)
2500
2000
1500
1000
500
0
50
40
30
20
10
0
05/03/13
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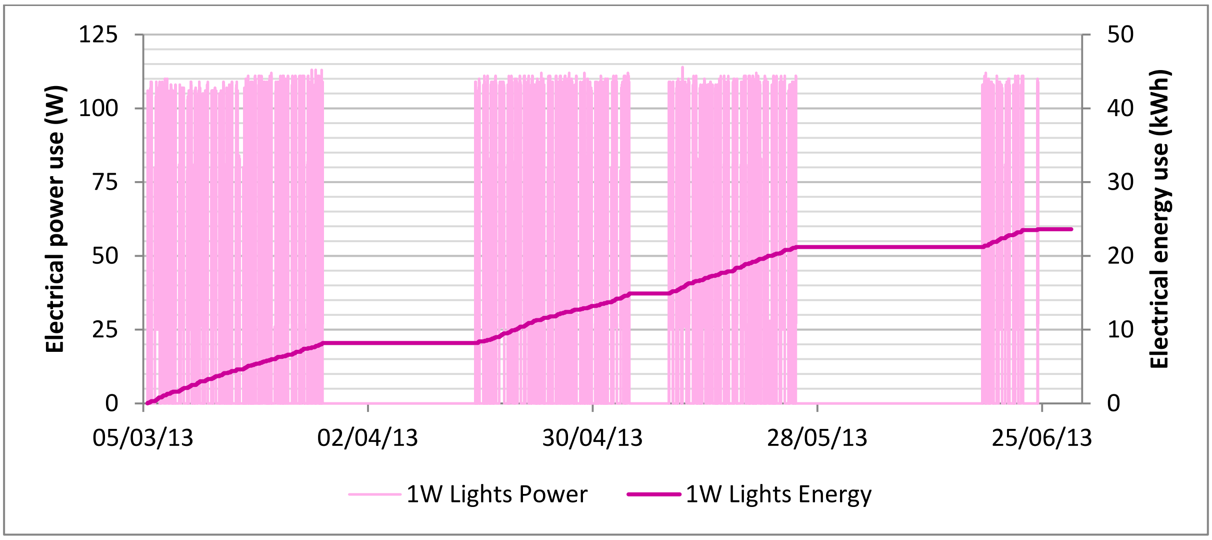
25/06/13
1W Sockets Power
1W Sockets Energy

Electrical power use (W)
Electrical energy use (kWh)
125
100
75
50
25
0
50
40
30
20
10
0
05/03/13
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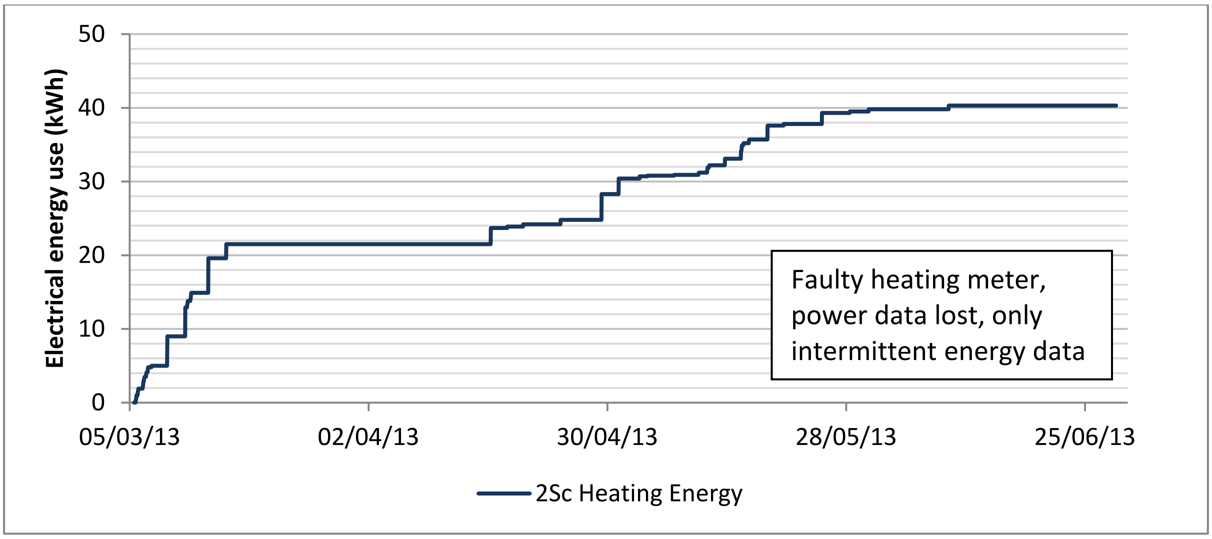
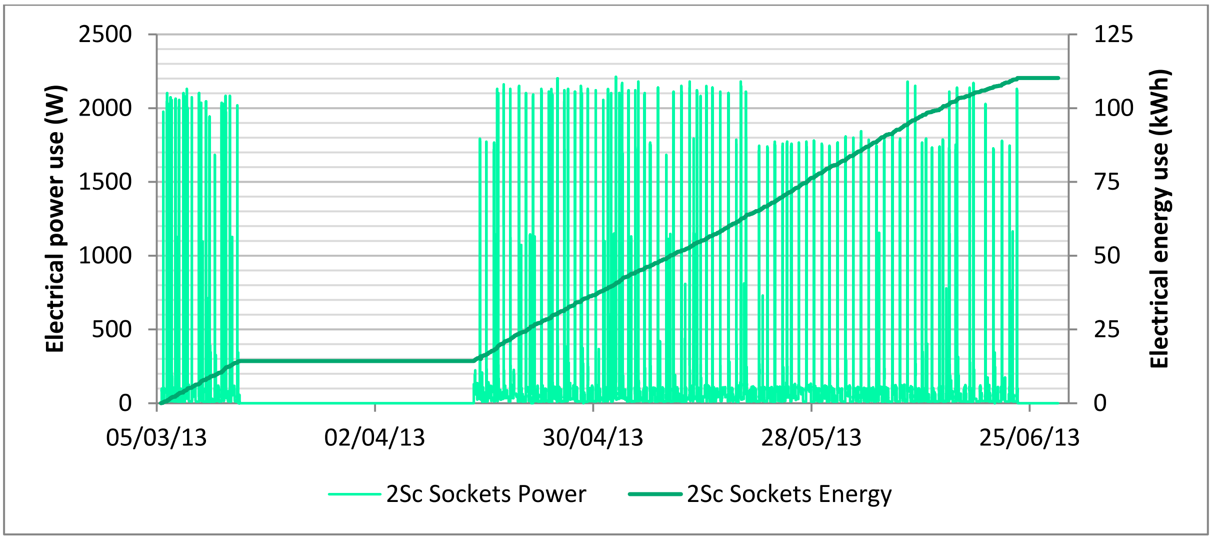
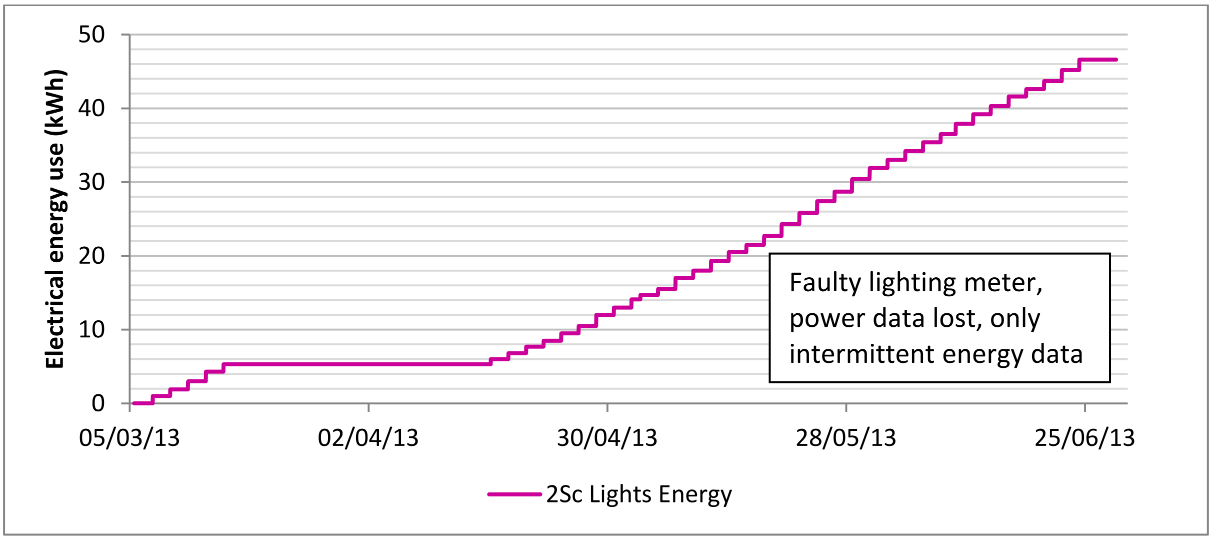
25/06/13
1W Lights Power
1W Lights Energy


Electrical energy use (kWh)
0
10
20
30
40
50
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
Faulty heating meter, power data lost, only intermittent energy data
2Sc Heating Energy


Electrical power use (W)
0
500
1000
1500
2000
2500
Electrical energy use (kWh)
0
25
50
75
100
125
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
2Sc Sockets Power
2Sc Sockets Energy


Electrical energy use (kWh)
0
10
20
30
40
50
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
Faulty lighting meter, power data lost, only intermittent energy data
2Sc Lights Energy

## Appendix L: Space Heating Data Extraction – Loughborough

The space heating load is quite distinct from the lighting and socket loads in the bedrooms (Figure M.1), which made it possible to split the data into electricity used for space heating and electricity used for lights and sockets (Figures M.2 to M.5). The loads for lights and sockets were often similar in size and duration and therefore it was not possible to distinguish between the two and further separate the data between lights and sockets. The data was separated manually, and there was often some uncertainty in how to split the data if other loads were being used at the same time as heating or if the load changed during the heating period, however the error is small and the it still gives a good indication of the split between end uses.

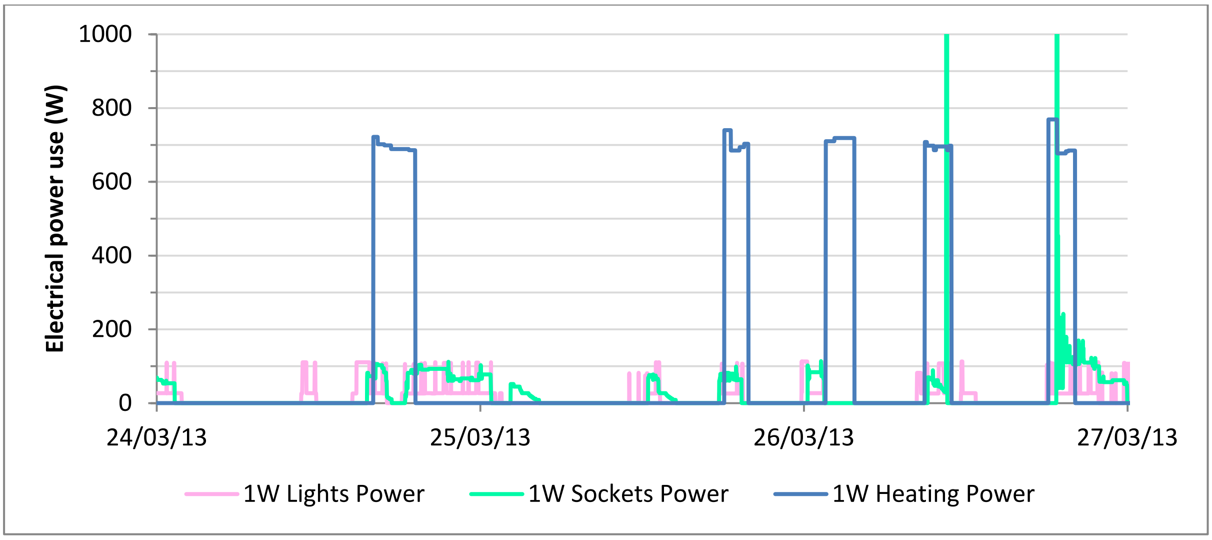



**Figure M.1: Space heating use has a distinct load profile compared to lights and sockets use – Room 1W**

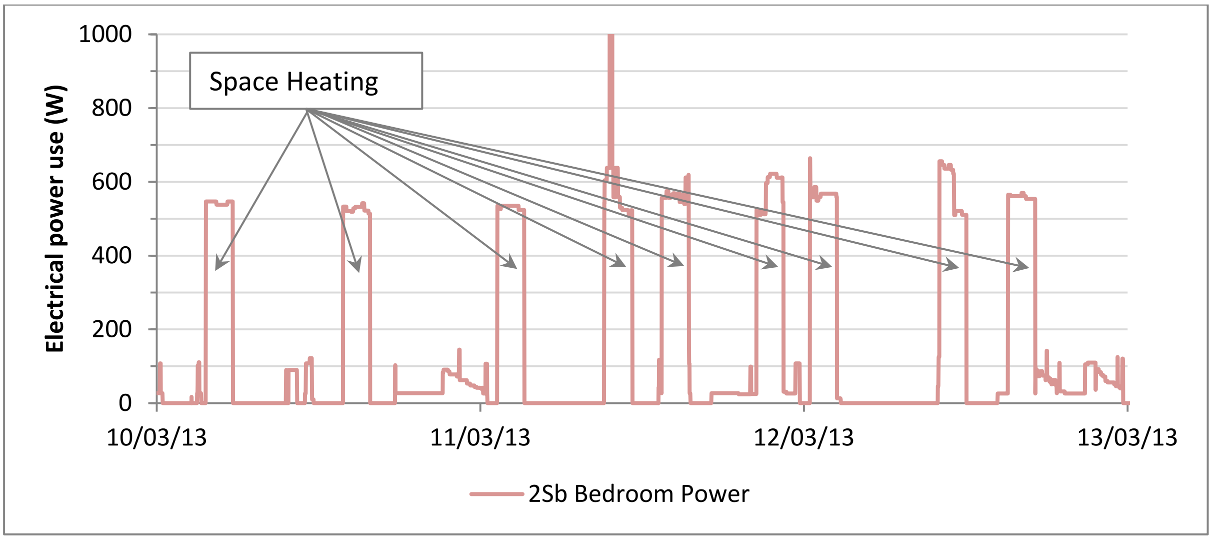



**Figure M.2: Space heating instances were identified in the room total electricity consumption**

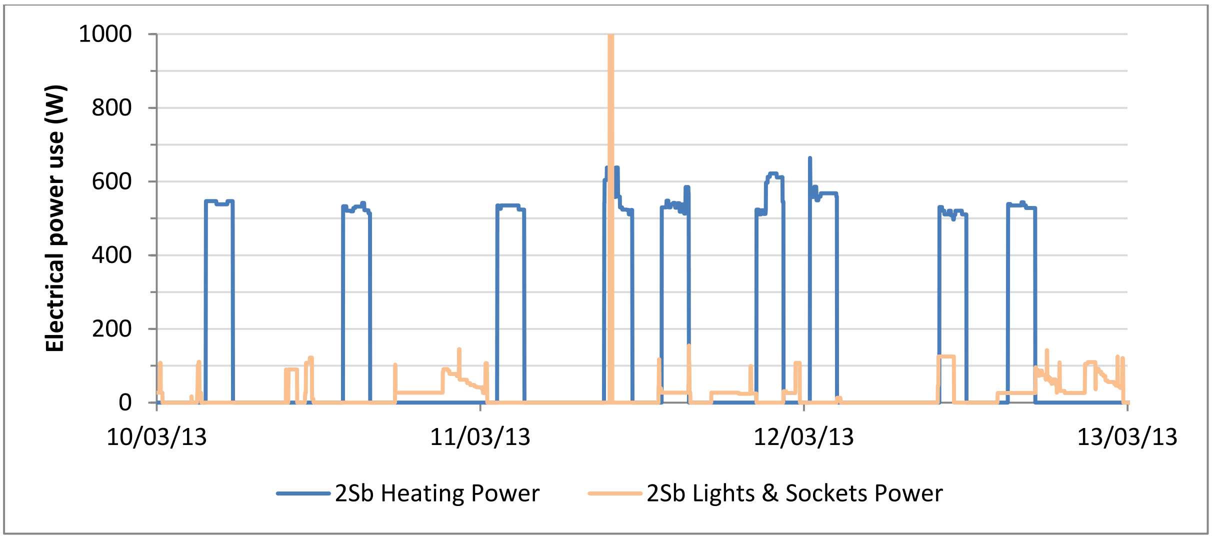



**Figure M.3: The room total electricity consumption was manually split to extract space heating data**

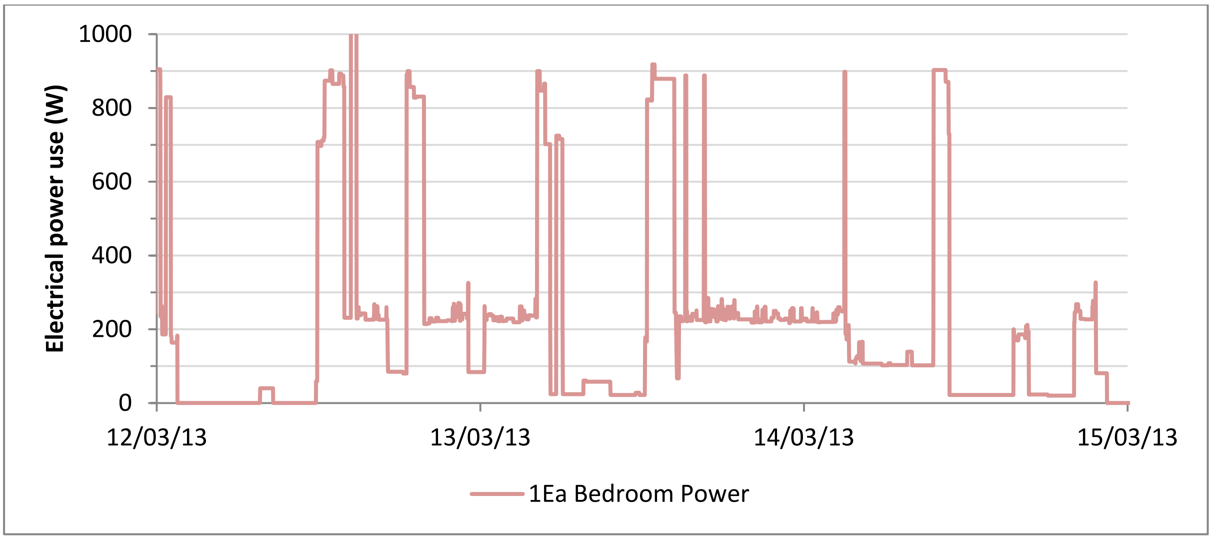



**Figure M.4 Space heating instances were identified in the room total electricity consumption**

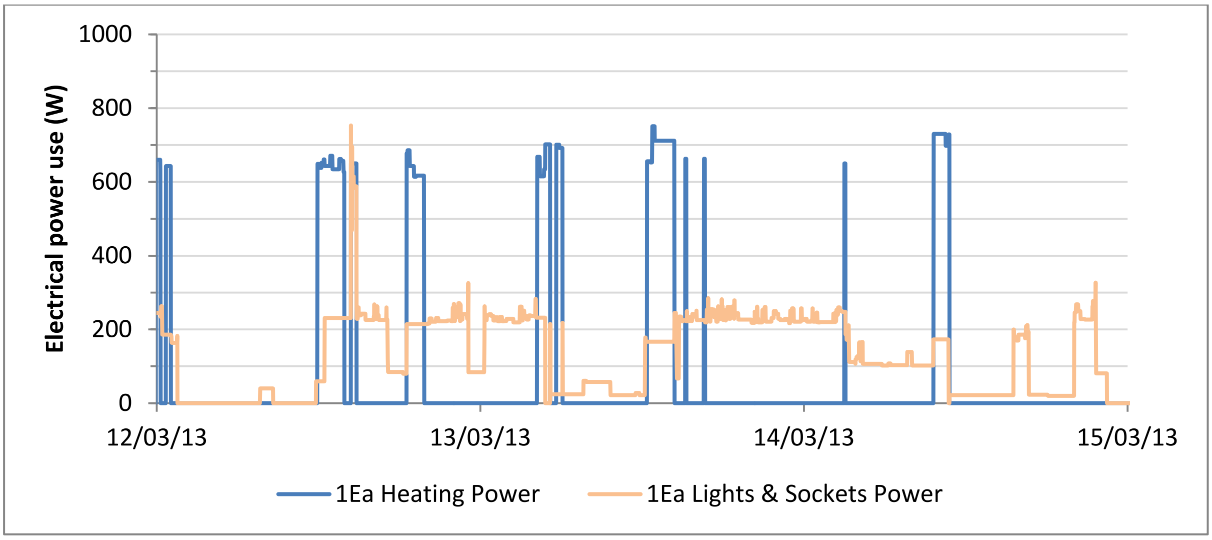
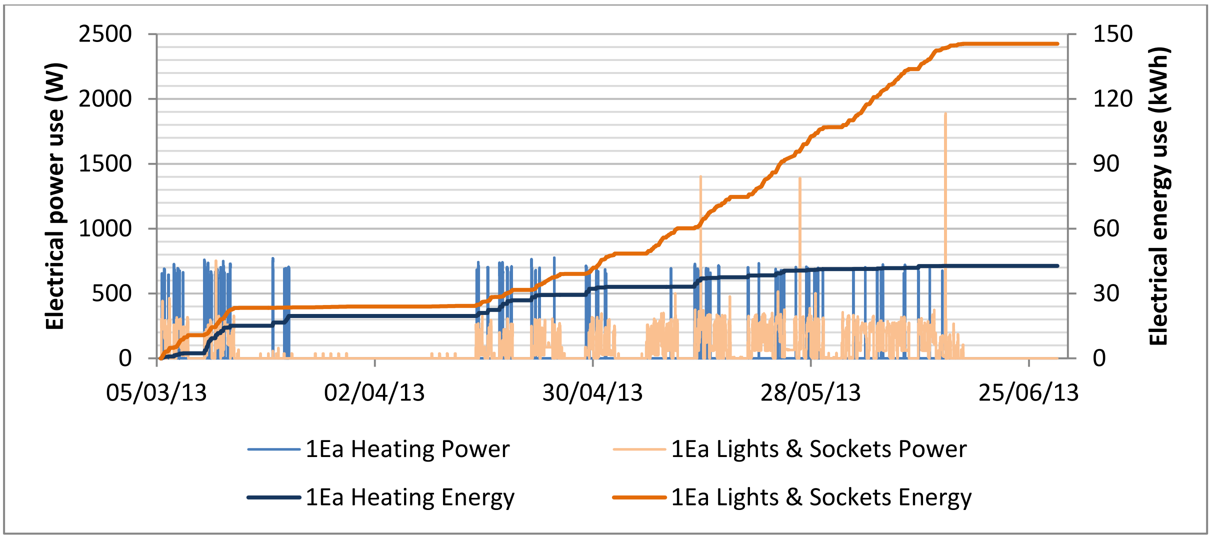
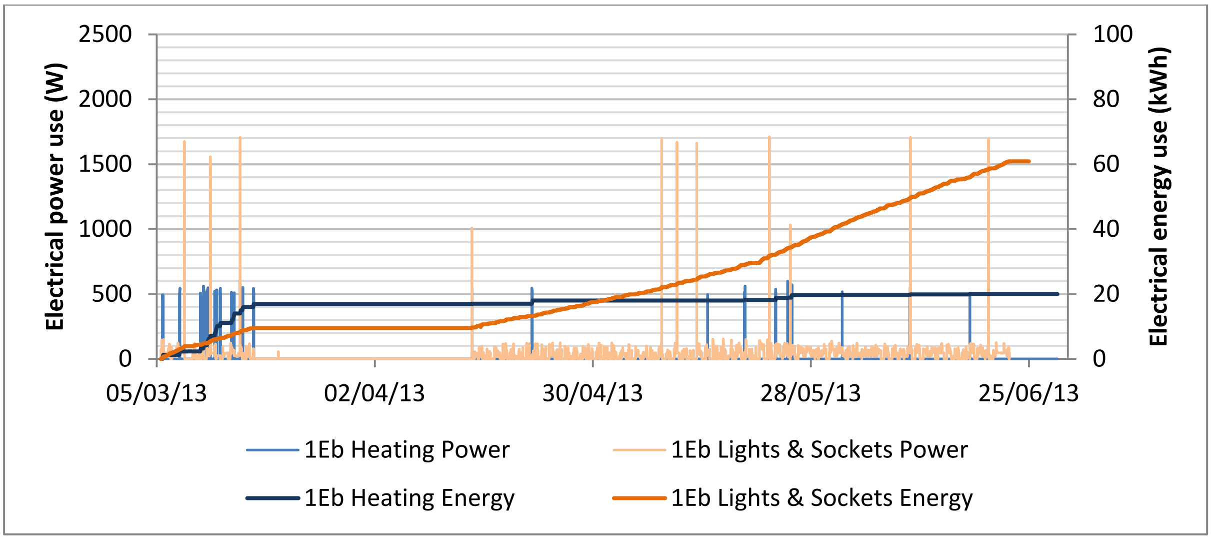
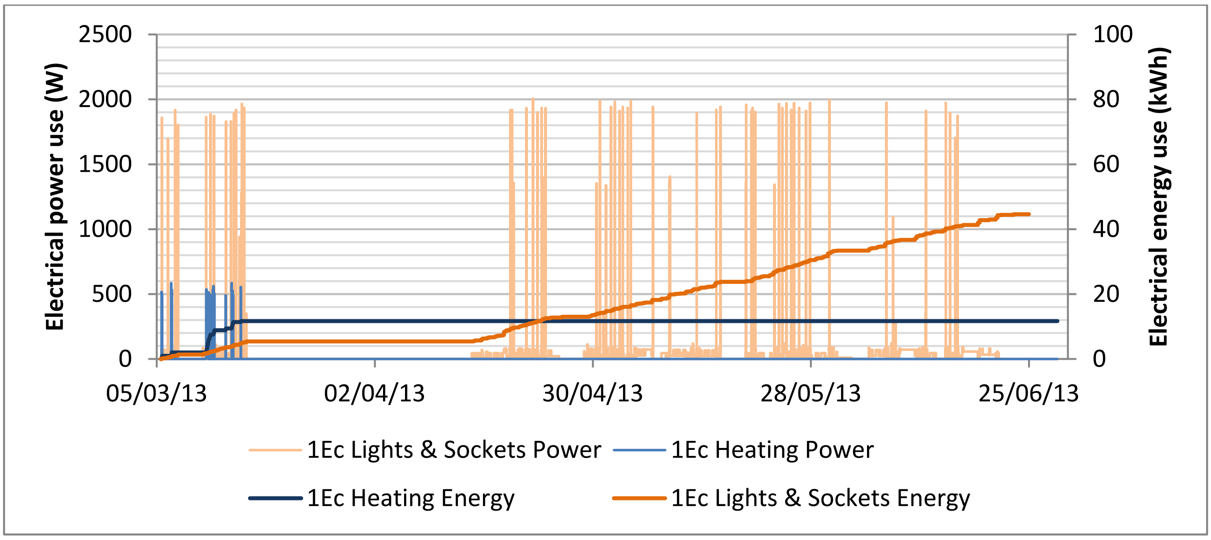


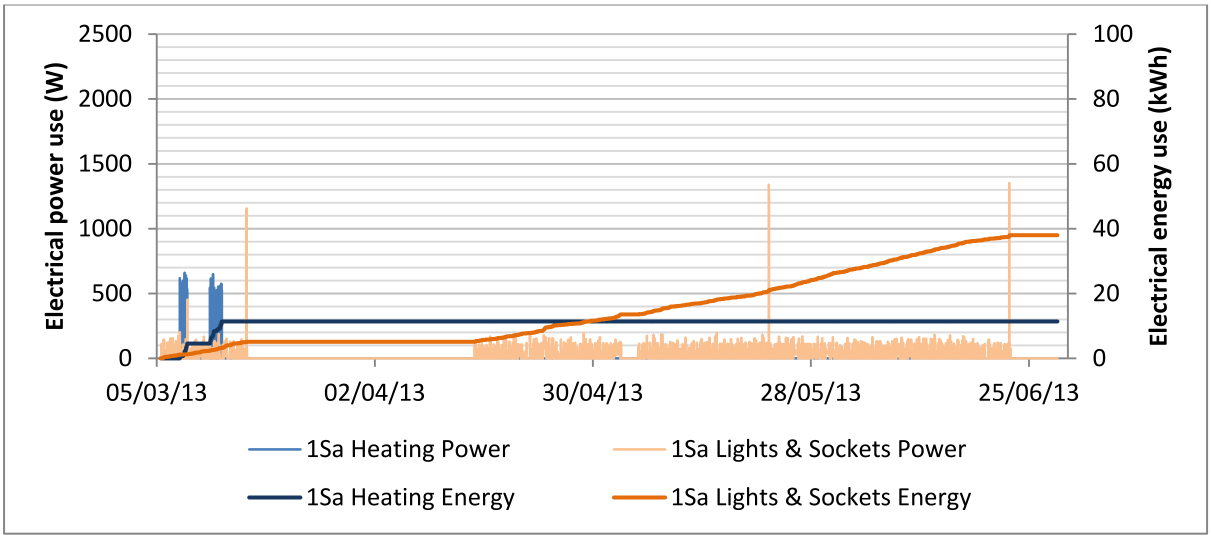

**Figure M.5 The room total electricity consumption was manually split to extract space heating data**

# Appendix M: Space Heating and Lights and Sockets Data – Loughborough

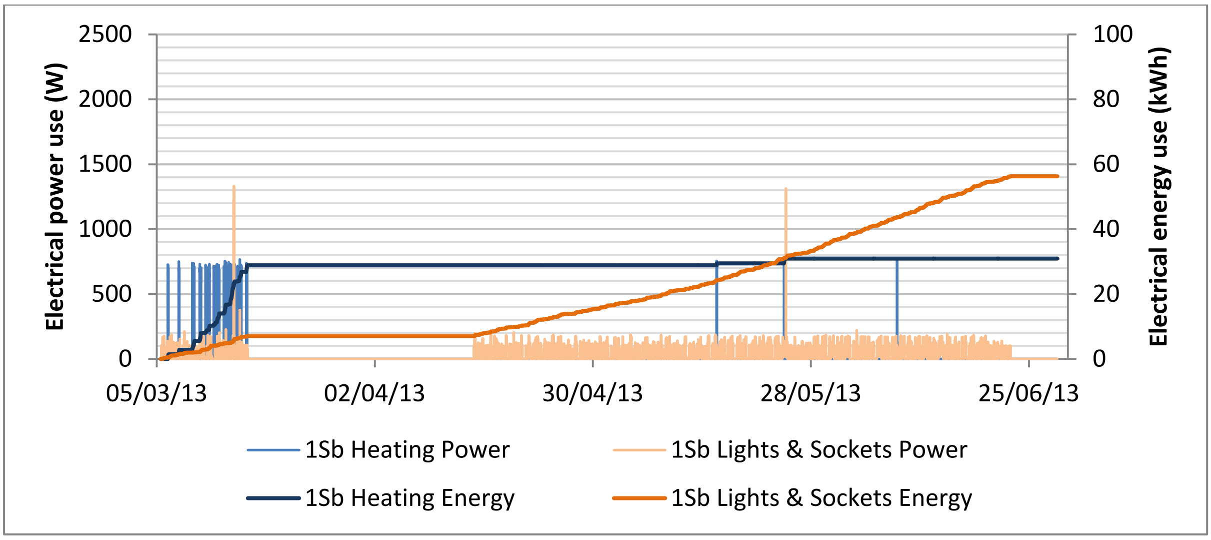


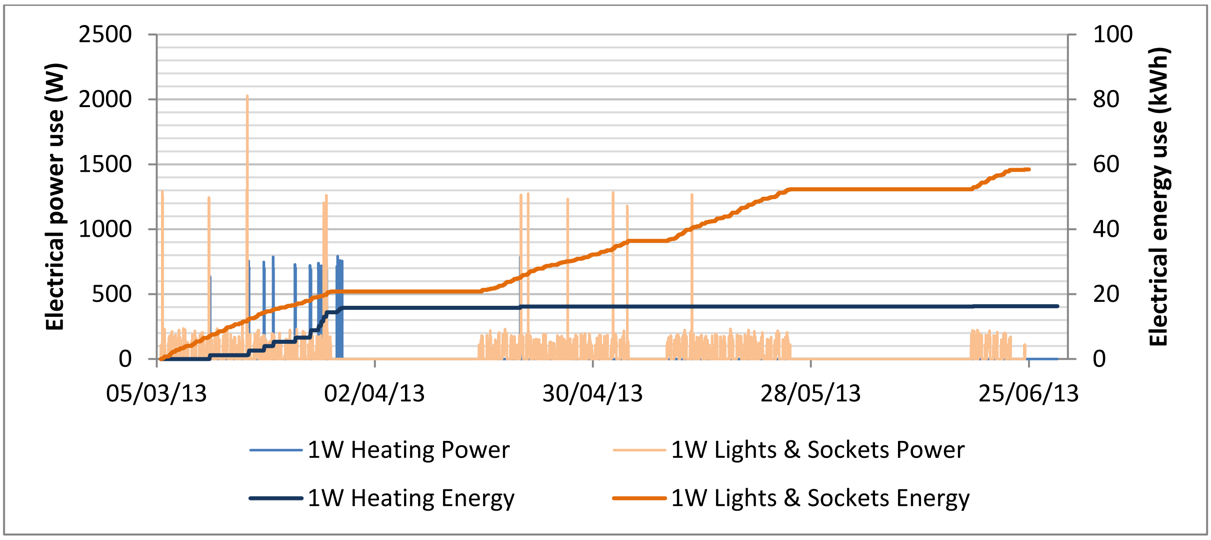





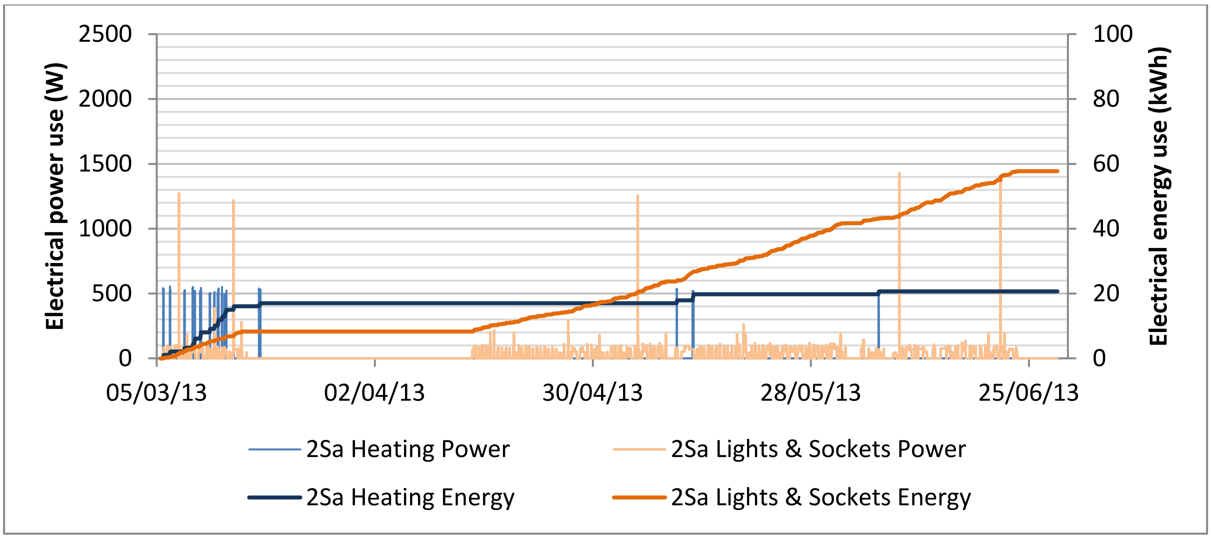
Electrical power use (W)
Electrical energy use (kWh)
2500
2000
1500
1000
500
0
100
80
60
40
20
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Sa Heating Power
1Sa Lights & Sockets Power
1Sa Heating Energy
1Sa Lights & Sockets Energy

