Evaluating Building Energy Performance:
A Lifecycle Risk Management Methodology

by
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"We don't have to save the world. The world is big enough to look after itself. What we have to be concerned about is whether or not the world we live in will be capable of sustaining us in it."

Douglas Adams

Abstract

There is widespread acceptance of the need to reduce energy consumption within the built environment. Despite this, there are often large discrepancies between the energy performance aspiration and operational reality of modern buildings. The application of existing mitigation measures appears to be piecemeal and lacks a ‘whole-system’ approach to the problem. This Engineering Doctorate aims to identify common reasons for performance discrepancies and develop a methodology for risk mitigation. Existing literature was reviewed in detail to identify individual factors contributing to the risk of a building failing to meet performance aspirations. Risk factors thus identified were assembled into a taxonomy that forms the basis of a methodology for identifying and evaluating performance risk. A detailed case study was used to investigate performance at whole-building and sub-system levels. A probabilistic approach to estimating system energy consumption was also developed to provide a simple and workable improvement to industry best practice. Analysis of monitoring data revealed that, even after accounting for the absence of unregulated loads in the design estimates, annual operational energy consumption was over twice the design figure. A significant part of this discrepancy was due to the space heating sub-system, which used more than four times its estimated energy consumption, and the domestic hot water sub-system, which used more than twice. These discrepancies were the result of whole-system lifecycle risk factors ranging from design decisions and construction project management to occupant behaviour and staff training. Application of the probabilistic technique to the estimate of domestic hot water consumption revealed that the discrepancies observed could be predicted given the uncertainties in the design assumptions. The risk taxonomy was used to identify factors present in the results of the qualitative case study evaluation. This work has built on practical building evaluation techniques to develop a new way of evaluating both the uncertainty in energy performance estimates and the presence of lifecycle performance risks. These techniques form a risk management methodology that can be applied usefully throughout the project lifecycle.

Key Words

Buildings; Energy Performance Gap; Performance Evaluation; Monitoring; Space Heating; Domestic Hot Water; Uncertainty; Risk Management

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I am also grateful to the iCon project team and tenants for giving up their time to participate in workshops, interviews and surveys; and the iCon operations team, in particular Richard Hardwick and John Simpson, for assisting with my evaluation of the building.

Thanks are also due to my friends and colleagues who, over the years, have been a source of ideas and inspiration, sowing the seeds of this research project.

Finally, I am deeply grateful for the love and patient support of my family and my wife, Nao. Thank you for believing in me!

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Abbreviations

AHU	**A**ir **H**andling **U**nit
BMS	**B**uilding **M**anagement **S**ystem
BUS	**B**uilding **U**se **S**tudies
BREEAM	**B**uilding **R**esearch **E**stablishment **E**nvironmental **A**ssessment **M**ethodology
CEI	**C**arbon **E**mission **I**ntensity
CIBSE	**C**hartered **I**nstitution of **B**uilding **S**ervices **E**ngineers
COP	**C**oefficient **o**f **P**erformance
DEC	**D**isplay **E**nergy **C**ertificate
DHW	**D**omestic **H**ot **W**ater
EAHP	**E**xhaust **A**ir **H**eat **P**ump
EPC	**E**nergy **P**erformance **C**ertificate
EST	**E**nergy **S**aving **T**rust
EUI	**E**nergy **U**se **I**ntensity
GIA	**G**ross **I**nternal **A**rea
ICT	**I**nformation and **C**ommunications **T**echnology
LEED	**L**eadership in **E**nergy and **E**nvironmental **D**esign
NCM	**N**ational **C**alculation **M**ethodology
O&M	**O**peration and **M**aintenance
PROBE	**P**ost-occupancy **R**eview **o**f **B**uilding **E**ngineering
RIBA	**R**oyal **I**nstitute of **B**ritish **A**rchitects
SBEM	**S**implified **B**uilding **E**nergy **M**odel
SL	**S**oft **L**andings
TSB	**T**echnology **S**trategy **B**oard
TUFA	**T**otal **U**sable **F**loor **A**rea

To my girls; sorry it took so long.

Chapter 1

Introduction

This thesis presents work carried out as part of an Engineering Doctorate (EngD) research project. This is a four-year programme that combines PhD-level research with a specialist taught element. It differs from a traditional PhD in its emphasis on finding practical solutions to significant problems or challenges within an industrial context. The project was administered by the Systems Engineering Doctorate Centre and financially supported by the Engineering and Physical Sciences Research Council (EPSRC) and the industrial sponsor East Midlands Sustainable Construction iNet.

1.1 Context

The consumption of energy resources has a wide range of social, economic and environmental consequences. The built environment is responsible for around 40% of final energy consumption in the European Union. Research has shown that new buildings often fail to meet energy performance targets, resulting in a discrepancy between design and operational energy consumption. This 'performance gap' occurs as a result of issues relating to the accuracy of building energy models, the design and construction process, and the operation of real-life buildings. Results obtained from building energy modelling tools can generate unrealistic expectations of operational energy performance due to model assumptions and omissions. In particular, energy modelling often fails to account for energy end-uses that are included in operational consumption figures; subsequent comparisons are therefore potentially misleading. The modelling is also unable to account for many socio-technical issues that affect the system lifecycle. Assumptions regarding sub-system performance such as heat pump coefficient of performance (COP) and boiler efficiency, which are rarely modelled in detail, can also affect energy consumption predictions. Despite a large body of existing guidance and process improvement techniques such as Soft Landings these issues are still widespread. Techniques that account for stochastic variability and uncertainty inherent in predictive models do exist and are successfully used in other fields; however, their application to the energy performance of buildings is currently limited. As the importance of accurate estimates of operational energy use grows, for example due to increasing interest in energy performance contracts, there is a need for improved management of uncertainties and risks relating to building energy performance.

1.2 Aims and Objectives

The overarching issue to be tackled is '**Why are discrepancies between design and operational energy consumption still commonplace?**'. This research aims to answer this question and to propose a method by which these discrepancies can be reduced. These aims are reflected in the following objectives:

- Identify significant causal factors resulting in discrepancies between design and actual building energy performance.
- Determine why, and where in the project life-cycle these factors occur with reference to a case-study building.
- Develop a technique for evaluating the effect of sub-system uncertainty on energy performance estimates.
- Propose a methodology for mitigating risks of performance discrepancy due to design and operational issues in the project lifecycle.

1.3 Thesis Outline

Chapter 2 sets the scene for the research, describing the context in terms of energy policy and commitments to CO_2 emission reductions. It then introduces the problem area, reviews evidence for the existence of an 'energy performance gap' and critically evaluates a range of current approaches to tacking the problem.

Chapter 3 describes the methodology by which the project's aims and objectives will be met. The case study approach is adopted as a means of taking a whole-system view of the problem area and providing much needed empirical data through 'real-world' research. The chapter also describes the case study building and outlines the monitoring and analysis carried out in technical evaluation of two key subsystems; space heating and domestic hot water. Finally, the work undertaken to develop a risk management framework based on qualitative evaluation of risk factors is introduced.

Chapter 4 describes the evaluation of technical factors relating to the case study building's energy performance at the whole-building level. Design stage energy performance estimates obtained from benchmarks and energy modelling are compared with disaggregated energy consumption data obtained from the monitoring system. The data is analysed to investigate trends over time relating to occupancy levels and sub-system operation. The chapter concludes with a energy assessment using the TM22 methodology and a discussion of the approach.

Chapters 5 and 6 investigate the energy performance of the case study building at subsystem level in an attempt to identify important sources of uncertainty. Benchmarks, design calculations and performance predictions are compared with measured performance data for space heating and domestic hot water. The comparison also considers calculation methods and assumptions used in the estimation of energy performance and the operating patterns and technical issues affecting operational energy performance.

Chapter 7 introduces a probabilistic approach to performance estimates based on widely used energy tree diagrams. This approach is a practical way of incorporating the effects of uncertainty in input parameters on energy performance estimates.

Chapter 8 describes the development of a risk management methodology for quantifying the presence and impact of energy performance risk factors throughout the building project lifecycle. The performance evaluation of the case study building is reviewed from a number of stakeholder perspectives and used to identify specify risk factors present in the project.

Chapter 9 concludes the thesis with a summary of the key findings and contributions of the research. The limitations of the research are also discussed along with potential improvements and areas for further work.

Figure 1.1 illustrates the thesis structure and the relationship between chapters.

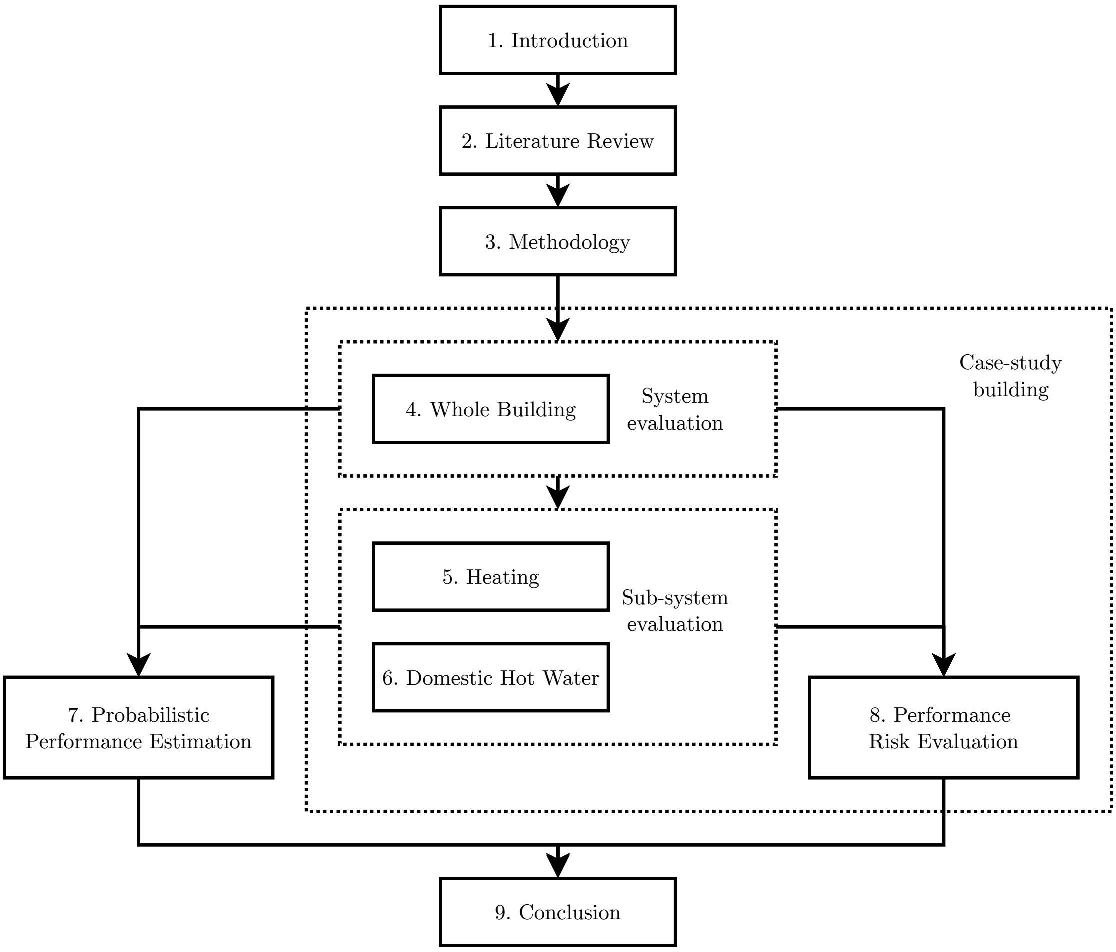

FIGURE 1.1: Thesis chapter structure

1.4 Contributions

This research makes the following contributions to the field:

- A deeper understanding of the whole-system nature of energy performance risk and its contributing factors
- The identification of specific operational issues affecting sub-system operation and the uncertainty associated with space heating and domestic hot water energy consumption
- The novel application of Monte Carlo simulation for evaluating uncertainty in industry-standard energy assessments
- The development of a methodology for managing energy performance risk throughout the building lifecycle

Chapter 2

Literature Review

2.1 Introduction

This chapter begins by describing the policy context, setting out the reasons why performance discrepancies are an important issue. It then reviews evidence for the existence of performance discrepancies based on published analysis of existing buildings and publicly available performance data. The implication of using both design and operational energy certification on perceived performance gaps is also discussed. The range of risk factors that contribute to performance discrepancies is investigated and the key areas are summarised. There are a wide range of existing techniques that aim to mitigate the problem, each of which takes a different view of the problem. The main themes are discussed and the chapter concludes by proposing a systems approach that integrates technical and non-technical factors.

2.2 Policy Context

2.2.1 CO_2 emissions and energy use

There is a consensus among the mainstream scientific community that current evidence supports the hypothesis that anthropogenic CO_2 emissions are a significant factor in climate change (AAAS, 2006). The generation of electricity and heat is responsible for nearly 25% of world greenhouse gas emissions, 77% of which is in the form of CO_2 (Herzog, 2009). An increased use of low or zero carbon energy sources is necessary to reduce long term global CO_2 emissions. However the current levels of low or zero carbon energy generation are low. In the UK for example, renewable energy is responsible for 6.8% of all grid electricity (DECC, 2011). The Stern Review, published in 2006, made clear the necessity of reducing emissions in order to mitigate the risks of global climate change (Stern, 2007). The urgency of action and the magnitude of the necessary reductions mean energy demand side measures are of primary importance in achieving short term reductions in CO_2 emissions. These measures will also support the longer term transition to a low-carbon economy.

Although it is common to relate energy use to the issue of CO_2 emissions and climate change there are other important reasons for reducing energy use (MacKay, 2009). There are geopolitical issues associated with the security of energy supply, not only the vulnerability of regional economies to interruptions in supply but also the potential for resource related conflict (Klare, 2001). The depletion of finite natural resources and environmental pollution due to the extraction, processing and use of fossil and nuclear fuels are also serious global issues (Michaelides, 2012). More locally, there is often public opposition to the development of new energy generation, whether in the form of a wind farm or a nuclear power station (Wüstenhagen et al., 2007; Pidgeon et al., 2008). However the most immediate reason to be concerned about energy consumption might simply be the impact of increasing cost of fuel on individuals, businesses and even entire economies (Bolton, 2010).

2.2.2 Emissions reduction targets

The European Commission has endorsed the objective of reducing EU greenhouse gas emissions to over 80% below 1990 levels by 2050 (European Commission, 2011). The UK's Climate Change Act (Great Britain, 2008) targets a net 80% emissions reduction on 1990 levels by 2050 (with at least a 26% emissions reduction on 1990 levels by 2020). More recently, the UK Low Carbon Transition Plan 2009 targeted emission cuts of 18% on 2008 levels by 2020, over a one third reduction on 1990 levels (DECC, 2009) The UK is making slow progress towards its emission reduction targets: During the period 2003-2007, CO_2 emissions reduced on average by 0.6% annually, compared with an annual reduction of 1.7% required to meet the current legislated budget (CCC, 2009) Although emissions fell significantly in 2009, the fall was due to the recession and fall in GDP and manufacturing output and increased fuel costs (CCC, 2010). Of greater concern is the 'extent to which CO_2 reduction has been due to implementation of measures to improve energy or carbon is very limited' (CCC, 2009).

2.2.3 The role of buildings

Around 40% of the EU's final energy consumption occurs in the residential and commercial sector, the majority of which is consumed in buildings (European Commission, 2003). The operational energy consumption of domestic and non-domestic buildings in 2008 was estimated to result in CO_2 emissions of 246 $MtCO_2$ (BIS, 2010), approximately 46% of the UK's net CO_2 emissions (DECC, 2010). Emissions from domestic and non-domestic buildings contributed 27% and 19% respectively to the national total. Although the non-domestic contribution is smaller in total than the domestic, the potential for CO_2 emissions reduction on a per-building basis is larger.

Energy consumption figures published annually by the UK Department of Energy and Climate Change (DECC) provide information on energy use by sector, end-use and fuel type (DECC, 2013b). Since 1970, the UK service sector's energy consumption has remained steady in comparison with increases in the domestic and transport sectors, and a decrease in the industrial sector (Figure 2.1). Over this period, a reduction at point of use in fossil fuel consumption has been offset by an increase in electricity consumption (Figure 2.2). Within the service sector, retail is the largest sub-sector by energy consumption. Together, the government and commercial offices sub-sectors are the second largest, responsible for about 39 TWh or 19% of the service sector energy consumption. Space heating, predominantly from fossil fuel, and electric lighting account for 39% and 19% respectively of the service sector energy consumption (Figures 2.3 and 2.4).

Because of the large percentage of CO_2 emissions resulting from buildings it is unsurprising that the construction industry is called upon to deliver significant reductions in CO_2 emissions by improving the energy performance of buildings. Recent governments have stated aspirations for a low carbon future in several policy documents and plans. In 2007, the Building a Greener Future Policy Statement set a target for all new homes to be zero-carbon by 2016 (DCLG, 2007). The following year, HM Government's Budget set a corresponding target for all new non-domestic buildings to be zero-carbon by 2019 (HM Treasury, 2008).