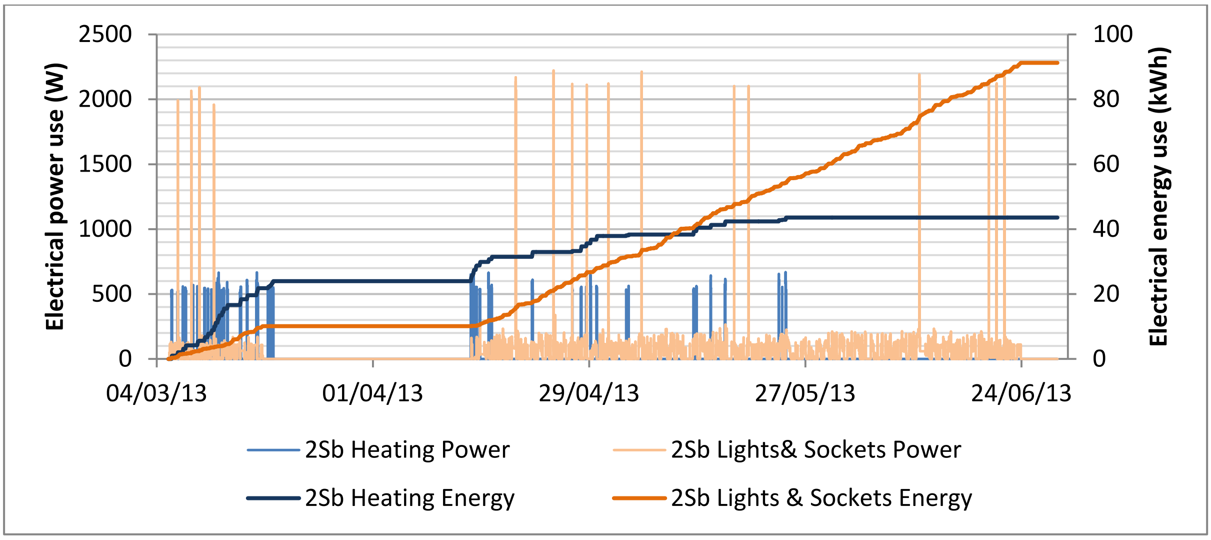



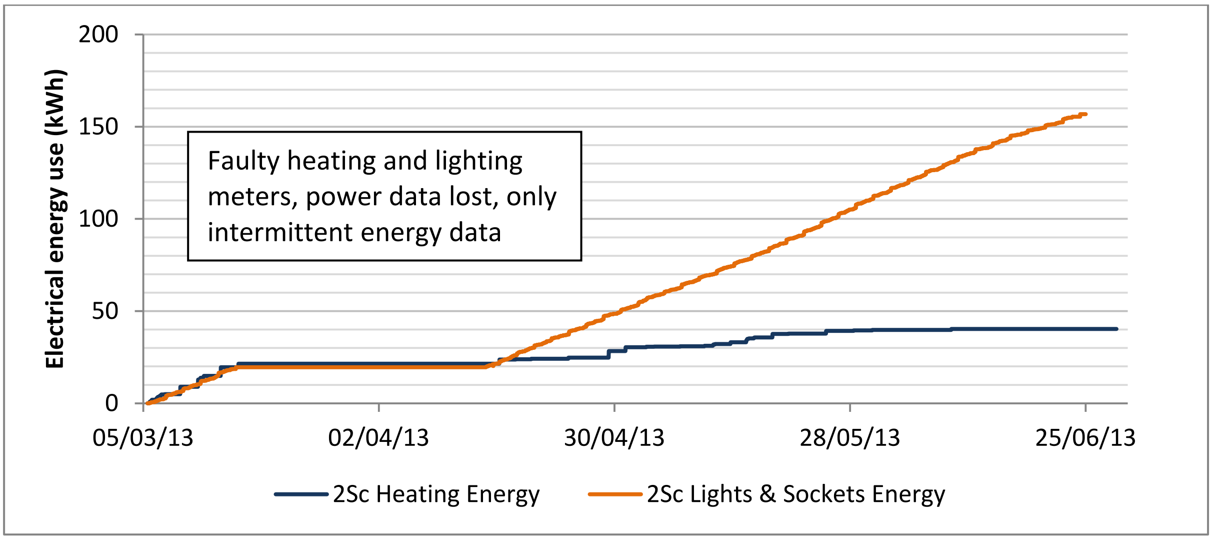
Electrical power use (W)
Electrical energy use (kWh)
2500
2000
1500
1000
500
0
100
80
60
40
20
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Sb Heating Power
1Sb Lights & Sockets Power
1Sb Heating Energy
1Sb Lights & Sockets Energy

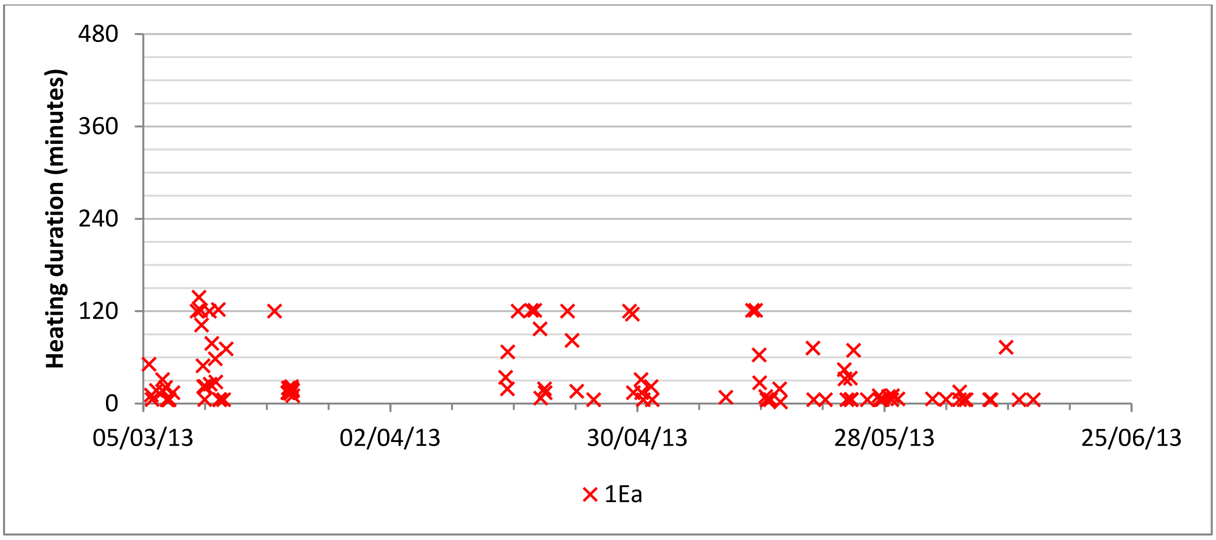
Electrical power use (W)
Electrical energy use (kWh)
2500
2000
1500
1000
500
0
100
80
60
40
20
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1W Heating Power
1W Lights & Sockets Power
1W Heating Energy
1W Lights & Sockets Energy

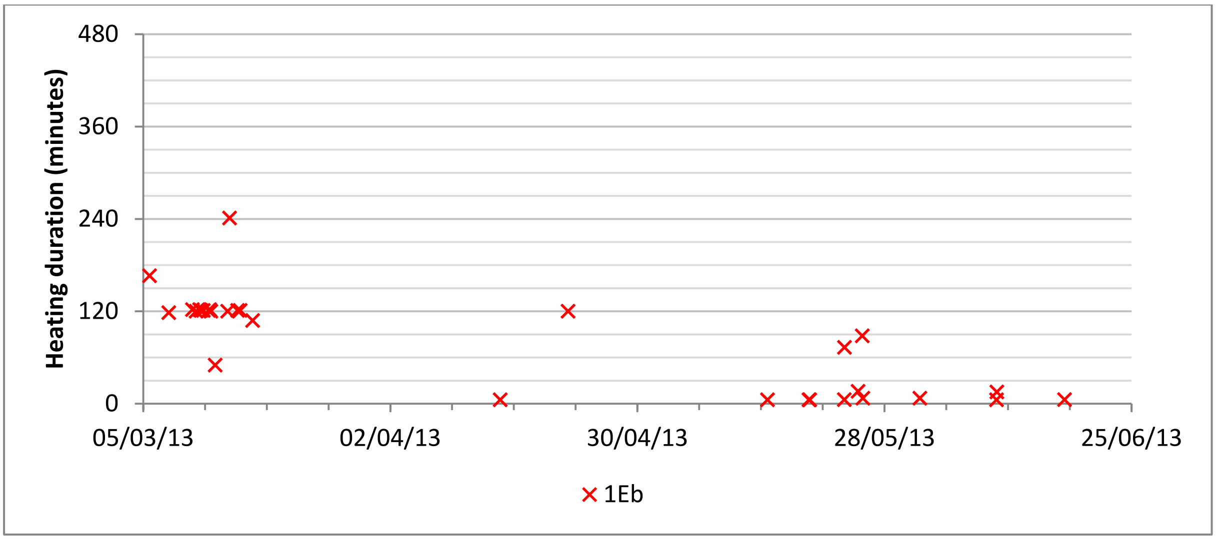

Electrical power use (W)
Electrical energy use (kWh)
2500
2000
1500
1000
500
0
100
80
60
40
20
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
2Sa Heating Power
2Sa Lights & Sockets Power
2Sa Heating Energy
2Sa Lights & Sockets Energy

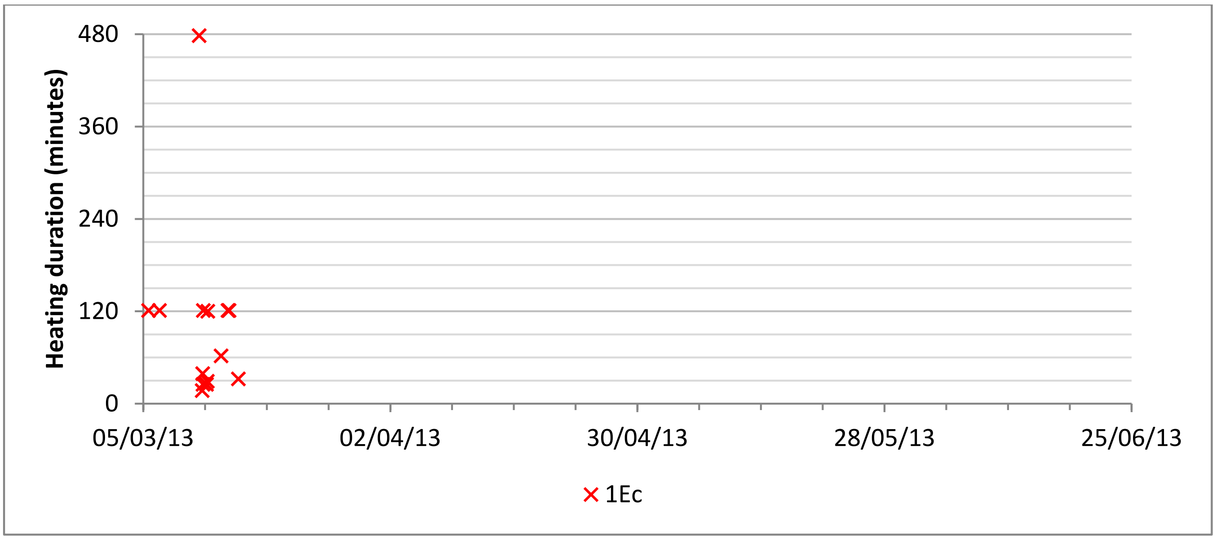

Electrical power use (W)
Electrical energy use (kWh)
2500
2000
1500
1000
500
0
100
80
60
40
20
0
04/03/13
01/04/13
29/04/13
27/05/13
24/06/13
2Sb Heating Power
2Sb Lights& Sockets Power
2Sb Heating Energy
2Sb Lights & Sockets Energy

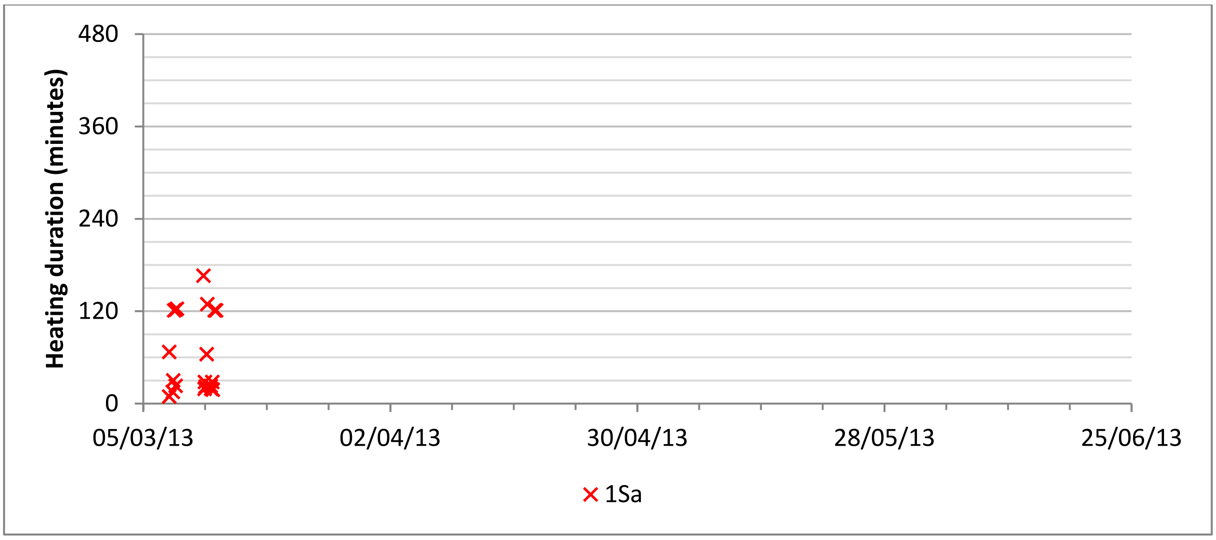

Electrical energy use (kWh)
200
150
100
50
0
Faulty heating and lighting meters, power data lost, only intermittent energy data
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
2Sc Heating Energy
2Sc Lights & Sockets Energy

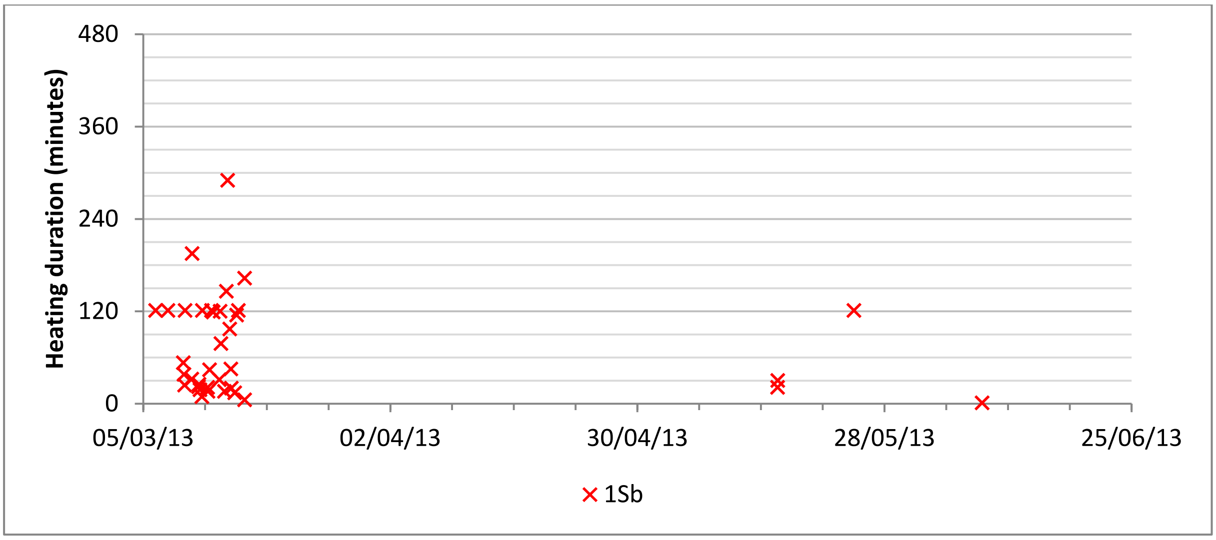
## Appendix N: Heating Durations and Heating Instances – Loughborough

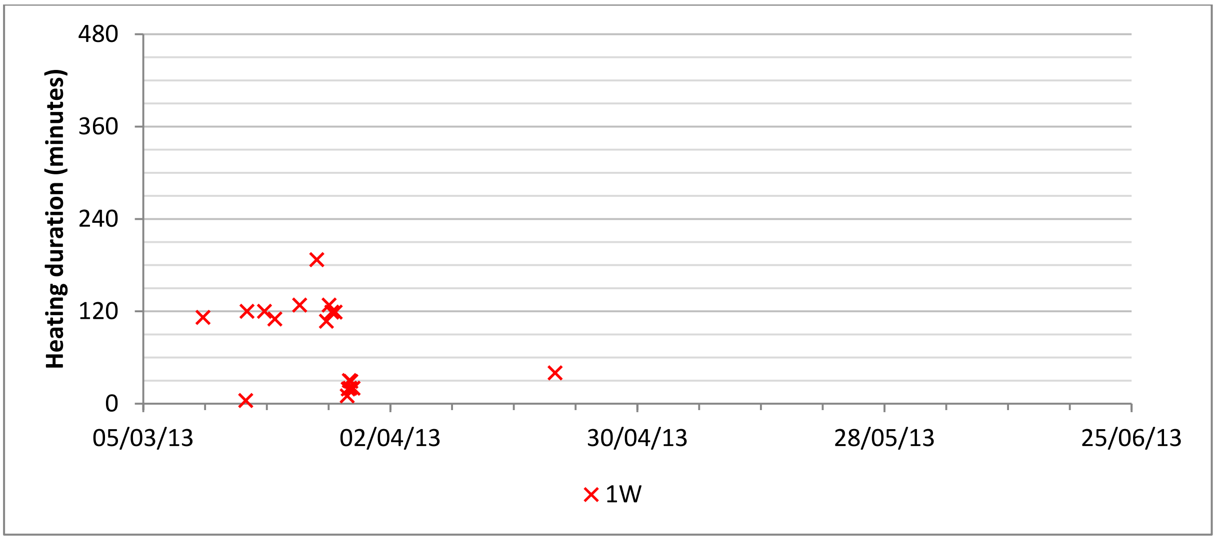


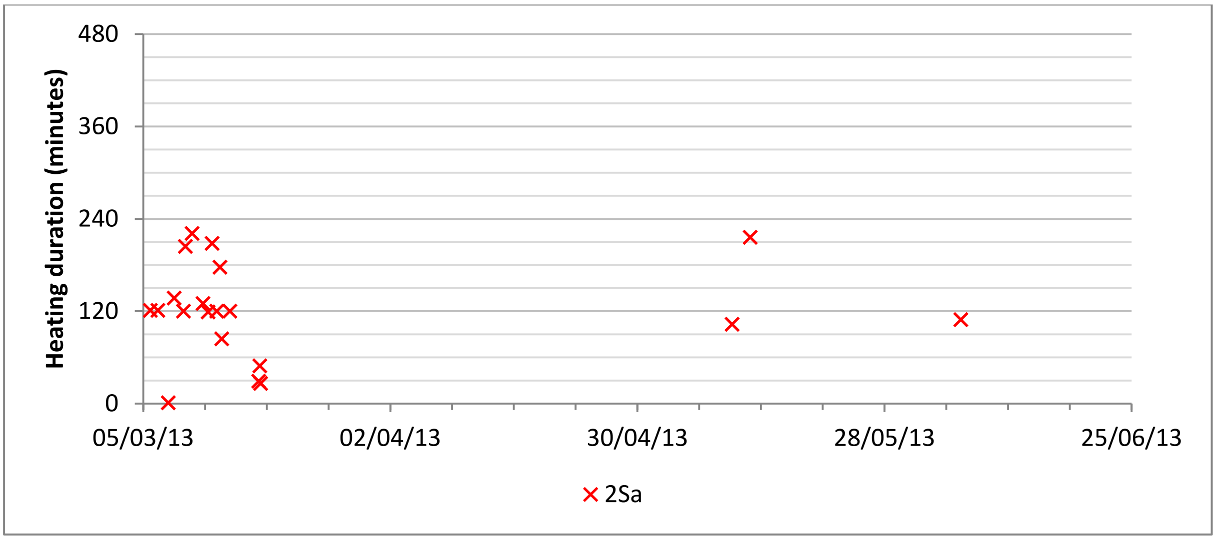



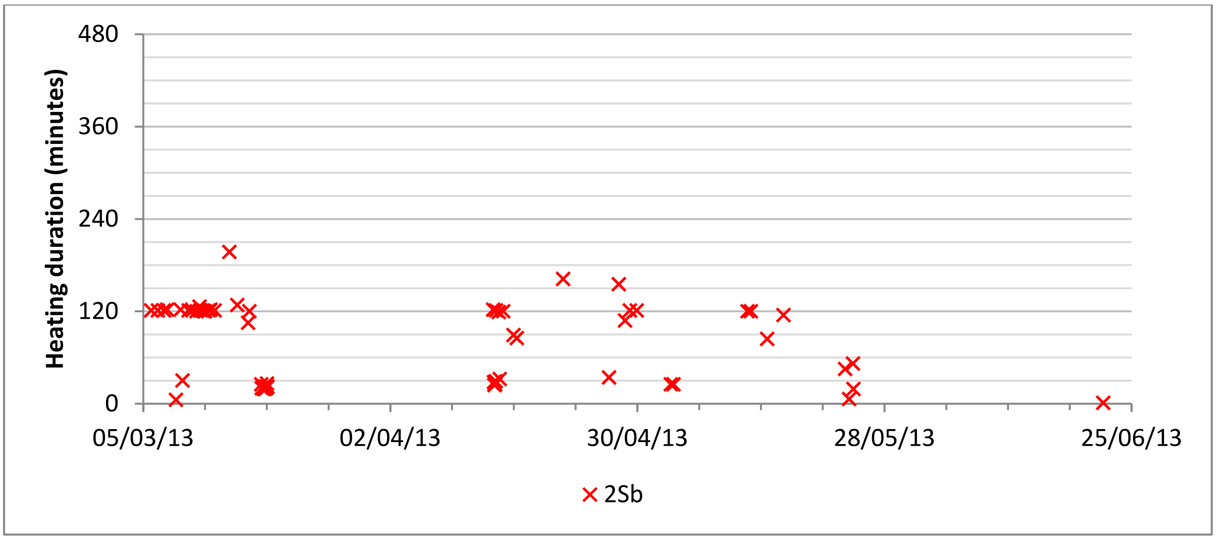



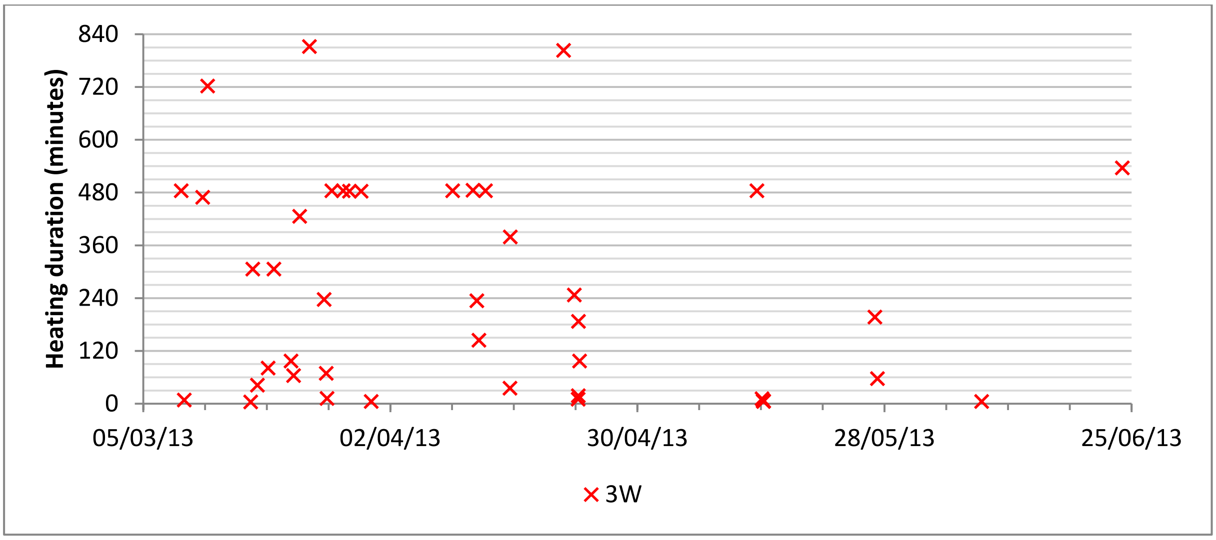

480
360
240
120
0
Heating duration (minutes)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Sa

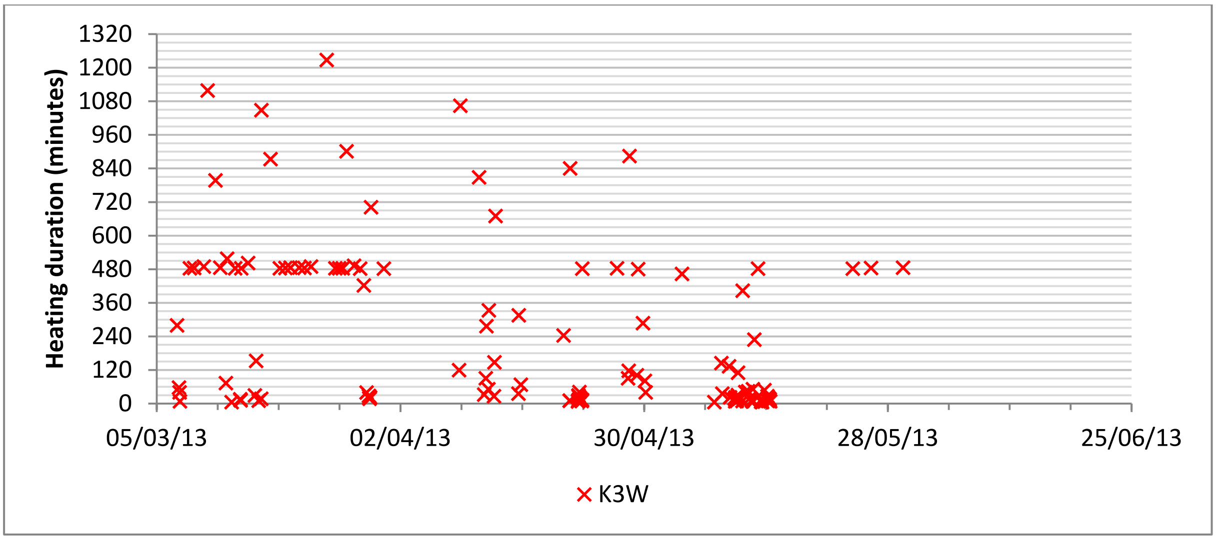

480
360
240
120
0
Heating duration (minutes)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Sb


480
360
240
120
0
Heating duration (minutes)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1W


Heating duration (minutes)
480
360
240
120
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
2Sa