2.2.4 CO_2 emissions scope

The definition of a 'zero carbon building' has been the subject of much debate and several government consultations (DCLG, 2009a,b). The government's current zero carbon homes policy states that zero carbon is achieved in three stages, two of which are achieved

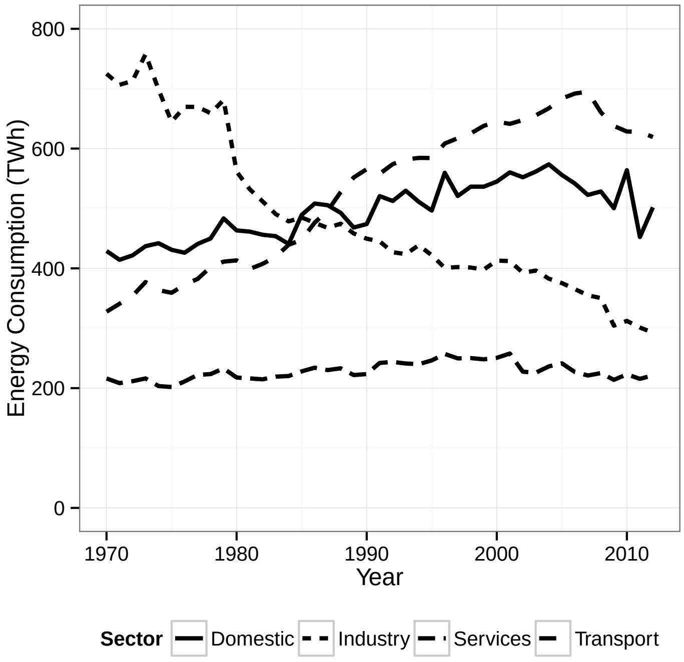

Figure 2.1: UK Final Energy Consumption by Sector (after DECC, 2013b)

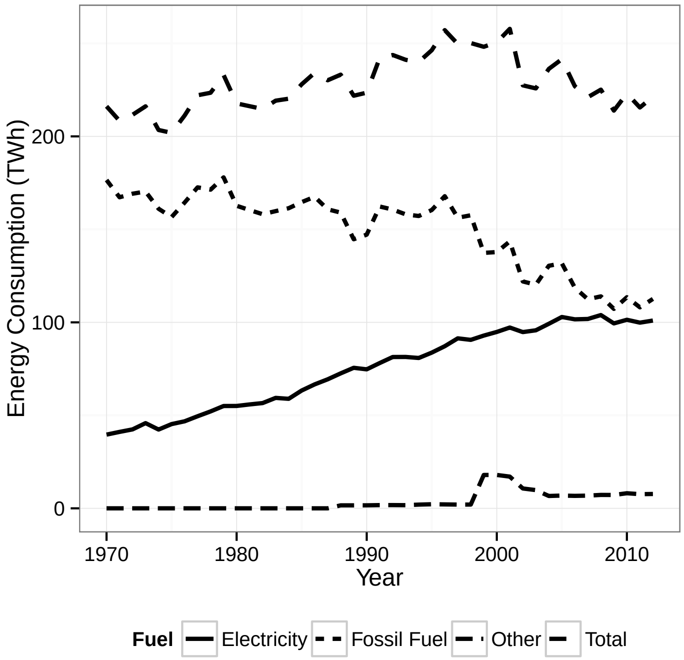

Figure 2.2: UK Services Sector Energy Consumption by Fuel (after DECC, 2013b)

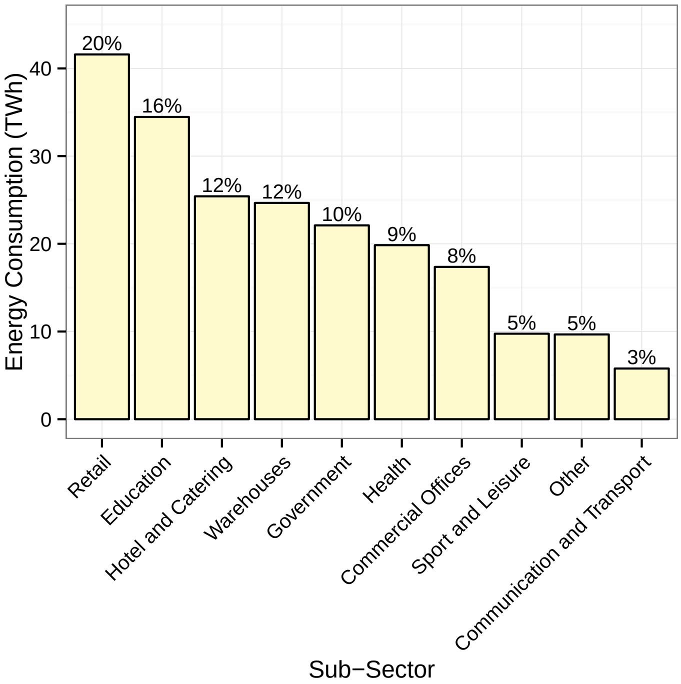

FIGURE 2.3: UK Services Sub-Sector Energy Consumption
(after DECC, 2013b)

on-site (good fabric energy efficiency and the inclusion of on-site low carbon heat and power technologies), and the use of 'allowable solutions' that may include contributing funds to off-site carbon reduction projects (ZCH, 2013). The definition for non-domestic buildings has not yet been finalised but it is likely to be similar to that used for domestic buildings (DCLG, 2011b). These definitions only consider the energy consumption of fixed building services under the control of building regulations (known as regulated energy consumption). Unregulated energy consumption, such as that of domestic appliances or office equipment, are excluded from the definition.

A whole-lifecycle interpretation of 'low carbon' would take into account a wider range of carbon emission sources, including the embodied carbon emissions resulting from manufacture of building components, the carbon emissions associated with transportation and the construction process, the operational carbon emissions due to the energy consumption of the building through its working life, as well as the carbon emissions resulting from refurbishment or disposal of the building. Currently however, buildings' operational energy use is responsible for at least 80% of built environment carbon emissions (Green Construction Board, 2013). As operational carbon emissions decrease as a result of energy efficiency and the use of on-site renewable energy sources the embodied carbon will become an increasingly important consideration (Yohanis and Norton, 2002; BSRIA,

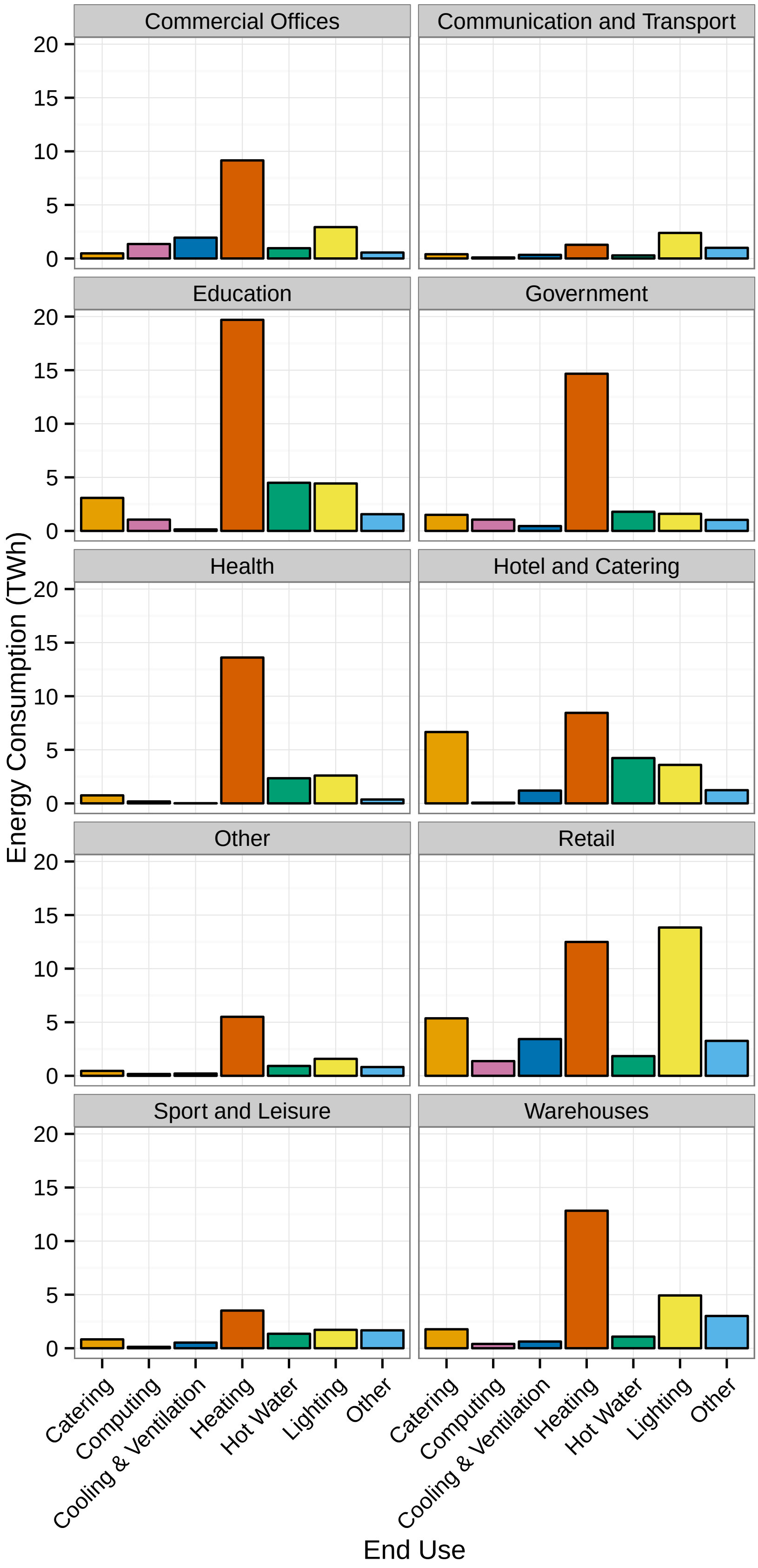

FIGURE 2.4: UK Services Sub-Sector Energy End Uses
(after DECC, 2013b)

2011). Under an 80% carbon reduction scenario, described as ‘challenging but technically possible’, by 2050 embodied carbon will represent nearly 40% of built environment carbon emissions (Green Construction Board, 2013).

Taking an even wider view, one might consider the difference in life-cycle carbon emissions between two identical office buildings, one constructed near a busy public transport interchange, the other on an out of town site accessible only by road. Public transport is usually considered to result in lower carbon emissions than private cars but there are practical difficulties in reflecting this in the building’s overall carbon footprint. Currently, factors such as site selection, which do have an indirect impact on carbon footprint, are taken into account by environmental assessment schemes such as LEED and BREEAM, which attempt to assess the sustainability of a building using a wide range of criteria (USGBC, 2006; BRE, 2010).

2.3 The ‘Energy Performance Gap’

In recent years it has become apparent that many new buildings designed to achieve high levels of environmental performance are failing to meet environmental targets and deliver substantial reductions in energy use. Curwell et al. (1999) described two case study buildings from the Green Building Challenge that both used more energy than their designers had predicted. Bordass et al. (2004) found that two years after completion the actual CO_2 emissions from one of these buildings was more than twice the design estimate.

In 2007, the National Audit Office reported on the extent to which UK government departments and agencies were meeting sustainability targets for new buildings and major refurbishments (National Audit Office, 2007). The report found that 80% of sampled projects would have failed to attain the required standards and that the standards alone would not be sufficient to ensure specific targets for carbon emissions, energy and water consumption are met. It was suggested that a similar incidence of failings may also occur within the commercial sector. A recommendation was made to move towards outcome-based performance targets for energy and water use in individual buildings that could be included in construction and refurbishment specifications.

The CarbonBuzz website, a result of collaboration between RIBA and CIBSE, was launched in 2008 to collect design information and energy consumption figures (CarbonBuzz, 2014). In early 2014 there were 74 case studies published on the site however only 22 provide both design and actual CO_2 emissions. The majority of these buildings were either offices or schools. Based on their combined carbon emission intensity (CEI)[1], the average design performance of these buildings was 40 $kgCO_2/m^2$, while the actual performance was 94 $kgCO_2/m^2$, an average discrepancy of 135%. Figure 2.5 shows the percentage difference between actual and design CEI for the buildings with positive CEI values. Buildings with negative design CEI values (i.e. where on-site generation exceeds consumption) have been omitted as the resulting percentage difference would be misleading. Per building the mean percentage difference is 74% with a standard deviation of 112%. There is clearly a large variability in the differences between actual and design CO_2 emissions, with a minority of buildings performing better than their design estimates.

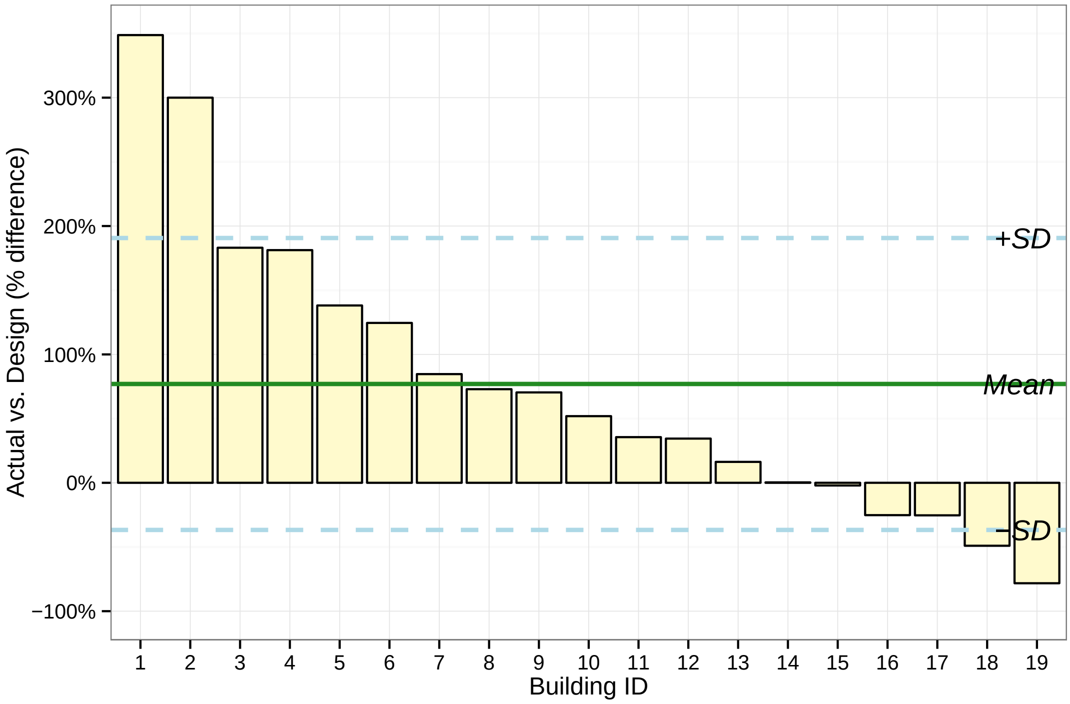

FIGURE 2.5: Actual vs. Design Energy Use Intensity (after CarbonBuzz, 2014).

Newsham et al. (2009) analysed data from 100 LEED-certified[2] commercial and institutional buildings in the USA. The results of this analysis showed that although on average LEED buildings used less energy per unit floor area than conventional buildings, there was little correlation between their measured energy performance and their certification level. Based on the analysis, it was suggested that further green building certification

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[1] annual CO_2 emissions divided by total floor area ($kgCO_2/m^2$)

[2] LEED (Leadership in Energy & Environmental Design) is a building rating scheme that awards credit based on a wide range of environmental criteria including energy performance (USGBC, 2014)

schemes require a demonstration of the sustainable performance once buildings are in operation. Earlier work by Turner and Frankel (2008) using the same dataset determined that the predicted-to-measured energy use ratio for individual projects achieving the highest LEED ratings ranged from less than 0.5 to more than 2.75, suggesting that energy modelling does not reliably predict actual energy use (Figure 2.6). It is interesting to note that the mean ratio of measured to design energy use intensity (EUI)[3] is less than one for the LEED Certified and Silver buildings, i.e. on average the buildings' measured performance is better than the design estimate. It is also worth noting that, even when disregarding outliers, there is a wide spread of points in the range 0.5 to 1.5. This suggests that although measured energy use does not always exceed design energy use there is nevertheless a substantial uncertainty in design estimates. This uncertainty, illustrated by the spread of points, appears to be greater at the higher LEED ratings. It is possible that buildings designed to achieve the top ratings make use of more sophisticated energy systems, which may be novel and untested, and therefore a greater source of uncertainty in design and operational energy performance.

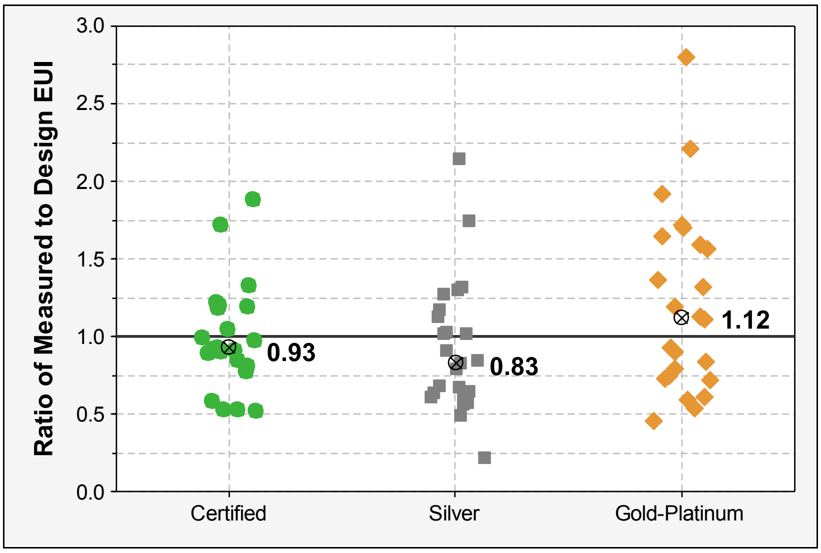

FIGURE 2.6: Measured vs. Design Energy Use Intensity (Turner and Frankel, 2008).

In response to the study by Newsham et al., Scofield (2009) reviewed the same data in terms of source energy, which accounts for energy used on-site and the off-site losses associated with the generation and distribution of electric energy, and also made comparisons in terms of total energy use divided by the total floor area of the survey buildings rather than averaging the energy use intensity for each building surveyed. This reduced the difference in energy performance between the LEED certified and non-LEED buildings to below the level of statistical significance. This finding underscores the importance of

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[3] annual site energy consumption divided by total floor area (kWh/m^2)

moving towards operational energy performance standards for buildings, since design performance appears to be an unreliable predictor of actual performance.

It is possible that the adoption of stricter construction standards could make design performance targets more achievable. The Passivhaus standard aims to minimise space heating and cooling demands by delivering high levels of fabric thermal performance. The standard includes stringent quality assurance measures to ensure that buildings are constructed according to their design specifications (NHBC, 2012b). The results of a building performance evaluation study carried out on a development of 14 Passivhaus dwellings in South East England suggest that the standard can deliver high quality buildings that meet their performance targets (Ingham, 2014).

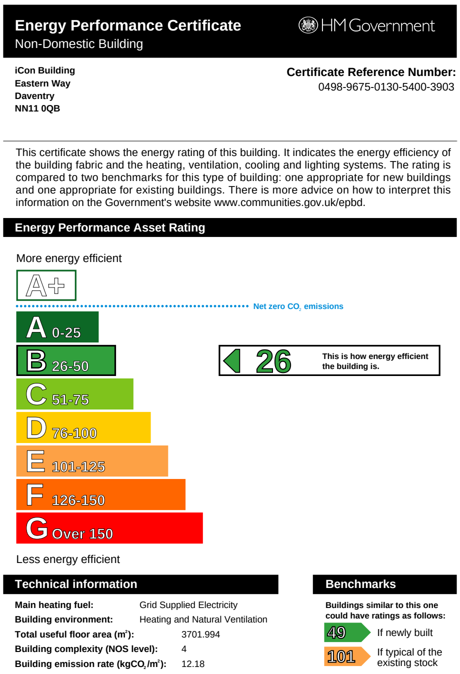
2.3.1 DECs & EPCs

The EU Energy Performance of Buildings Directive (EPBD) came into force in 2003. Its objective is to improve the energy performance of buildings. This is to be achieved by requiring a whole building energy performance calculation methodology, minimum energy requirements for new and renovated existing buildings, regular inspection of boilers and air conditioning systems and the energy certification of buildings (European Commission, 2003). There are two forms of energy certification: Energy Performance Certificates (EPCs) (Figure 2.7), which reflect a building's design energy performance and Display Energy Certificates (DECs) (Figure 2.8), which reflect a building's operational energy performance. Both certificates feature an energy performance rating, displayed on a colour-coded A to G scale. Although the certificates are superficially similar, it is not possible to make a direct comparison between them due to fundamental differences in the rating methodologies. The EPC asset rating is a model-derived estimate of the theoretical performance of the building as a result of its fabric and fixed services (regulated loads such as heating and lighting). The DEC operational rating expresses the actual performance of the building including, in addition to regulated loads, unregulated loads such as office equipment, catering and external lighting. Discrepancies between asset and operational ratings may be perceived as a performance gap even when they are due to differences in energy certification methodology rather than any performance failings in the actual building. The asset and operational ratings can differ markedly not only due to differences in rating methodology but also due to physical differences between the building *as-designed* and the building *as-built*. Factors such as occupancy, building operation, weather and changes in the carbon intensity of fuel supply are all beyond the scope of the regulations but can impart significant variability in achieved performance. A recent survey of over 200 buildings found little or no correlation between asset ratings and operational ratings, with a wide variation of operational ratings with each asset rating band (Hogg and Botten, 2012).

Electronic copies of the DECs are held in an on-line database (Anon, 2011a). While the database is publicly accessible, it is only possible to download individual DECs for which the unique certificate identifier or property address is known. In practice this inhibits the collection of bulk data for analysis. In 2009, in response to a request under the Environmental Information Regulations, DCLG made available a limited dataset containing certificate information, which was published on the BBC Open Secrets blog (Rosenbaum, 2009). A more complete dataset containing data from 2008, 2009 and 2010 is currently available on the Centre for Sustainable Energy's website (Anon, 2011b). Although this dataset contains energy use intensity data for several thousand buildings it does not provide sufficient information on the nature of the buildings themselves. In particular there is no indication of the building category used to determine the benchmark. As a result there is no straightforward way to analyse the dataset by building type, which limits the dataset's value. In 2011, CIBSE published an analysis of a more comprehensive dataset as part of a review of the benchmarks used (Bruhns et al., 2011). This analysis was concerned with assessing the appropriateness of the category benchmarks. The review found that for most categories, the median operational rating was close to the category benchmark however there is a tendency for electrical use to be somewhat higher and thermal-fuel use somewhat lower than the energy use benchmarks.

2.4 Origins of the Gap

Torcellini et al. (2004) monitored the performance of six sustainably designed non-domestic buildings in the USA. Although the buildings performed better than comparable code compliant base-case models they all failed to meet their predicted design targets. This was mainly due to actual occupant densities being greater than design estimates and building systems not operating together in an ideal manner, for example due to poorly designed control algorithms. Turner (2006) compared the actual and design energy performance of ten office, library and multi-family residential buildings in the North Western USA and found that four performed worse than design, with one of the office buildings exceeding design energy performance by 200%. This was attributed to unspecified problems with the HVAC and lighting control systems during the first few years of operation. Diamond et al. (2006) reviewed the modelled and actual energy performance of 21 non-domestic


Energy Performance Certificate
Non-Domestic Building

iCon Building
Eastern Way
Daventry
NN11 0QB

Certificate Reference Number:
0498-9675-0130-5400-3903

This certificate shows the energy rating of this building. It indicates the energy efficiency of the building fabric and the heating, ventilation, cooling and lighting systems. The rating is compared to two benchmarks for this type of building: one appropriate for new buildings and one appropriate for existing buildings. There is more advice on how to interpret this information on the Government's website www.communities.gov.uk/epbd.

Energy Performance Asset Rating

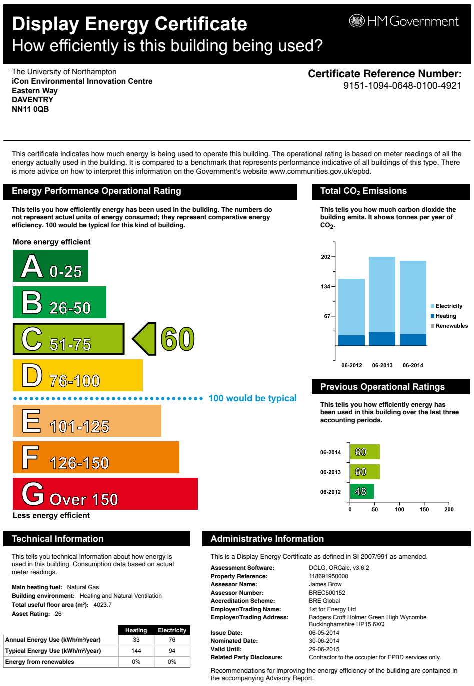
Technical information

Main heating fuel: Grid Supplied Electricity
Building environment: Heating and Natural Ventilation
Total useful floor area (m^2): 3701.994
Building complexity (NOS level): 4
Building emission rate ($kgCO_2/m^2$): 12.18

Benchmarks

Buildings similar to this one could have ratings as follows:
49 If newly built
101 If typical of the existing stock

FIGURE 2.7: Energy Performance Certificate (EPC)


Display Energy Certificate
How efficiently is this building being used?

The University of Northampton
iCon Environmental Innovation Centre
Eastern Way
DAVENTRY
NN11 0QB

Certificate Reference Number:
9151-1094-0648-0100-4921

This certificate indicates how much energy is being used to operate this building. The operational rating is based on meter readings of all the energy actually used in the building. It is compared to a benchmark that represents performance indicative of all buildings of this type. There is more advice on how to interpret this information on the Government's website www.communities.gov.uk/epbd.

Energy Performance Operational Rating

This tells you how efficiently energy has been used in the building. The numbers do not represent actual units of energy consumed; they represent comparative energy efficiency. 100 would be typical for this kind of building.

Total CO_2 Emissions

This tells you how much carbon dioxide the building emits. It shows tonnes per year of CO_2.

Previous Operational Ratings

This tells you how efficiently energy has been used in this building over the last three accounting periods.

Technical Information

This tells you technical information about how energy is used in this building. Consumption data based on actual meter readings.

Main heating fuel: Natural Gas
Building environment: Heating and Natural Ventilation
Total useful floor area (m^2): 4023.7
Asset Rating: 26

	Heating	Electricity
Annual Energy Use ($kWh/m^2/year$)	33	76
Typical Energy Use ($kWh/m^2/year$)	144	94
Energy from renewables	0%	0%

Administrative Information

This is a Display Energy Certificate as defined in SI 2007/991 as amended.

Assessment Software:	DCLG, ORCalc, v3.6.2
Property Reference:	118691950000
Assessor Name:	James Brow
Assessor Number:	BREC500152
Accreditation Scheme:	BRE Global
Employer/Trading Name:	1st for Energy Ltd
Employer/Trading Address:	Badgers Croft Holmer Green High Wycombe Buckinghamshire HP15 6XQ
Issue Date:	06-05-2014
Nominated Date:	30-06-2014
Valid Until:	29-06-2015
Related Party Disclosure:	Contractor to the occupier for EPBD services only.

Recommendations for improving the energy efficiency of the building are contained in the accompanying Advisory Report.

FIGURE 2.8: Display Energy Certificate (DEC)

and multi-family residential buildings in the USA. These buildings had all achieved LEED certification between 2001 and 2005. Simulated design and actual energy data were available for 18 of the 21 buildings. Although the mean difference between design and actual performance was only -1% (i.e. the actual energy consumption was slightly less than the modelled energy consumption), the standard deviation was 46%, due to a range of differences from -82% to 124% (Figure 2.9). Like the Turner and Frankel study, this suggests the performance gap is symptomatic of a wider uncertainty in actual energy performance.

A review by the Carbon Trust of 28 case studies in the UK across a range of sectors including retail, education, offices and mixed use residential buildings, revealed that 75% did not perform as well as expected (Carbon Trust, 2011b). The Zero Carbon Hub has reported on performance studies in the UK domestic sector, which identified discrepancies between design and actual fabric heat loss, background ventilation rates and heat pump performance, all of which contribute to overall performance gaps (ZCH, 2010). Unintended fabric losses have been found in other studies in the UK, along with issues associated with installation and commissioning of low carbon technologies, lack of co-ordination during the construction phase and complexity of controls interfaces (Gupta and Dantsiou, 2013). Similar findings have emerged from studies across Europe. Results

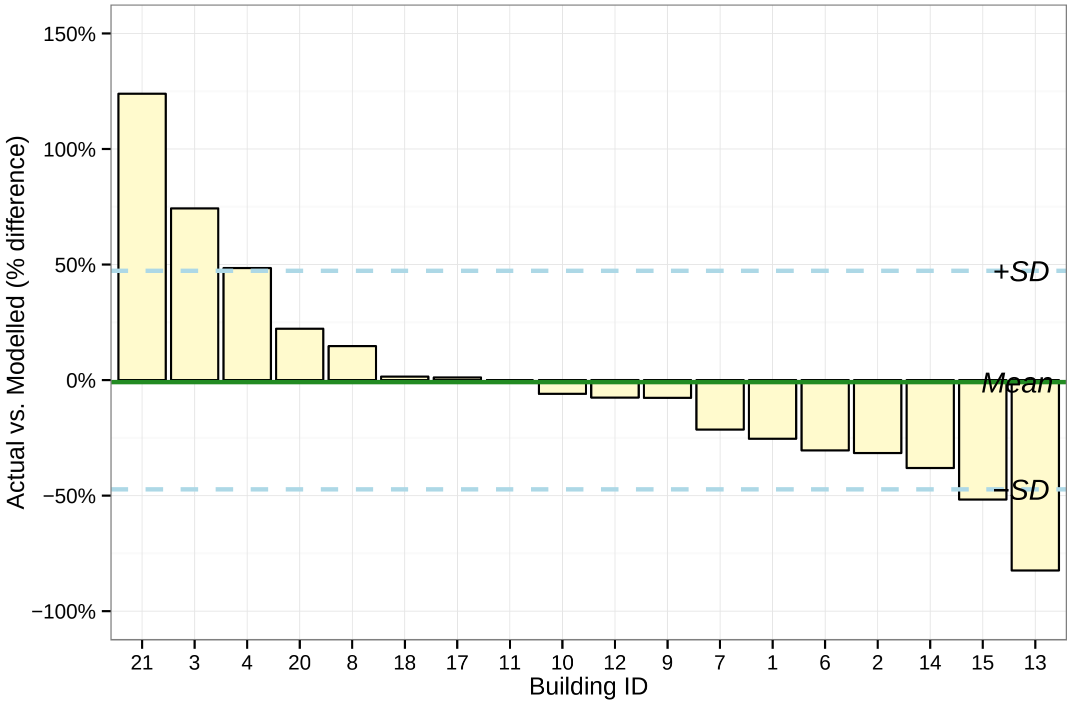


FIGURE 2.9: Actual vs. Modelled Energy Use Intensity (after Diamond et al., 2006).

from a case-study investigation of a low-energy dwelling in Denmark revealed a 35% discrepancy between measured and calculated electricity consumption for heating, possibly as a result of technical issues with the building's heat pump and higher than anticipated indoor temperatures (Mørck et al., 2012). Assumptions regarding background ventilation rate were suspected of contributing to significant discrepancies between projected and actual heating demand of seven residential buildings in Austria (Housez et al., 2014). In the Netherlands, a large-scale comparison of theoretical and actual energy consumption revealed that low-energy buildings have a tendency to consume more than predicted (the situation is reversed in buildings with high theoretical energy use, which were found to consume less than predicted) (Majcen et al., 2013).

These studies have highlighted a number of difficulties in comparing design and actual performance. These included significant differences in occupancy density, usage patterns and installed loads between design assumptions and actual use. The possibility of poor modelling, construction defects and design changes, as well as poor commissioning and operation are also identified as contributing to discrepancies between design and actual performance.

Diamond et al. (2006) recommended a coordinated and well documented collection of modelled and actual energy consumption data. To be of use, this data must be consistent in terms of its definition and normalisation. While the CarbonBuzz platform described above aims to provide a collection of this nature it lacks some transparency in data quality, which makes it difficult to differentiate between performance gaps due to design-stage assumptions or omissions of end-uses and operational performance issues. Bordass et al. (2004) noted that all too few designers monitor performance after their buildings are completed and that the surveys that have been carried out nearly always reveal avoidable waste, the origins of which occur throughout the project life cycle, from early briefing stages all the way though to the building's operation. Turner (2006) also notes that the design community needs better feedback to help improve its ability to model actual performance outcomes.

Bannister (2009) identified two sets of issues that can result in low actual energy performance. The first is a diverse range of factors that can cause problems even for buildings achieving high design energy performance. Such factors include loss of design intent, overcomplexity, poor commissioning, operation and maintenance, and unanticipated user behaviour. These factors are generally the result of decisions made by different project stakeholders and do not follow clear lines of responsibility. The second set of factors falls within the responsibility of the design and construction team, and includes poor design decisions and equipment, oversized plant, inadequate documentation and conflicting design goals. Hinge et al. (2008) summarised a similar range of issues from which performance gaps arise. These include usage and occupancy patterns that differ from design assumptions, sub-systems that fail to achieve assumed levels of performance or reliability, inadequate system commissioning and a lack of knowledge of how to maintain and operate the building efficiently. Bordass et al. (2004) noted that faulty control systems and confusing user interfaces are a widespread problem that can result in unnecessary equipment operation. Users may bypass control systems perceived as hindrances, particularly where they lack an understanding of the building's intended operating strategy, leading to unintended modes of operation. These issues, combined with the lack of feedback on the performance of real buildings, result in unrealistic expectations being placed upon buildings designed to achieve high levels of energy performance. Furthermore, current modelling practice is subject to a number of limitations in its ability to predict the actual energy performance of buildings.

2.4.1 Limitations of simulation

Building energy performance issues are not a new phenomenon: Norford et al. (1986) described two buildings in New Jersey that were the subject of a detailed performance evaluation study carried out in the early 1980s. Designed in the late 1970s, the buildings were intended to showcase innovative energy efficient design features including the use of natural daylight and passive solar design with a double-skin façade and ground air cooling pipes. The actual performance of one of these buildings was compared with its simulated design performance and found to be over twice the simulated value (Norford et al., 1994). Upon investigation, it was discovered that unanticipated tenant energy consumption was responsible for 64% of the discrepancy. This included higher lighting and office equipment consumption, particularly out-of-hours, central computing equipment and a kitchen. Out-of-hours operation of building services equipment contributed a further 24% with the remainder being due to inaccuracies in design stage assumptions. The researchers point out that a building's energy performance is influenced by factors beyond the control of the architect and building services designers. Design levels of energy performance may depend on an 'ideal world' scenario where occupants have both a conservation ethic and a low-energy business and the building operators are conscientious and capable personnel who fully understand the building systems. Changes to any of these factors could yield entirely different results. The 'ideal world' of simulation models also assumes ideal operation of building systems, which is very rarely the case in the real world, leading to underestimates of energy consumed (Torcellini et al., 2004). The complexity of building systems and their response to user behaviour results in a large number of model parameters capable of influencing results of the simulation. Modelling decisions including simplifications and assumptions about sub-system performance (Maile et al., 2010) as well as occupancy and usage patterns (Menezes et al., 2012) can therefore be responsible for significant variation in energy consumption estimates.

Despite these limitations, Bannister (2005) noted that design teams as well as the development and regulatory community tend to place a great deal of faith in the ability of simulation to indicate potential performance. Furthermore, when simulation tools are used to create building models to demonstrate regulatory compliance there may be an implicit pressure to prove that the design meets performance targets. Arnold et al. (2005) warn that due to the many parameters and variables involved in building simulation it is possible to 'tweak' a model to achieve a desired result. Turner and Frankel (2008) note that most design-stage models of energy performance are provided with caveats and disclaimers that they should be used to identify relative energy performance rather than predict actual energy use. Despite these caveats, which are based on an understanding of the inherent complexity of buildings and the uncertainty in operational factors, the use of deterministic modelling to predict actual energy use is still widespread.

In the UK, regulatory compliance is demonstrated using the output from building simulation tools applying the National Calculation Methodology (NCM). The main criterion for compliance is that the predicted CO_2 emissions of the actual building design (the Building Emission Rate, BER) are less than the predicted CO_2 emissions of an equivalent 'notional' building that meets a baseline energy performance standard[4] (the Target Emission Rate, TER). There are two classes of software tool suitable for NCM calculations: the first is based on the Simplified Building Energy Model (SBEM), which uses a quasi-steady-state simulation that calculates room heat balances on a monthly basis; the second is the approved Dynamic Simulation Models (DSMs), which calculate heat balances on shorter time steps (typically hourly). Tools based on SBEM are suitable for simpler buildings, while DSMs offer greater flexibility and the ability to model more complex building features (DCLG, 2010b). Although certain features such as ventilated double-skin façades and automatic blind control can be modelled by approximations in SBEM, in practice the pre-processing necessary is likely to discourage users from using SBEM-based tools in favour of DSMs (Raslan and Davies, 2010). Models created using the NCM must use a number of standardised input parameters as the compliance methodology is intended to compare buildings on the basis of their intrinsic potential performance, regardless of how they may actually be used in practice. These parameters include occupancy profiles, temperature set-points, outdoor air rates, heat gain profiles and illuminance levels for each type of space in the building. In addition, standard weather data from one of 14 UK locations must be used (DCLG, 2010b). The results of NCM calculations will, by definition, exclude unregulated loads, which are not under the control of building regulations. As a result, it is unsurprising that asset ratings based on CO_2 emissions predicted by NCM calculations often differ markedly from operational ratings based on CO_2 emissions calculated from measured energy consumption.

Reddy (2006) describes calibration techniques that have been proposed to improve the accuracy of energy predictions. Although calibration is a retrospective process for improving models of existing buildings, lessons from calibration exercises may have indirect benefit in improving the assumptions used in developing design stage models. The real value of model calibration lies in establishing baseline models for evaluating the effectiveness of energy conservation measures (provided the measures themselves can be simulated accurately within the calibrated model). Ahmad and Culp's comparison of calibrated and uncalibrated models demonstrated the need for calibration when energy use figures are to be used for financial decision making, as the uncalibrated models may not adequately represent the real operations of buildings (Ahmad and Culp, 2006).