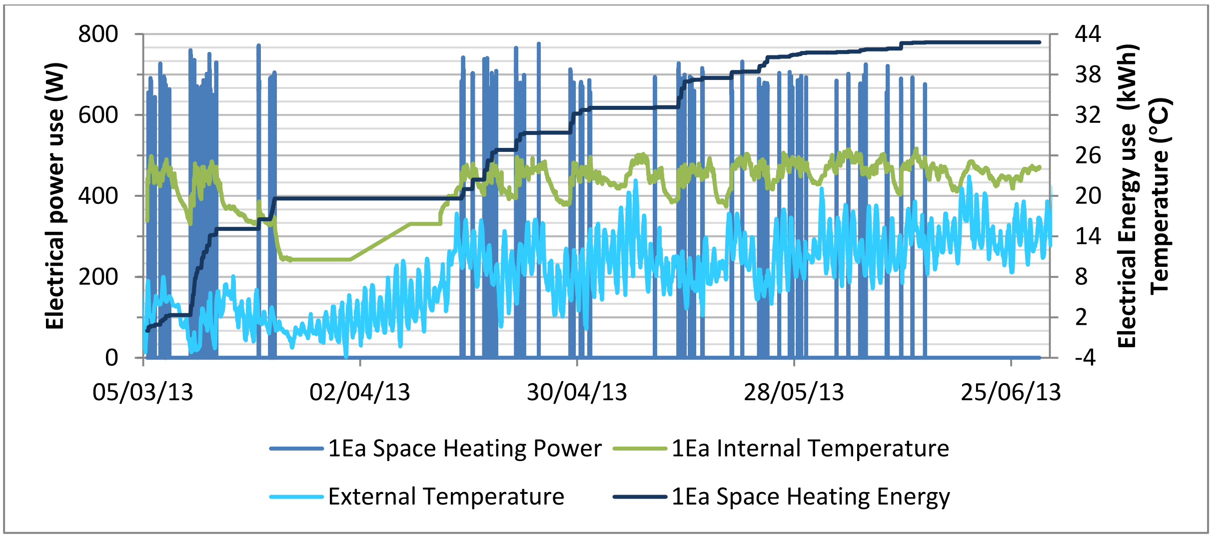

Heating duration (minutes)
480
360
240
120
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
2Sb

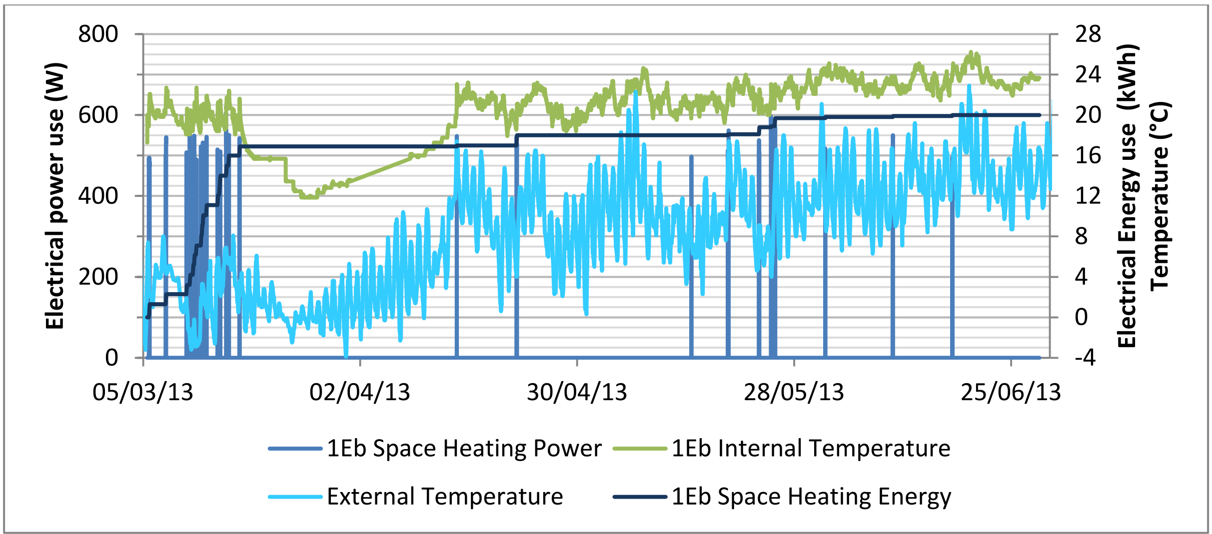

Heating duration (minutes)
840
720
600
480
360
240
120
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
3W

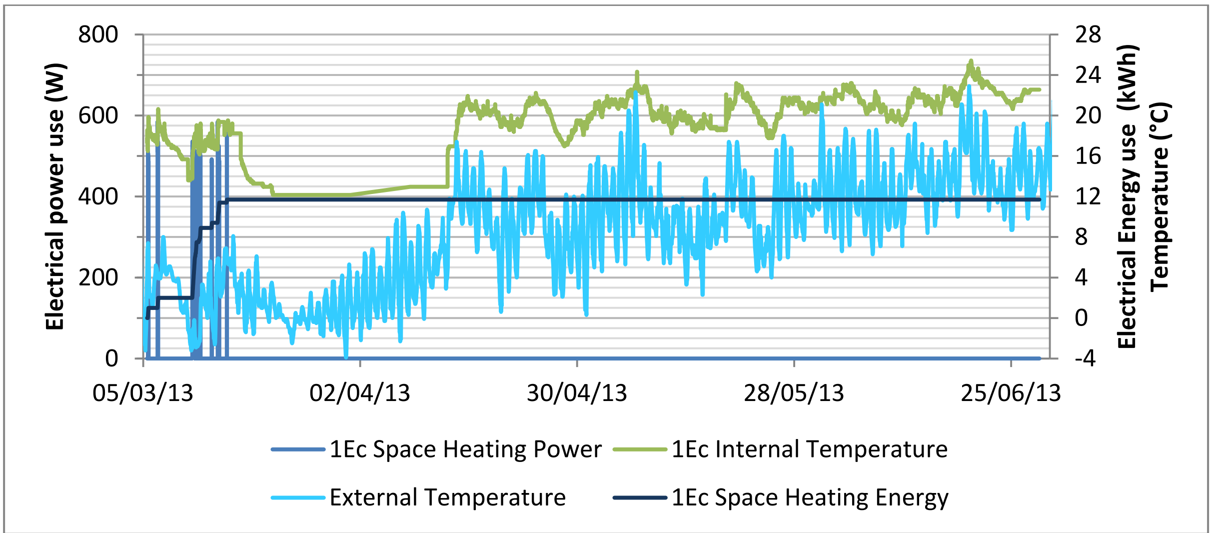


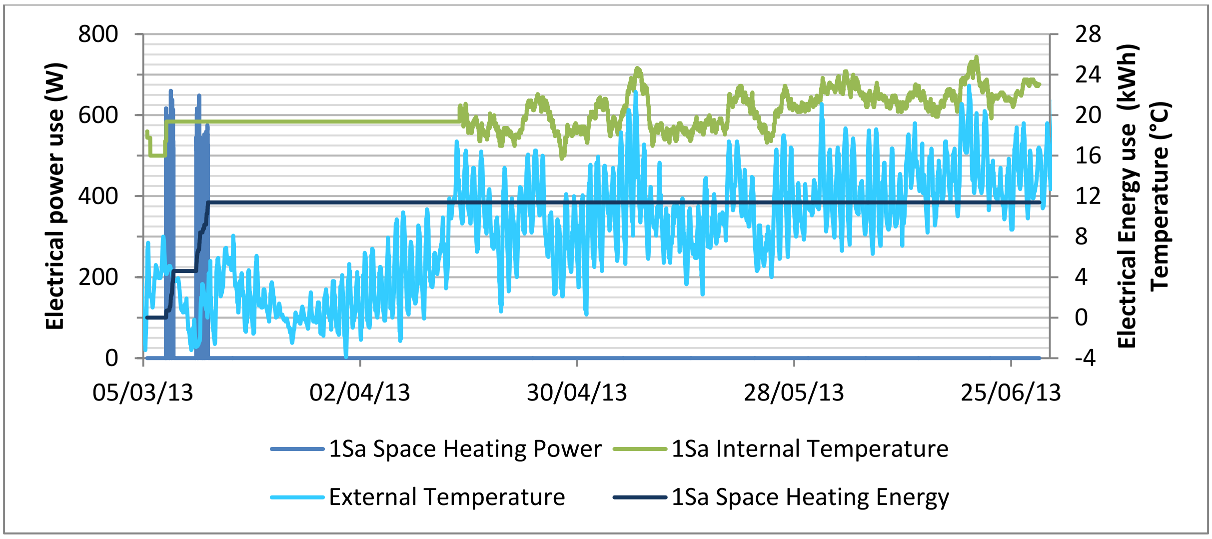
Heating duration (minutes)
1320
1200
1080
960
840
720
600
480
360
240
120
0
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
K3W

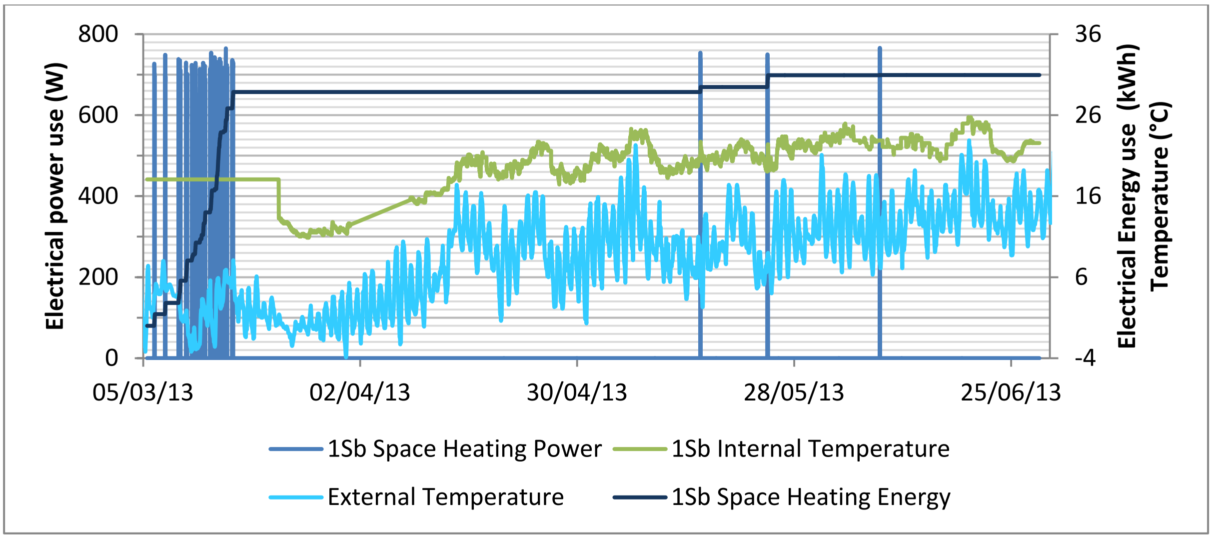
# Appendix O: Space Heating Electricity Use Data – Loughborough

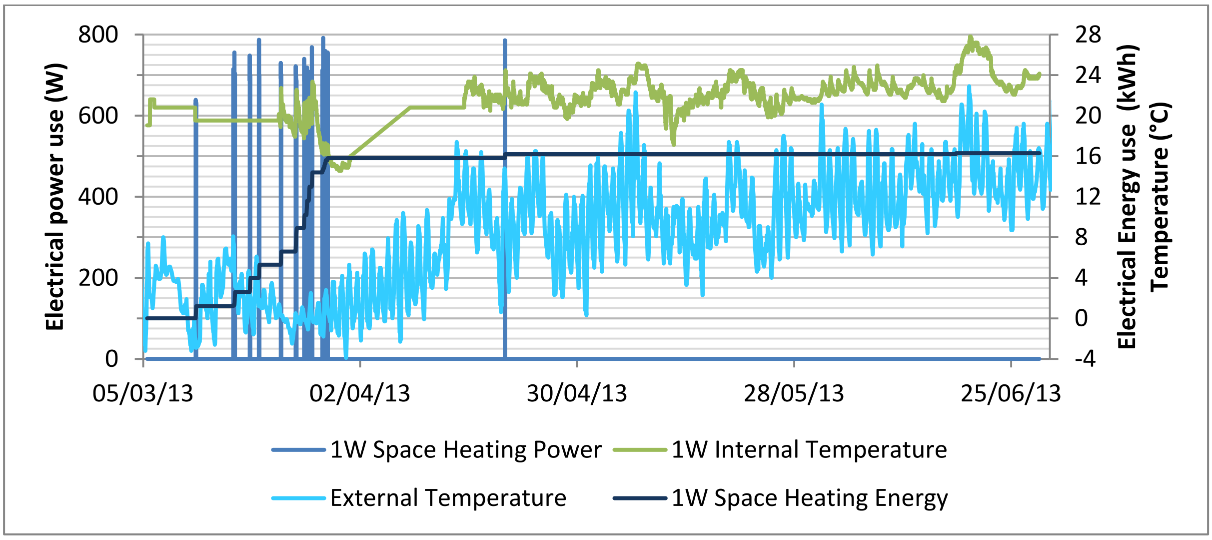


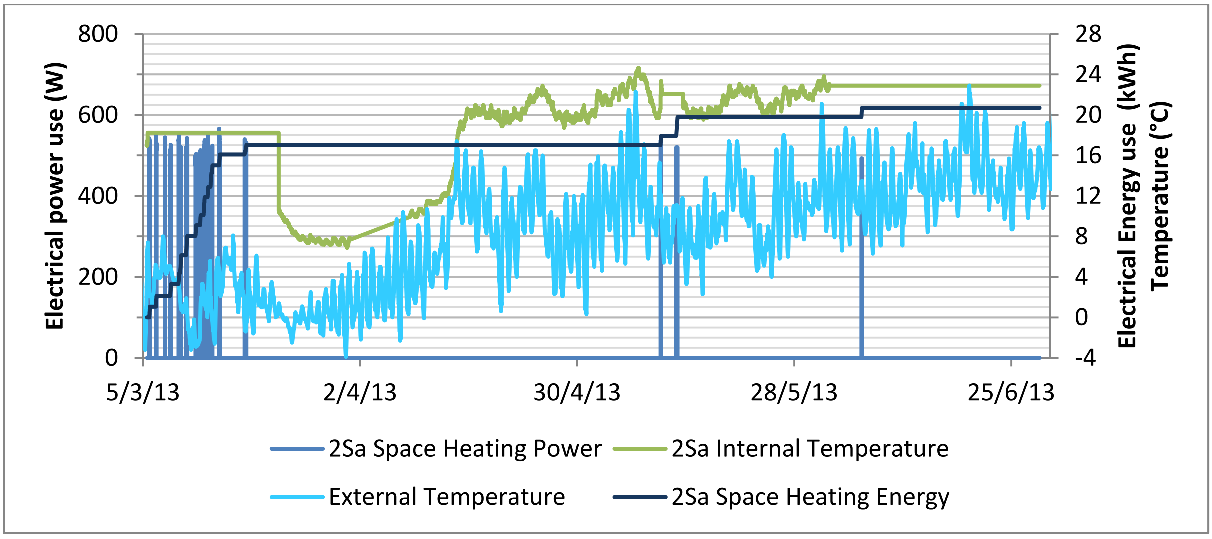



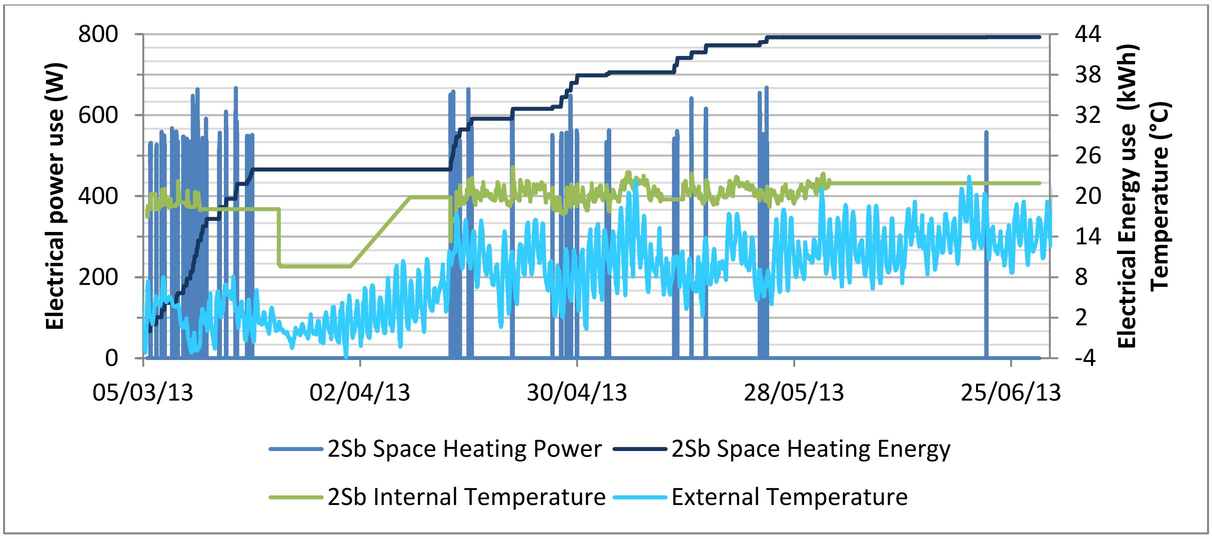

Electrical power use (W)
800
600
400
200
0
28
24
20
16
12
8
4
0
-4
Electrical Energy use (kWh)
Temperature (°C)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Sa Space Heating Power
1Sa Internal Temperature
External Temperature
1Sa Space Heating Energy


Electrical power use (W)
800
600
400
200
0
36
26
16
6
-4
Electrical Energy use (kWh)
Temperature (°C)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1Sb Space Heating Power
1Sb Internal Temperature
External Temperature
1Sb Space Heating Energy

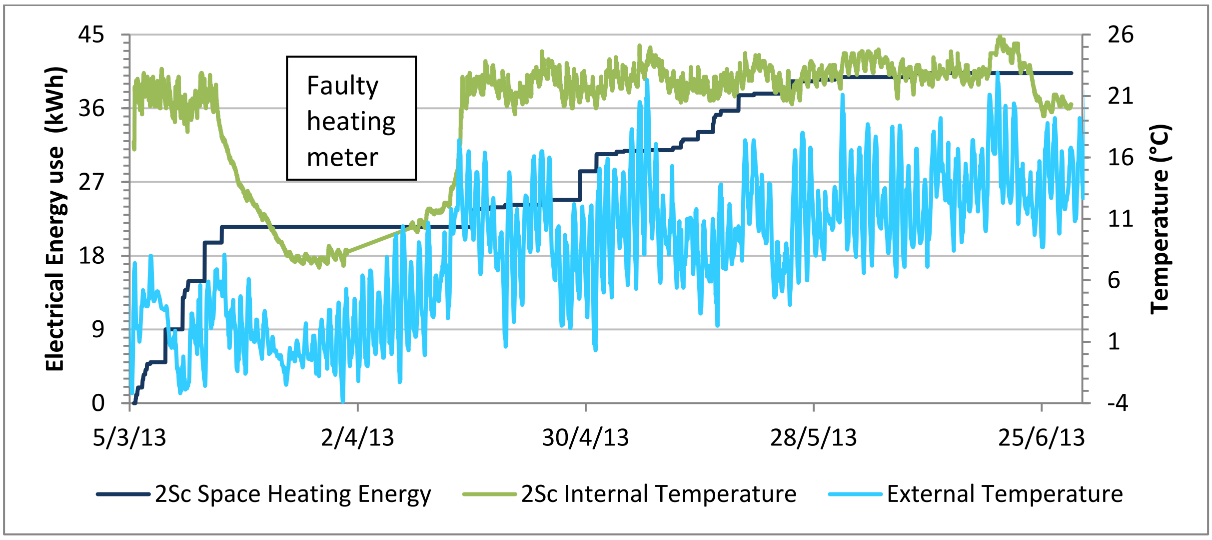

Electrical power use (W)
800
600
400
200
0
28
24
20
16
12
8
4
0
-4
Electrical Energy use (kWh)
Temperature (°C)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
1W Space Heating Power
1W Internal Temperature
External Temperature
1W Space Heating Energy



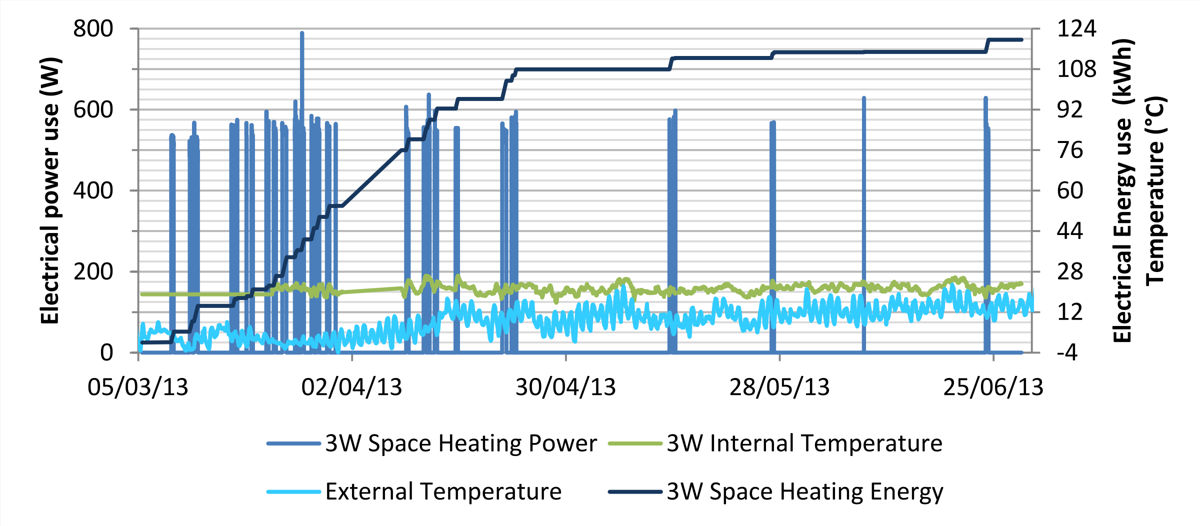
Electrical power use (W)
800
600
400
200
0
28
24
20
16
12
8
4
0
-4
Electrical Energy use (kWh)
Temperature (°C)
5/3/13
2/4/13
30/4/13
28/5/13
25/6/13
2Sa Space Heating Power
2Sa Internal Temperature
External Temperature
2Sa Space Heating Energy

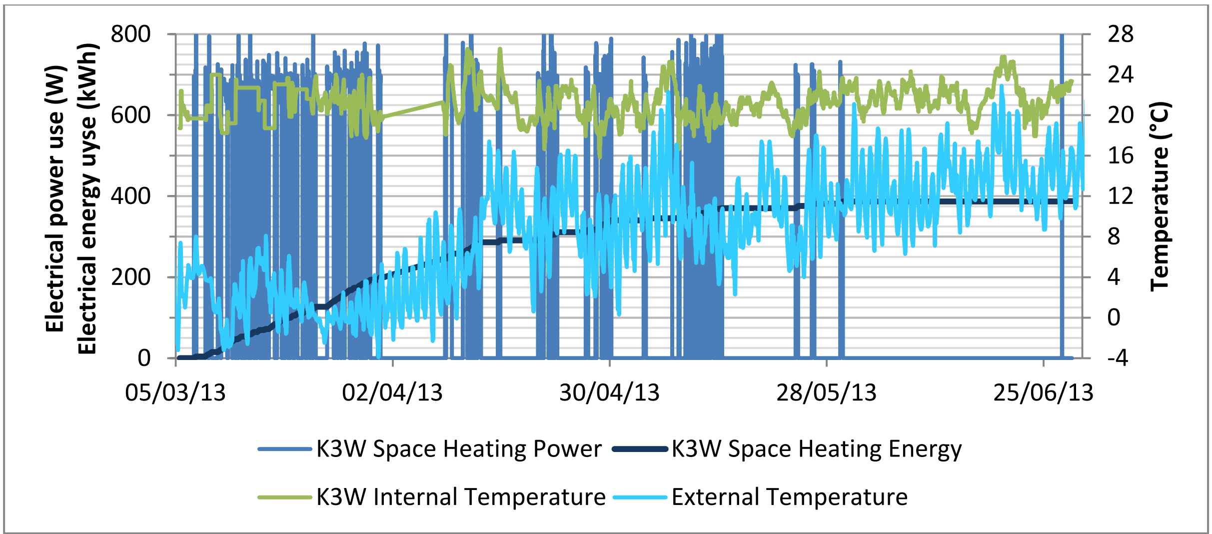



Electrical power use (W)
800
600
400
200
0
44
38
32
26
20
14
8
2
-4
Electrical Energy use (kWh)
Temperature (°C)
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
2Sb Space Heating Power
2Sb Space Heating Energy
2Sb Internal Temperature
External Temperature

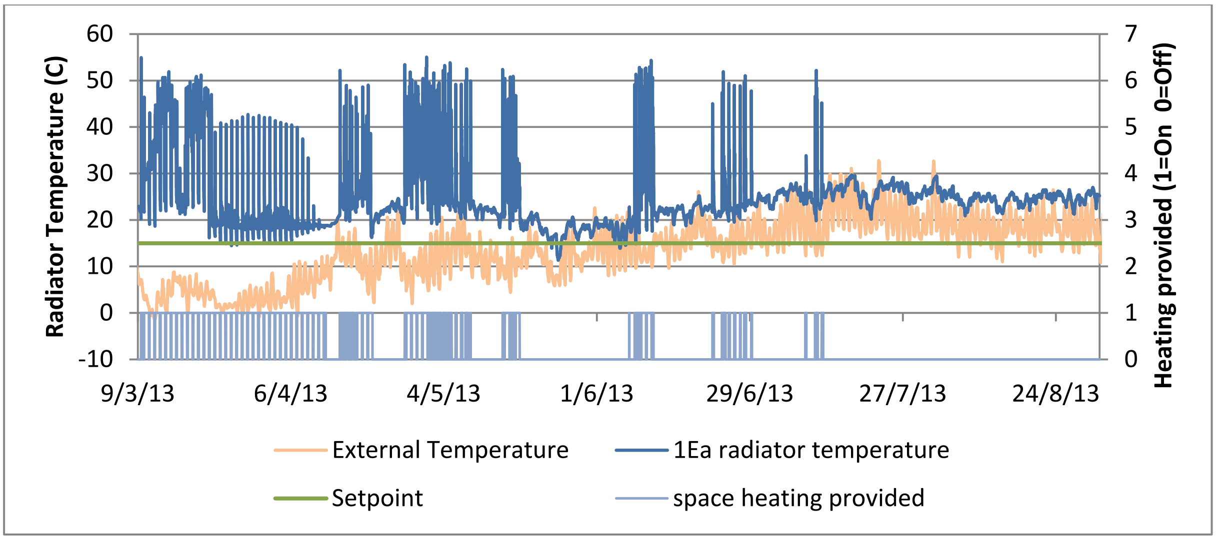



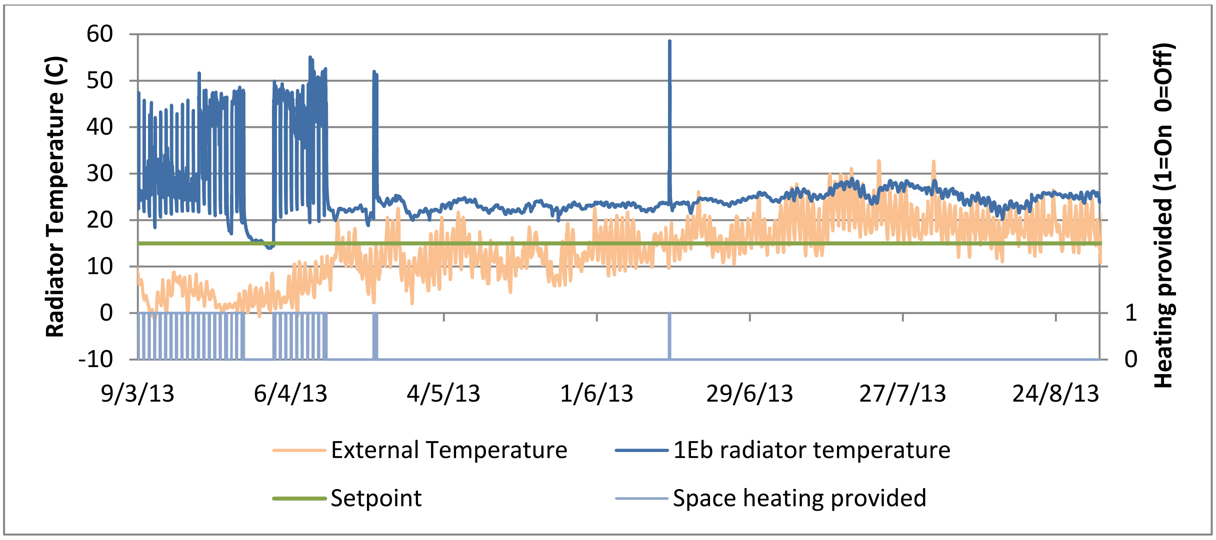
Electrical Energy use (kWh)
45
36
27
18
9
0
Faulty heating meter
26
21
16
11
6
1
-4
Temperature (°C)
5/3/13
2/4/13
30/4/13
28/5/13
25/6/13
2Sc Space Heating Energy
2Sc Internal Temperature
External Temperature

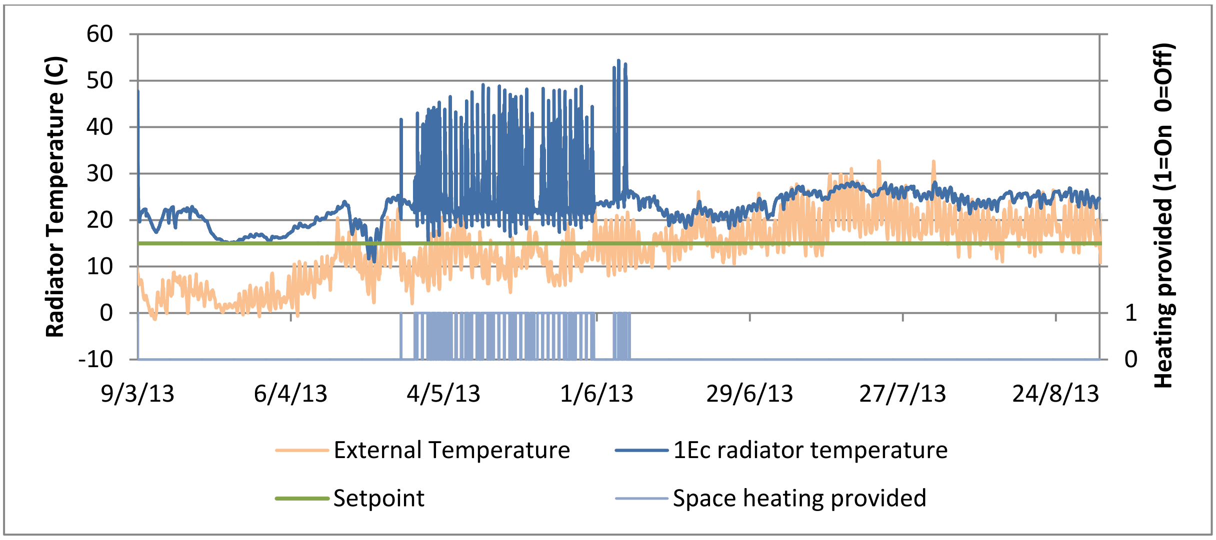

Electrical power use (W)
Electrical Energy use (kWh)
Temperature (°C)
800
600
400
200
0
124
108
92
76
60
44
28
12
-4
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
3W Space Heating Power
3W Internal Temperature
External Temperature
3W Space Heating Energy

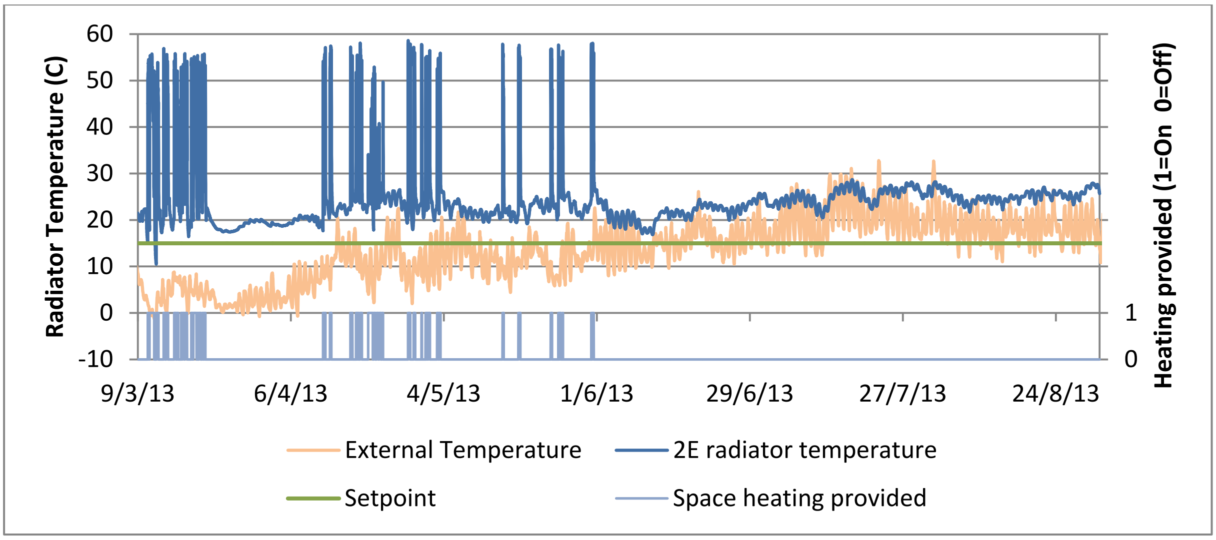

Electrical power use (W)
Electrical energy uyse (kWh)
Temperature (°C)
800
600
400
200
0
28
24
20
16
12
8
4
0
-4
05/03/13
02/04/13
30/04/13
28/05/13
25/06/13
K3W Space Heating Power
K3W Space Heating Energy
K3W Internal Temperature
External Temperature

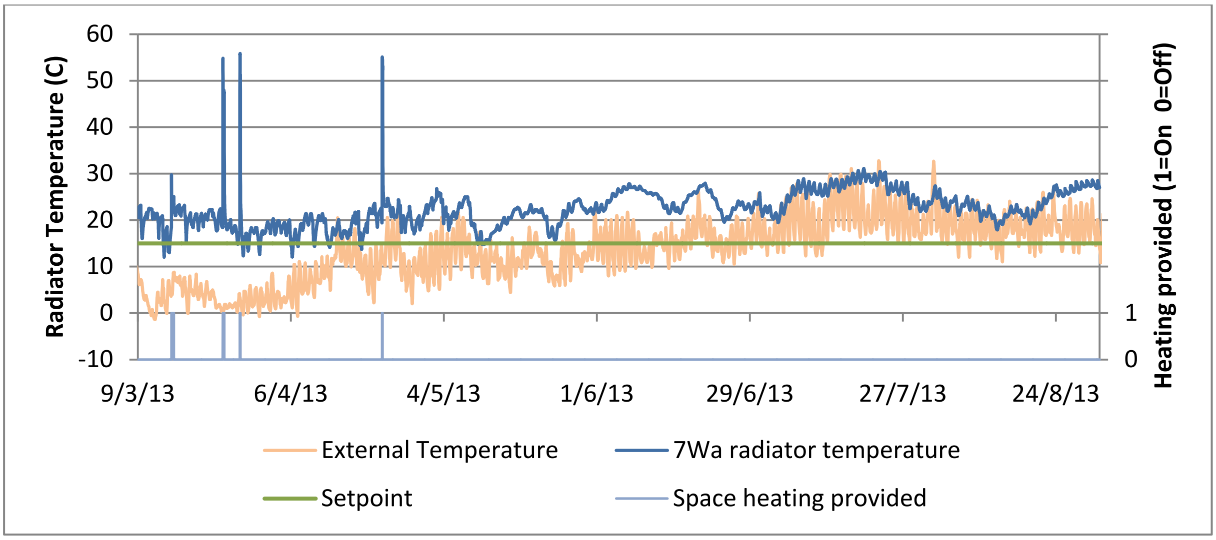
# Appendix P: London Radiator Surface Temperature Data – London

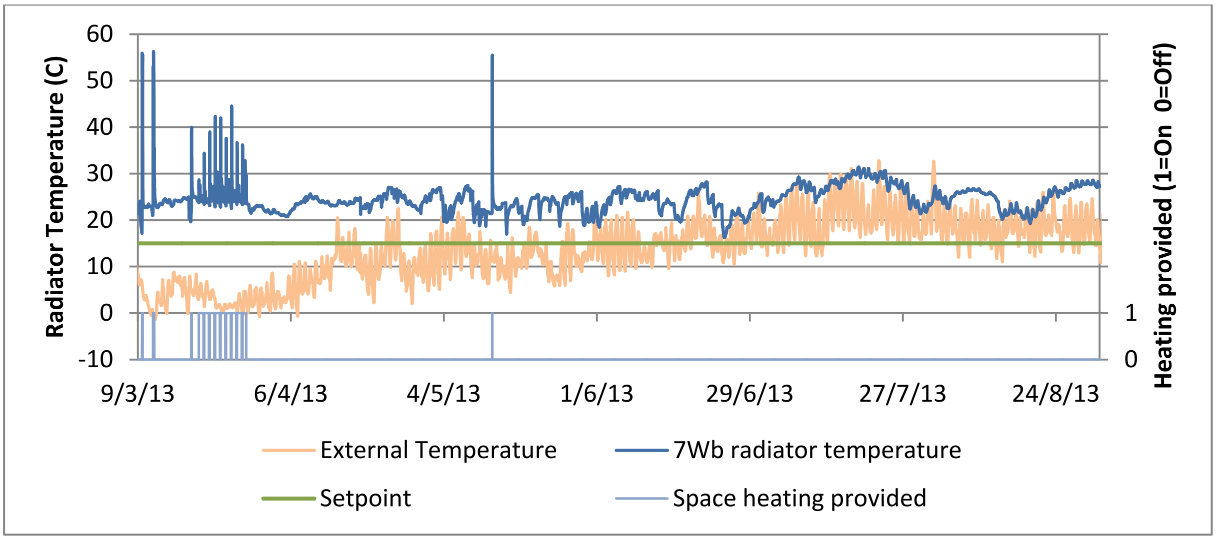


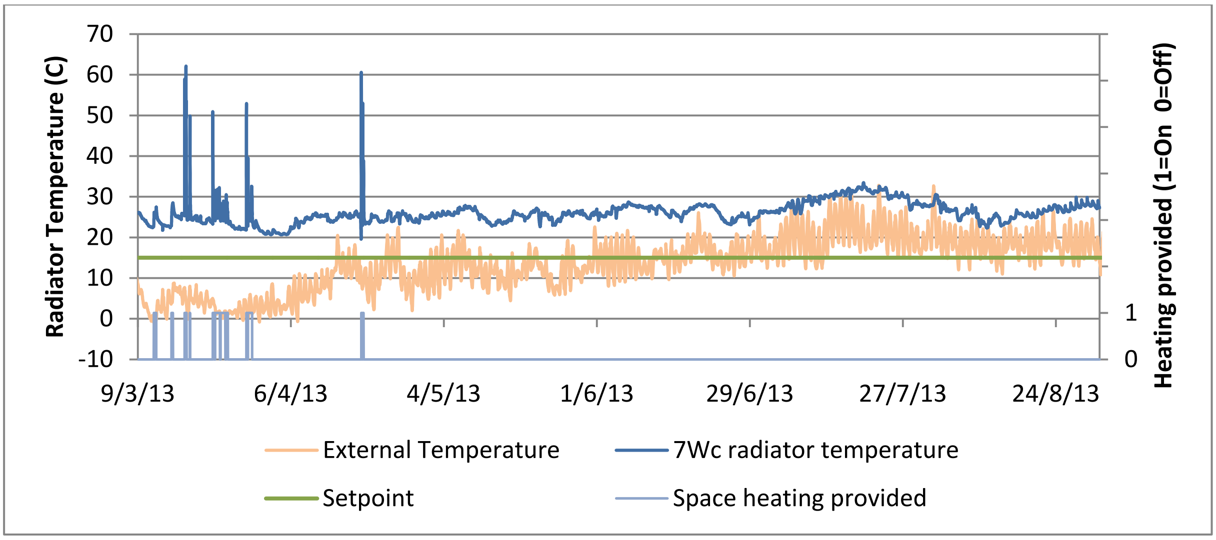



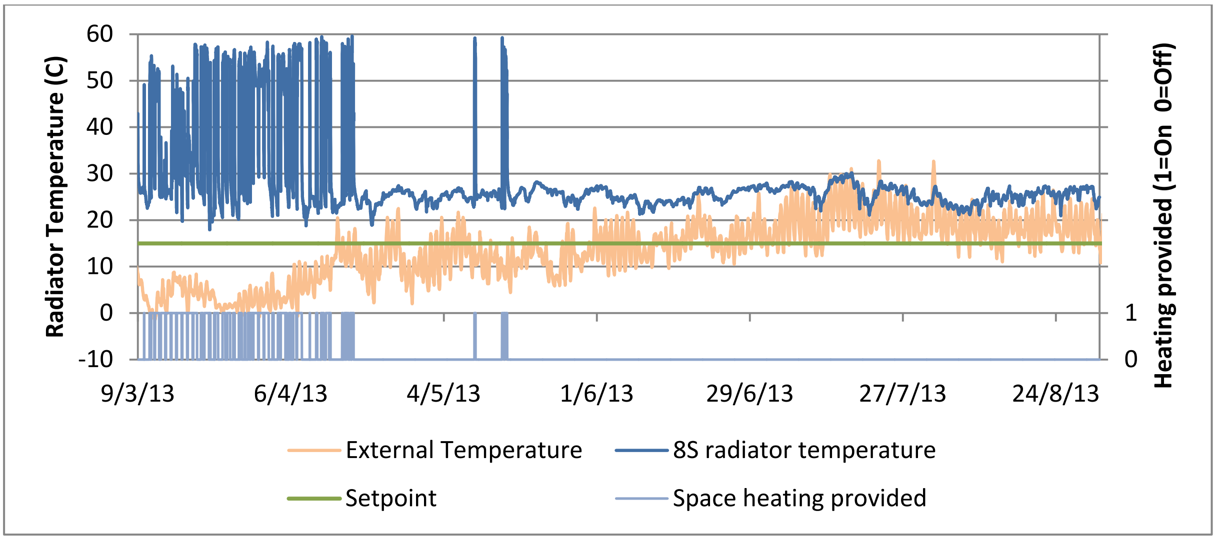

Radiator Temperature (C)
Heating provided (1=On 0=Off)
60
50
40
30
20
10
0
-10
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
2E radiator temperature
Setpoint
Space heating provided


Radiator Temperature (C)
Heating provided (1=On 0=Off)
60
50
40
30
20
10
0
-10
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
7Wa radiator temperature
Setpoint
Space heating provided

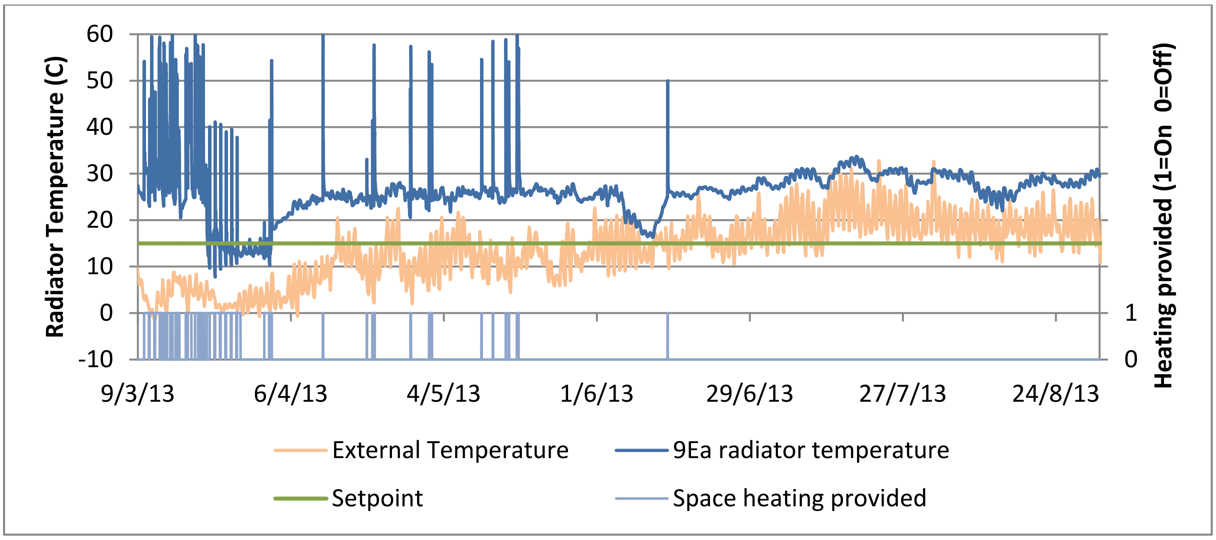

Radiator Temperature (C)
Heating provided (1=On 0=Off)
60
50
40
30
20
10
0
-10
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
7Wb radiator temperature
Setpoint
Space heating provided



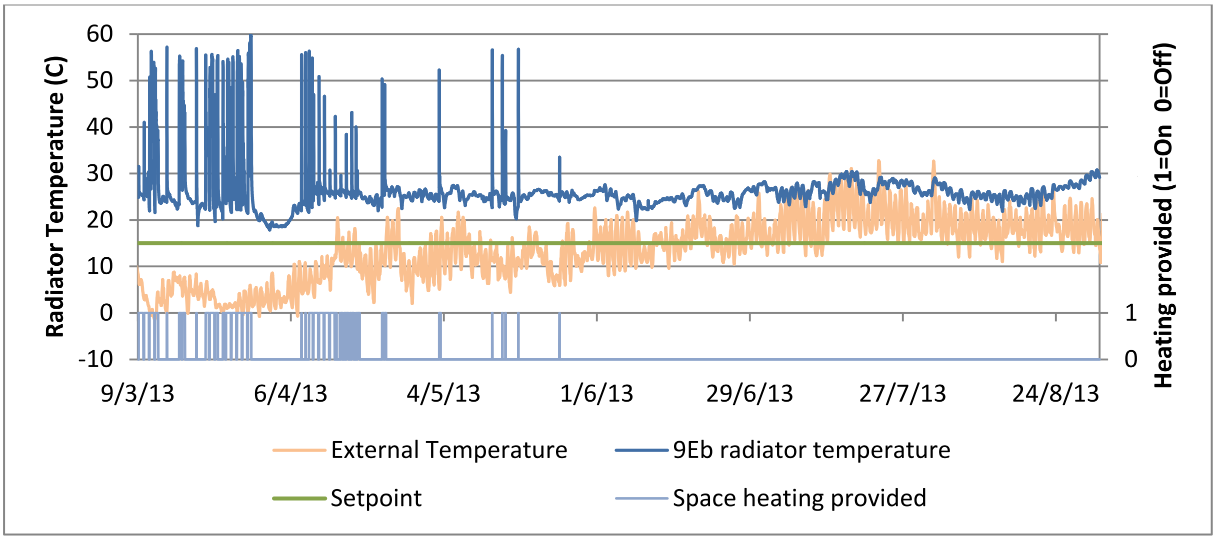
70
60
50
40
30
20
10
0
-10
Radiator Temperature (C)
Heating provided (1=On 0=Off)
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
7Wc radiator temperature
Setpoint
Space heating provided

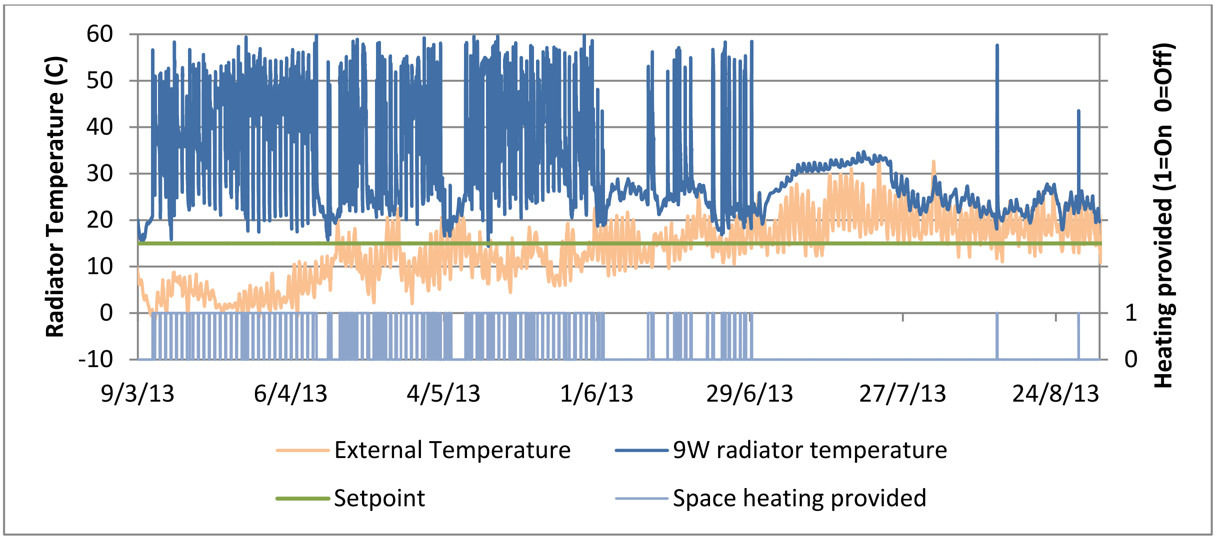
60
50
40
30
20
10
0
-10
Radiator Temperature (C)
Heating provided (1=On 0=Off)
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
8S radiator temperature
Setpoint
Space heating provided

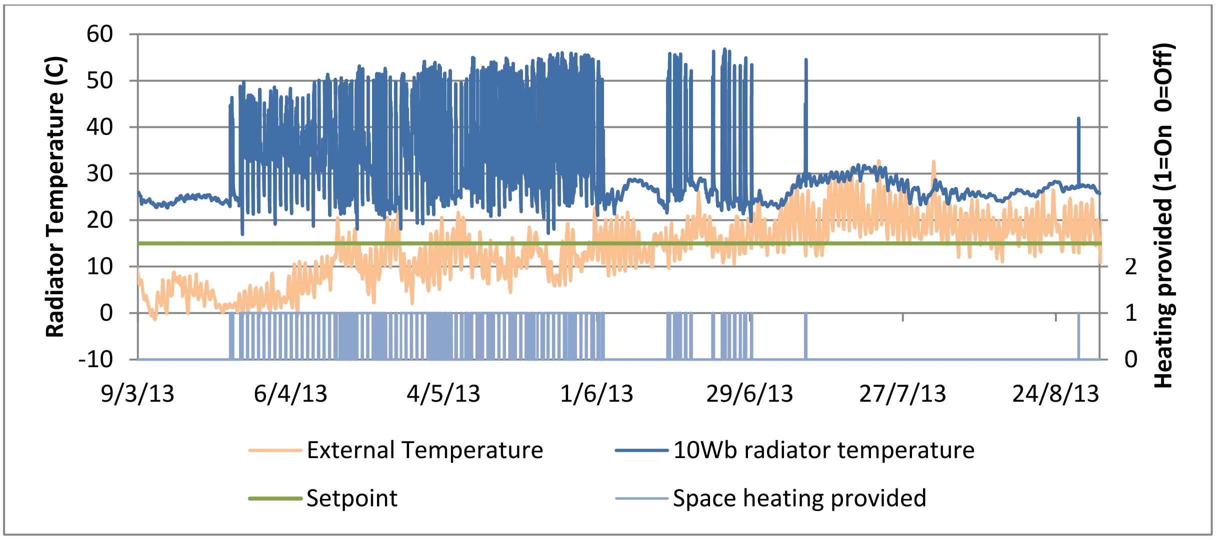
60
50
40
30
20
10
0
-10
Radiator Temperature (C)
Heating provided (1=On 0=Off)
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
9Ea radiator temperature
Setpoint
Space heating provided



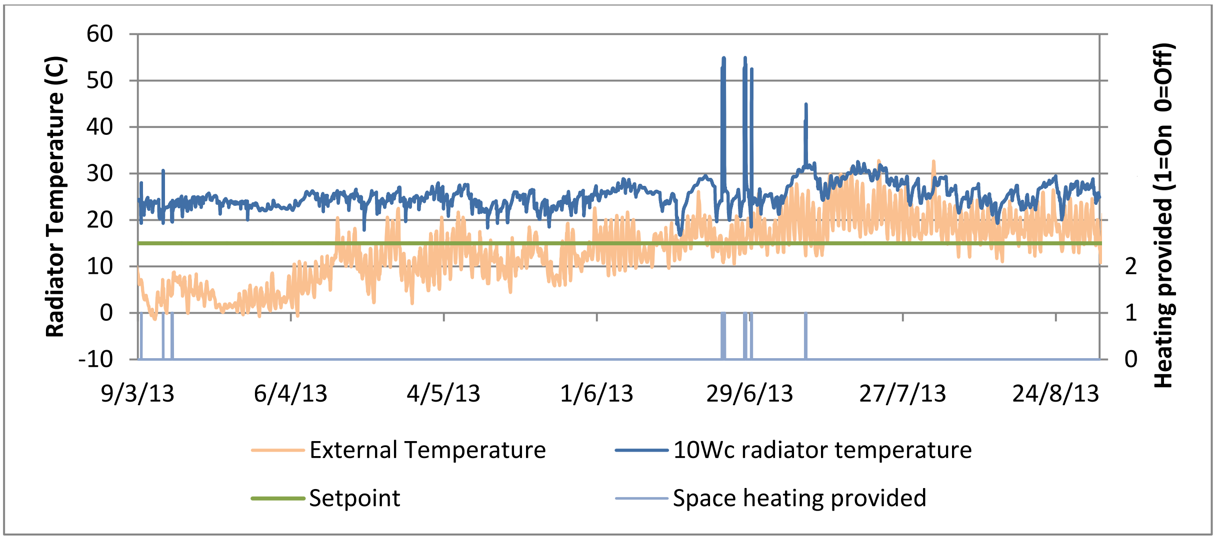
Radiator Temperature (C)
Heating provided (1=On 0=Off)
60
50
40
30
20
10
0
-10
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
9Eb radiator temperature
Setpoint
Space heating provided

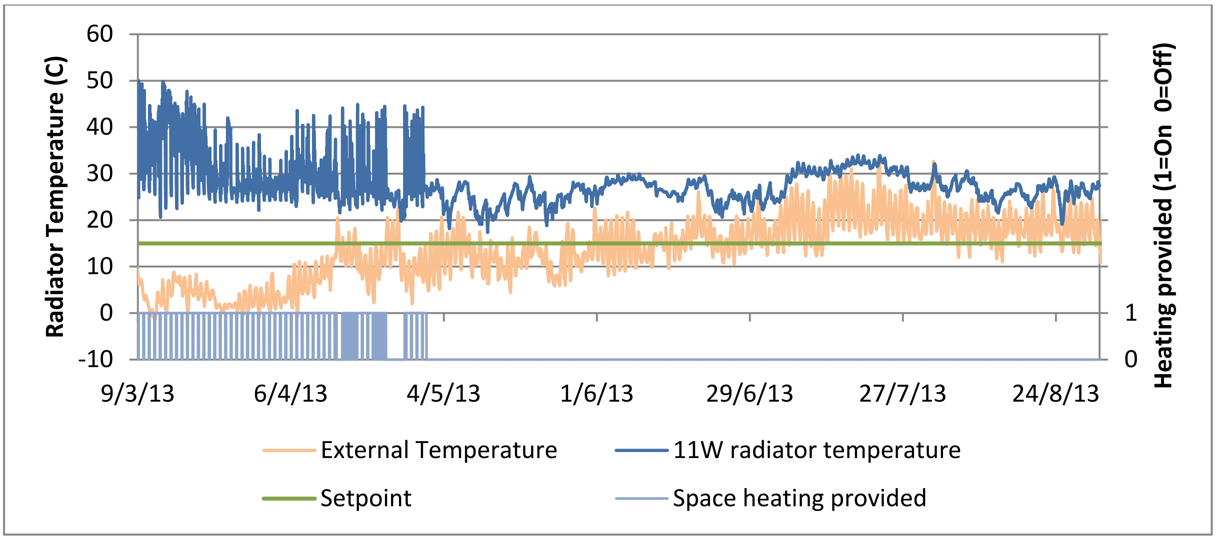
Radiator Temperature (C)
Heating provided (1=On 0=Off)
60
50
40
30
20
10
0
-10
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
9W radiator temperature
Setpoint
Space heating provided

Radiator Temperature (C)
Heating provided (1=On 0=Off)
60
50
40
30
20
10
0
-10
2
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
10Wb radiator temperature
Setpoint
Space heating provided

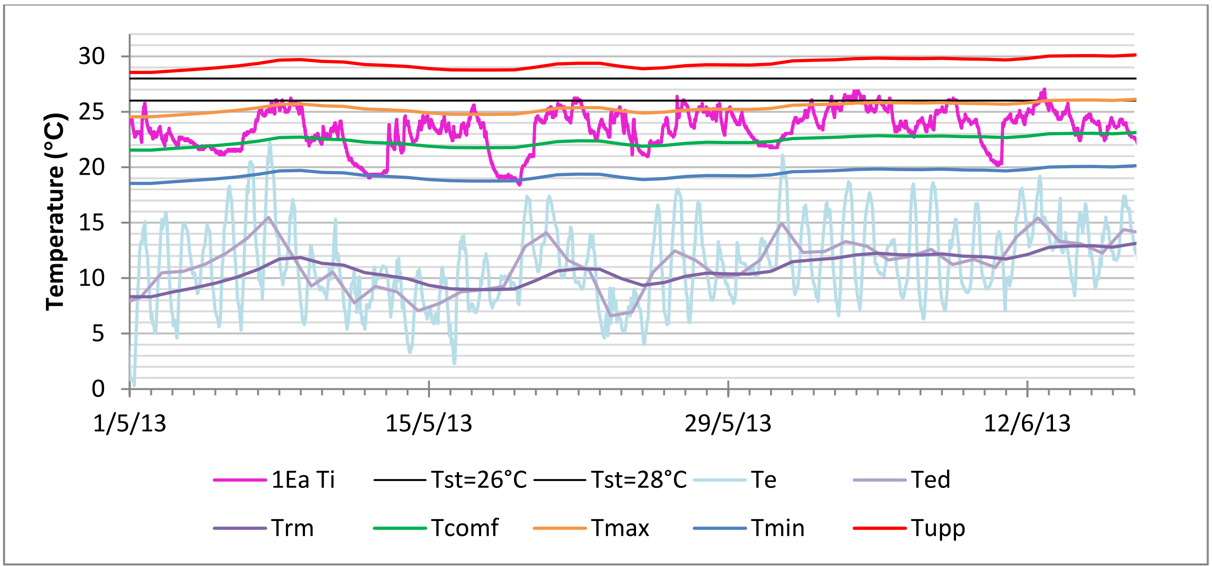


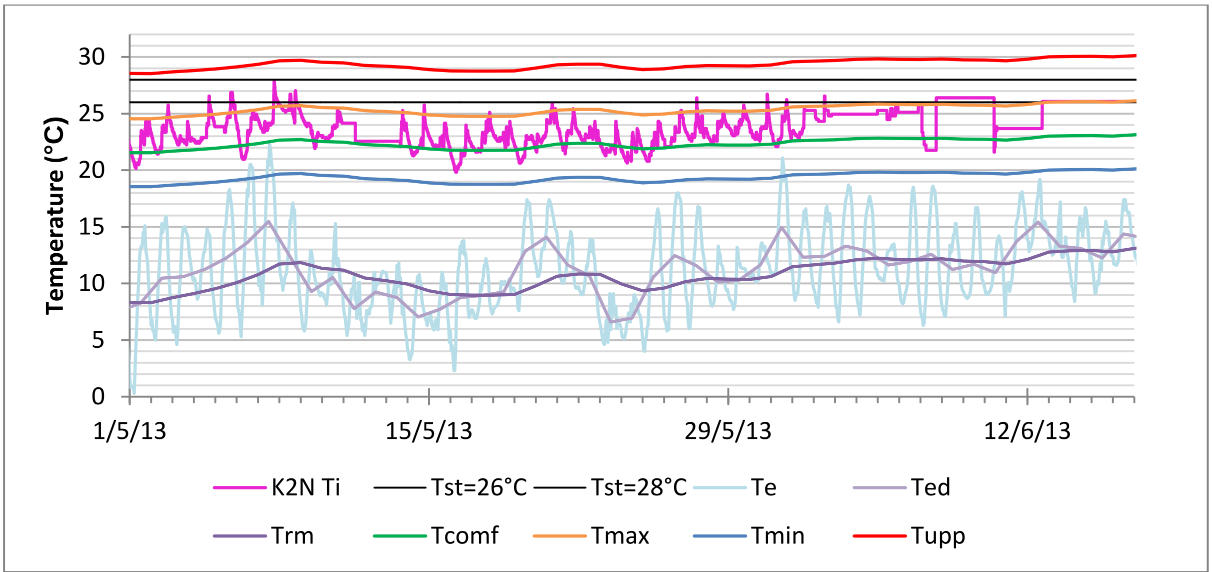
Radiator Temperature (C)
Heating provided (1=On 0=Off)
60
50
40
30
20
10
0
-10
2
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
10Wc radiator temperature
Setpoint
Space heating provided

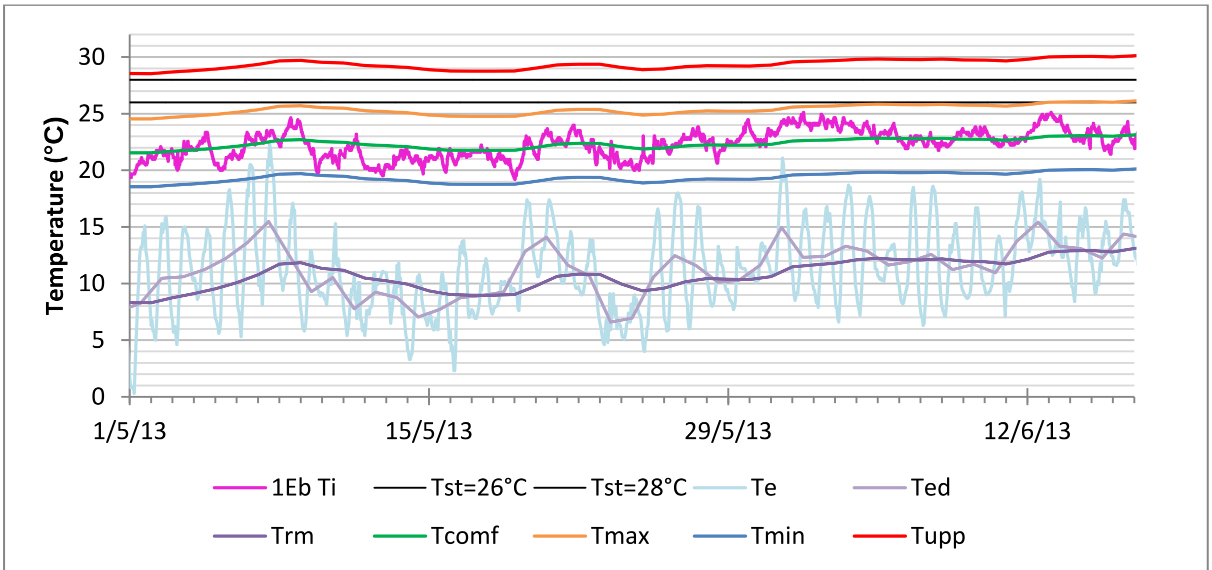



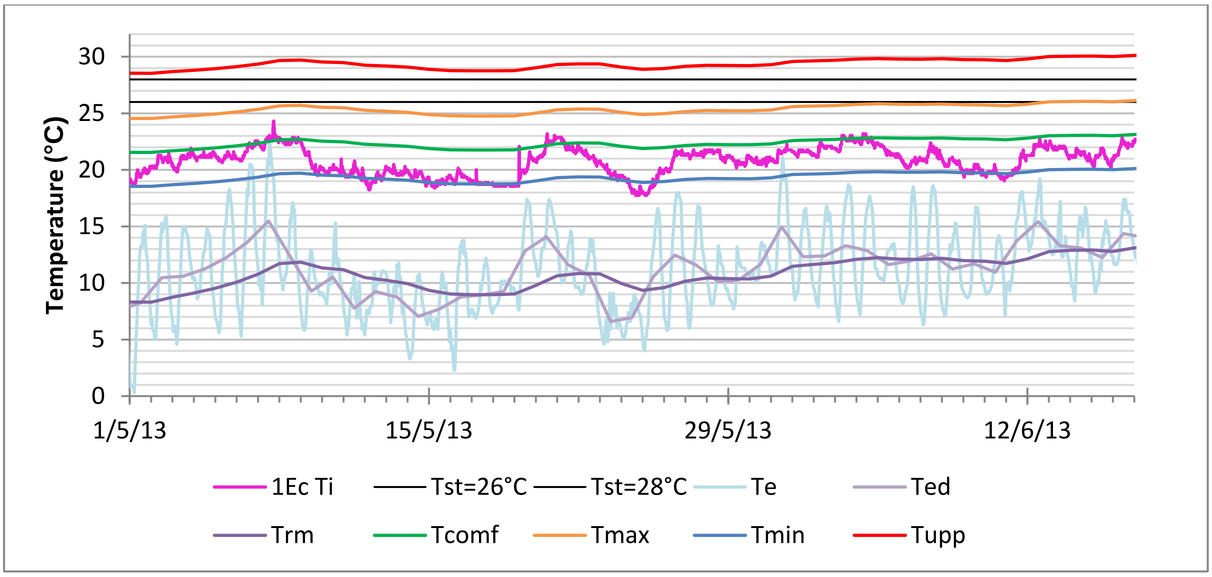
Radiator Temperature (C)
Heating provided (1=On 0=Off)
60
50
40
30
20
10
0
-10
1
0
9/3/13
6/4/13
4/5/13
1/6/13
29/6/13
27/7/13
24/8/13
External Temperature
11W radiator temperature
Setpoint
Space heating provided