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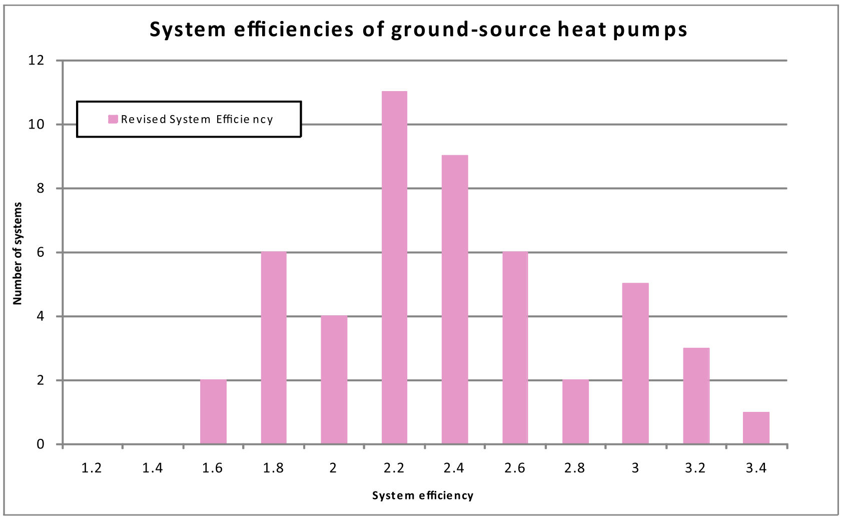
[4] Approximately 25% better than the 2006 building regulations standard

The building evaluated by Norford et al. (1994) was the subject of a comprehensive calibration exercise by the same authors. This exercise relied on extensive building instrumentation to measure electrical loads, equipment performance and indoor and outdoor conditions. In addition it was necessary to carry out experiments and surveys to disaggregate electrical loads, a task made somewhat easier by the lack of variability in many loads. The authors pointed out today's offices are more likely to incorporate variable lighting and office equipment loads as a result of trends towards improved part-load performance, which will therefore require more complicated energy analysis.

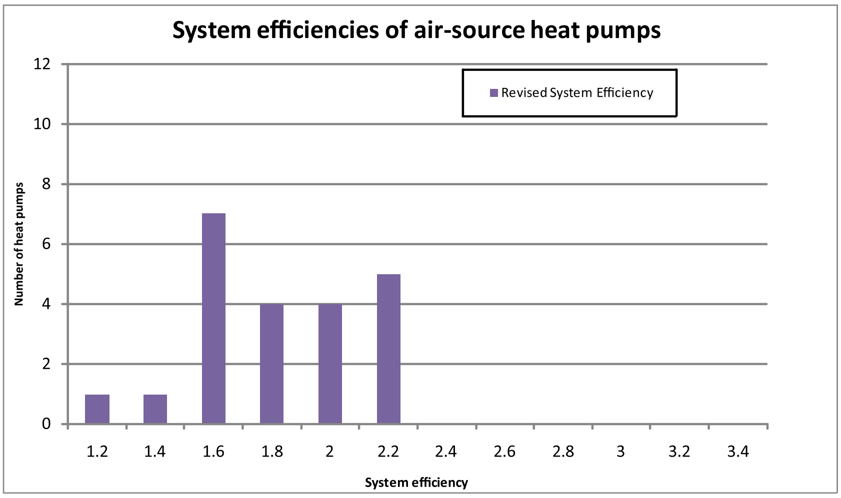
2.4.2 Sub-system performance

Performance evaluation of sub-system elements is typically carried out by manufacturers applying standard test methodologies under controlled conditions. In this way, standardised efficiency figures are obtained, for example for air conditioning and heat pump units (BSI, 2013) and boilers (SI 1993/3083). Once integrated into a complete building system, further performance testing of sub-system elements is rarely carried out. One reason is simply commercial; there is very little incentive for manufacturers to carry out testing beyond the statutory requirement. The use of performance figures obtained under standardised test conditions, used to avoid the uncertainty of 'real life' operation, may result in unrealistic expectations of actual performance (NHBC, 2012a). In-situ testing can provide a more realistic indication of actual performance, however the potentially wide variation in external factors (such as weather and operating conditions) reduces the comparative value of individual studies.

The UK Energy Saving Trust (EST) carried out a field trial of 83 ground and air-source heat pumps in residential properties between April 2009 and April 2010 (DECC, 2012). The mean COP obtained from 49 ground-source heat pumps was 2.4, with a standard deviation of 0.45 (figure 2.10a). The mean COP obtained from 22 air-source heat pumps was lower, at 1.8 with a standard deviation of 0.28 (figure 2.10b). The investigation revealed several technical factors relating to design quality and commissioning that resulted in poorer than expected sub-system performance. These are reproduced in Table 2.1, which gives the estimated loss of performance (in terms of reductions in system efficiency i.e. COP) resulting from each factor. Heat pump undersizing was estimated to have the greatest impact on system efficiency, as a result of direct electric heating being used to make up shortfalls in heat pump output. Other significant design issues include incorrect sizing of sub-system components and poor insulation of pipework and storage cylinders. Poor equipment reliability was also observed in two installations, which resulted in loss of refrigerant and brine leakage.



(A) Ground-source heat pumps



(B) Air-source heat pumps

FIGURE 2.10: Distribution of measured heat pump efficiencies (DECC, 2012)

Gleeson and Lowe (2013) conducted a meta-analysis of European heat pump field trials. This revealed a variety of conventions for assigning system boundaries. After accounting for these differences the seasonal performance factors in the EST trial were found to be lower than in other studies. The authors speculated that design and installation issues may be responsible. Kelly and Cockroft (2011) compared simulated air-source heat pump performance with field trial data from eight houses in central Scotland. Their initial results showed a discrepancy between the simulated and actual data, which was attributed to an installation issue where a feature of the heat pumps (outside air temperature compensation) had not been enabled. Once this had been accounted

Category	**Factor**	**Estimated potential loss of performance as measured by system efficiency**
Design	Under-sizing of heat pump	Up to 1.5
	Under-sizing of borehole/ground loop	Up to 0.7
	Insufficient insulation of pipework and hot water cylinders	0.3–0.6
	Under-sizing of hot water cylinder	Up to 0.4
	Too many circulation pumps	0.1–0.3
	Over-sizing/control strategy results in overuse of back-up heating	<0.1
Installation / commissioning	Central heating flow temperature too high: radiators	0.2–0.4
	Central heating flow temperature too high: under-floor heating	
	Circulation pumps always on	0.1–0.3

Table 2.1: Factors influencing heat pump performance loss (DECC, 2012)

for the simulation results reflected the observed relationship between efficiency and ambient temperature. The simulation results showed that the heat pump would achieve a coefficient of performance (COP) of between 2.5 and 3.1 during the September to May heating season. Although the heat pump's annual CO_2 emissions were 12% lower than an equivalent gas boiler its annual running cost was 10% higher than the gas boiler. The CO_2 and cost benefits of heat pumps over gas boilers are sensitive to grid electricity CO_2 factors and fuel prices and will therefore depend on future de-carbonisation of the electricity supply and fuel price trends (Braun and Rowley, 2013).

The EST carried out a second field study of heat pump performance between April 2011 and March 2012 to investigate the impact of a range of interventions that included replacement of incorrectly sized units and other technical improvements to the heat pump systems (DECC, 2013a). Following the interventions, the system efficiencies for both ground and air-source heat pumps increased to 2.5 and 2.2 respectively, with standard deviations of 0.47 and 0.44.

A field study of domestic condensing boiler efficiency was carried out between 2007 and 2008 on behalf of the EST (Orr et al., 2009). The mean efficiency of the 10 regular boilers in the trial was 85.3% with a standard deviation of 2.5%. The efficiency figures were calculated based on gas input and heat output measured at the boiler, and can be therefore be compared with manufacturers' stated efficiencies. A boiler's stated efficiency is given by its SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) rating, which is intended to reflect the average annual efficiency achieved in typical domestic conditions. The mean SEDBUK efficiency of the regular boilers in the trial was 90.4%, significantly more than the actual monitored efficiency, with a standard deviation of 1.1%.

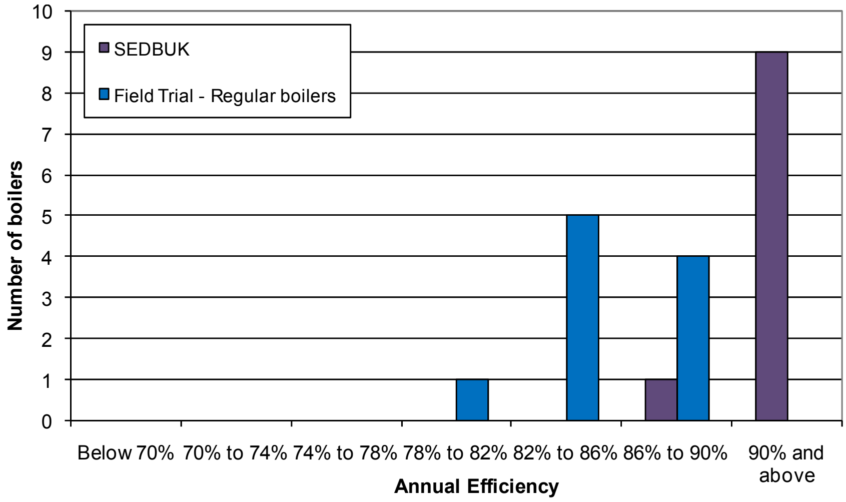


Figure 2.11: Distribution of measured boiler efficiencies (Orr et al., 2009)

Another field trial of condensing boilers was carried out as part of the the Carbon Trust's Micro-CHP Accelerator project (Carbon Trust, 2011a). The mean measured annual efficiency of the 36 boilers in the study was 85% despite the fact that all but two of the boilers were SEDBUK A-rated, with quoted seasonal efficiencies of over 90%. This discrepancy could be due to the fact that condensing boilers achieve their design efficiencies only when the return water temperature is low enough to condense water vapour in the exhaust gases. Since a significant number of boilers in the trial were found to be oversized it is unlikely that they are able to consistently achieve low enough return water temperatures.

Like the EST field trial, the efficiency figures were obtained by dividing the total heat output at the boiler by its gas consumption and are therefore directly comparable to the SEDBUK figures. The field trial also monitored combi-boilers and combined primary storage unit (CPSU) boilers however as the measured efficiencies also include hot water generation it is not possible to make a like-for-like comparison with SEDBUK figures, which only tests boilers in space heating mode. The regular boilers were found to be efficient in generating domestic hot water during the summer months however the efficiency of delivered hot water was found to be dominated by standing losses from the

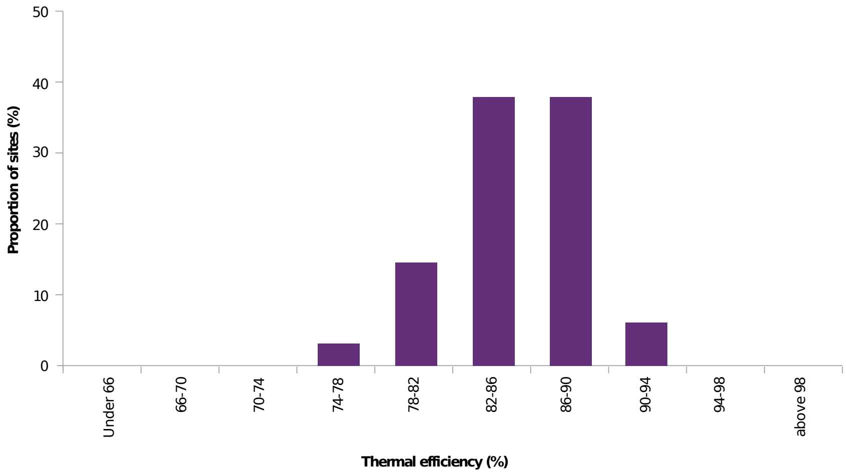


FIGURE 2.12: Distribution of measured boiler efficiencies (Carbon Trust, 2011a)

cylinder and primary pipework, resulting in overall efficiencies estimated to be as low as 40%.

The EST's condensing boiler field trial was followed by a second phase that investigated the impact of upgrades to central heating controllers (Kershaw et al., 2010). The results from the trial did not identify a significant improvement in system efficiency. The authors acknowledged the complexity of achieving energy efficiency savings from sub-system improvements, noting that technical intervention cannot solely compensate for a poor thermal envelope or a lack of effective operation from the occupant. The efficiency of a heating system is dependent on a myriad of factors, some that can be remedied through technical developments and structural works, and others that are dependent on the less tangible factors relating to human behaviour.

2.5 Current Risk Management Approaches

It is evident that the energy performance gap is a complex problem involving human as well as technical issues, which must be addressed throughout the building's lifecycle. There are a number of existing techniques to mitigate the risk of poor building performance including industry guidance and design frameworks, process improvement techniques and approaches to managing uncertainty in performance estimates.

2.5.1 Design guidance and benchmarking

There exists a wide range of design guidance aimed at delivering buildings with improved energy performance. The Chartered Institute of Building Services Engineers (CIBSE) first published Guide F Energy Efficiency in Buildings in 1998. The current edition of Guide F (CIBSE, 2012) provides information on improving energy performance throughout the building life-cycle, from the initial design process to the operation, maintenance and refurbishment of existing buildings. The evidence of the performance gap suggests that the availability of good quality guidance does not necessarily translate to buildings that meet performance expectations.

Benchmarking tools can be used during the design process to 'reality check' design assumptions and performance estimates. They also form part of an array of tools used in evaluating the performance of existing buildings. In the UK, Energy Consumption Guide 19: Energy use in offices (ECON19) provides benchmarks for four types of office building: naturally ventilated cellular, naturally ventilated open-plan, standard air-conditioned and prestige air-conditioned. The benchmarks are divided into typical, representing median values, and good practice, representing lower quartile values, derived from data collected from a range of office buildings in the mid-1990s (Action Energy, 2003). Despite their age, the ECON19 benchmarks are still widely used and are incorporated in the current edition of CIBSE Guide F (CIBSE, 2012).

More specific guidance on the evaluation of energy performance is provided by CIBSE TM22 Energy Assessment and Reporting Method, which describes a procedure for assessing the energy performance of buildings and their sub-systems (CIBSE, 2006b). The method allows the comparison of sub-metered energy consumption with design estimates, if available. Establishment of sub-system consumption is carried out using the concept of tree diagrams (Field et al., 1997), whereby annual consumption estimates are built up progressively from levels of service (such as design illuminance) multiplied by efficiency to obtain load densities, which are in turn multiplied by equivalent annual running hours (the product of actual hours of use and factors to account for part load operation) (Figure 2.13).

As a method for evaluating existing buildings, the TM22 approach can be helpful, provided sufficient and reliable information can be gathered. At design stage it faces similar limitations to detailed building simulation tools, in that its output is no more reliable than its input data. In acknowledgement of the widespread failure to predict operational energy consumption, CIBSE has recently published TM54 Evaluating operational energy

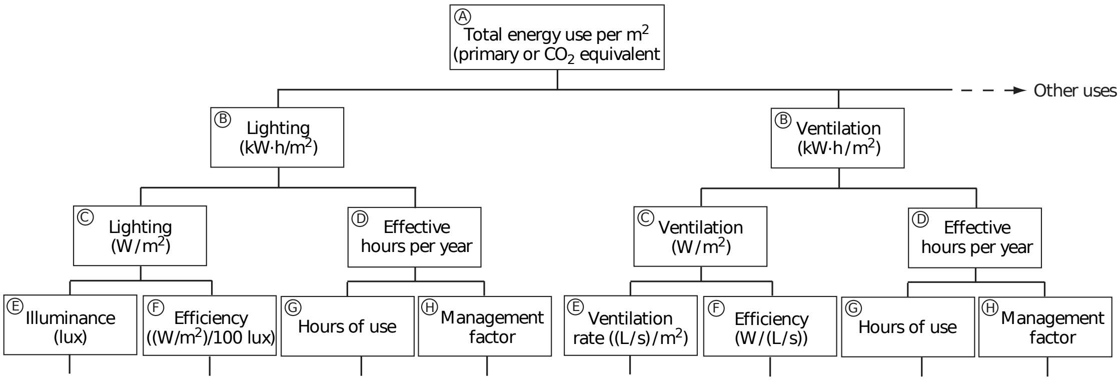


FIGURE 2.13: TM22 Energy-use tree diagram (CIBSE 2006).

performance of buildings at the design stage, which provides guidance on making more accurate estimates of sub-system (particularly electrical) consumption (CIBSE, 2013). The methodology combines the approach from the earlier energy assessment and reporting method with the dynamic simulation modelling used for compliance calculations and design energy certification. It also emphases the importance of benchmarking to assess the reliability of the estimates. Additional calculations are introduced to account for loads such as office equipment that are typically excluded from performance estimates. The guidance also emphasises the importance of appropriate assumptions regarding operating hours, occupancy levels and the energy management characteristics of the building. This final parameter, which can have a large impact on energy performance, is expressed as a percentage correction factor. This introduces a further source of uncertainty as the guidance provides no quantitative means for its estimation. One advantage the overall methodology has over other techniques for incorporating the effect of uncertainty is its simplicity. It does not however include explicit consideration of the uncertainty in the estimates of input parameters. Instead it proposes that the final results are presented in terms of three scenarios based on low-, mid- and high-range estimates and an accompanying sensitivity analysis. This is an improvement on current practice but does not provide any indication of the relative likelihood of the estimates.

2.5.2 Process improvement

Many of the issues affecting building performance occur as a result of the building design and delivery process (Bannister, 2009). The formal discipline of Systems Engineering, which emerged as a result of twentieth century advances in technology, initially during World War II and the Cold War, and more latterly the ‘information revolution’ of computing and communication, provides a number of useful techniques for addressing issues in the design and delivery of complex systems (Kossiakoff and Sweet, 2003). Systems engineering is an interdisciplinary approach that takes a holistic view of problem identification and solution development to deliver satisfactory results. It encompasses a wide range of activities from requirements identification to design synthesis and system validation while considering the complete problem and the whole system's interaction with its social, physical and economic environment (INCOSE, 2011).

The building-in-use can be viewed as a complex system of systems, the performance of which depends on the interaction of many interdependent elements (Figure 2.14). These elements include technical systems such as heating, ventilation, and the fabric of the building as well as socio-technical systems such as the building's occupants and operation and maintenance processes. The design and construction process, which also influences operational performance, is also a complex socio-technical system involving the interaction of interdependent stakeholder groups at various stages in the procurement lifecycle.

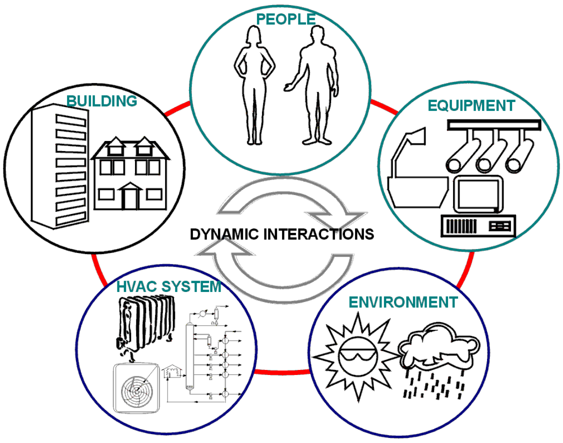


Figure 2.14: The systems nature of the building-in-use (Hensen 2002).