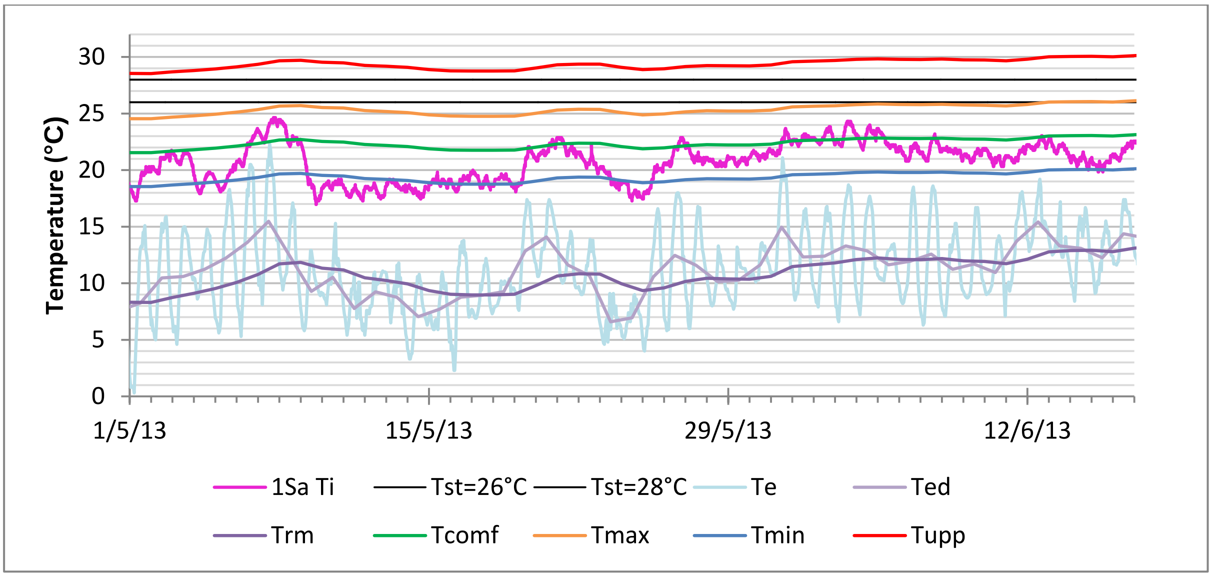
# Appendix Q: Overheating Results: May-June 2013 – Loughborough

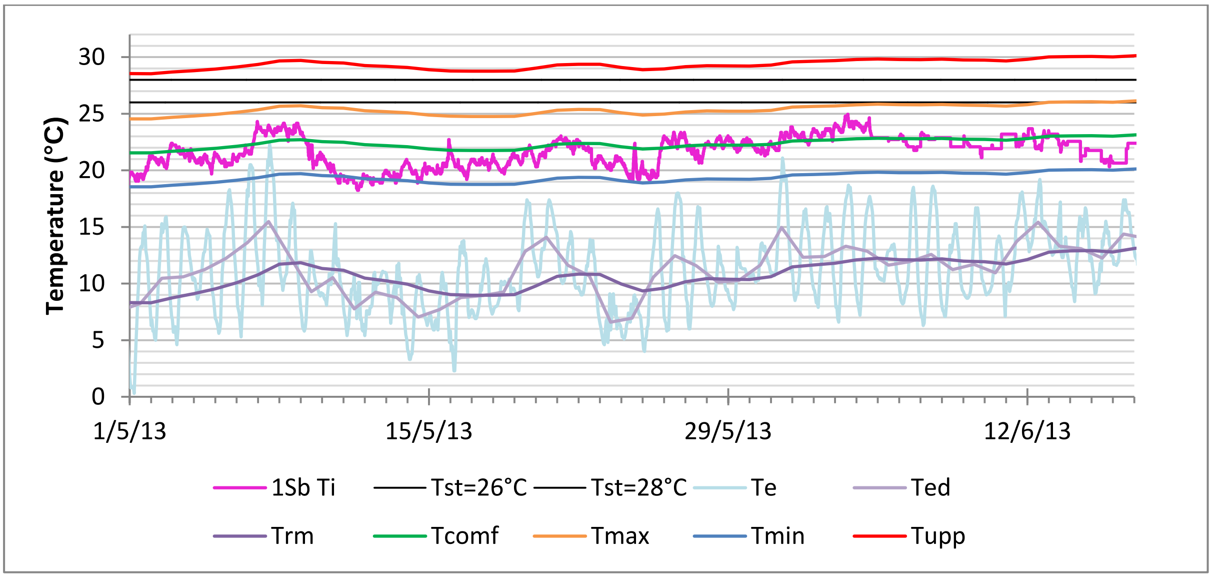


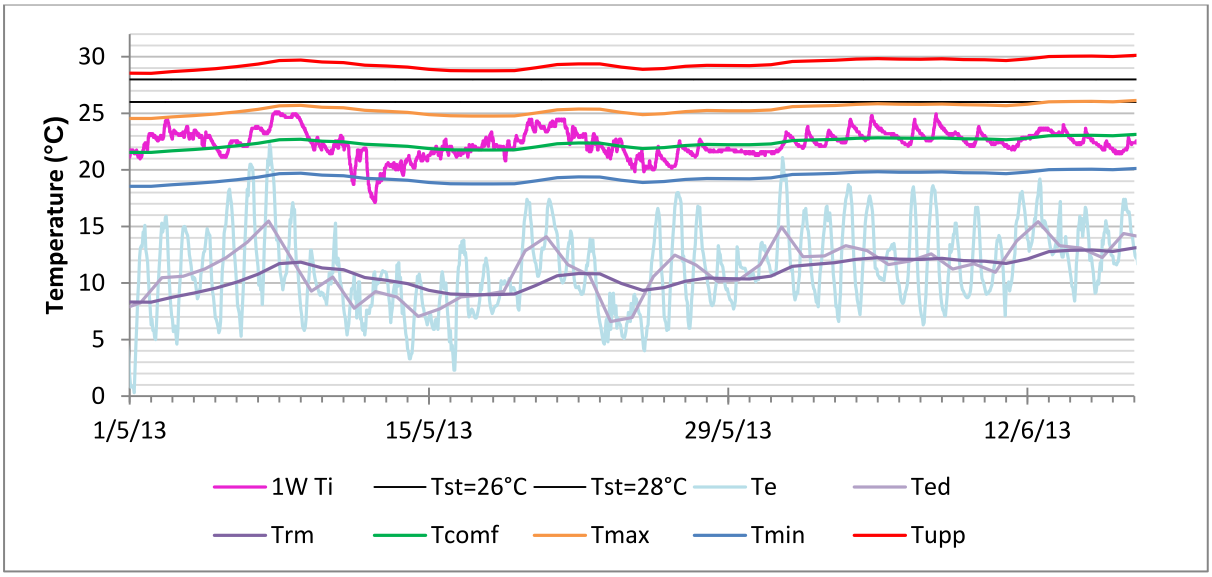



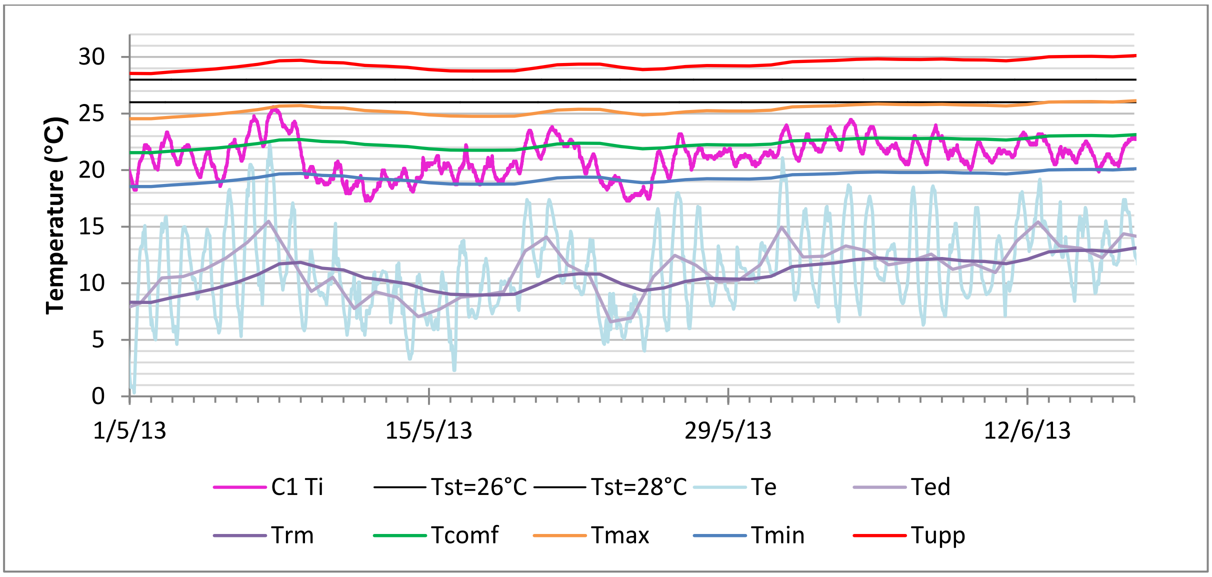



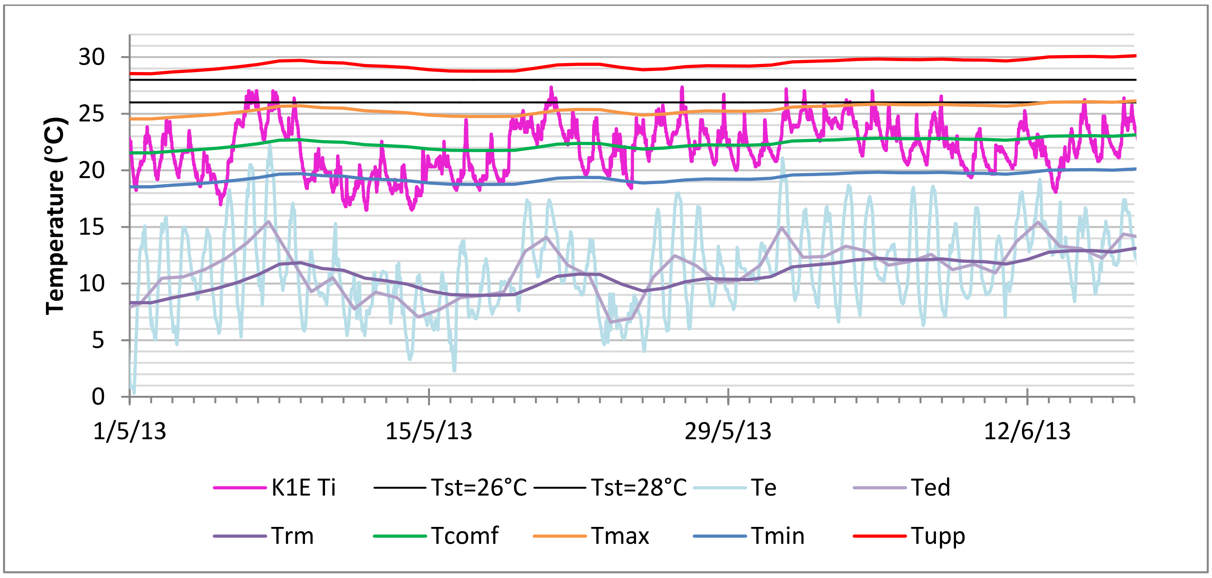

Temperature (°C)
30
25
20
15
10
5
0
1/5/13
15/5/13
29/5/13
12/6/13
1Ec Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

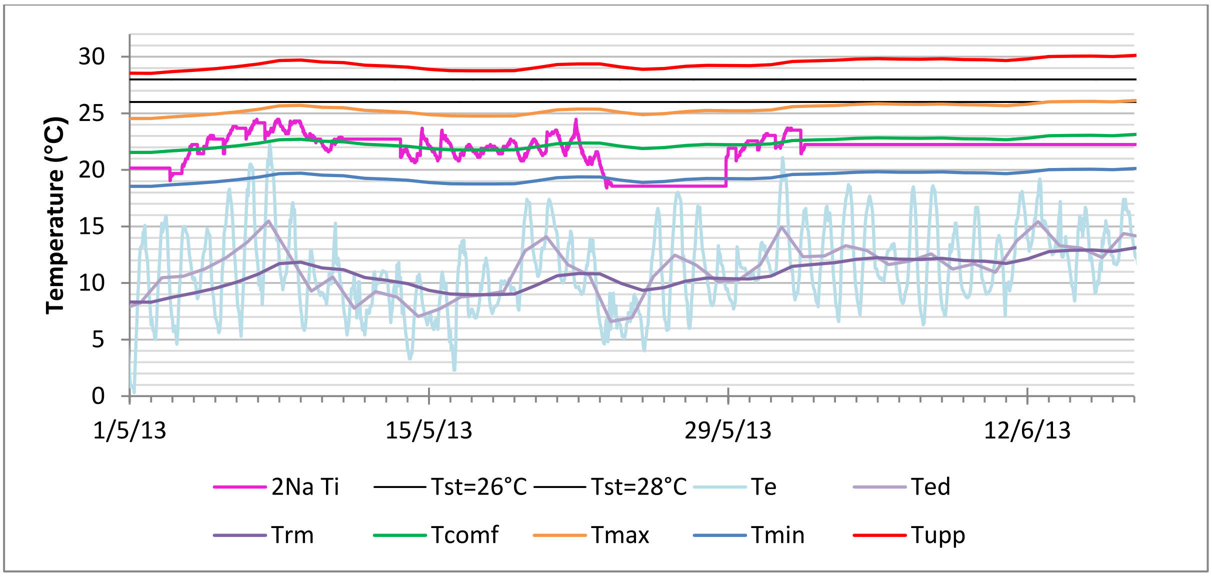

Temperature (°C)
30
25
20
15
10
5
0
1/5/13
15/5/13
29/5/13
12/6/13
1Sa Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp


Temperature (°C)
30
25
20
15
10
5
0
1/5/13
15/5/13
29/5/13
12/6/13
1Sb Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

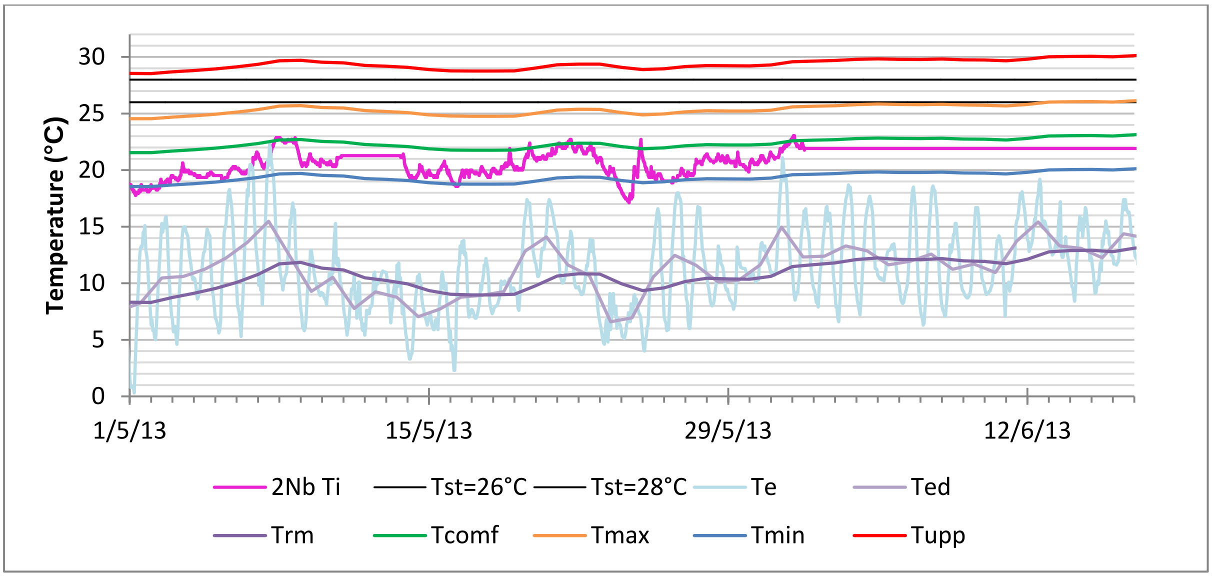

Temperature (°C)
30
25
20
15
10
5
0
1/5/13
15/5/13
29/5/13
12/6/13
1W Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp


Temperature (°C)
30
25
20
15
10
5
0
1/5/13
15/5/13
29/5/13
12/6/13
C1 Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

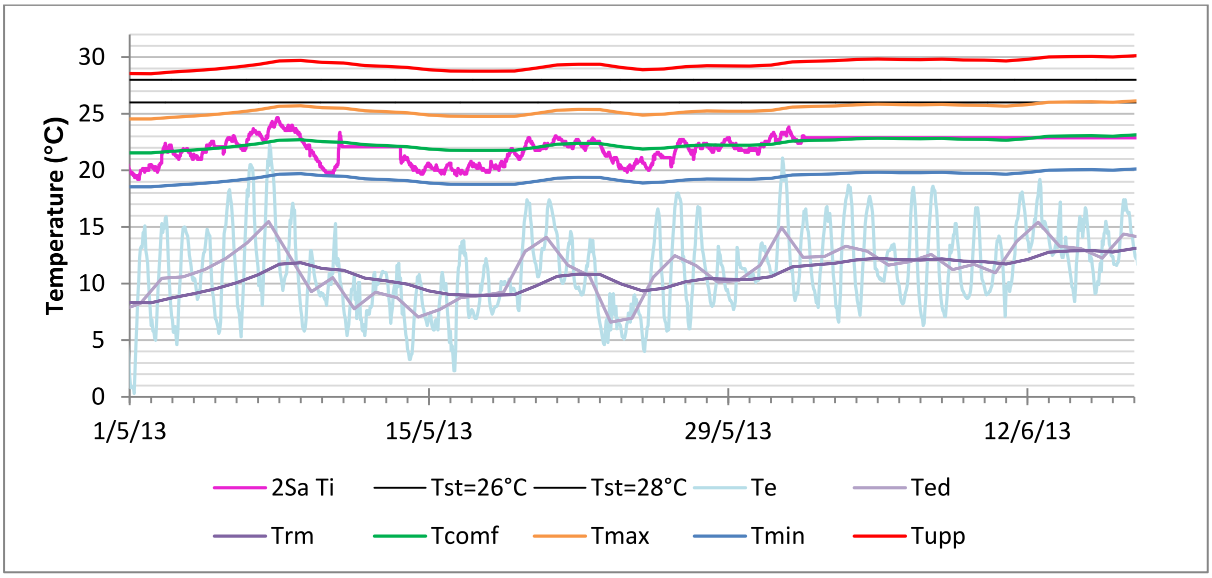

Temperature (°C)
30
25
20
15
10
5
0
1/5/13
15/5/13
29/5/13
12/6/13
K1E Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp



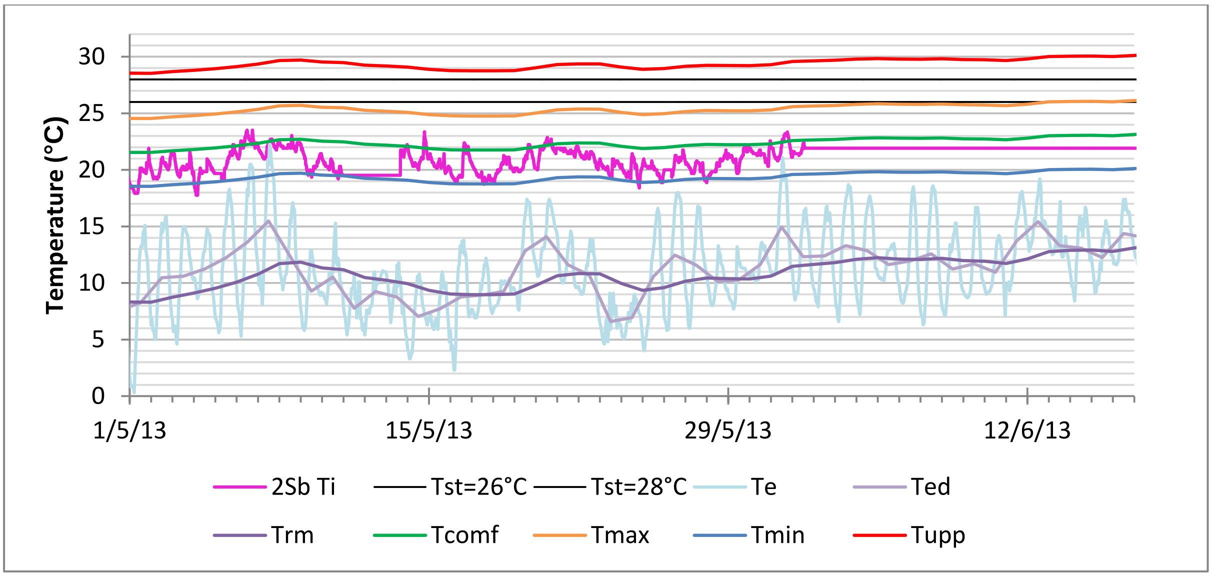
Temperature (°C)
30
25
20
15
10
5
0
1/5/13
15/5/13
29/5/13
12/6/13
2Na Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

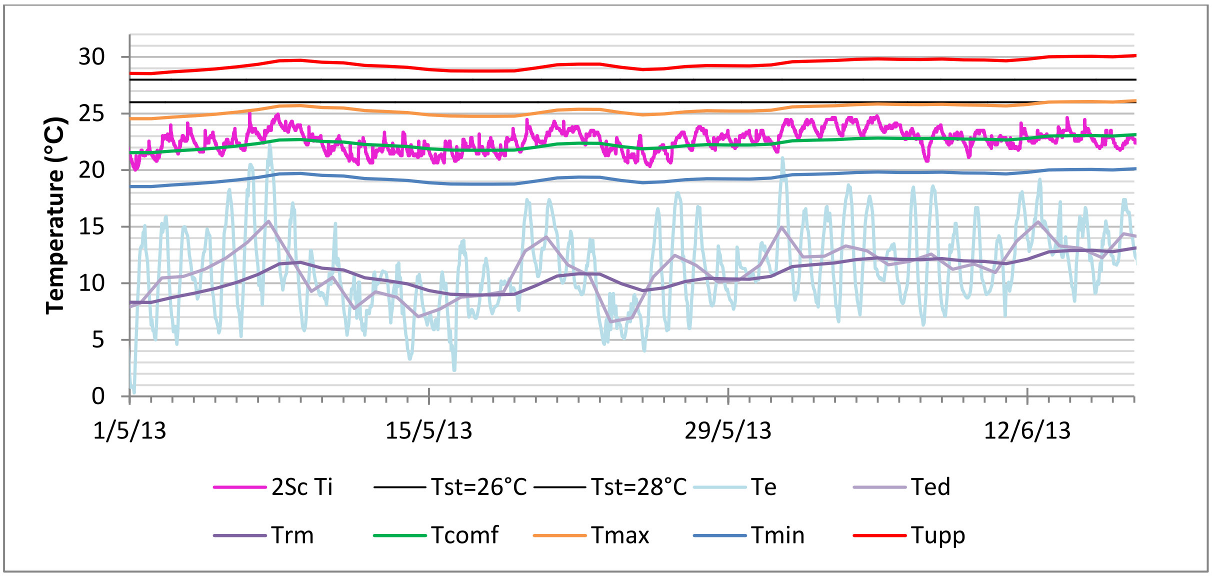



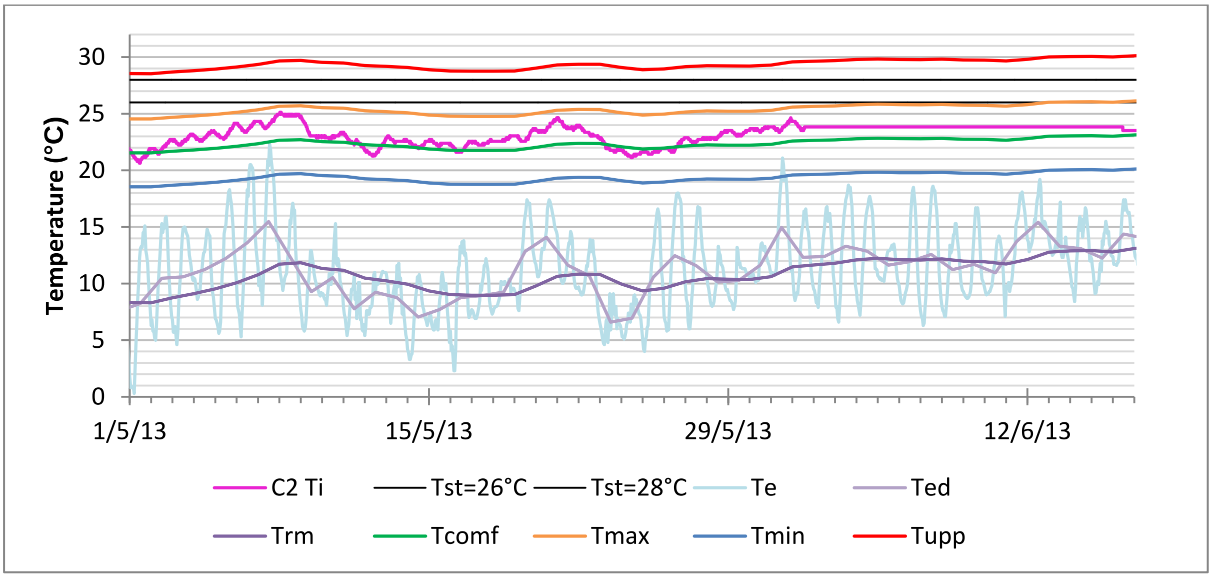
Temperature (°C)
30
25
20
15
10
5
0
1/5/13
15/5/13
29/5/13
12/6/13
2Nb Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

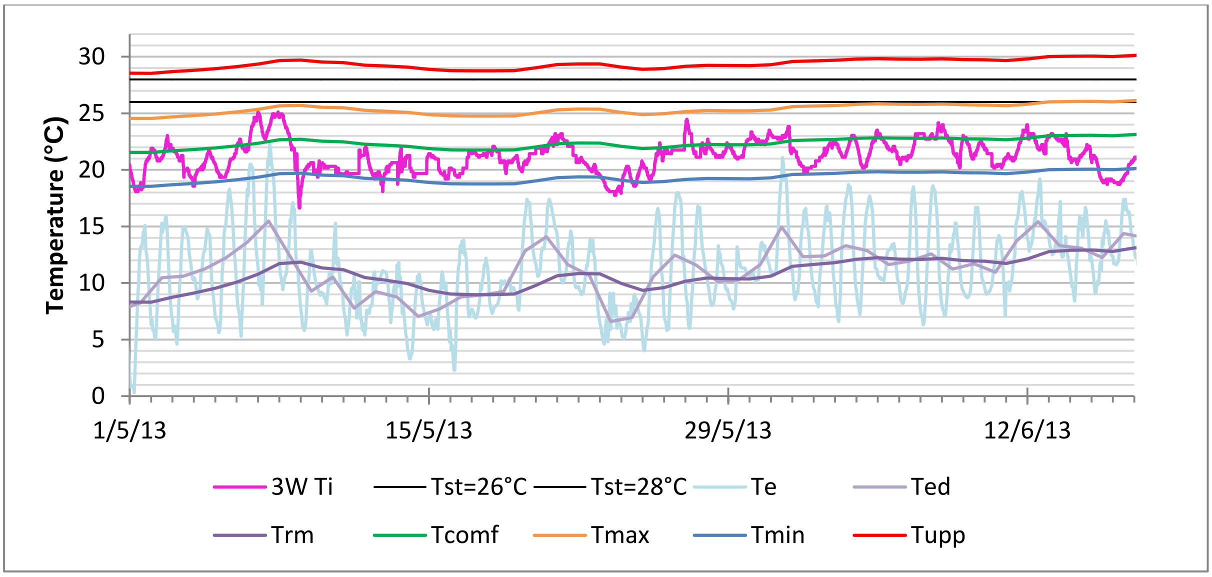



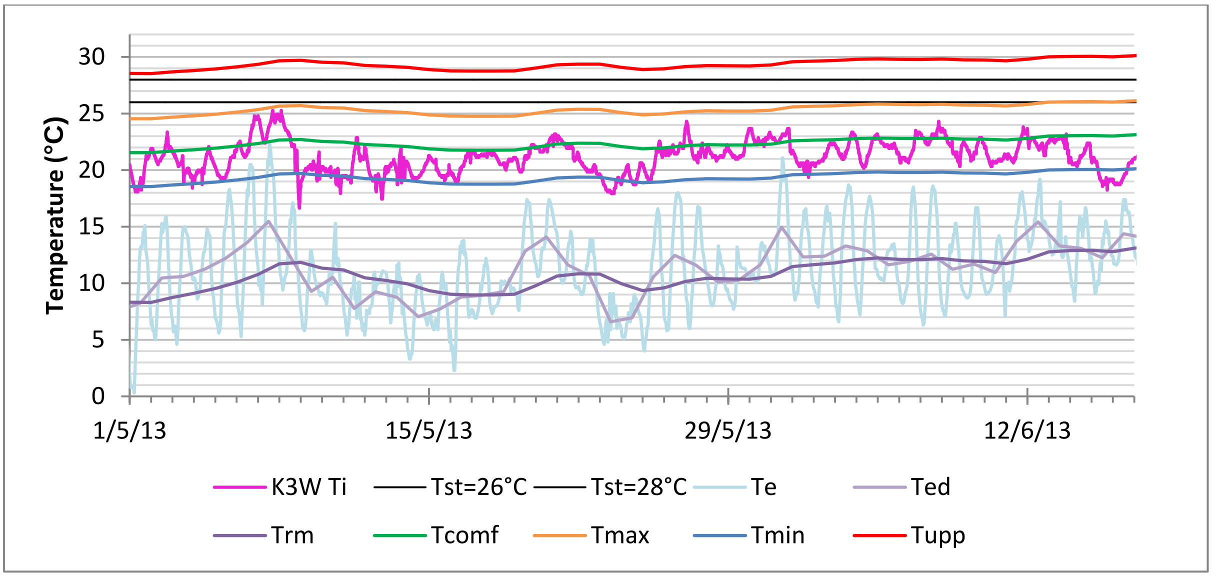
Temperature (°C)
30
25
20
15
10
5
0
1/5/13
15/5/13
29/5/13
12/6/13
2Sa Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp


30
25
20
15
10
5
0
Temperature (°C)
1/5/13
15/5/13
29/5/13
12/6/13
2Sb Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