Technological advances are evident in all aspects of modern buildings, particularly in the proliferation of sophisticated mechanical, electrical and control systems (Bachman, 2003). Despite this, the practical application of systems engineering techniques in the construction industry is at a lower level of maturity than in other fields such as defence, aerospace and communications where systems engineering practice is well established. This is partly due to the fragmented nature of the construction industry and the complexity of the building procurement process. It has been argued that the construction industry is radically different from other manufacturing oriented industries (Fernández-Solís, 2008). The difference is not due to the level of engineering complexity, as this is managed well in other fields using systems engineering, but the nature of the end-product; designed each time to satisfy unique client requirements, by a team assembled specifically for that project, and assembled more than likely on a muddy construction site than in a clean workshop (Groak, 1992). There have however been attempts to apply various systems engineering techniques to different aspects of the industry including integrated building design (Yahiaoui et al., 2006), intelligent buildings (Elliott, 2009) and design option appraisal based on sustainability criteria (Kouloura et al., 2008). The successful construction of the Emirates Stadium on time and within budget was due in part to the adoption of project management techniques common to systems engineering (Elliott and Deasley, 2007). Tuohy (2009) explores the analogy between the building industry and the microelectronics industry. The microelectronics industry has also fragmented due to the increasing use of low-cost subcontractors, however strong quality processes and risk management have maintained the performance of its output. Commonly used techniques with potential application to the building industry include the use of failure mode effect analysis (FMEA), fault diagnostics, design for robustness to variability in operating parameters, and the use of simulation modelling from the earliest project stages. The concept of performance based building is especially applicable to energy issues as it places an emphasis on required performance-in-use as opposed to prescriptive specifications. It is characterised by differences in language describing requirements and solutions that meet these requirements as well as the need for validation and verification of solutions against the requirements (Szigeti and Davis, 2005). Quality Function Deployment (more commonly known as QFD) provides a means of translating from functional and performance requirements specified by the user or client (or regulator) into the technical requirements understood by the supply chain (Chan and Wu, 2002). Huovila (2005) describes the use of QFD and other decision support tools such as design structure matrix that can also assist performance based building. Austin et al. (2002) describe how such tools have been integrated into frameworks developed to manage multidisciplinary design processes. The authors also identified the need for a common IT framework and a culture of collaboration and continuous improvement.

Otto et al. (2012) describe the application of FMEA and building simulation to rank failure modes according to their impact on energy performance. Within the construction industry however, the most widespread use of simulation models is compliance checking for the purpose of meeting building regulations targets or achieving specific credits under building performance rating schemes. The building design will therefore be at an advanced stage by the time its performance is modelled. By this stage it may be too late to address fundamental energy performance issues with the design, instead the tendency is to address non-compliance with supplemental energy saving techniques or renewable energy technologies. This approach increases construction costs and reinforces the general perception that energy efficient buildings are more expensive to construct than conventional designs. With careful design however, energy efficient buildings can be less expensive than conventional alternatives, particularly if a systems engineering approach is adopted, which integrates from project inception principles of low energy design and clear performance requirements (King, 2010).

Feedback and process improvement is an inherent part of systems engineering (INCOSE, 2011). Its importance is also recognised in construction, an industry whose output is essentially a series of prototypes which are built and occupied (Bordass et al., 2001). The PROBE (Post Occupancy Review of Building Engineering) feedback studies, carried out from 1995 to 2002, provided valuable information on the in-use performance of buildings by identifying both factors for success and things that can go wrong. Leaman et al. (2010) describe an approach to carrying out building performance evaluation developed by the authors from their involvement in these and other studies. They emphasise the importance of a wider uptake of process improvement techniques that include follow-through, feedback and building evaluation. The industry however has been slow to act on the recommendations of published studies and the systematic changes needed to close the feedback loop have yet to take place (Leaman et al., 2010).

The lack of wider adoption of feedback on project performance may result partly from an element of distrust within the construction industry about the evaluation process due to concerns about potential liability and the impact on professional indemnity insurance (Hadjri and Crozier, 2009). Conducting performance evaluation in a spirit of non-judgemental openness is a key principle of the Technology Strategy Board's building performance evaluation programme and an important component of frameworks such as Soft Landings, which aim to make building evaluation and feedback common practice. The latest edition of the RIBA Plan of Work (RIBA, 2013) makes explicit the cyclic nature of building projects and the need for evaluation and feedback.

2.5.3 The Soft Landings Framework

The Soft Landings Framework is an attempt to improve the operational usability and performance of buildings through a process of feedback and continuous improvement (BSRIA, 2009). It provides a generic set of activities that can be applied throughout the life-cycle of new construction, refurbishment and alteration. The motivation for developing Soft Landings was the disconnect between building design and delivery and building operation, due to commercial pressures to move to new projects immediately post-completion, which was believed to be exacerbating minor problems and resulting in the loss of learning and feedback opportunities. The framework covers the project life-cycle from the briefing stage, increasing project participants' awareness of performance-in-use issues and the need for realistic targets, through the design and construction stage and on to a period of up to five years of post-handover 'aftercare'. Some of the potential outcomes from the application of the Soft Landings Framework include:

- Closer cooperation between traditionally fragmented construction disciplines
- Greater levels of understanding among clients and building users
- Improved building performance due in part to more comprehensive commissioning, fine-tuning and ongoing performance monitoring
- Longer-term benefits including feedback and dissemination of lessons learned to the wider construction sector

The applicability of the Soft Landings (SL) Framework has been investigated in a series of case studies of school building projects (BSRIA, 2010). Evidence of the direct benefit, in terms of improved operational performance, however has not yet been reported in the literature. The case study technical report identifies five of the school buildings by name (Bordass and Buckley, 2010). At Joseph Leckie Academy, the whole project team was appointed at an early stage and contributed to the briefing and design. The contractor organised a lessons learned workshop to review the project against the Soft Landings stages. This concluded that the first phase of the project had covered many aspects of the SL process and it was agreed to adopt SL for the next phase in the project. At Hackney City Academy, the environmental services consultant applied the SL framework in a series of pre-handover meetings and training sessions for staff and students. The involvement of the facilities management contractor was less satisfactory however, with limited discussion and training prior to handover. The team concluded that SL principles for pre-handover should have been implemented earlier in the project. The SL reviews at Estover Community College and RSA Academy also focussed on the pre-handover process. At Estover, the architect reviewed its designs and specifications with the design-and-build contractor to identify changes that could smooth the handover process. The review identified the need to consider ICT integration early enough to avoid conflict with the building's servicing strategy. At RSA Academy, the production of better and more relevant O&M manuals was considered to be helpful in reducing the need for post-handover involvement of the design team. At Northampton Academy, the SL review occurred at the extended after-care stage, four years after the building had opened. The architect conducted a post-occupancy evaluation that provided feedback on usability issues and energy performance however found it difficult to convince the school management of the need for performance tuning to improve the situation.

Two other developments, Heelis, Swindon and the Centre for Mathematical Sciences (CMS), Cambridge are used as case studies in the Soft Landings literature (BSRIA, 2008). Heelis was developed according to the SL principles, in particular the involvement of the design team in providing after-care including post-occupancy studies and fine tuning. The construction of CMS provided the prototype for the SL framework including design reviews, evaluation and feedback.

Activities including lessons-learned workshops, early involvement of specialist subcontractors and facilities managers, and post occupancy evaluation were believed to be beneficial however has been no quantitative evaluation of their impact on building energy performance. Although the extent to which the framework was applied varied amongst the projects described above they have all had some SL input so may be expected to perform better than typical buildings of a similar category. Recent DEC operational ratings for these buildings are shown in Figure 2.15.

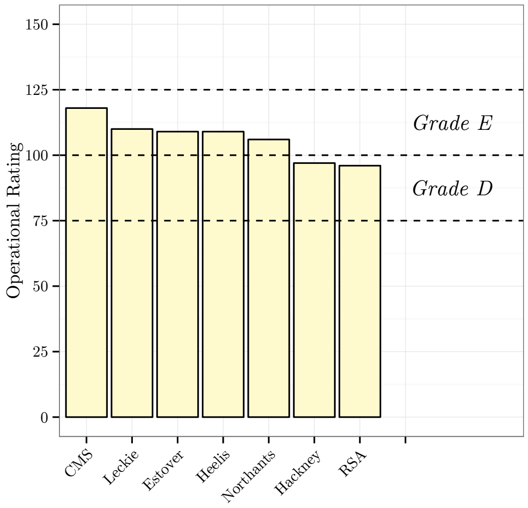


Figure 2.15: DEC ratings for Soft Landings case study building

Although the design and construction teams involved found the SL activities to be beneficial (BSRIA, 2010), the operational performance, as demonstrated by DEC operational ratings, does not show the case study buildings to be performing significantly better than the benchmark average. This finding is supported by Kimpian et al. (2014), who noted that although Soft Landings provides useful guidance, its use has not led to improvements on the projects they evaluated. Despite the lack of evidence for improved energy performance and some practical difficulties encountered in the case studies, SL is believed to represent current best practice and is being widely promoted in the construction industry, with the 2013 RIBA Plan of Work making reference to SL and incorporating its key principles (RIBA, 2013). The Low Carbon Construction Innovation and Growth Team recommended that the principles of Soft Landings be routinely embedded by the Government and construction industry into their contracts and processes (BIS, 2010). They suggest that a building should not be regarded as complete until it performs in accordance with its design criteria.

2.5.4 Managing uncertainty

The management of uncertainty in the output of simulation models is of current relevance to the issue of performance discrepancies between design and reality. There are several well-established techniques for sensitivity analysis and the propagation of uncertainty from input to output. These include differential sensitivity analysis and Monte Carlo analysis (Lomas and Eppel, 1992). Macdonald and Strachan (2001) describe the incorporation of uncertainty analysis based on these techniques into the thermal simulation software ESP-r. Smith (2009) used this software in research to assess the effect of variations in physical form on national stock-level energy performance. Despite the common use of uncertainty analysis in other fields it has not entered the mainstream of building simulation and use of ESP-r outside the academic environment is typically limited to specialised analysis rather than whole-building energy prediction. Many studies that have considered the effect of uncertainty in building simulation have been concerned with uncertainties such as physical properties that can be derived from observed relative frequencies. Silva and Ghisi (2014) conducted an uncertainty analysis on the thermal performance and energy consumption of a residential building modelled in EnergyPlus. This was based on 45 uncertain physical parameters and 33 uncertain parameters relating to occupancy and usage profiles, temperature set-points and internal heat gains.

De Wit (2004) identifies three broad categories of uncertainty:

- Lack of knowledge about the properties of the building or building component
- Lack of knowledge about external factors that affect the building
- Simplifications in the computer simulation models

The first of these is particularly relevant in the early stages of the design when specifications do not provide sufficient unambiguous detail to develop a building model. It may also be an issue when modelling existing buildings if there is no as-built information available or if the information provided, for example in the operation and maintenance (O&M) manuals, is inaccurate or outdated. External factors such as occupant behaviour and weather conditions can affect a variety of significant parameters in the building's energy consumption. Uncertainty relating to natural factors such as weather can be modelled statistically however it is more difficult to include occupant behaviour correctly in models due to the large variability in occupancy patterns and behaviours. Finally, the simplifications and assumptions necessary to model the building and its components will introduce uncertainty. This has been demonstrated by the variability in results for a set of simple models created with SBEM (Raslan and Davies, 2010). More sophisticated tools including widely used dynamic simulation models have the potential to model with greater fidelity; however, increasing the complexity and number of parameters also increases uncertainty due to differences in calculation algorithms, variability in input data and human input error (Schwartz and Raslan, 2013). Research by Guyon (1997) compared measured consumption data from a single dwelling with the results from models created by twelve different users working with the same software and document package. The results varied from -41% to +39% of the measured value and were generally due to input errors and differing interpretations of the source data.

Some of the uncertainties associated with modelling software can be addressed through verification of model assumptions and validation of model output however the complexity of real buildings has restricted validation exercises to simple buildings and test cells (Reddy, 2006). Drawing on work in the field of climate modelling, Williamson (2010) cites a recommendation that, where model uncertainties are present, it is preferable to present forecasts in probabilistic terms rather than as a deterministic mean of a range of possible values. It is also important that simulation users remain mindful of the distinction between the abstraction of reality provided by their models and the physical world itself.

2.5.5 Alternative modelling approaches

The techniques typically used to predict building energy consumption are based on deterministic models that simulate the performance of buildings according to pre-defined input data describing the building's sub-systems, usage patterns and weather conditions. However, the complexity of real-life buildings is such that the causal mechanisms influencing their whole-system behaviour are not fully understood. This reduces the accuracy of deterministic approaches, which are limited in their ability to deal with unknown or uncertain input parameters. In contrast, stochastic modelling approaches allow for uncertainty and random variability in model parameters. Stochastic sub-models have been incorporated in building energy consumption models to account for randomness in factors such as outdoor weather conditions and occupants' use of windows and lighting controls (Oldewurtel et al., 2012; Rijal et al., 2007; Bourgeois et al., 2006). Richardson et al. (2010) described the development of a residential electrical demand model based on a combination of occupant time use data from a national survey and statistical appliance ownership data. The model was validated against measured data and found to provide a good representation of the electricity consumption of multiple dwellings. It was found however to under-predict the variation in demand between individual dwellings. The authors speculated that additional socio-economic factors were responsible, but it was not possible to model them due to a lack of such data in the source datasets.

Wang and Meng (2012) discuss a number of statistical approaches used in regional energy consumption forecasting. Both multivariate and univariate regression models have been used for this purpose. The accuracy of multivariate models is sensitive to the availability and reliability of data for the model's independent variables over the forecast period. Univariate models, such as autoregressive integrated moving average (ARIMA), on the other hand, can generate forecasts based only on the historical behaviour of the variable of interest. ARIMA models are based on the assumption that the future value of a variable is a linear function of a series of past observations and random errors however this assumption may not be the case in complex systems. Artificial neural networks (ANNs), as described by Kalogirou (2000) are better-suited to problems involving non-linear relationships. An ANN mimics the human brain's learning process by storing knowledge in the form of inter-neuron connections. These connections encode the relationships between the network's input layer, a series of hidden layers and its output layer. The network must be trained using a dataset containing a series of inputs and their corresponding outputs. Once trained, ANNs are well suited to tasks involving incomplete datasets, fuzzy or incomplete information and for complex and ill-defined problems. One important shortcoming is the requirement for training data that is spread evenly throughout the system's entire range of operation (Nannariello and Fricke, 2001).

Tso and Yau (2007) compared the use of regression analysis, neural networks and decision trees for the prediction of electrical energy consumption in dwellings. Empirical decision trees are created by applying a series of simple rules to segment a dataset. These models can be used for prediction by evaluating each rule in turn to progressively refine the model's output. Both the neural network model and the decision tree model were found to be slightly more accurate than the regression model in predicting energy consumption.

Statistical approaches using Bayesian Inference have been used to quantify the impact of uncertainty in model parameters. Bayesian Inference is based on *subjective probabilities* that express degrees of uncertainty, such as evidence from expert judgement, even when there are no historical data from which to calculate frequentist probabilities. Heo et al. (2012) describe a Bayesian technique used to calibrate quasi-steady-state models for evaluating retrofit performance. The output of the calibrated models is presented in terms of probability distributions that reflect the degree of uncertainty in the input parameters. The Bayesian calibration approach was found to deliver results from simple models that were comparable with results from calibrated deterministic models, with the benefit of reduced modelling effort and computation time. Like other calibration approaches however, it is dependent on the availability of (albeit uncertain) information on actual building behaviour.

Bayesian networks are probabilistic models that are able to combine quantitative and qualitative data and allow reasoning with incomplete data (Fenton and Neil, 2007). In formal language, Bayesian networks are directed acyclic graphs with associated probability tables. The graphical structure consists of nodes, which represent uncertain variables and edges (connections), which represent causal or influential links. Each node contains information that describes the probabilistic relationship between itself and its parent nodes (Lauritzen and Spiegelhalter, 1988). Bayesian networks have several advantages over the approaches described above, including their ability to incorporate expert judgement and model explicit causal relationships in an auditable graphical model (Fenton and Neil, 2007). Janssens et al. (2004) compared Bayesian network and decision tree approaches in activity-based transport models and found the Bayesian network approach outperformed the decision tree approach in predicting transport activity.

The use of Bayesian networks in relation to building energy performance is not widespread; however, they have been used by Tarlow et al. (2009) to model building energy use, by Leicester et al. (2013) to model the environmental and socio-economic impacts of community deployed renewable energy sources, by Thirkill and Rowley (2013) to model solar thermal system yield and by Naticchia et al. (2007) to design passive solar roofponds. In these examples, the networks were built by manually specifying the network structure and combining physical models with empirical data to determine the probabilistic relationships. In building a network to model temperatures within dwellings, Shipworth (2010) used a different approach and derived both the network structure and the probabilistic relationships from empirical data. The former approach is arguably better suited to building forward models of building energy performance as they can then incorporate well-established physical models as well as empirical data.

2.5.6 Managing risk

Risk management within the construction industry has been traditionally concerned with minimising the adverse effects of change on project cost and programme (Smith et al., 2006). The growth in energy performance contracting, where energy services companies typically guarantee project savings, has begun to focus attention on the financial implications of energy performance risk (ICF International and National Association of Energy Services Companies, 2007). Under an energy performance contract, the provider (usually an energy service company) conducts an energy audit to identify suitable energy efficiency improvement measures, then arranges financing to cover the cost of the measures at no cost to the building owner. The provider will generally guarantee a certain level of future savings, with the obligation to compensate the building owner for any shortfall. Once installed, the improvement measures are monitored to verify the savings. If the savings are achieved the building owner must return a proportion of the cost saving to the provider for the duration of the contract. In this way, both the provider and building owner benefit from the energy efficiency improvements. Providers face a need to mitigate performance risks, generally by being conservative in technology selection and the level of savings they guarantee. At the same time they also need to be able to make competitive bids by offering higher energy saving guarantees and shorter contract periods. To this end, Mills et al. (2006) argue for the introduction of financial risk management techniques to facilitate effective decision making about cost-effective energy efficiency retrofit measures. This requires the energy efficiency engineering perspective, in which uncertainty is a liability to be minimised, to move towards the financial investment viewpoint, in which risk is seen in terms of opportunity to maximise value as well as liability. Rather than attempting to provide an accurate point estimate of a building's future energy performance the emphasis is on identifying the probable range of future performance along with the most likely estimate. Quantitative risk analysis can provide a shared framework and language for the engineering and financial realms allowing investment decisions to be made on the basis of risk versus return (Mills et al., 2006).

Mathew et al. (2005) describe the development by the energy services company Enron of a probabilistic approach to evaluating performance risk in energy efficiency projects, pointing out that the company's spectacular collapse may have masked the value of this legitimate business innovation. The approach is based on the concept of actuarial pricing used in the insurance industry, whereby insurers develop actuarial tables based on statistical models that relate the probability of future claims to relevant customer characteristics. These models must be developed by collecting data from existing energy efficiency projects, including details of the measures implemented, equipment and operational parameters and the energy savings achieved. The models can generate probability distributions of energy savings based on similar existing projects. As the proposed project is described in more detail the more specific the probability distribution becomes, however the statistical confidence in the distribution will decrease according to the sample size. One advantage of this approach, particularly for the more common efficiency improvement projects, is its scalability to large portfolios compared with the traditional approach of carrying out detailed energy audits. There are weakness of this approach however; it requires a large database of standardised and high quality information from actual projects and may not be applicable to particularly unique projects. It also cannot address the non-energy benefits that may be associated with efficiency improvement measures, such as reduced maintenance cost, increased comfort and productivity.

Hubbard (2009) argues that qualitative risk management techniques such as risk matrices are not fit-for-purpose and should be replaced by Monte Carlo simulation techniques. These are probabilistic techniques that model a large number of possible scenarios with input parameters randomly generated according to their frequency distributions. The results are also expressed in terms of frequency distributions of likely values. Hubbard also recommends that these simulations should make use of structural models composed of sub-system elements that can be described by empirically validated data (either calibrated probability estimates or available historical data), and proposes that Bayesian approaches, with the ability to update prior knowledge with new information, be used to address the limitation of inadequate data.

Rickard et al. (1998) demonstrated the use of a simple technique using the coefficient-of-variation to compare uncertainty in competing energy saving measures, which would allow them to be evaluated in terms of risk and return. A more sophisticated technique is described by Lee et al. (2013), who applied a probabilistic simulation-based approach to the evaluation of energy efficiency improvements made to the cooling system serving a development of three high-rise buildings in Hong Kong. Their approach comprised four distinct stages; pre- and post-retrofit energy models were created and calibrated against measured energy data, a sensitivity analysis was then carried out to identify the factors with the greatest influence on energy use, frequency distributions were then assigned to the most influential parameters, and finally a Monte Carlo simulation was run to account for the likely variation in input parameters. The input frequency distributions were based on empirical evidence (e.g. the annual average dry bulb temperature) or judgement of likely ranges (e.g. the chiller's COP). The predicted frequency distribution of energy savings (Figure 2.16) was the result of 10,000 iterations of the simulation, which took 8 hours to run on 10 dual-processor PCs. Predicted savings, which were found to differ by a factor of over 3.5 at the 90% statistical significance level, were expressed as a Weibull distribution with a mean of 5.2% and standard deviation of 1.6%.

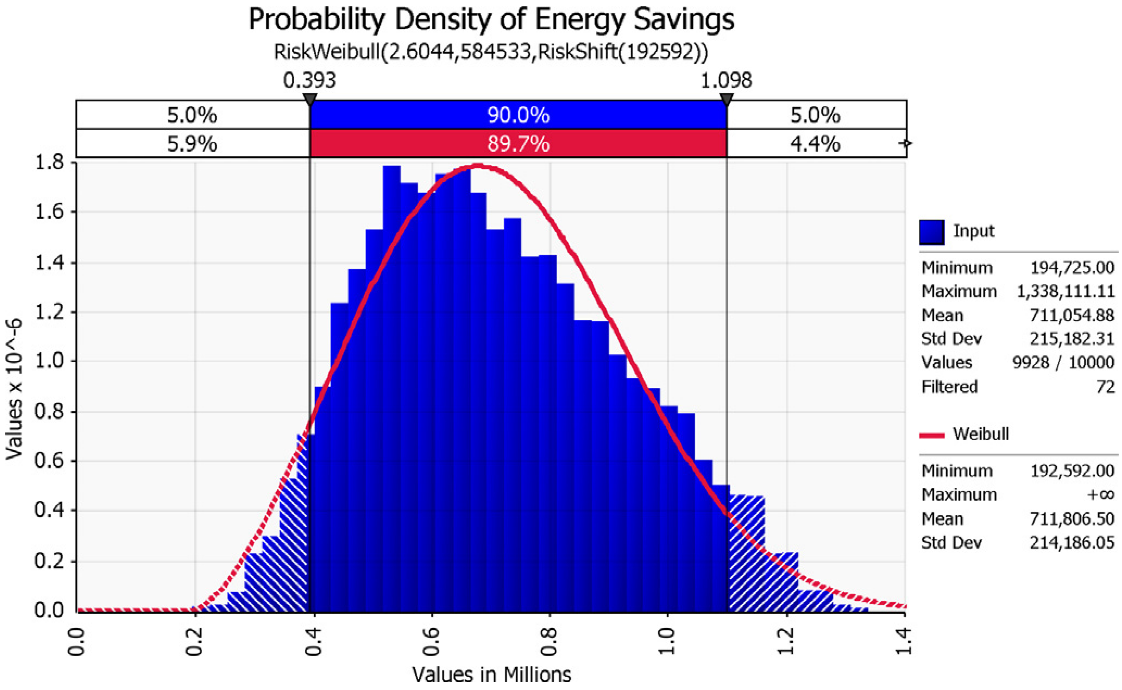


FIGURE 2.16: Frequency distribution of predicted energy savings (Lee et al. 2013)

Although this probabilistic approach appears promising, as it involves the development of calibrated simulation models for both the baseline and improved scenarios, it is not possible to tell whether it could be used a priori to established the potential performance of a future development, which would necessarily involve the use of an uncalibrated model.

2.6 Conclusions

The wide variability in the relationship between design and actual performance, i.e. the presence of ‘performance gaps’, will affect the accuracy of lifecycle cost assessments, and given the ambitious nature of the CO_2 reduction targets for the built environment, are a serious cause for concern. Although wider issues influencing the environmental impact of the built environment were identified, the scope of this research is restricted to the total operational energy consumption of buildings. Policy-making decisions, however, should also consider the impact of embodied energy and overall carbon footprint.

Performance gaps were found to occur as a result of three related issues: The first is the inherent difficulty of predicting the future behaviour of complex systems with uncertain operational parameters. The second is the risk that the final building fails to meet design specifications, either due to construction defects or unanticipated design changes. The third is the difficulty of ensuring these systems are operated and maintained in accordance with their design expectations. The realism of these expectations is an important aspect of the problem; unrealistic expectations can result in buildings being designed and operated without a real understanding of how their actual performance relates to their potential performance. The factors that contribute to these issues are both technical and non-technical in nature and often arise fundamentally from a lack of feedback of practical reality into design-stage assumptions.

There is an extensive range of guidance available to construction industry stakeholders on improving the energy performance of new and existing buildings. The evidence suggests however that the guidance alone is failing to significantly reduce the discrepancy between design expectations and actual performance. Improvements targeted at the whole project life-cycle may be more successful in changing industry culture. The adoption of systems engineering techniques such as feedback and process improvement, which have been successfully applied in other fields, could be beneficial for the wider industry. The Soft Landings Framework, which has been found valuable in several case studies, provides an outline of how such techniques can be integrated into the construction process. Building performance evaluation is a fundamental part of the Soft Landings process but the extent to which its findings are acted upon varies widely.

An increased awareness of the systems nature of buildings may contribute greatly to the improvement of design processes as well as potentially more accurate performance evaluation techniques. Buildings and the systems that service them should be designed and optimised at the whole-system level, rather than as the sum of separately designed and optimised sub-systems (Hensen, 2002). Within current techniques there is limited allowance for uncertainty among the many input parameters, however an understanding of this uncertainty, particularly in uncalibrated design-stage energy models is necessary to make more realistic predictions of the range of possible energy performance. Current building energy prediction techniques are largely based on deterministic models, developed from a ‘bottom-up’ understanding of the underlying causal mechanisms. While these models can produce accurate results when calibrated, calibration can be an arduous task and is impossible at design stage, when no calibration data is available. A further limitation of approaches based on current simulation models is their inability to account for factors beyond the scope of the simulation. As Bannister (2009), Bordass et al. (2004)

and others have pointed out, building performance fails to meet expectations for a variety of reasons, many of which cannot currently be modelled.

Statistical techniques such as regression models and neural networks are based on 'top-down' approaches that capture the relationships between input and output datasets. Although these techniques frequently demonstrate good predictive power, particularly when modelling at stock level where the stochastic variation in their output is averaged out over a large sample size, they are limited in their ability to establish the causal mechanisms behind the input-output relationships. Another limitation of these techniques is the need for a dataset from which to train or develop the model. The lack of sufficiently fine-grained performance data limits the practical application of the actuarial approach described by Mathew et al. (2005). Although the DEC dataset provides information on the annual electrical and fossil fuel energy consumption of some UK public buildings it does not contain information necessary to identify specific building characteristics or use classes. Current benchmarks, such as those in CIBSE Guide F, are provided as single values (or typical and good practice values) rather than providing any indications of uncertainty, such as the range, standard deviation and sample size. CarbonBuzz is a step in the right direction and provides a useful tool to raise awareness of the wide variation between design estimates and measured performance. There is however, still a need for the development of standardised, high quality datasets for statistical modelling and benchmarking.

Chapter 3

Case Study and Context

3.1 Introduction

This chapter describes how the research aims and objectives stated in the introduction will be met. It also describes the system context within which the work will be carried out. The work follows a case study approach to evaluate risks relating to energy performance in a newly constructed non-domestic building. The findings of the case study are used in the development of the uncertainty evaluation technique described in Chapter 7 and the taxonomy-based risk management framework described in Chapter 8.

Despite the growing awareness of the factors that contribute to performance gaps, there is little evidence of a coordinated implementation of existing mitigations. Recent UK industry-wide research on energy performance gaps has concentrated largely on the the domestic sector (ZCH, 2014). Research activity in the non-domestic sector is at a less developed stage, possibly as a result of the diversity and complexity of non-domestic buildings. The systems nature of buildings, outlined in the previous section, requires a coordinated approach to knowledge management that the industry has been slow to adopt, due in part to its fragmented nature and prevalent 'silo mentality' (Egbu et al., 2003). Hensen (2002) reminds us of the need to treat buildings as whole systems rather than as a collection of separately designed and optimized sub-systems. Although the Soft Landings framework, described previously, is believed to have the potential to improve performance through a more coherent design, construction and operation life-cycle it is not yet backed by empirical evidence. Similarly, although the need to focus on as-built performance is beginning to be recognised there is little confidence that the construction industry has the ability to deliver expected levels of in-use performance (Bordass and Leaman, 2013).

3.2 Case Study Background

Bordass et al. (2004) attribute performance gaps in general to a lack of well-informed assumptions about the characteristics of real buildings. This is the result of the disconnect between design and operation that occurs because ‘buildings last a long time and continue to evolve, long after their creators are gone’ (Brand, 1995). In recent years, widening gaps between expectation and reality have eroded confidence in the ability of the construction industry to deliver buildings that work. Building professionals are still believed to lack a robust body of knowledge about the in-use performance of their buildings. In order to move forward, Bordass and Leaman (2013) propose a ‘New Professionalism’, whose key requirements include a shared vision, improved processes and a greater knowledge about building performance in use.

Oreszczyn and Lowe (2010) suggest that a lack of appropriate use of empirical data in support of evidence-based policymaking is contributing to the widening performance gap. Since then, however there have been two notable developments. In 2010 the UK’s Technology Strategy Board launched an industry focussed research programme aimed at helping builders and developers improve the performance of new and existing buildings (TSB, 2010). The following year, the UK’s Zero Carbon Hub made a recommendation that from 2020 at least 90% of dwellings would meet or exceed their design energy performance. To support this aim, a collaborative research project was established to collect evidence necessary to understand the scale of the performance gap and technical issues involved in domestic buildings (ZCH, 2011).

The objectives of the TSB’s Building Performance Evaluation (BPE) programme were:

- To identify what works and what does not work in low impact buildings
- To develop tools for evaluation
- To identify where research and guidance may be needed
- To encourage the habit of monitoring and feedback

The dissemination of lessons learned from building performance evaluation studies are an important part of linking education, practice and research to contribute to the development of a body of knowledge. As Duffy and Rabeneck (2013) point out, ‘A superior knowledge base would be derived from never being afraid of admitting “We got it wrong.” ’

Leaman et al. (2010) adopt the term ‘real-world research’ from Robson (2002), to describe building evaluation, which at the whole-system level is a multi-disciplinary activity, encompassing aspects of architectural and engineering design, facilities management and user psychology. The research approach is primarily empirical and draws from a range of techniques from technical measurements to social-science research. The PROBE research project (Cohen et al., 2001) applied the approach to a series of building evaluations carried out between 1995 and 2002. The TSB’s Building Performance Evaluation programme is also based on a similar approach. The case study element of this research adopts the four principal aspects of building evaluation identified by Bordass et al. (2004):

- Observations
- Questionnaire and interviews
- Facilitated discussions
- Physical monitoring, testing and analysis of performance statistics

Amaratunga and Baldry (2001) note that the case study approach is particularly valuable in situations where controlled studies are not possible. They also acknowledge certain limitations and propose means of overcoming them. In particular, the uniqueness of individual case studies makes it difficult to generalise findings to wider populations. Although carrying out multiple case studies using similar data collection procedures is one way of addressing this issue, it was not possible to do so in this research. Instead, a triangulation technique based on combining qualitative and quantitative methods within a single study has been used to increase the robustness of the research.

The evaluation is used to identify whether the energy performance of the case study building meets its design target and to identify the presence of specific performance risk factors and their interrelations. The use of the case-study approach allows the identification of contextual factors that may affect different aspects of building performance. The functional aspects of the building were evaluated from the point of view of the building’s end-users and its operation and maintenance staff. The evaluation provides a valuable opportunity to provide on-going feedback to the building design and operations team during the course of the research. This stakeholder engagement is an important aspect of the project, as it not only provides information that can be used to make targeted improvements to the building’s operation but also provides a route to wider dissemination of findings to the construction industry.

3.3 Case Study Building

The building used for the case study was the iCon Building in Daventry, a commercial office building that opened in 2011. The building was developed from a design competition for a sustainable centre of excellence supporting education, training, conferences and business incubation. The building consists of two blocks separated by an atrium space known as the street. The three storey north western block houses 55 self-contained office units and support facilities. The south eastern 'showcase' block houses a conference facility incorporating a 300 seat hall, 60 cover café, 3 meeting rooms and ancillary functions. The internal street provides a full height exhibition, breakout and circulation space between the incubator and showcase blocks. The building's south façade, which contains the café and auditorium, follows the curve of the road and is faced with vertical timber fins. Figure 3.6 shows the building's ground floor plan, colour coded to indicate space types. Further plans, sections and elevations are included in Appendix A.

FIGURE 3.1: South façade showing café, street and incubator office block

3.3.1 Procurement Process

The competition-winning design team was led by architects Consarc, along with their building environmental services consultants Synergy. Design to RIBA stage C was completed in December 2008, and went out to tender in February, approximately between RIBA stage D and E. The design and build contract was won by Winvic. Preliminary work on site started in August 2009 and foundations were completed during the autumn.

FIGURE 3.2: Internal street used as exhibition space

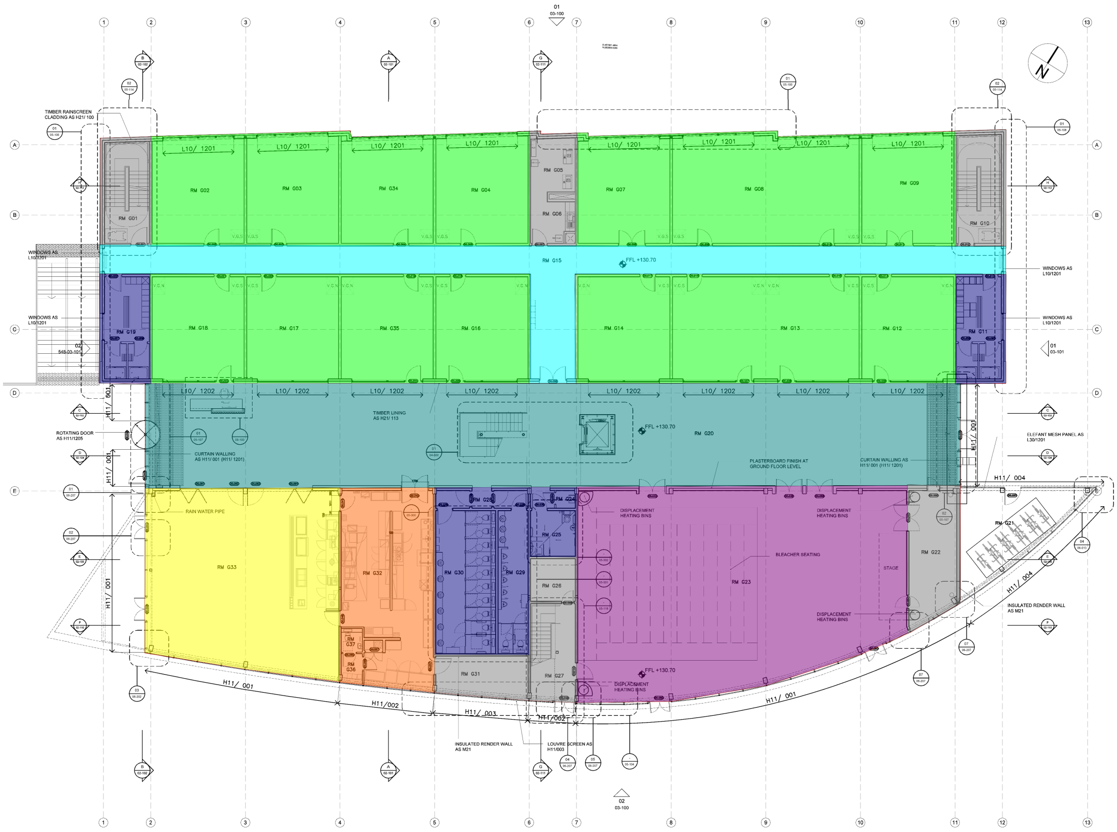
FIGURE 3.3: Internal view towards main entrance

FIGURE 3.4: Café

FIGURE 3.5: Auditorium

3.3.2 Building fabric

The building fabric was developed with consideration for low embodied energy and passive design intended to minimise the use of active environmental control. Lightweight timber frame construction is used throughout the building. A panelised system-build approach was used in order to increase the speed of construction. Additional thermal mass is provided to a selection of the incubator office units by the incorporation of phase change material (PCM) panels into the ceiling. This was originally included in all the units but the contractor's design-stage thermal modelling suggested that the risk of summertime overheating was low, and therefore additional thermal mass was unnecessary. PCM panels were retained in some of the units with the intention of comparing units with and without to evaluate their effectiveness. In practice however the varying occupancy and load densities in the units makes comparison extremely difficult. The incubator units are timber-clad. Thermal insulation is typically twice that required by building regulations Part L2A 2006. Although a low air permeability of $3\,\mathrm{m^3/m^2{\cdot}hr}$ @ 50 Pa was proposed the contractor was only able to commit to a figure of $7\,\mathrm{m^3/m^2{\cdot}hr}$ @ 50 Pa. On completion the building achieved a better figure of about $5\,\mathrm{m^3/m^2{\cdot}hr}$ @ 50 Pa. The showcase block



🟩 Incubator units (offices)

🟦 Corridor

🟪 Toilets & showers

⬜ Other spaces

🟦 Internal street

🟨 Café

🟧 Kitchen

🟪 Auditorium

FIGURE 3.6: iCon internal layout (ground floor level) (adapted from Consarc, 2011)

features a sedum ‘biodiversity’ roof. The internal street, roofed with translucent ETFE pillows, is intended to act as a climatic buffer, reducing heat loss from adjacent spaces while maintaining a connection with the external environment.