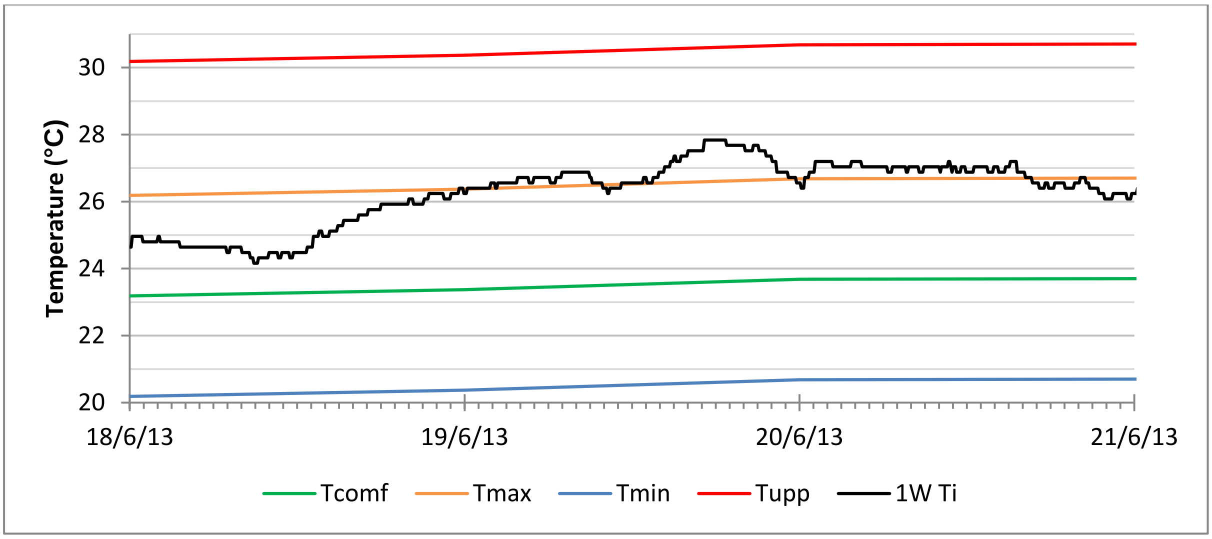

30
25
20
15
10
5
0
Temperature (°C)
1/5/13
15/5/13
29/5/13
12/6/13
2Sc Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

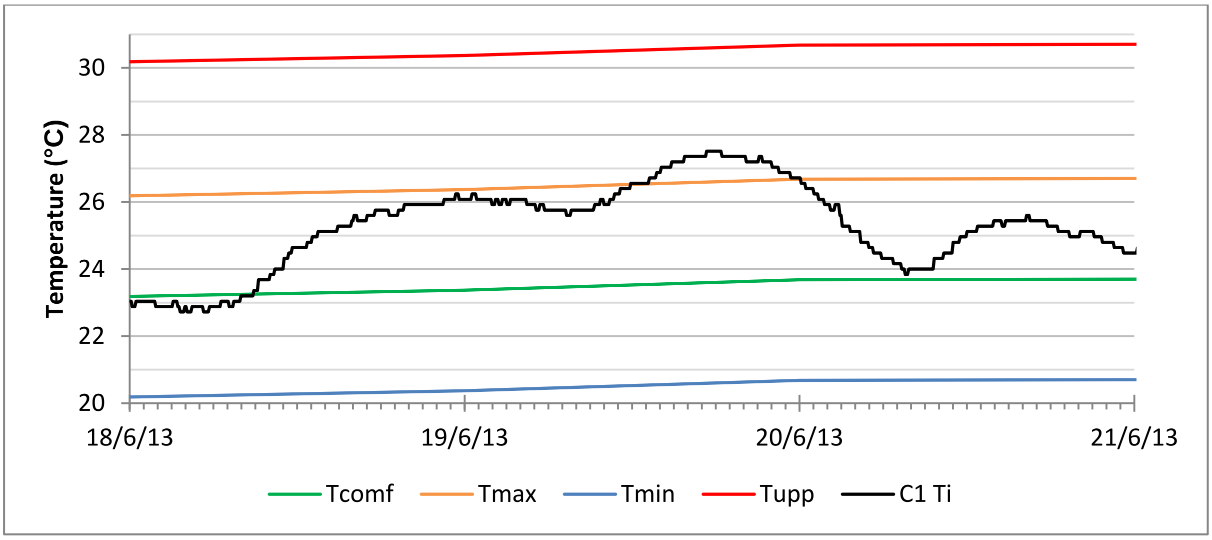

30
25
20
15
10
5
0
Temperature (°C)
1/5/13
15/5/13
29/5/13
12/6/13
C2 Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

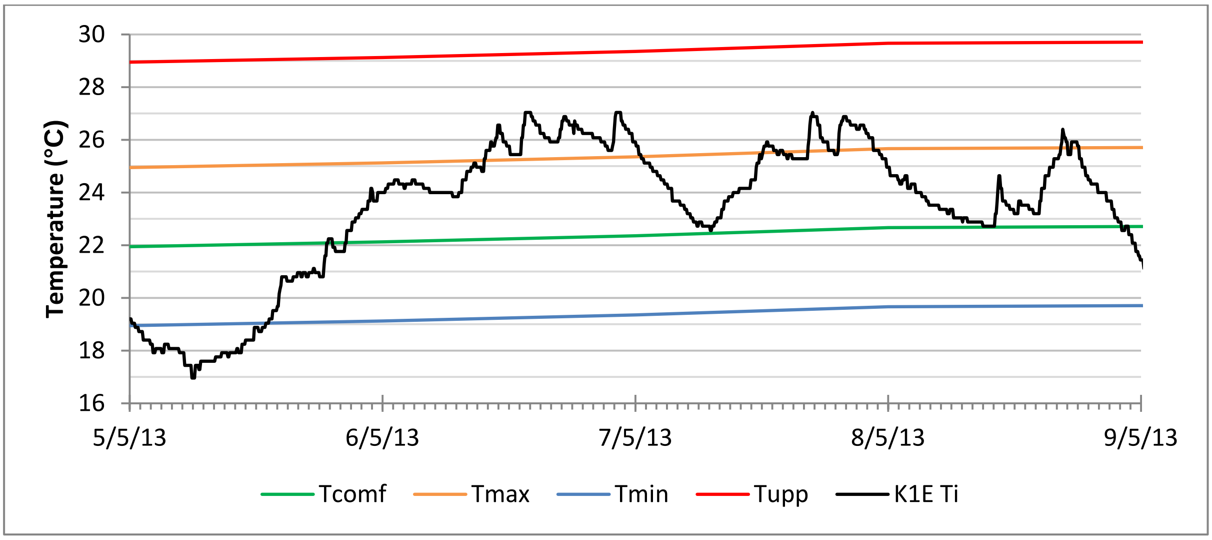

30
25
20
15
10
5
0
Temperature (°C)
1/5/13
15/5/13
29/5/13
12/6/13
3W Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

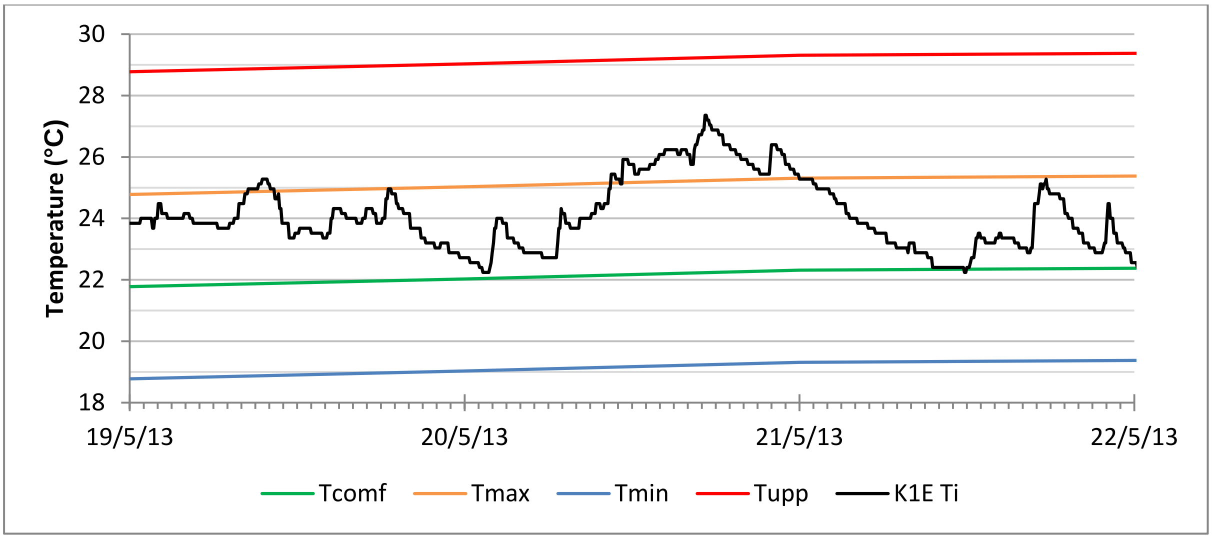

30
25
20
15
10
5
0
Temperature (°C)
1/5/13
15/5/13
29/5/13
12/6/13
K3W Ti
Tst=26°C
Tst=28°C
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp

# Appendix R: Adaptive Overheating: Weighted Exceedance – Loughborough

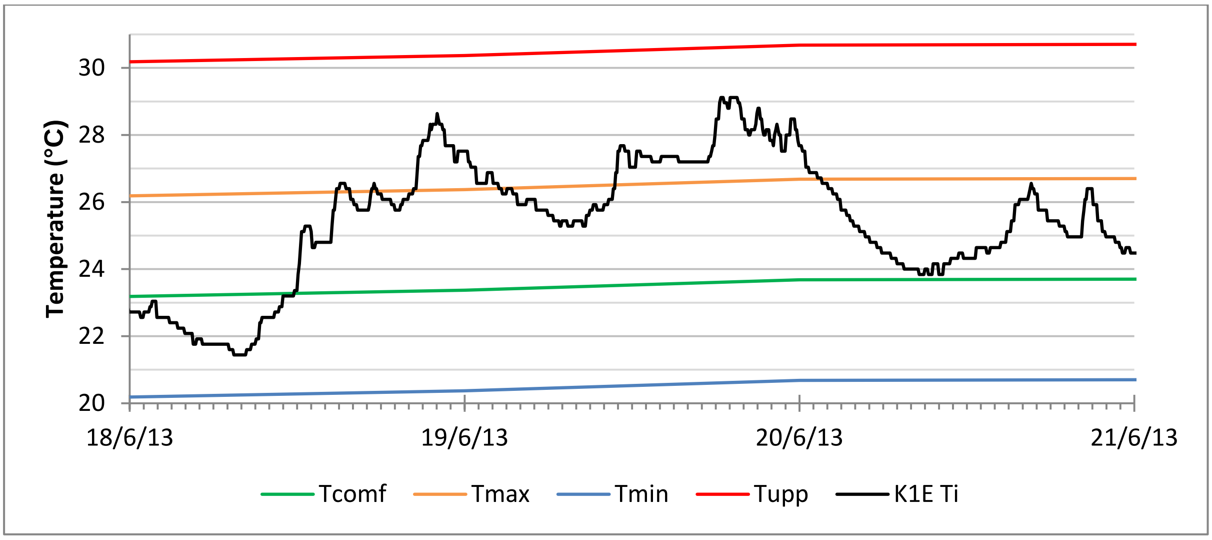


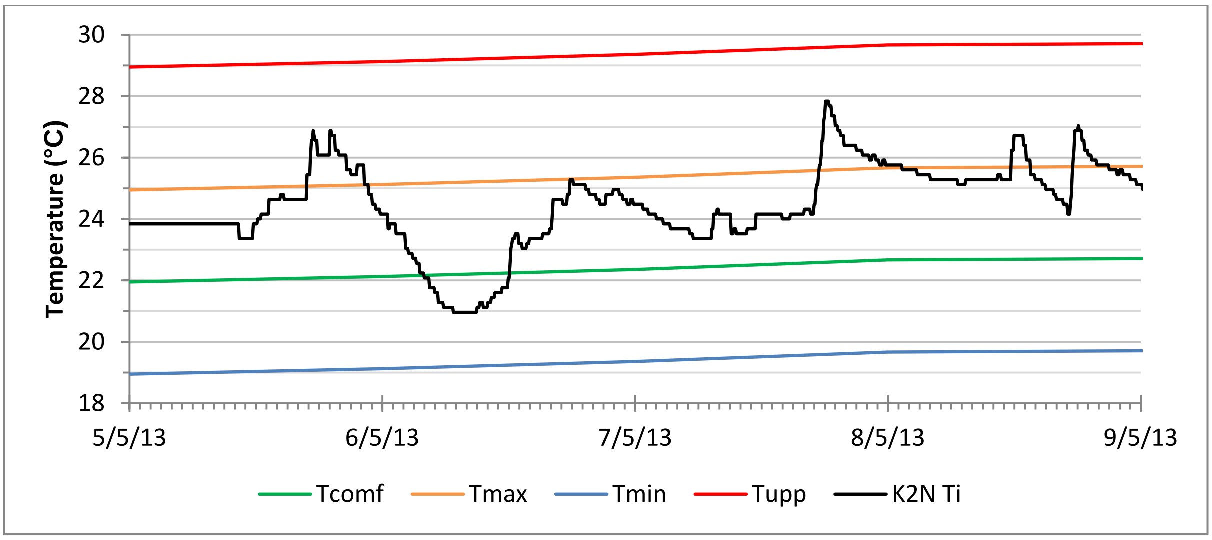





Temperature (°C)
30
28
26
24
22
20
18
19/5/13
20/5/13
21/5/13
22/5/13
Tcomf
Tmax
Tmin
Tupp
K1E Ti

Temperature (°C)
30
28
26
24
22
20
18/6/13
19/6/13
20/6/13
21/6/13
Tcomf
Tmax
Tmin
Tupp
K1E Ti

Temperature (°C)
30
28
26
24
22
20
18
5/5/13
6/5/13
7/5/13
8/5/13
9/5/13
Tcomf
Tmax
Tmin
Tupp
K2N Ti

## Appendix S: Room Temperature from Radiator Temperature Data – London

The lack of internal temperature data presented major problems for the planned overheating analysis, which was the key parameter of interest in the London study.

However, it was found that the radiator temperature sensors could be used to approximate internal room temperate during free-running periods.

This conclusion was made from the following analyses during free-running periods:

1. Comparison of air temperature data from Room 10Wa with radiator temperature data from Rooms 10Wb and 10Wc in the same flat
2. Comparison of radiator temperature data with external air temperature
3. Identification of suspect temperature increases

### Comparison of air and radiator temperature data

The air temperature data from Room 10Wa was compared with the radiator temperature data from Rooms 10Wb and 10Wc in the same flat during free-running periods, (Figure X.1). There are clear similarities between air and radiator temperature data. The diurnal fluctuation of temperature is comparable, with similar daily maximum and minimum temperatures and rates of change of temperature. If a low level of heat were provided to the sensor via the radiator, then temperature drops would be more gradual and would be unlikely to fall to as low a temperature as the air temperature sensor and would likely "flat-out" at some point. Clearly, there are differences in the temperatures measured in these rooms at any given time, but this is to be expected because internal gains and ventilation will vary between the rooms. Figure shows that there is as much variation between rooms 10Wb and 10Wc, as there is between 10Wa and either of these rooms.

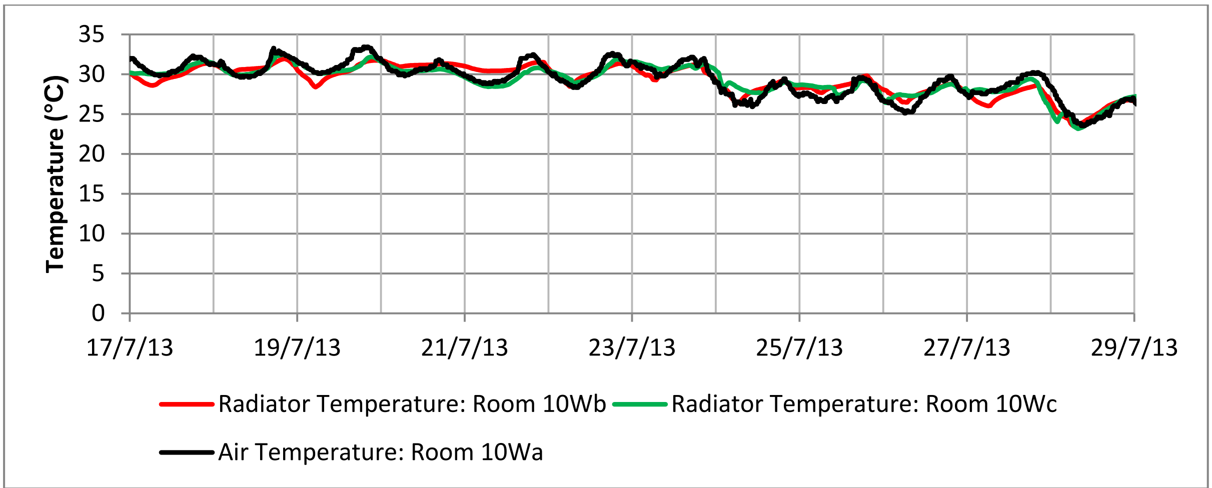



**Figure S.1: Comparison of air temperature and radiator temperature data**

The main difference between the data is that the daily maximum temperature is slightly higher for the air temperature data in room 10Wa than the radiator temperature data in rooms 10Wb and 10Wc. There are a number of possible explanations for this:

1. The radiator temperature sensor measures a higher proportion of radiant temperature than the air temperature sensor due to different surfaces to which they are attached, and the different fixing method.
2. The radiator temperature sensors are fitted at approximately 20cm above floor level, whereas the air temperature sensor is fitted at approximately 140cm above floor level. The difference in height within the room could account for the difference in observed temperatures due to temperature stratification in each room.
3. Room 10Wa may actually experience warmer daily maximum temperatures than Rooms 10Wb and 10Wc, due to occupant behaviour.

In reality, the differences between the air and radiator temperature data could be due to one or more of these reasons, and there is no way of knowing with certainty. However, the differences between the air and radiator temperature measurements is small, and it appears that the radiator temperature sensor data can be used as a good approximation for room temperature, although due to their thermal connection with the radiators, they may measure a higher proportion of radiant temperatures and have a slower response, therefore underestimating the maximum, and perhaps minimum, daily air temperatures within a room.

### Comparison of radiator temperature data with external air temperature

Comparison of the internal and external temperatures during free-running periods shows that the internal temperature tends to track the external temperature, which suggests the radiator temperature sensors are approximating room temperature, and are not receiving unintended heat from the radiator.

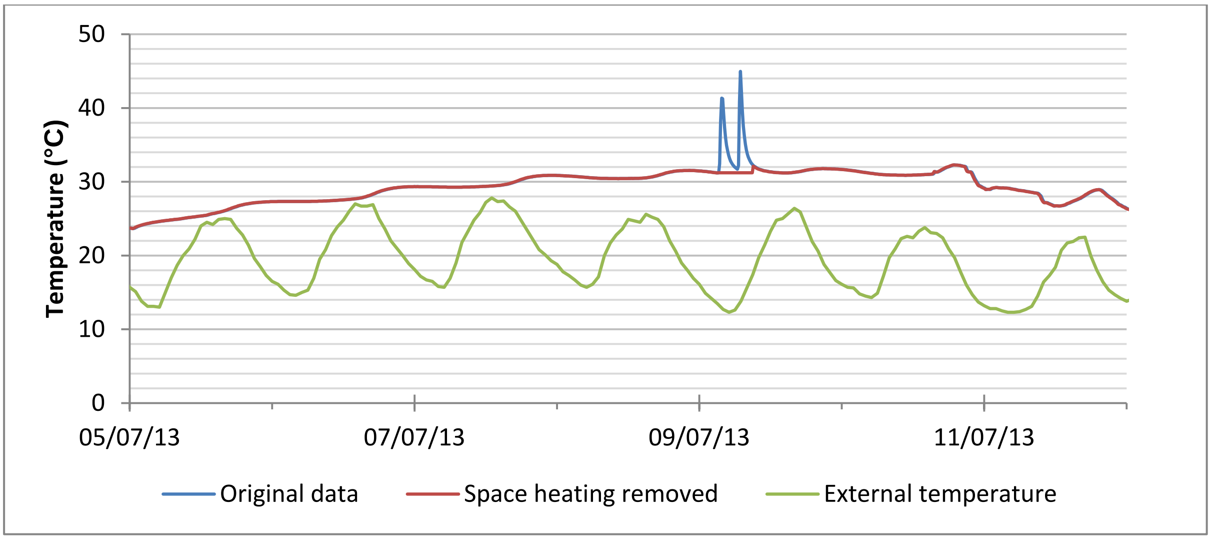
### Identification of suspect temperature increases

The data was checked for unexpected increases in temperature, to try to identify any low level heating. There were occasional blips in the temperature trends in many rooms, but these often occurred when space heating was not available ($T_e$>15°C) and could have been caused by other factors (as was observed in the Loughborough study), such as electrical gains, shower use or solar gains. There was no evidence to suggest the radiators were providing heat when external temperature exceeded 15°C.

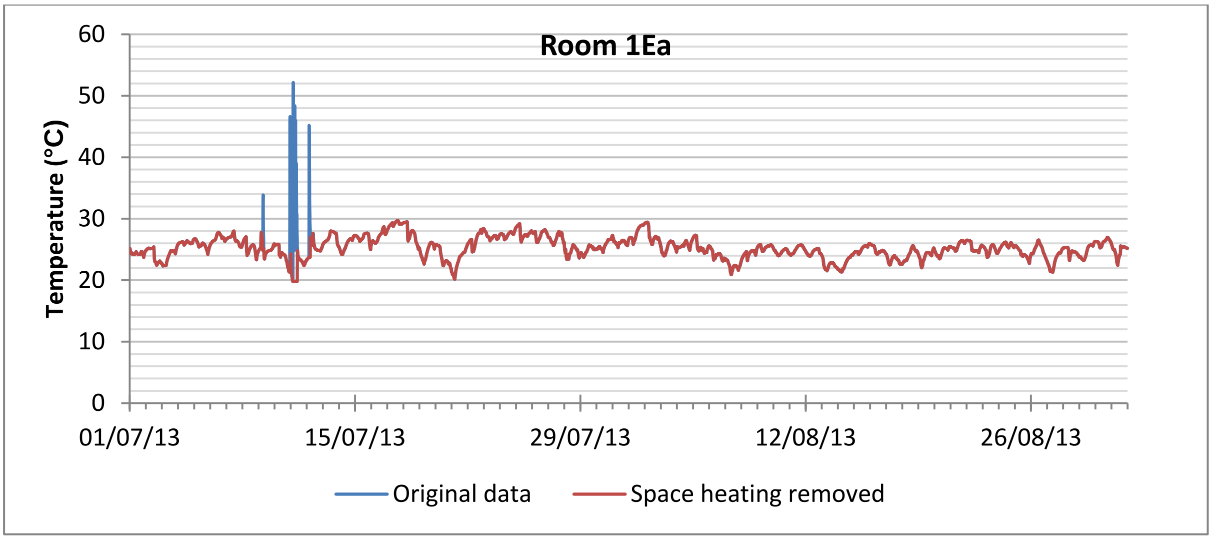
## Appendix T: Summer Time Space Heating Removed – London

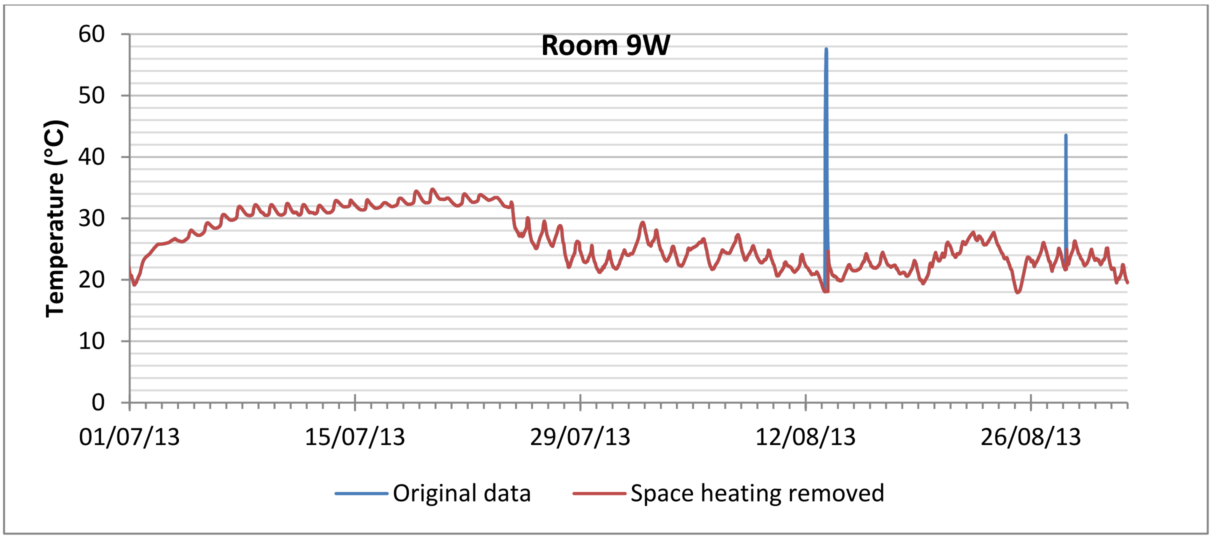
Space heating was removed from the four bedrooms that used space heating in July and August, rooms 1Ea, 9W, 10Wb and 10Wc.

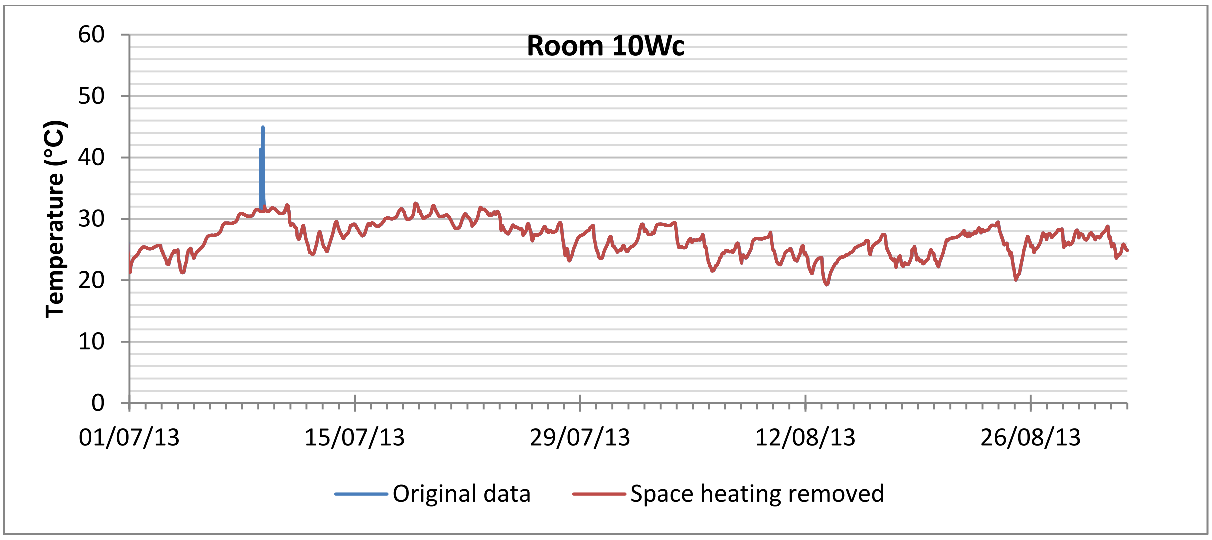
The summer time space heating was short in duration and had limited impact on the internal temperature. For example, the only space heating in Room 10Wb during July and August, was between 3:15am and 9am on 9th July, and it can be seen that the temperature on 9th and 10th July, after the use of space heating, was comparable with the temperature on 8th July, prior to the use of space heating.

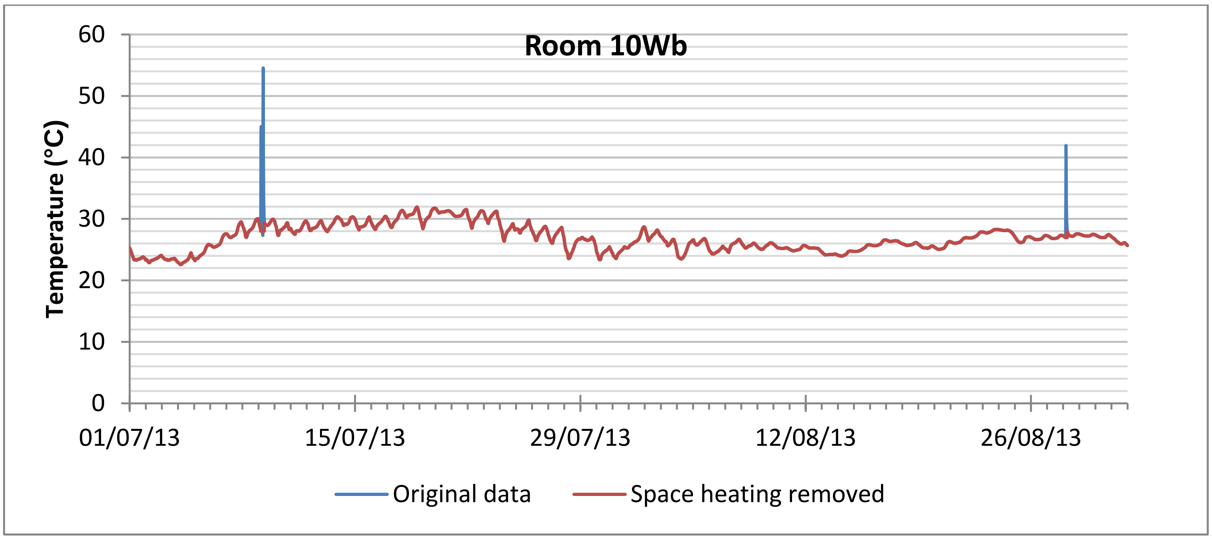



The space heating removed from the four bedrooms is shown in the plots below.