3.3.3 Building services

The building services strategy is a mixture of passive and active systems. The building is predominantly naturally ventilated, although the auditorium uses a displacement ventilation system served by its own air handling unit. Mechanical cooling is also provided to areas of higher heat gain such as the IT server rooms and meeting rooms. The office units are naturally ventilated via operable windows and actuated roof-level ventilation doors. During the heating period these doors are closed and air is mechanically extracted from the incubator units. Heating was originally intended to be provided by a ground-source heat pump that used pipework embedded in the building's foundations, however to address cost and buildability concerns, the designers adopted an air-source heat pump as an alternative. The 30 kW air-source heat pump draws heat from the air extracted from the offices. A single 65 kW gas boiler provides top-up heating during periods of peak demand. The heat pump and gas boiler are connected to the same primary circuit supplying heat into a 1000 litre buffer vessel. Domestic hot water for wash hand basins, showers and the café's kitchen is provided by another 65 kW gas boiler serving two 300 litre storage calorifiers. Daylight is provided to the outward-facing office units by windows accounting for approximately 40% of the external façade area. Inward-facing units receive daylight from the street through windows of a similar size. Glare and solar gain control is provided by internal roller blinds. Electric lights are fitted with occupancy sensors and daylight-linked dimming control.

Space heating

The primary space-heating source is an EcoCiat 90V exhaust air heat pump, with a maximum heat output of 30 kW. This unit is located on the roof of the office block and recovers heat from the exhaust air extracted from the offices. The heat pump is intended to provide the building's base heating load. A Broag Remeah Quinta 65 kW gas boiler is intended to provide supplemental heating during periods of peak demand. The boiler is connected via a small header to the primary heating circuit running from the heat pump to a 1000 litre buffer vessel. The boiler header is bypassed by a three-port valve when only the heat pump is running. Figure 3.7 shows a schematic diagram of the primary heating system. The heating secondary circuit draws hot water at a design temperature of between 40 °C and 55 °C (depending on ambient temperature) from the buffer vessel to serve radiators throughout the building.

The space heating system control strategy includes an optimum start-stop controller, which attempts to minimise unnecessary use of the heating system while ensuring the building remains above a target internal temperature during occupied hours. The controller will calculate an optimum start time, based on the building's observed heating time constant, average internal temperature and ambient temperature.

Domestic hot water

Domestic hot water in the case study building is provided by a centralised storage system. Heat is generated by a single Broag Remeha Quinta 65 gas boiler, with a maximum

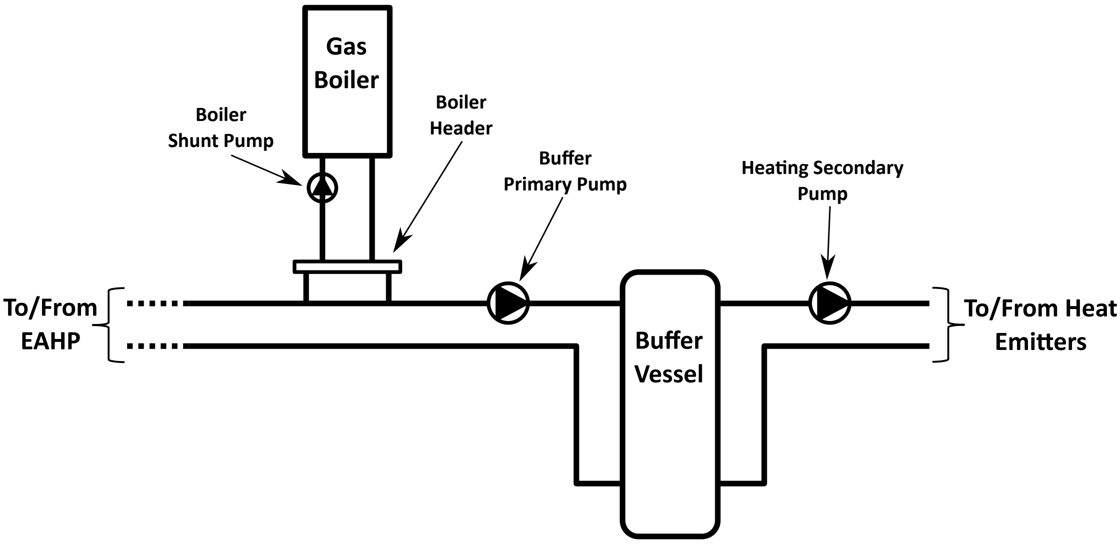


Figure 3.7: Heating system schematic

rated output of between 61 kW and 65 kW depending on flow and return temperatures. The boiler's stated maximum efficiency at 80 °C flow and 60 °C return is 89% by gross calorific value. The boiler serves two Hamworthy PS300 calorifiers with a total capacity of 584 l. The calorifiers are maintained at a temperature of 60 °C using 70 °C primary circulation from the boiler. The hot water from the calorifiers is circulated in a pumped loop around the building with a design flow rate of 0.11 l/s. The weekly operating schedule is controlled by the BMS.

3.4 System Context

Since a building's energy performance is influenced by a wide range of disparate factors (Figure 3.8) it is helpful to adopt a whole-system approach and apply a combination of techniques to identify these factors in different areas. Furthermore, the combined approach must be cost-effective and practical, with the ability to be applied to a range of buildings. The building performance evaluation approach described above satisfies this requirement.

Building performance discrepancies occur as the result of interactions within a complex web of factors. Both technical and non-technical factors were identified in the literature review. Technical factors are often evaluated in terms of sub-system performance, such as the heat pump and boiler field studies described below. Non-technical factors are more typically evaluated in the context of whole building studies such as the PROBE series.

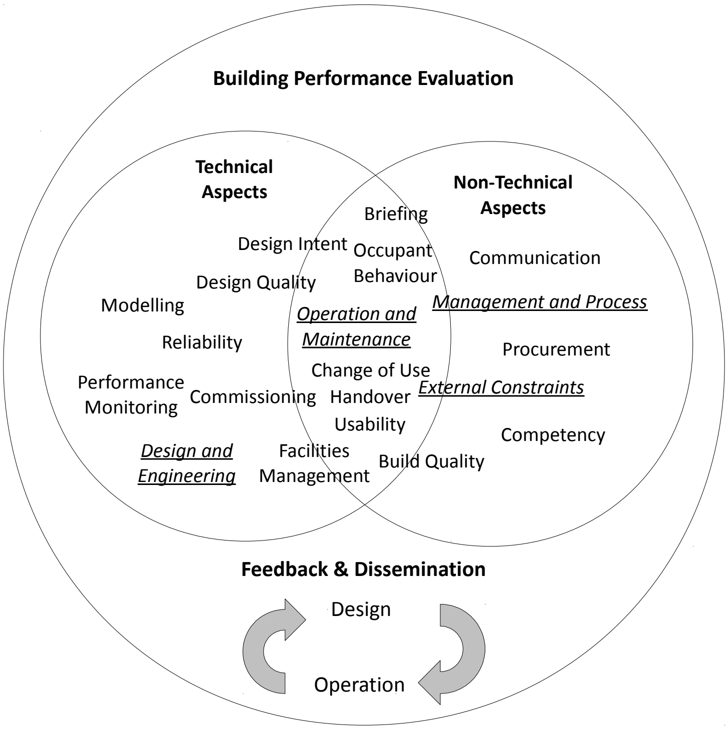


Figure 3.8: Technical and Non-Technical aspects of BPE (adapted from Blyth, 2001)

The distinction between technical and non-technical factors provides a convenient way of organising a complex set of issues; however it is not intended to be applied rigidly, as they often overlap, for example when considering issues of building operation and maintenance. This thesis is organised pragmatically on the basis of technical consequences and their lifecycle-related causes.

3.4.1 Technical system hierarchy

The hierarchical relationship between systems and system elements is described in ISO/IEC 15288 (ISO 15288:2008). Within this research project, technical factors are investigated at high and low levels and a range of temporal resolutions. The initial investigation was carried out at the system level, i.e. whole-building energy performance, before drilling down into more detailed consideration of sub-systems and sub-system elements. Figure 3.9 illustrates part of the system hierarchy for the case-study building.

The focus of this work is on the discrepancies between design and actual energy consumption. At the whole-system level, this consumption is considered in terms of the delivered energy demand of a building's technical sub-systems to meet the demand for energy services (such as heat and light) within the building. When considered in this way,

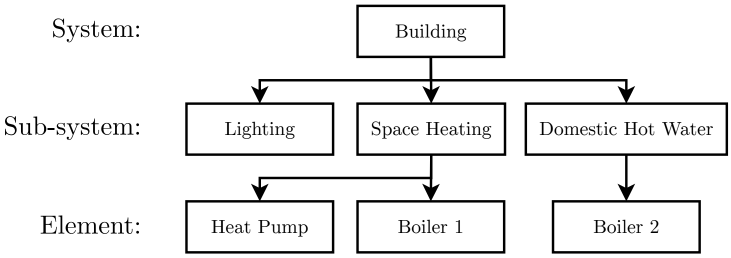


Figure 3.9: System hierarchy

there are clearly two aspects of a building's energy consumption; the demand for energy services, for example to meet comfort requirements, which is more directly influenced by occupant behaviour, and the efficiency of the sub-systems in meeting this demand. While sub-system efficiency (including the conversion efficiency of on-site renewables) can reduce a building's energy consumption it does not reduce the demand for energy services. This idea is encapsulated in the 'Fabric First' approach, which emphasises the importance of the building envelope's energy performance in reducing energy demand at source. This approach may increase a building's robustness in delivering occupant comfort as it reduces reliance on the performance of the building's technical systems. Figure 3.10 shows the system boundaries resulting from this approach; an outer system boundary encompassing whole-building energy consumption, and two inner system boundaries encompassing the energy use of building sub-systems and the energy demand of end-uses such as heating and hot water. This research takes a similar approach and considers whole-building energy consumption, sub-system energy consumption and heating and hot water thermal energy demand.

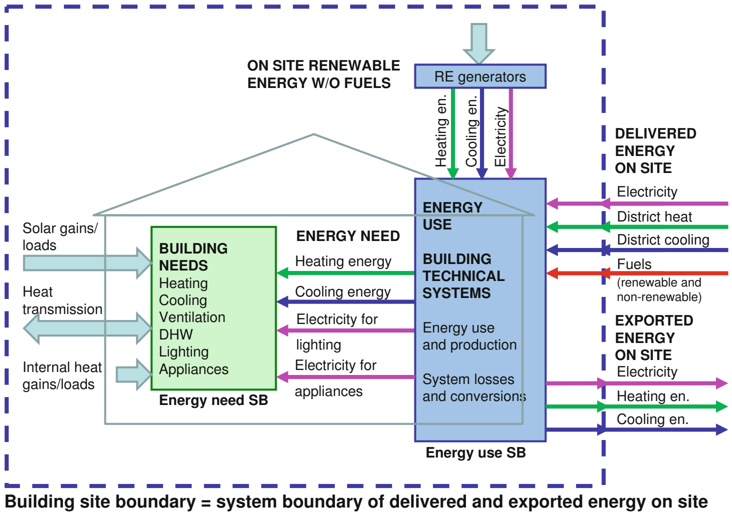


Figure 3.10: System boundaries (Kurnitski, 2013)

3.5 Technical Evaluation

The technical evaluation began with a review of design information to develop a detailed understanding of the building's systems and their predicted performance. An energy and environmental monitoring system was specified to supplement and extend the logging capabilities of the BMS. Although the TSB specified performance requirements for monitoring equipment in domestic BPE studies (TSB, 2012), there were no formal requirements for non-domestic studies. The guidance was, however, used in the development of an outline specification that was issued to the M&E subcontractor for procurement. The monitoring system was installed towards the end of the building construction phase. Relevant equipment datasheets are included in Appendix B. The building services systems were inspected to obtain details missing from the as-built documentation. The operational performance of the building was investigated through analysis of the data acquired once the monitoring system was commissioned. A series of operational review meetings took place during the evaluation period. These involved building management and maintenance staff and were intended to identify specific areas for more detailed investigation. The technical evaluation methodology demonstrates the application of a pragmatic approach based on monitored data, which could be scaled to more widespread use.

3.5.1 Whole-system evaluation

Energy monitoring was carried out in order to identify whether the building's in-use performance reflected the aspirational emissions target expressed in the building's competition brief. The monitoring was also used to relate the building's energy performance to published benchmarks and to identify the end-uses responsible for the building's observed energy consumption patterns. The building's modelled energy consumption was compared with measurements made during the building's second year of operation.

3.5.2 Sub-system evaluation

The variability found in field studies (DECC, 2012, 2013a; Orr et al., 2009; Carbon Trust, 2011a; Kershaw et al., 2010) illustrates the risk associated with relying on assumptions regarding sub-system efficiency. The case study evaluation investigates whether similar risks are likely to apply to larger, non-domestic, installations using the same technologies. Close attention was given in the case-study to the sub-systems providing space heating, which is still the most significant energy end-use in the UK services sector (DECC, 2013b), and domestic hot water generation. The case-study building's primary heat source is an exhaust air-source heat pump. As this unit is originally intended to provide top-up heating to domestic hot water systems (CIAT, 2009), its untested application as a primary space heating source potentially raises the risk of under-performance. Two identical gas boilers provide top-up heating to the space heating and domestic hot water, both separate and independent sub-systems. Monitoring of energy consumption and heat output was used to provide evidence of sub-system efficiency in reality that can be compared to the manufacturer's stated efficiencies, the figures assumed by the building designers and those used in the EPC and Part L compliance models.

3.6 Monitoring and Analysis

The BMS strategy includes logging of plant and space temperatures, with measurements recorded at 15 minute intervals. Output pulses from the incoming utility meters (gas and electricity) are also recorded by the BMS and used to calculate an average hourly rate. By default the supervisor software keeps a log of the last 1000 readings of monitored parameters. At a monitoring interval of 15 minutes this represents just over 10 days of recorded data. As it was necessary to record data over a longer period the supervisor was later configured to save its logs to disk on a daily basis. The PC running the supervisor software is not accessible remotely so data must be transferred periodically to a USB stick. The supervisor software is used on a day-to-day basis by the building manager, usually to adjust ventilation set-points, enable and disable the auditorium AHU and check the operation of heating and ventilation plant.

The supplementary monitoring system, installed as part of this research, was intended to operate autonomously from the other building systems, in particular the BMS, as the operation of the BMS is one of the factors that influences the building's energy and environmental performance. The original proposal for the monitoring system included a large number of measurement points, typically one per occupied room. Because of this, it was decided to opt for a central data logging system rather than using sensors with integrated data collection such as swappable flash memory cards that would need to be read at intervals. To avoid incurring the expense of installing additional data cabling or tapping into the building's existing data infrastructure it was proposed that a wireless network be used to link sensors and meters to the central data collection point. The system is based on a network of ZigBee wireless sensing modules that communicate with a ZigBee wireless dongle attached to a standard desktop PC running a bespoke logging application. This PC is accessible via the Internet through the use of a remote desktop client, allowing data to be downloaded periodically.

The majority of the wireless sensing modules have six data channels for local connection to analogue sensors and pulse meters. The exact configuration of individual modules depends on the requirements for monitoring individual zones and end-uses. In the office incubator units for example, analogue signals are received from temperature, relative humidity, CO_2 and Lux sensors. Pulse signals are received from two electricity meters, one measuring total consumption, the other measuring small-power consumption. While it was generally not possible to monitor individual electrical circuits, large plant items such as the exhaust air heat pump and auditorium air handling unit have dedicated electricity meters. The logging application polls the wireless sensing modules in sequence and writes the returned data into a daily text file containing comma separated values. These values include date and time stamps of each reading, identifiers for module and channel and the channel data itself. Data from the analogue channels is saved as a floating point value in the range 0-100, representing the sensor's full-scale voltage range from 0-10 V. Data from the pulse channels is saved as an integer value representing the cumulative meter pulse count since the module was powered-up.

By default the modules are polled approximately every 10 minutes. The logging application has the ability to decrease the measurement interval to two minutes, which is about the shortest time taken to poll all the modules on the network. The temporal resolution was a compromise between capturing sufficient variation in energy consumption and environmental conditions and the size of the accumulated log files. Brown et al. (2010) describe a longitudinal study carried out using half-hourly electricity and water consumption data, which corresponds to the measurement interval often used for billing commercial electricity customers. Widén et al. (2010) compared hourly and 10-minute averaging of higher resolution data and found little overall difference, particularly when considering aggregated loads. Both Wright and Firth (2007) and Bagge and Johansson (2011), however, point out that much higher resolutions are necessary to capture short duration load spikes, with intervals of 1 minute or lower required to capture cyclic loads such as heating appliances. With integrating meters the rate at which pulses are recorded will often limit the temporal resolution. For example, a meter of 1 Wh pulse resolution will generate 100 pulses per hour at a load of 100 W, equivalent to 1.67 pulses per minute, so there would be no benefit for loads of less than 100 W of reducing the sample rate below 1 minute.

The analysis workflow is based around several Perl scripts that can load daily text files into a MySQL database, query the database to obtain data for specific modules and date ranges, and pre-process the data to calculate interval consumption and account for pulse count resets. This data is then imported into R (R Core Team, 2014) for further processing and analysis. Since the wireless monitoring system does not take readings at regular intervals (although the monitoring interval is set to ten minutes it takes up to five minutes to obtain data from all modules in sequence) the R package pastecs (Grosjean and Ibanez, 2014) is used to convert the data to a regular 15-minute time series. The majority of the plots were generated using the R package ggplot2 (Wickham, 2009).

3.6.1 Space heating

Figure 3.11 illustrates the monitoring of the space heating system. The temperature sensors shown are all connected to the BMS; although additional sensors were installed as part of the wireless monitoring system they were not used in the following analysis due to practical difficulties with calibration described below. The main gas meter serves both the space heating boiler and the domestic hot water boiler. The meter's output has a resolution of 0.1 m^3/pulse. The monitoring of the EAHP is illustrated in Figure 3.12.