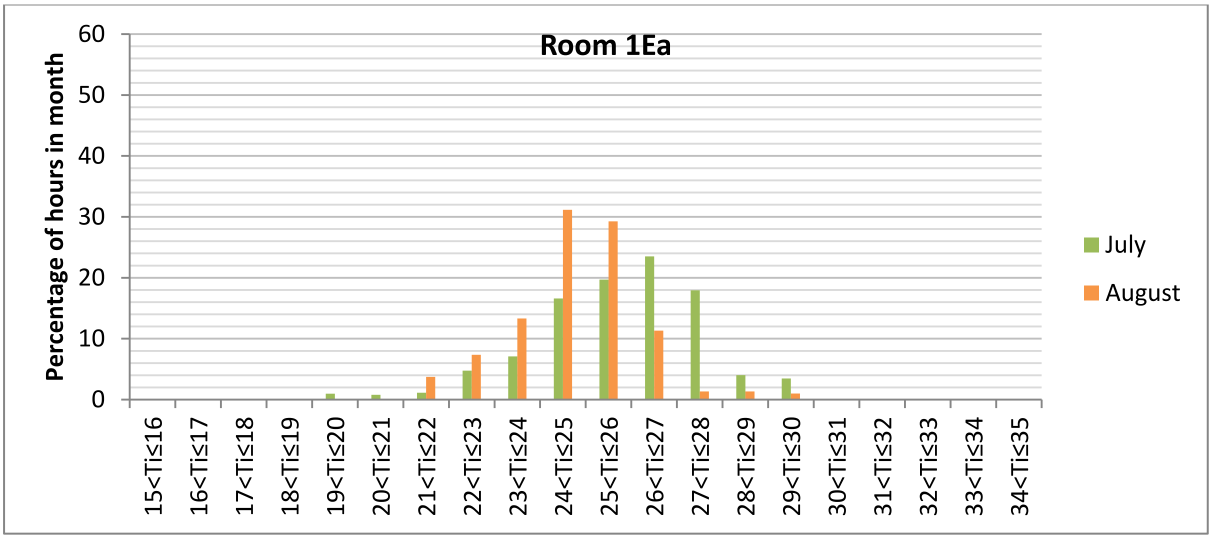


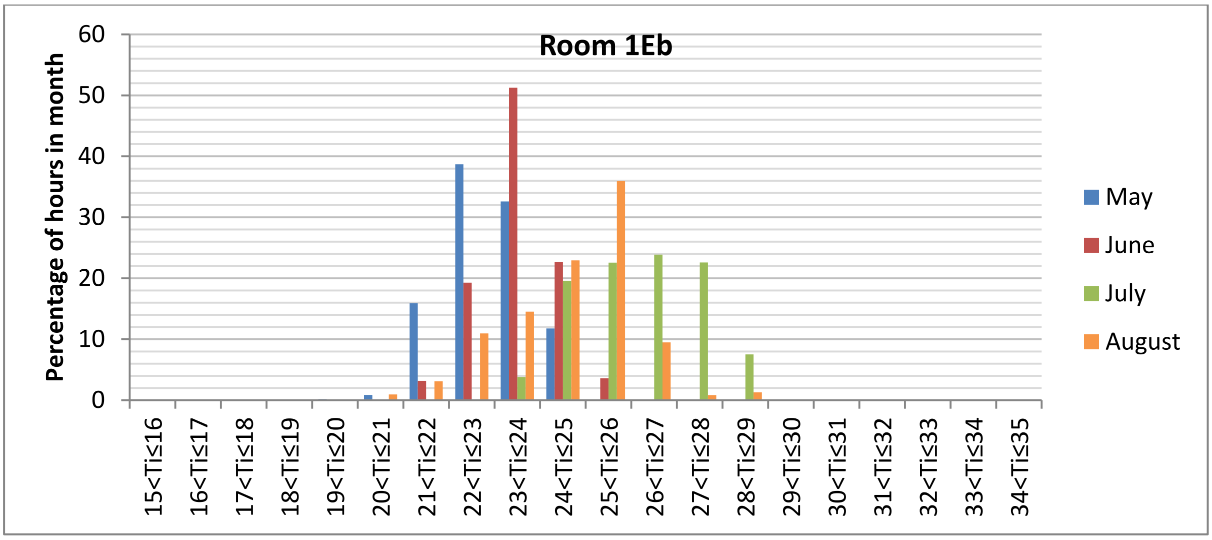

Room 9W
Temperature (°C)
60
50
40
30
20
10
0
01/07/13
15/07/13
29/07/13
12/08/13
26/08/13
Original data
Space heating removed

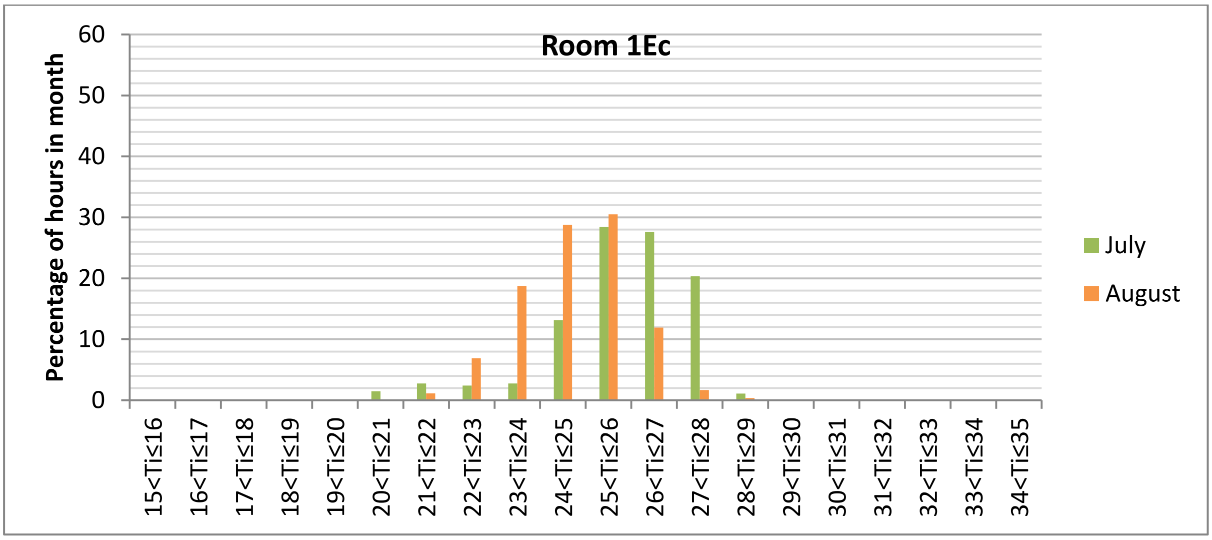

Room 10Wc
Temperature (°C)
60
50
40
30
20
10
0
01/07/13
15/07/13
29/07/13
12/08/13
26/08/13
Original data
Space heating removed

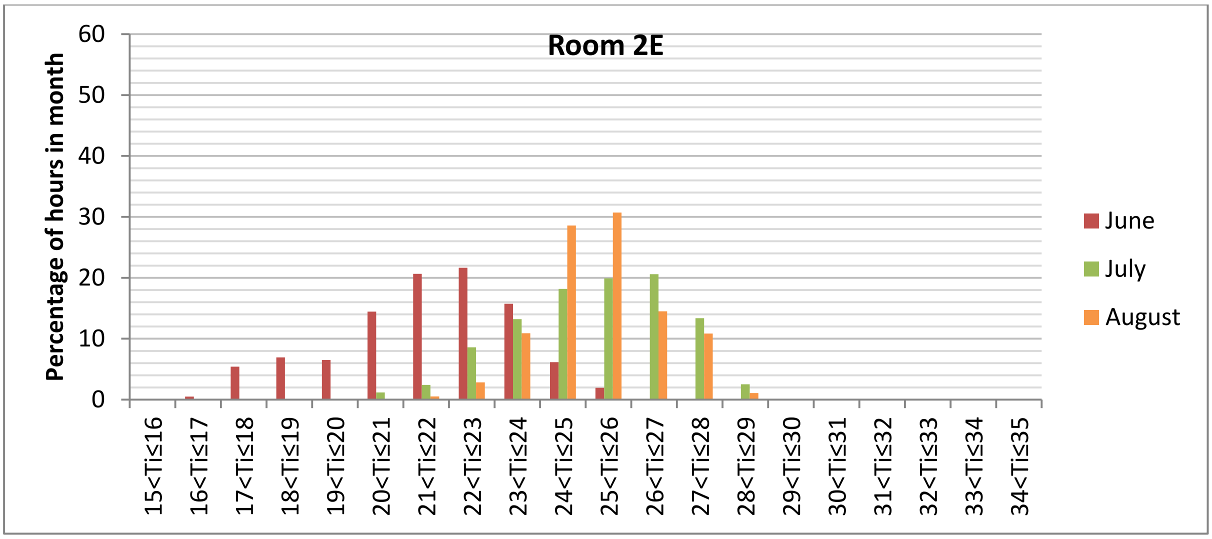

Room 10Wb
Temperature (°C)
60
50
40
30
20
10
0
01/07/13
15/07/13
29/07/13
12/08/13
26/08/13
Original data
Space heating removed

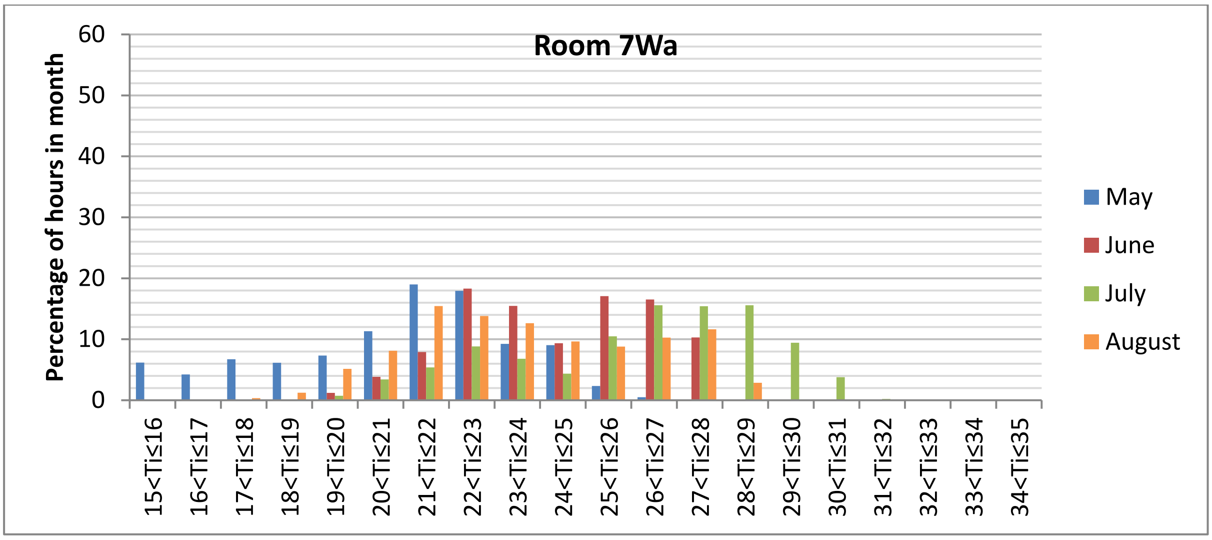
# Appendix U: Distribution of Internal Temperatures – London

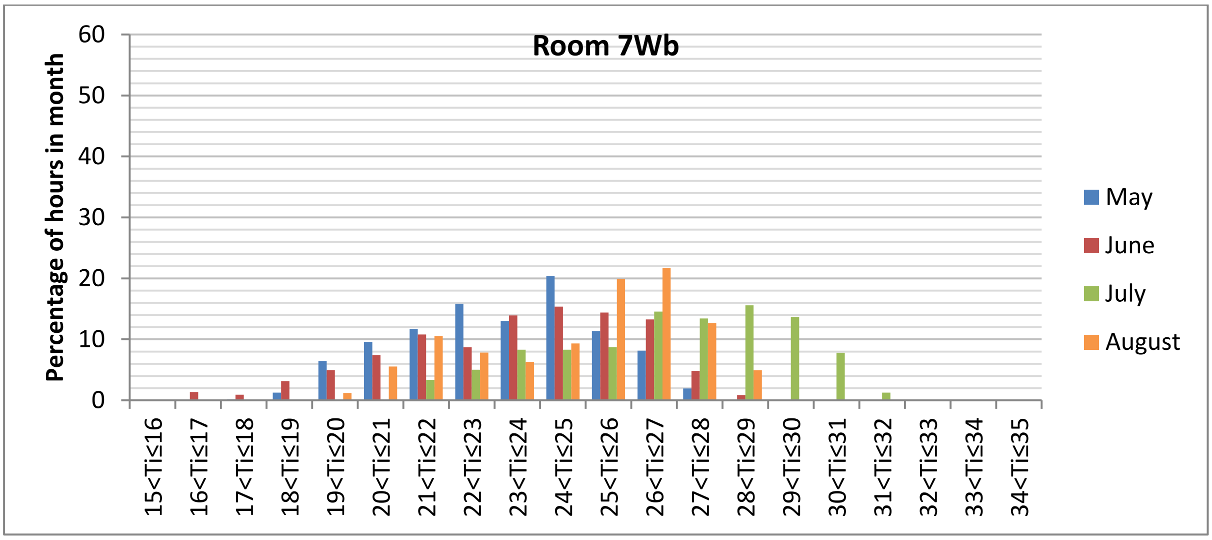


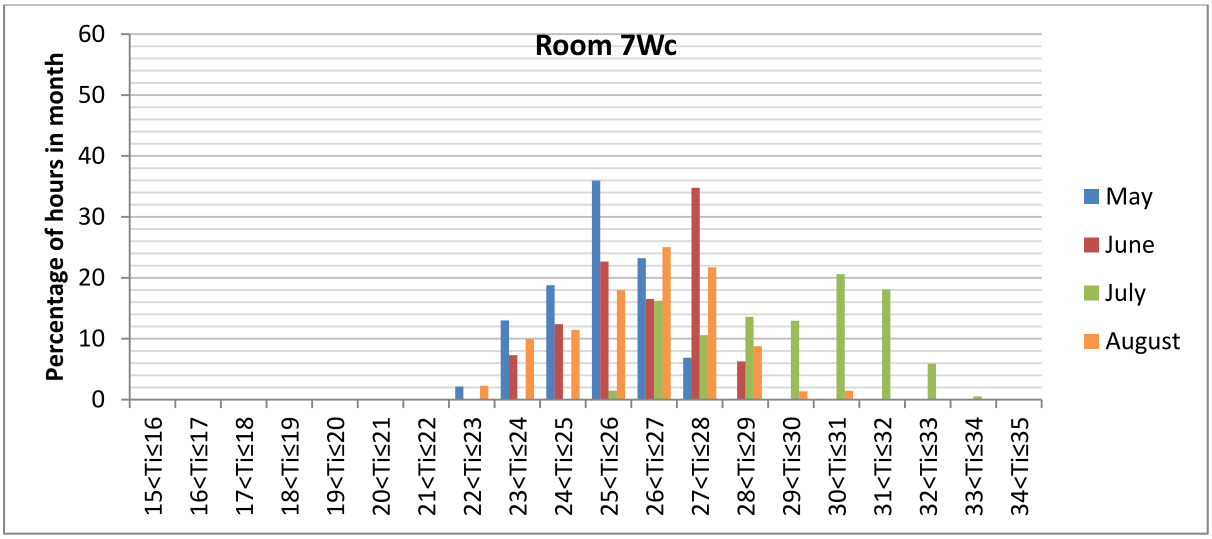



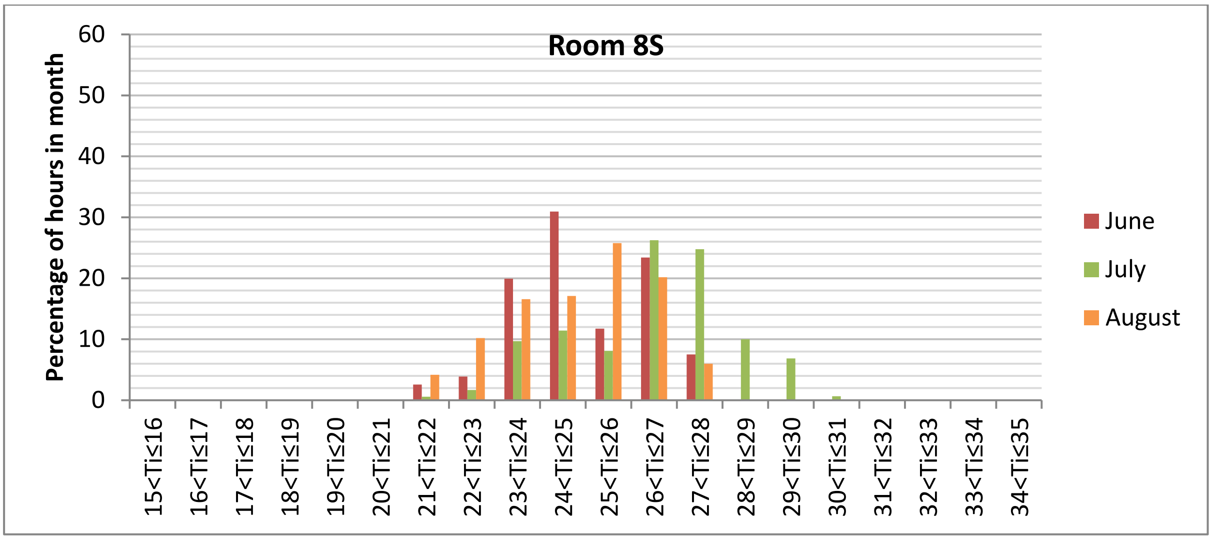



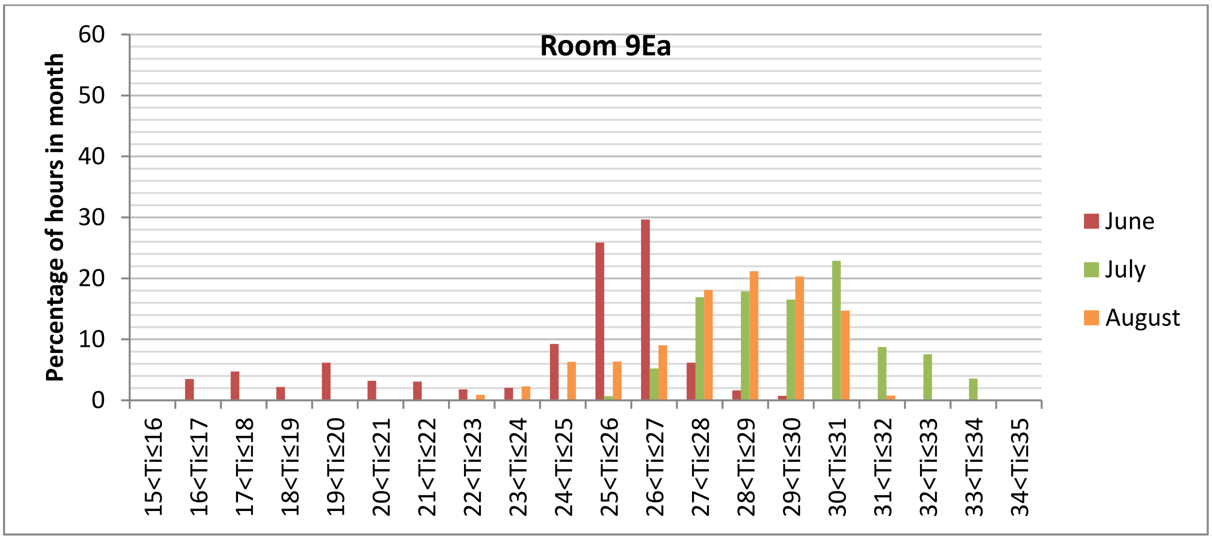

Room 2E
Percentage of hours in month
0
10
20
30
40
50
60
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
June
July
August

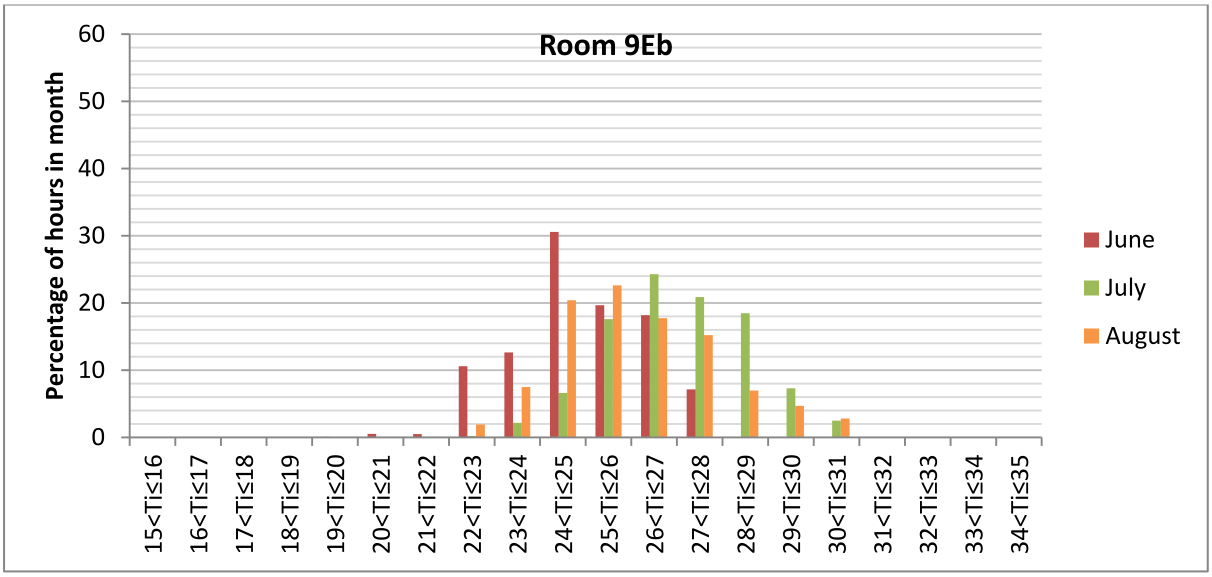

Room 7Wa
Percentage of hours in month
0
10
20
30
40
50
60
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
May
June
July
August

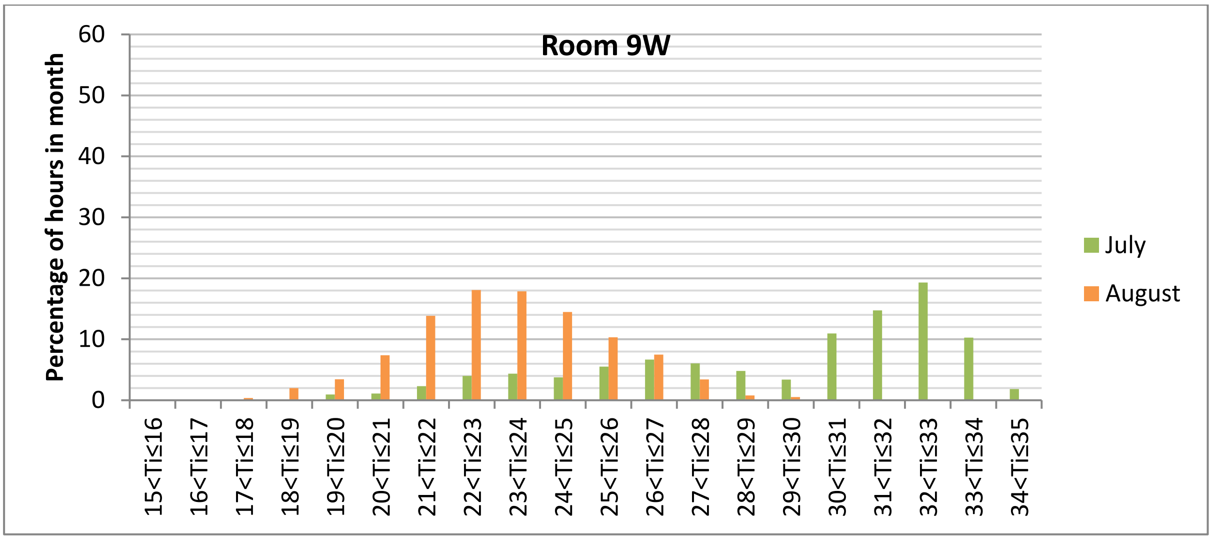

Room 7Wb
Percentage of hours in month
0
10
20
30
40
50
60
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
May
June
July
August

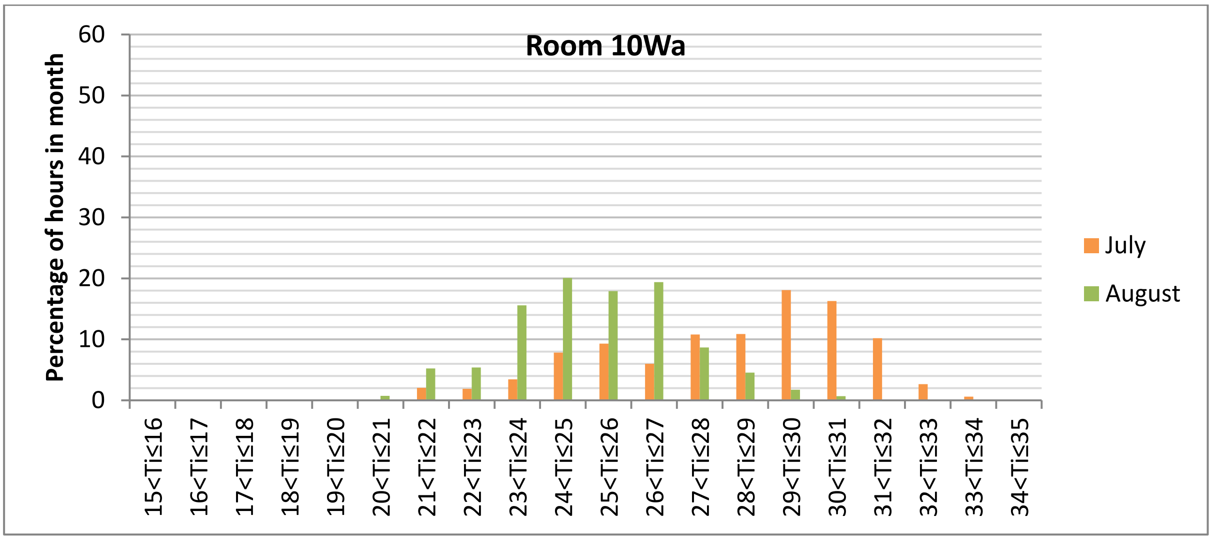

Room 7Wc
Percentage of hours in month
60
50
40
30
20
10
0
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
May
June
July
August

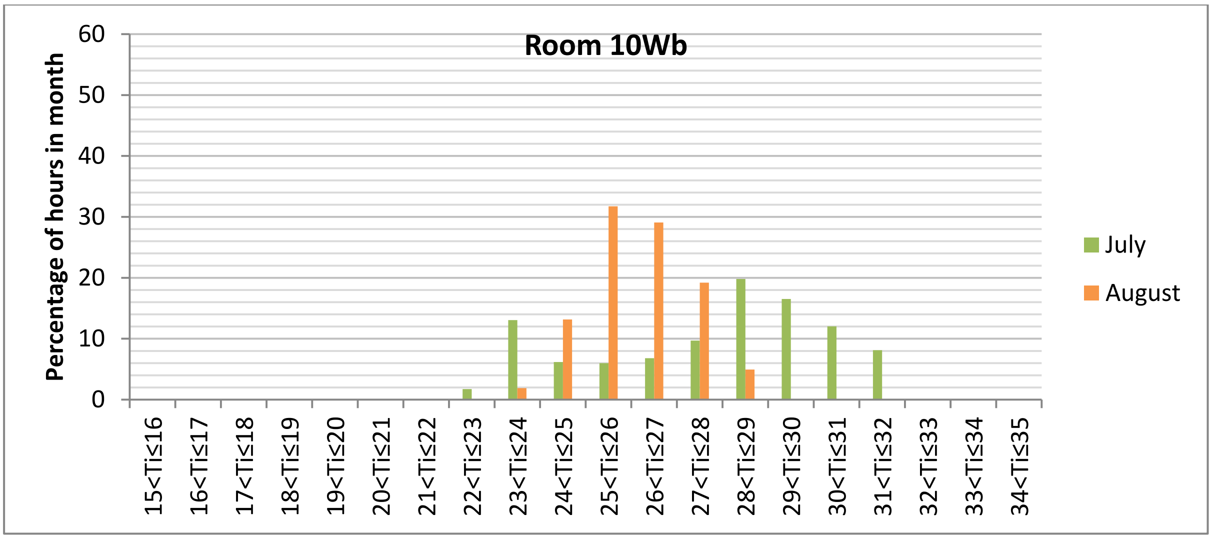

Room 8S
Percentage of hours in month
60
50
40
30
20
10
0
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
June
July
August

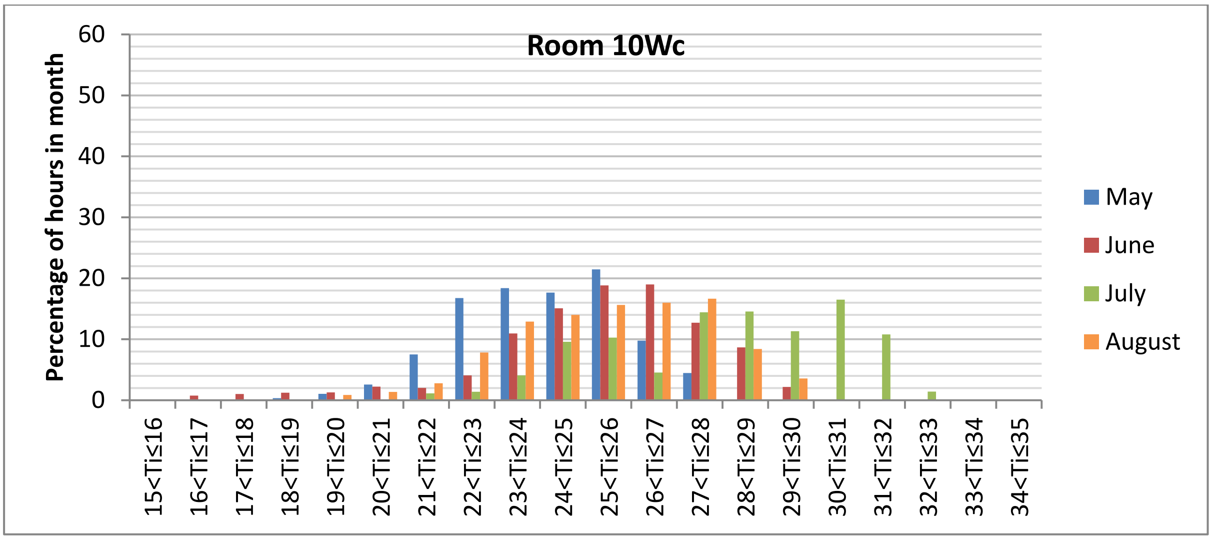

Room 9Ea
Percentage of hours in month
60
50
40
30
20
10
0
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
June
July
August

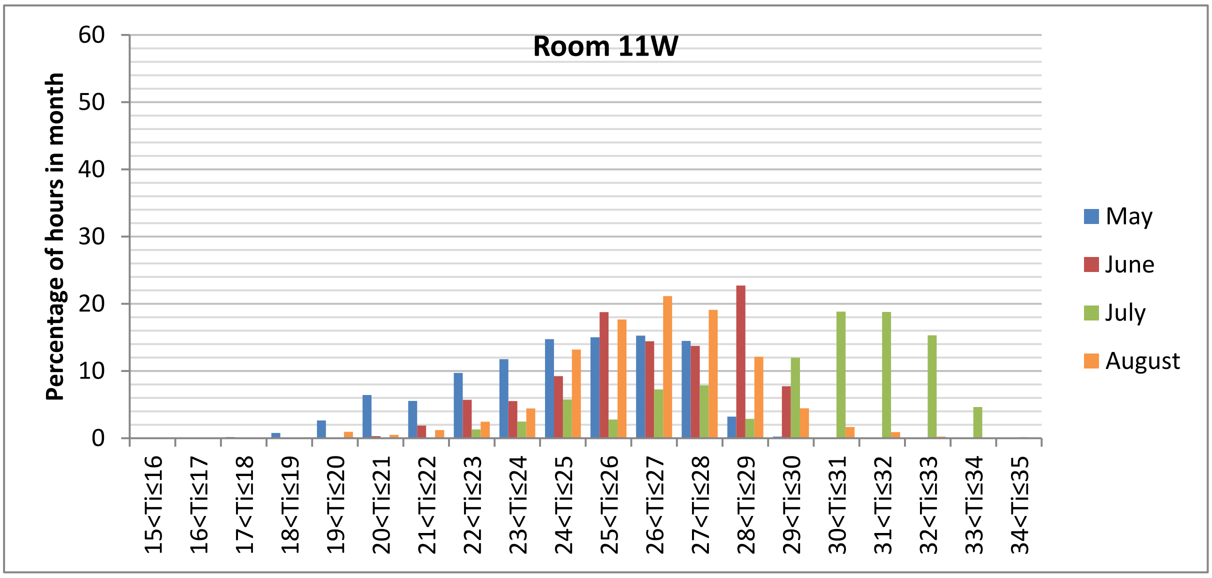

Room 9Eb
Percentage of hours in month
60
50
40
30
20
10
0
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
June
July
August


Room 9W
Percentage of hours in month
60
50
40
30
20
10
0
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
July
August

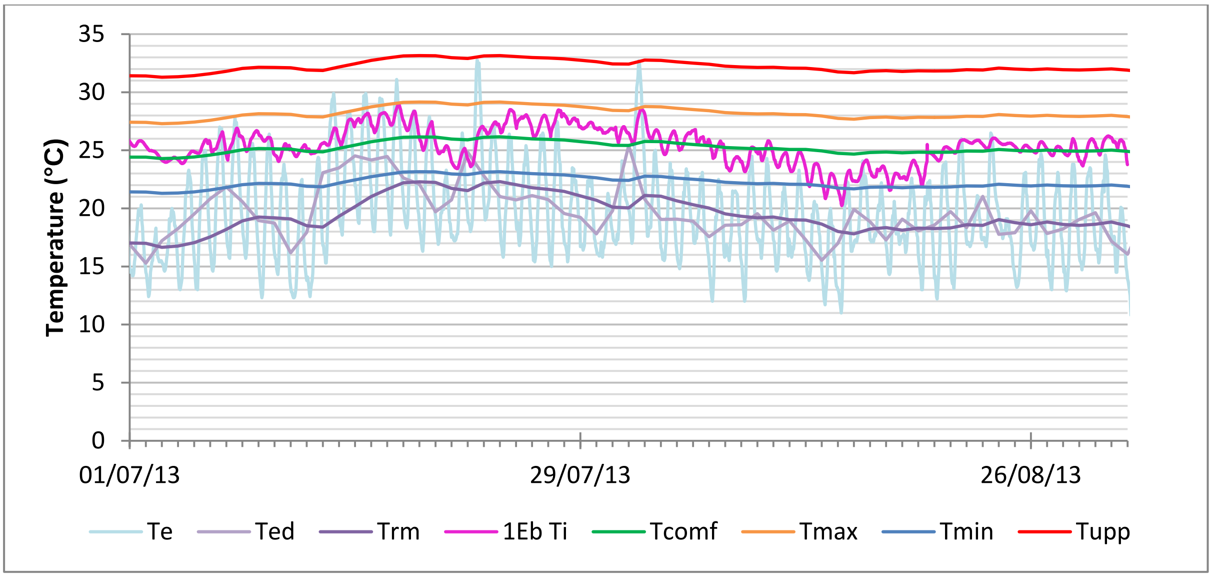

Room 10Wa
Percentage of hours in month
60
50
40
30
20
10
0
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
July
August

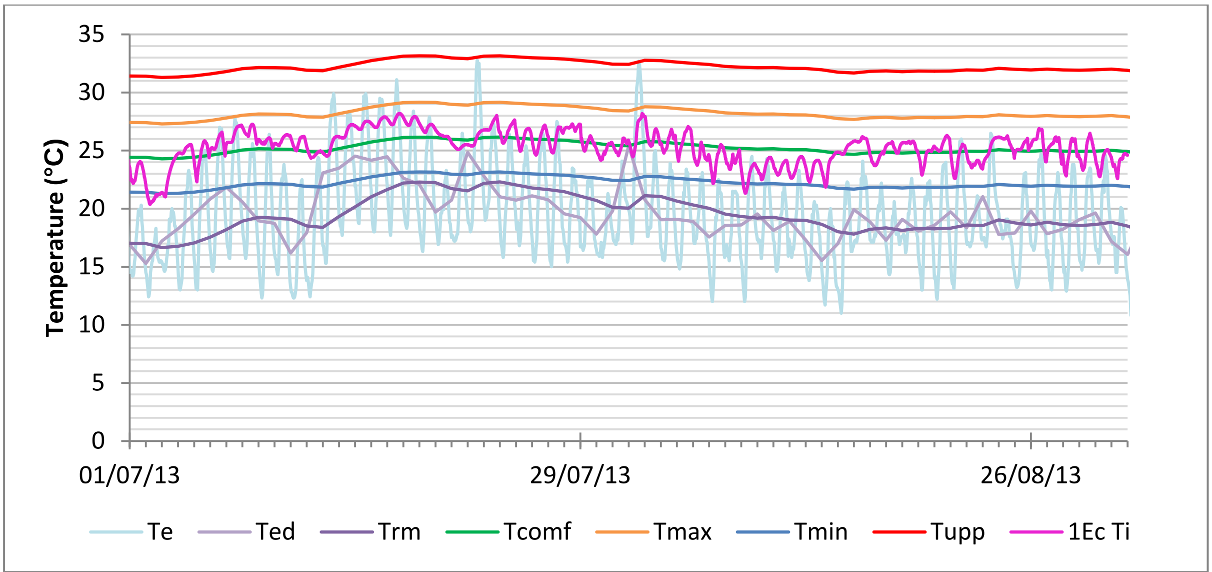

Room 10Wb
Percentage of hours in month
60
50
40
30
20
10
0
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
July
August

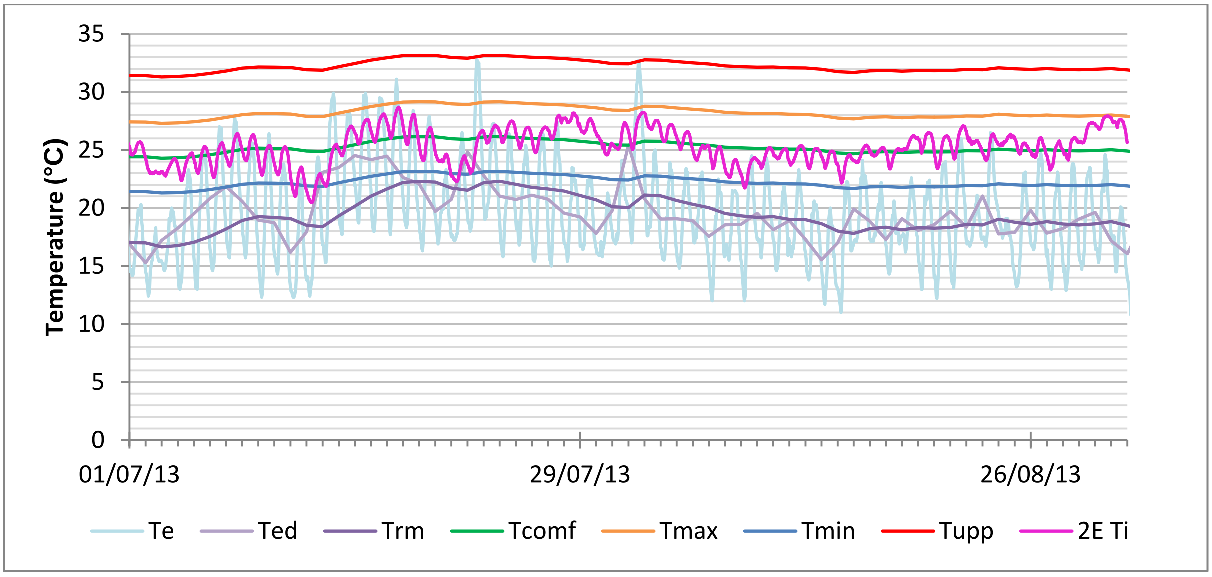

Room 10Wc
Percentage of hours in month
60
50
40
30
20
10
0
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
May
June
July
August


Room 11W
Percentage of hours in month
60
50
40
30
20
10
0
15<Ti≤16
16<Ti≤17
17<Ti≤18
18<Ti≤19
19<Ti≤20
20<Ti≤21
21<Ti≤22
22<Ti≤23
23<Ti≤24
24<Ti≤25
25<Ti≤26
26<Ti≤27
27<Ti≤28
28<Ti≤29
29<Ti≤30
30<Ti≤31
31<Ti≤32
32<Ti≤33
33<Ti≤34
34<Ti≤35
May
June
July
August

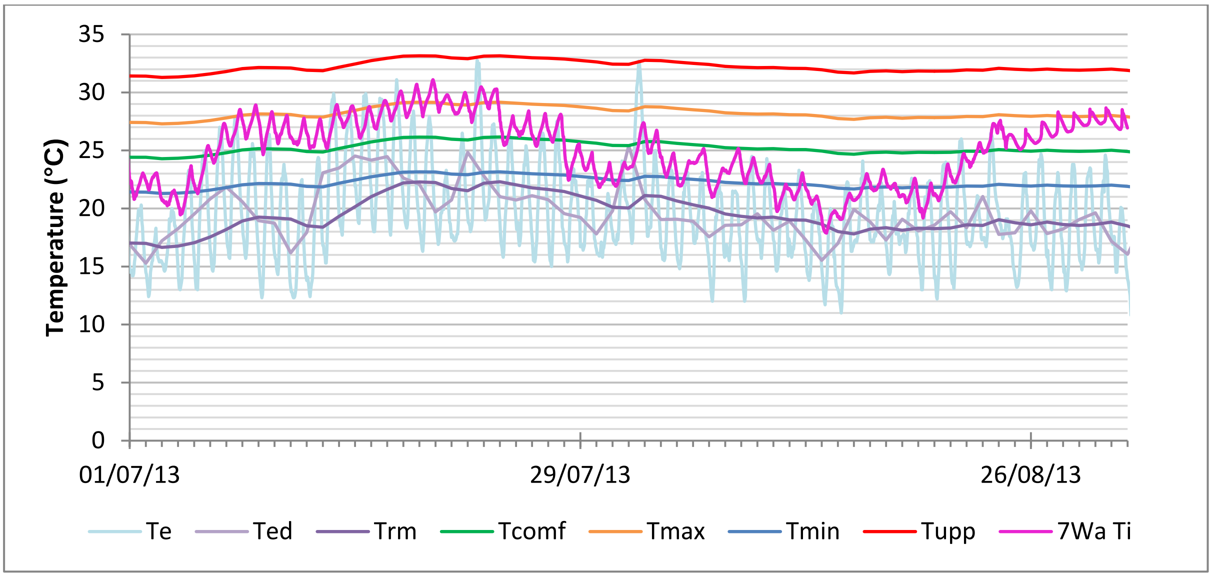
## Appendix V: Overheating Results: July-August 2013 – London



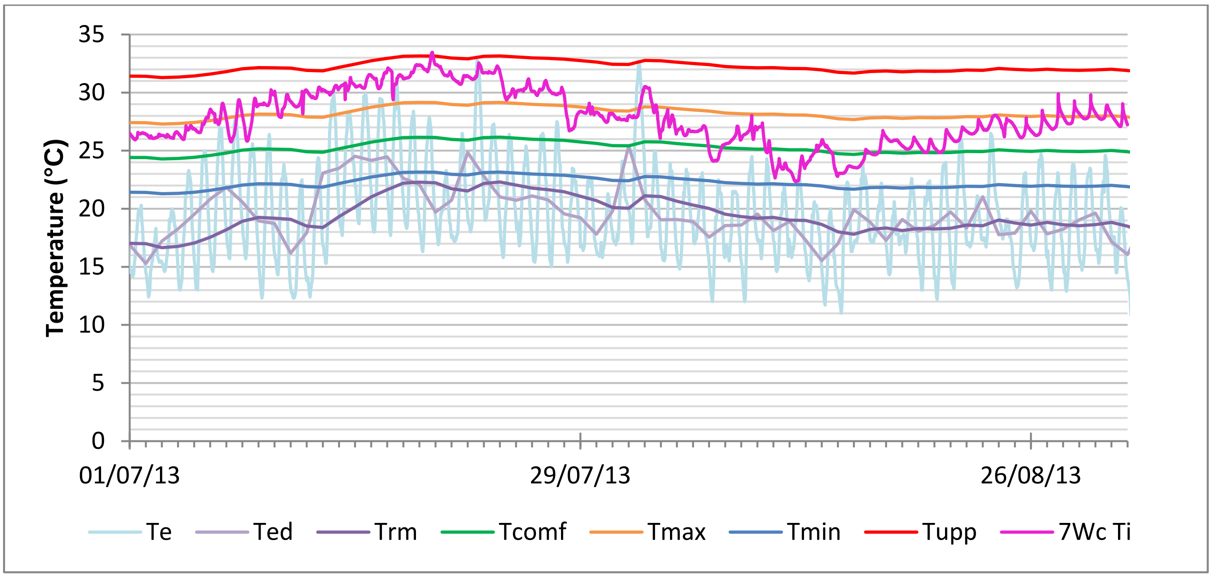





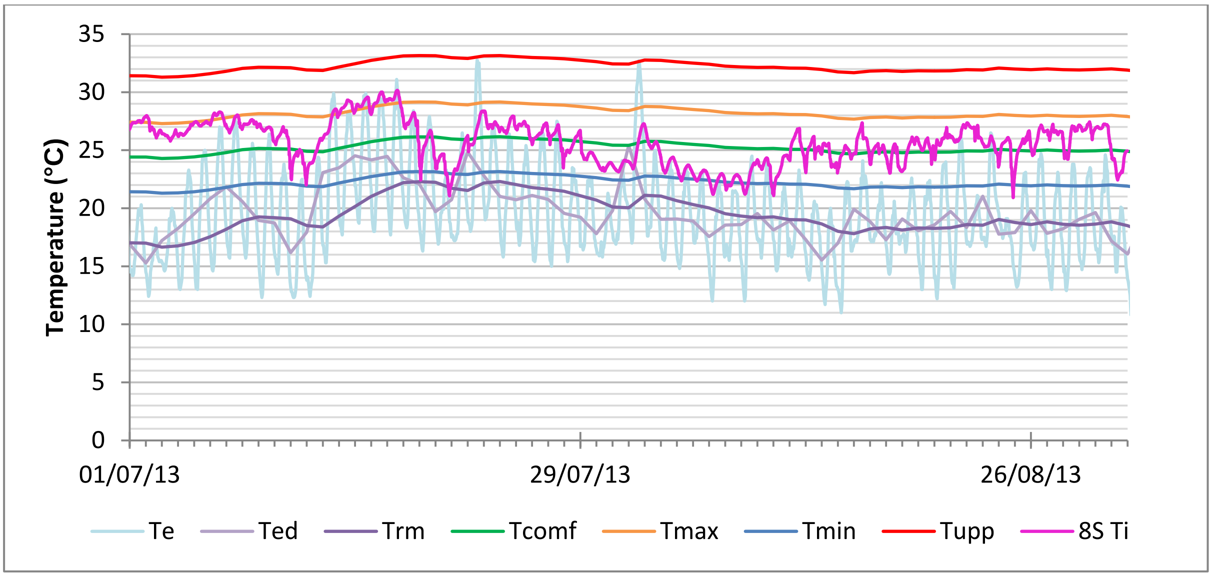
Temperature (°C)
35
30
25
20
15
10
5
0
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
2E Ti

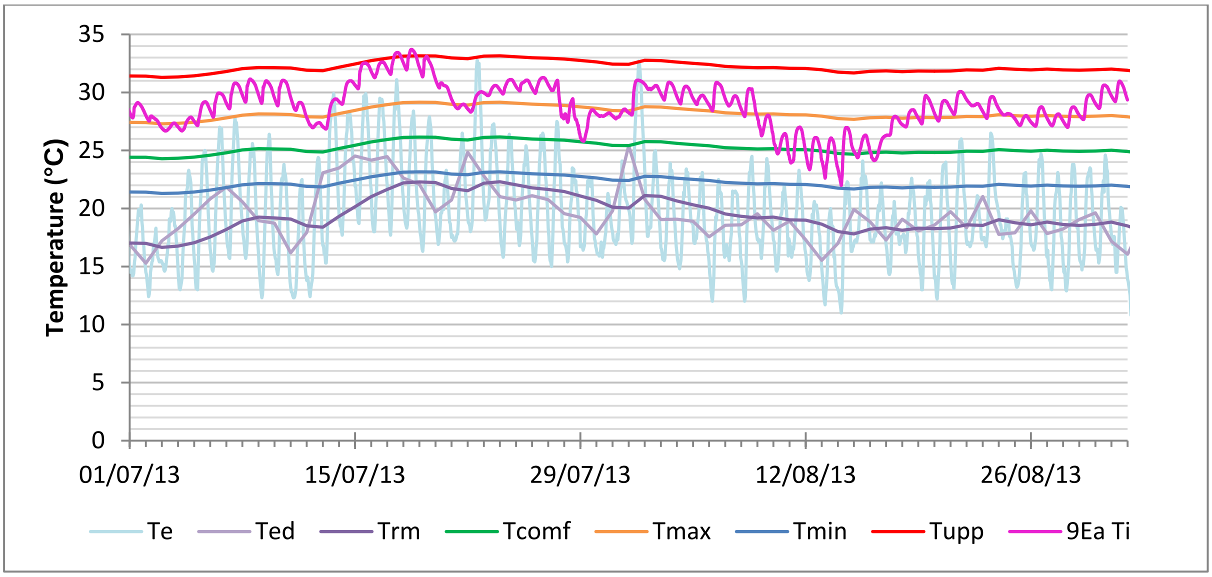



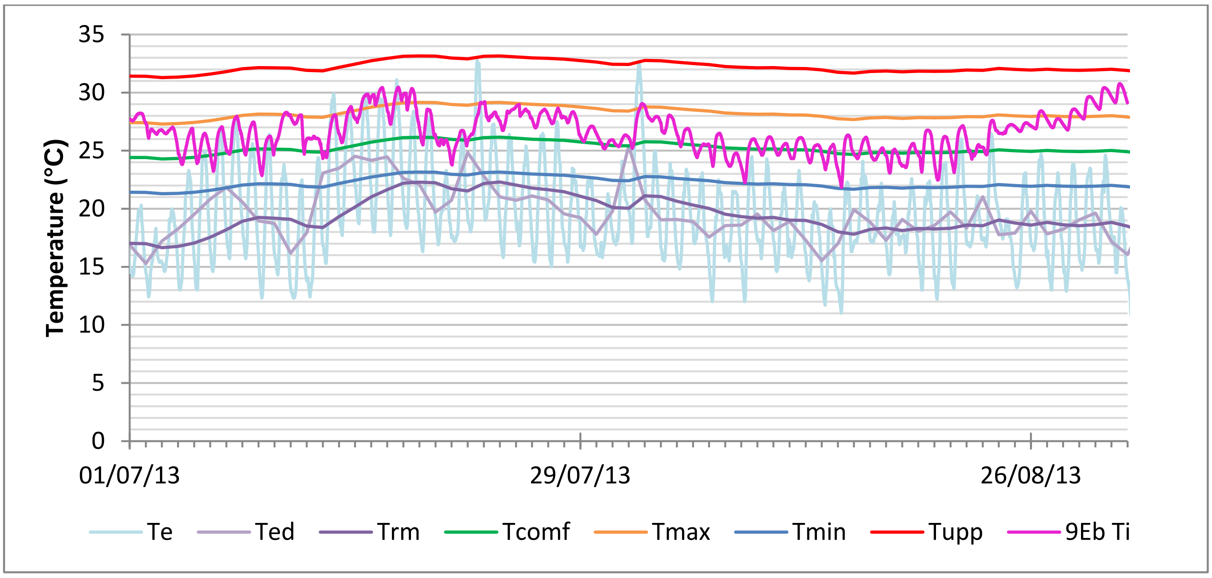
Temperature (°C)
35
30
25
20
15
10
5
0
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
7Wa Ti

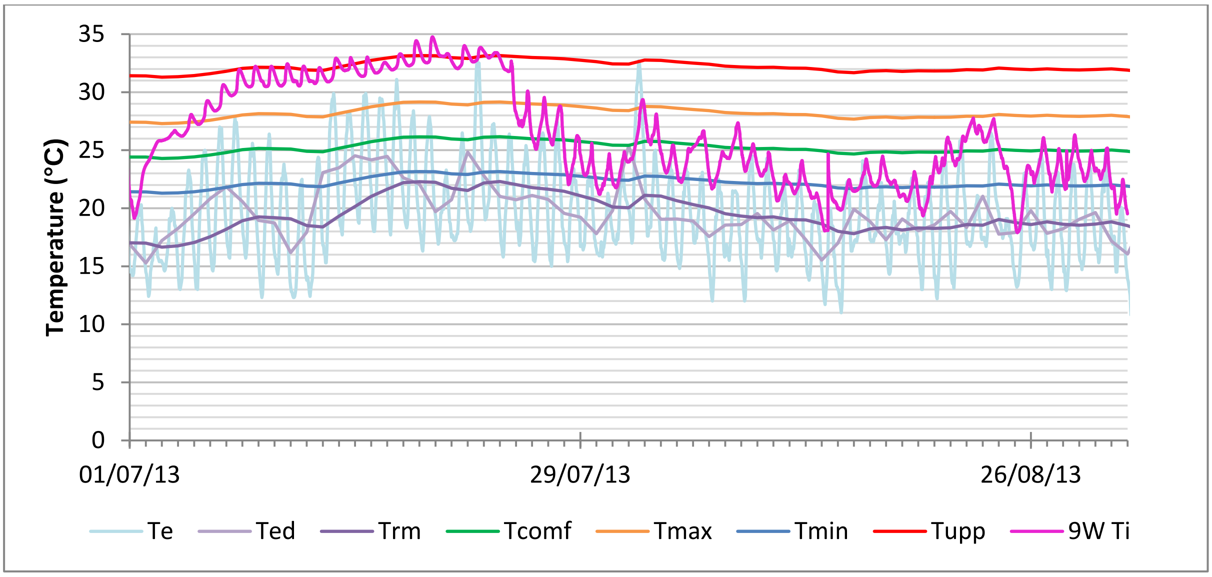



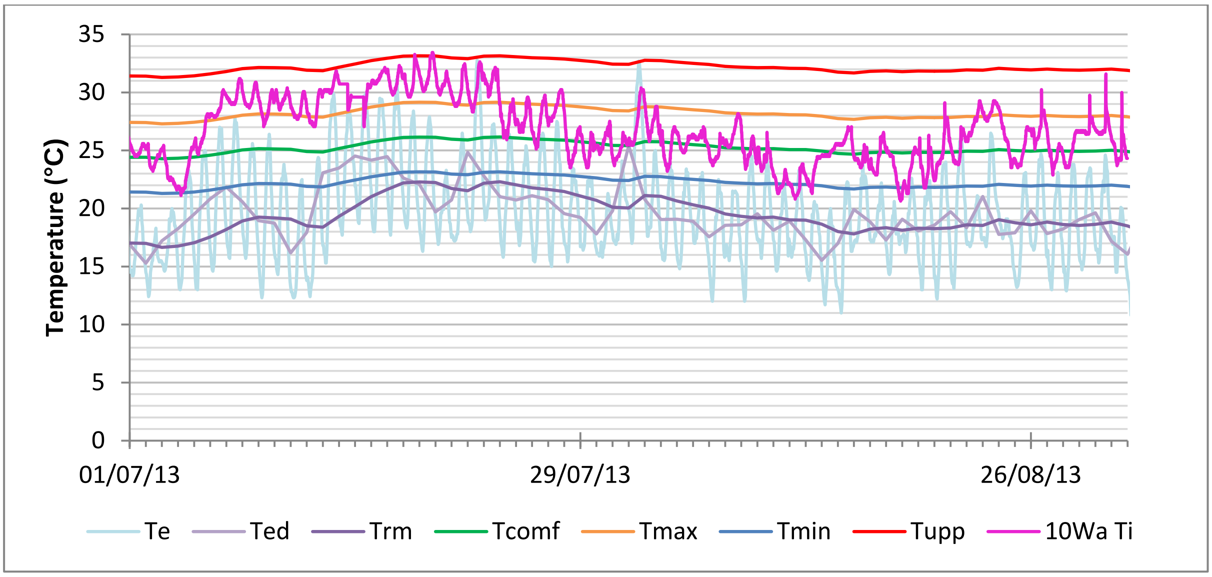
Temperature (°C)
35
30
25
20
15
10
5
0
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
7Wc Ti

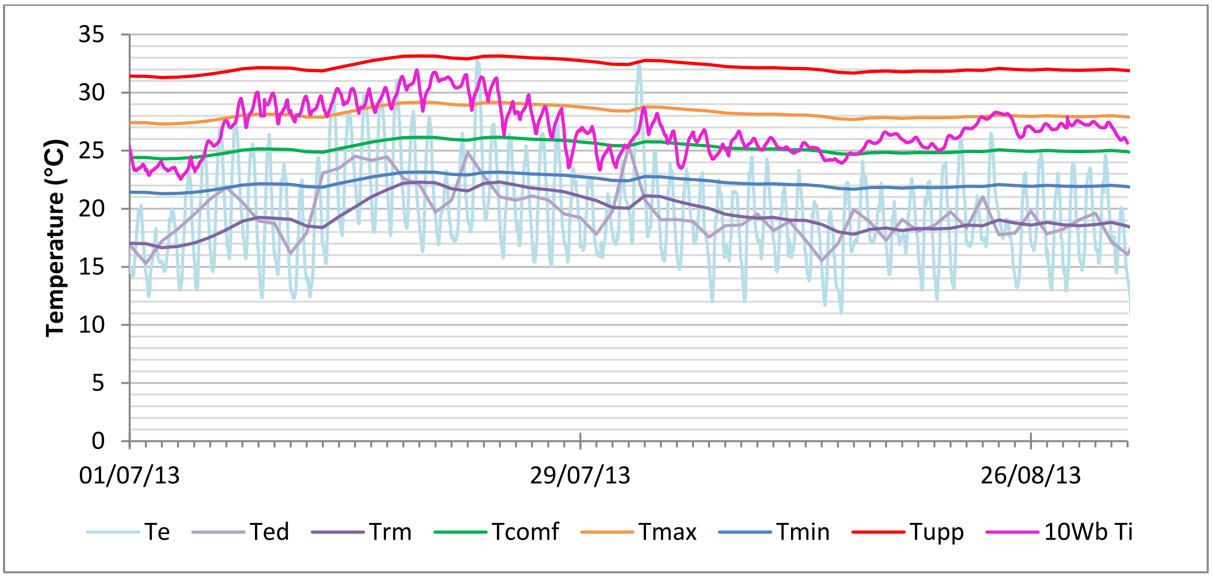

35
30
25
20
15
10
5
0
Temperature (°C)
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
8S Ti

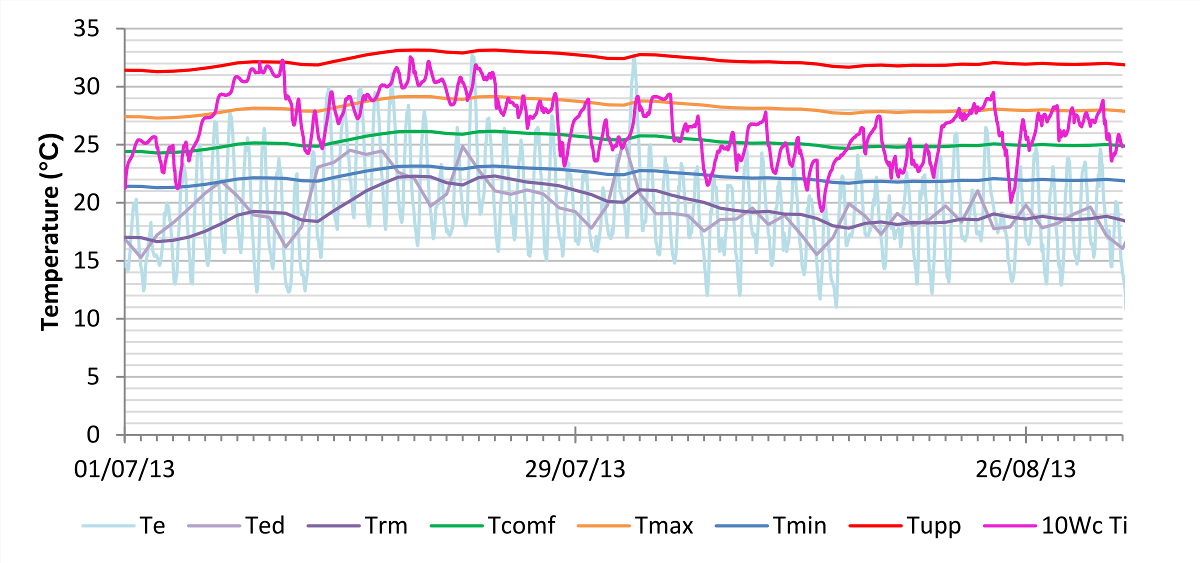

35
30
25
20
15
10
5
0
Temperature (°C)
01/07/13
15/07/13
29/07/13
12/08/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
9Ea Ti


35
30
25
20
15
10
5
0
Temperature (°C)
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
9Eb Ti

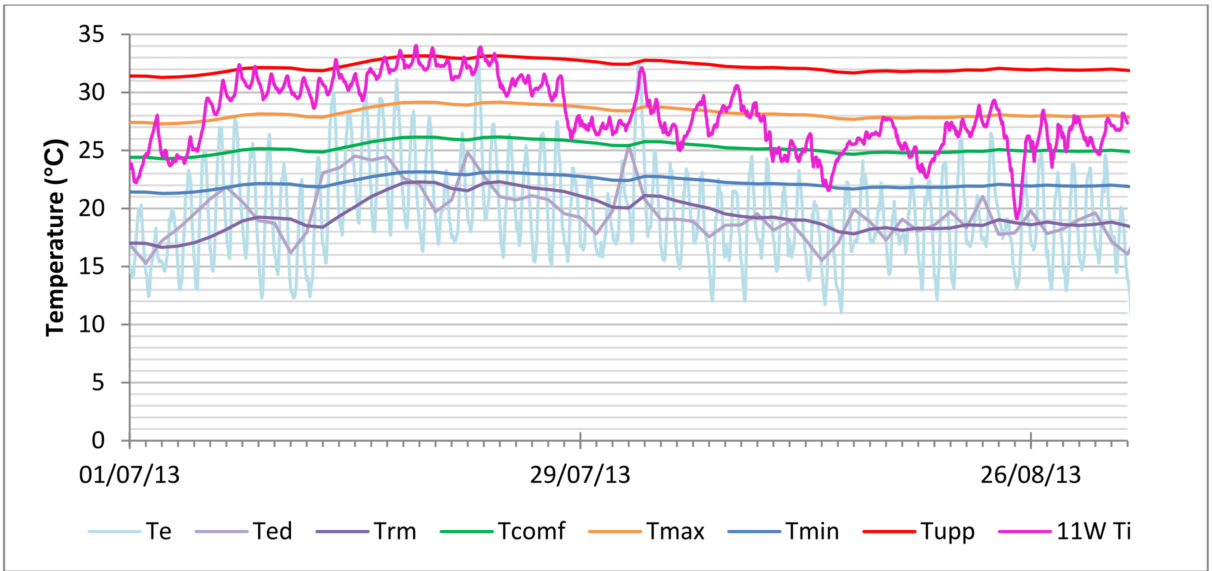

35
30
25
20
15
10
5
0
Temperature (°C)
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
9W Ti


35
30
25
20
15
10
5
0
Temperature (°C)
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
10Wa Ti

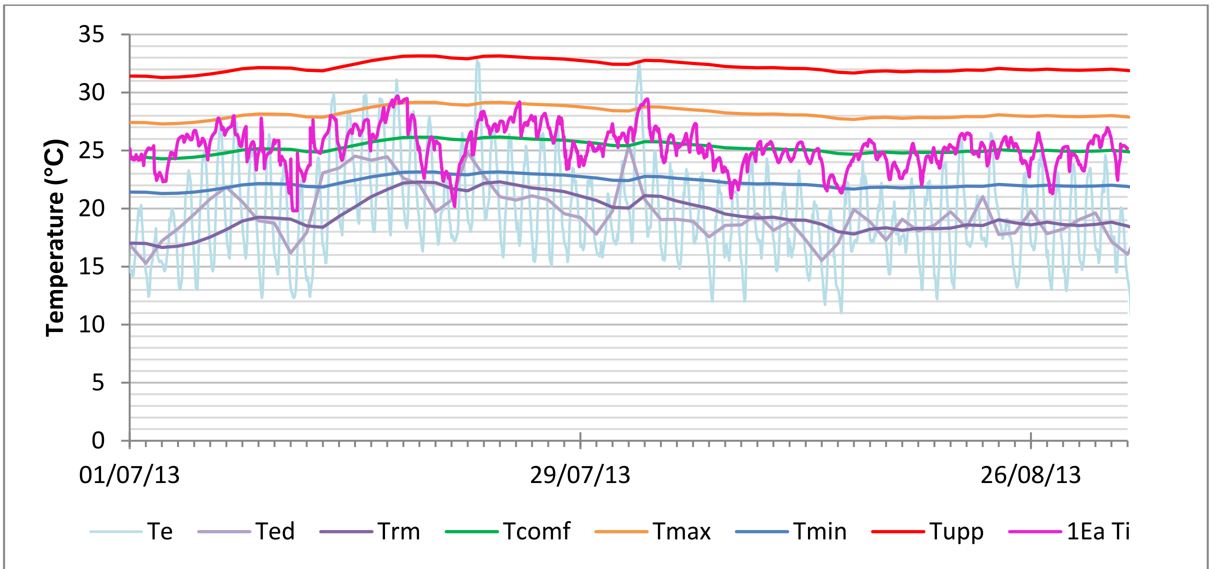

35
30
25
20
15
10
5
0
Temperature (°C)
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
10Wb Ti



Temperature (°C)
35
30
25
20
15
10
5
0
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
10Wc Ti

Temperature (°C)
35
30
25
20
15
10
5
0
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
11W Ti

Temperature (°C)
35
30
25
20
15
10
5
0
01/07/13
29/07/13
26/08/13
Te
Ted
Trm
Tcomf
Tmax
Tmin
Tupp
1Ea Ti