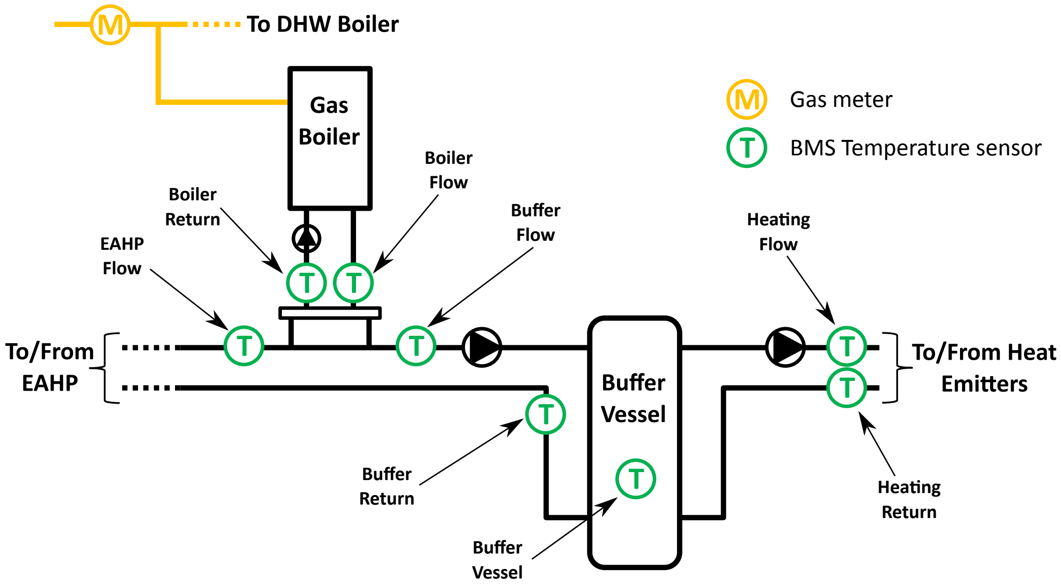


Figure 3.11: Location of space heating sensors

The EAHP's electricity consumption is measured by a dedicated meter (pulse resolution 1 Wh/pulse); its heat output is measured by a heat meter (pulse resolution 1 kWh/pulse),

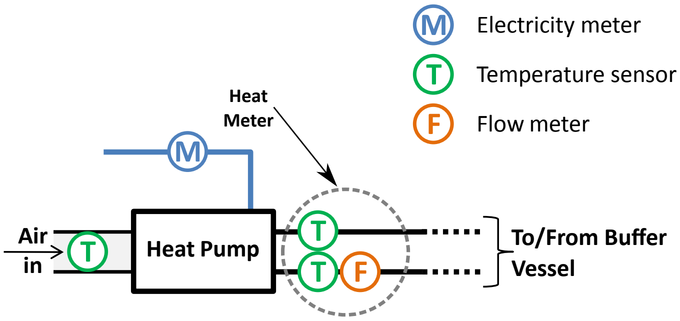


FIGURE 3.12: Location of EAHP sensors

which also records volume flow (pulse resolution 0.001 m^3/pulse). There is also a temperature and humidity sensor mounted in the duct supplying the EAHP with exhaust air from the offices.

3.6.2 Domestic hot water

The monitoring of the DHW primary side (i.e. the supply of heat to the calorifiers) was based on the approach used in the Energy Saving Trust's 2009 study on condensing boiler efficiencies (Orr et al., 2009). Figure 3.13 illustrates the monitoring configuration. The gas supplied to the DHW boiler is metered by a pulse output gas meter (pulse resolution 0.01 m^3/pulse). The heat output from the boiler is measured by a heat meter (pulse resolution 1 kWh/pulse), which also records volume flow (pulse resolution 0.001 m^3/pulse). In addition there are flow and return temperature sensors connected to the BMS.

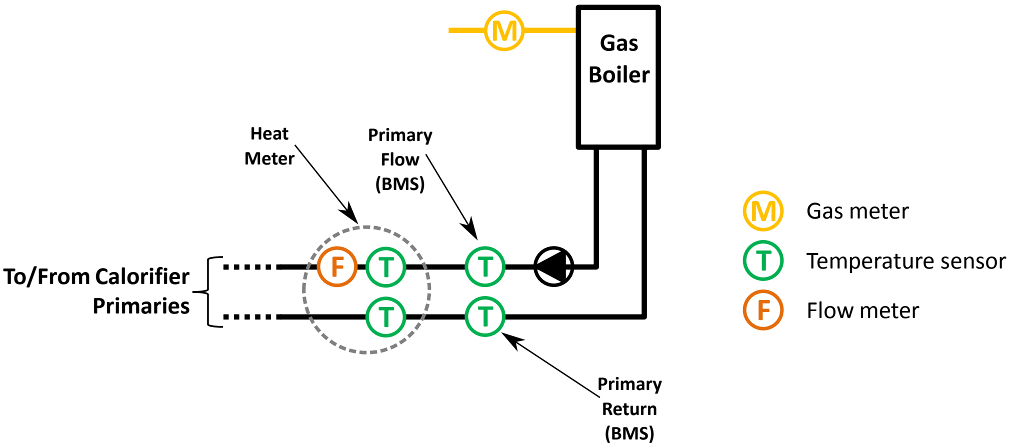


FIGURE 3.13: Location of DHW primary-side sensors

The monitoring of the DHW secondary side (i.e. the supply of hot water from the calorifiers) was based on the approach used in the Energy Saving Trust's 2008 study on domestic hot water consumption (EST, 2008). Figure 3.14 illustrates the monitoring configuration. The supply of cold water into the system is metered by a pulse output water meter (pulse resolution $0.01\,\mathrm{m}^3$/pulse) There are flow and return temperature sensors connected to BMS as well as a temperature sensor on the cold fill, which is connected to the wireless monitoring system. This sensor was intended to allow a more accurate calculation of the heat content of the hot water supply however because of its location close to the secondary return connection it does not reflect the temperature of the incoming cold supply. Instead, it remains at a temperature close to the secondary return temperature and drops momentarily during periods of hot water use, when cold water enters the system to replace the hot water drawn off (Figure 3.15).

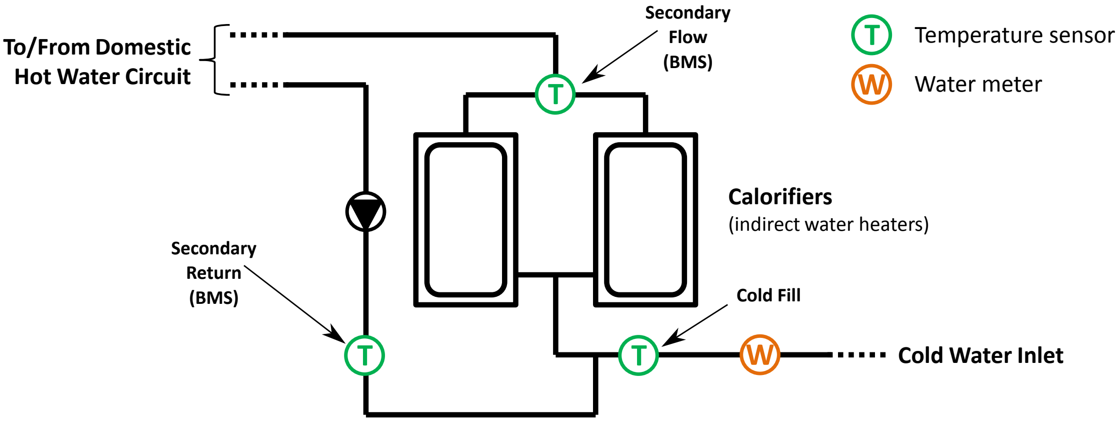


FIGURE 3.14: Location of DHW secondary-side sensors

3.6.3 Limitations

The supplementary monitoring system was to be self-contained due to the desire to maintain independence from the BMS and the practical difficulty of integrating with the BMS monitoring. The installation of extensive sub-system monitoring in existing buildings can be difficult due to potential disruption to the operation of the building and the expense of installing additional heat metering (CIBSE, 2009a), furthermore there may be insufficient space or a lack of suitable locations for temporary monitoring equipment. By specifying monitoring equipment to be installed during the construction process, rather than fitting it post-construction, it was hoped that some of these difficulties would be avoided. However the construction process was well under way while the details of the monitoring system were still being established due to protracted negotiation about its scope and available funding. By the time the equipment had been delivered to site, much of the first-fix had been completed. As a result, the installation of plant monitoring equipment such as pipework temperature sensors and heat meters was severely constrained by the space available for installation. This could have been avoided had the funding

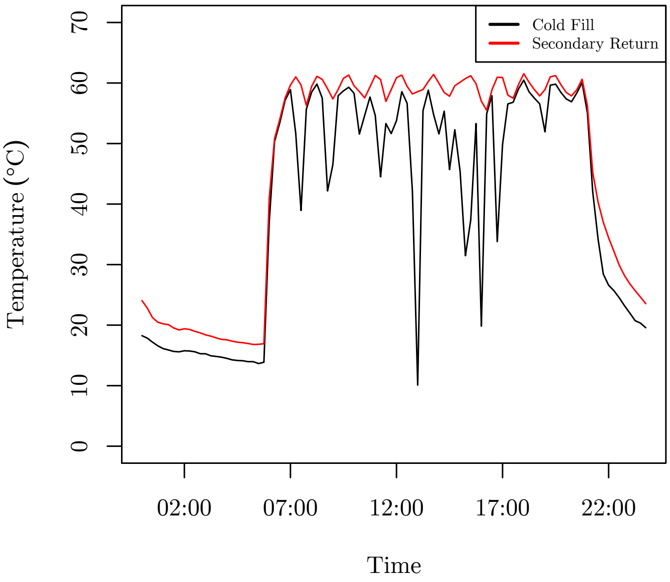


FIGURE 3.15: DHW cold fill and secondary return temperature readings

been secured earlier, allowing the design and specification of the monitoring system to take place with closer cooperation with the M&E contractor.

The environmental sensors used with the wireless monitoring were straightforward to integrate, each having a linear 0-10 V output. The temperature sensors installed in the heating pipework however were standard building control thermistor sensors. When used in building control applications the BMS carries out the necessary linearisation and scaling of the thermistor resistances. It was necessary to have several of the wireless sensing modules modified to interface with the thermistor sensors and to create a data processing script to convert the resulting resistance measurement to a linear temperature measurement. In practice, it was found that more accurate and consistent results could be obtained from the corresponding BMS temperature measurement. A similar problem was found with the sensor mounted in the office exhaust duct. However as there were no corresponding BMS sensors it was not possible to obtain reliable measurement of the temperature and humidity of air supplied to the EAHP.

A more serious problem was the reliability of the EAHP heat meter, which appeared to be giving erratic heat output readings that were significantly lower than anticipated. This was traced to the heat meter's flow sensor, which was either faulty or producing incorrect readings due to air bubbles entrained in the water flow. The sensor was reoriented to make it less sensitive to air bubbles however this did not solve the problem. Temporary heat metering was attached to the buffer vessel flow and return pipework in order to check the flow rate in the heating primary. The results of this investigation are described in detail in Appendix C.

The measurement of meter pulses was affected by issues relating to pulse resolution and a number of defective meters. The electricity meters connected to the main distribution boards have pulse resolutions of 1 kWh/pulse, which is sufficient for calculating monthly energy consumption however it is too low a resolution to determine reliable daily load profiles for distribution boards with relatively small loads. Electricity consumption in the incubator offices is measured by two meters; one recording the consumption of both lighting and small power outlets, the other recording the consumption of small power outlets. The lighting consumption is obtained from the difference in pulse count between the two. Three or four meters appear to be defective so it is not possible to determine the lighting consumption or in one case the combined consumption in the affected offices. Metering by difference also causes an issue with the calculation of heating gas usage. Since the heating gas boiler does not have its own meter, its consumption must be calculated from the difference in pulse count between the main gas meter and the DHW boiler's meter. The difference in pulse resolution of the meters introduces errors when calculating consumption over short intervals, as the DHW gas meter may have recorded consumption not yet registered by the main gas meter. Over the course of a longer interval such as a day the relative impact of these differences becomes less significant.

The PC running the wireless logging software failed on a number of occasions, resulting in gaps of up to several days until the failure was noticed and the server restarted, or in two cases, fitted with replacement hardware. It is recommended that future installations make use of automatic server monitoring, which could help to reduce downtime in the event of server failures. Despite the limitations encountered it has been possible to carry out a reasonably detailed analysis of the building's sub-system performance. Although the level of monitoring in the case study building is higher than usual, the basic level of monitoring provided by the electrical sub-metering and the BMS is likely to be found in other buildings of similar size and age. The lessons learnt are therefore applicable to future performance analyses in a wider selection of buildings.

3.7 Framework Development

In order to minimise risks by identifying and managing root causes, Smith et al. (2006) suggest the following systematic approach forms the core of any risk management process:

1. Identify the risk sources
2. Quantify their effects
3. Develop management responses to risk
4. Provide for residual risk in the project estimates

This research deals principally with the first point and the development of a framework to address the second point. This in turn provides the foundation for the final two points, which must be considered by individual project teams.

The evaluation of whole-building and sub-system energy performance (Chapters 4, 5 and 6) identify technical risk factors, sources of uncertainty and their consequences.

3.7.1 Probabilistic energy performance evaluation

Chapter 7 describes the development of a probabilistic performance evaluation technique that can be used to estimate building sub-system performance in the presence of uncertainty regarding operational parameters. This is based on the novel application of Monte Carlo simulation to the proven industry-standard energy estimation techniques used in CIBSE TM22 and TM54. The theoretical background is introduced and the technique is then applied to an example calculation for electric lighting and a calculation for domestic hot water based on the case-study building. The results of the probabilistic calculations are compared with those from the deterministic calculation and the sensitivity to uncertain parameters is discussed.

3.7.2 Energy performance risk evaluation

Chapter 8 describes the development of a means of evaluating energy performance risk due to the presence of technical and lifecycle risk factors. Existing literature is reviewed in more detail to identify these factors, which are then organised into a risk taxonomy based on the work of Carr et al. (1993), to provide a framework for organizing and studying the breadth of issues involved. A taxonomy-based questionnaire is then developed to establish the presence of specific risk factors.

The taxonomy provides a way of identifying and classifying performance risks; its hierarchical structure is helpful in developing an understanding of root causes but it does not capture the interrelationship between the risk attributes of different elements. These can be captured through the use of causal maps that provide a graphical model of concepts and relationships, which can be used in risk mitigation to help anticipate unintended consequences (Al-Shehab et al., 2005). A robust technique for developing causal maps described by Nadkarni and Shenoy (2004) is adopted. This involves the use of structured methods (questionnaires and adjacency matrices) to elicit causal relationships from domain experts.

Having identified and categorised the energy performance risk factors it is necessary to quantify them in some way for further analysis. Causal maps can be developed into Bayesian networks, which quantify the probabilistic relationships between factors, using the methodology described by Nadkarni and Shenoy. The probability tables underlying the network can be derived from data in the form of probability distributions; however, there is a lack of existing quantitative data on the presence and effects of risk factors. In this situation, where existing data is scarce or difficult to manipulate, a process of expert elicitation can be used. Since this can be an extremely time-consuming process, the approach described by van der Gaag et al. (1999) is adopted. This asks experts to assess conditional probabilities, expressed in the form of text fragments describing a particular situation, against a verbal and numerical scale, and is intended to reduce the time taken in probability elicitation.

3.8 Lifecycle Evaluation

Chapter 8 also describes the results of the qualitative evaluation of factors relating to the energy performance of the case study building. Data was obtained through a combination of observations, questionnaires, interviews, and facilitated discussions with a range of building stakeholders. In order to obtain a deeper understanding of the issues involved, the viewpoints of stakeholders involved in different stages of the construction project were considered. The research therefore considers impacts on the building's energy performance from three different perspectives; design and construction, operation and maintenance and the end-user.

3.8.1 Design and construction perspective

Many of the performance issues identified in the literature review result from decisions made during the design and construction process. To attempt to capture the impact of design decisions and assumptions members of the design and construction team took part in a facilitated workshop. The findings from the workshop were reviewed to capture useful lessons learnt and develop a picture of risk factors as they relate to the case study building. Some of the workshop participants were later interviewed individually to pick up on specific issues they identified and to trial a risk identification questionnaire.

3.8.2 Operation and maintenance perspective

The operation and maintenance of the building was subject to a quarterly review process to identify issues and plan appropriate actions with the building management and maintenance staff. Information was fed into this process from the end-user and technical evaluation activities. During spring 2013 a walk-though took place with the building manager to identify usability issues affecting the day-to-day operation of the building.

3.8.3 End-user perspective

An office building uses energy to provide its occupants with a comfortable and productive working environment. In turn, the building occupants have a significant impact on the building's energy consumption (Janda, 2011). It is therefore important to include the end-users in evaluation of this nature. Early in the project the tenants were given a short presentation to introduce the project, its aims and the evaluation techniques that would be used. Tenants also took part in semi-structured interviews to investigate their experience settling in to the building. In February 2013 tenants completed a standard three-page Building Usage Studies (BUS) questionnaire. This is a well established occupant feedback technique, having been originally developed in 1985 and used in the PROBE studies during the 1990s. In summer 2013 a selection of tenants were interviewed again to provide further information on issues identified by the BUS questionnaire. The building walk-through was also used to identify a range of issues, some of which relate to building usability.

The evaluation from these three perspectives was then summarised in terms of the factors present in the risk taxonomy.

3.9 Summary

This research makes use of a range of techniques in order to identify energy performance risk factors throughout the construction project lifecycle. A detailed performance evaluation of a newly-constructed non-domestic building provides the opportunity to identify factors at whole-building and sub-system level. Extensive physical monitoring was used to investigate technical performance and compare in-use energy consumption with design predictions. The analysis of monitoring data was also used to develop a straightforward means of quantifying sub-system performance uncertainty. A probabilistic technique for evaluating sub-system energy performance was then developed. Root causes were identified by combining the technical analysis with occupant surveys and interviews with construction team members and building management staff. The root causes were then related to a risk taxonomy that forms part of a new framework developed to evaluate energy performance risk.

Chapter 4

Whole-Building Energy Performance Analysis

4.1 Introduction

This chapter investigates energy performance at a whole-building level, disaggregated where possible into the major end-use categories. The building's design energy performance at concept stage is compared with the modelled energy performance at compliance stage, when estimates are generated to demonstrate compliance with building regulations and to obtain the building's EPC asset rating. Although these estimates were similar in total, their component end-uses were found to be very different. The building's actual energy performance, indicated by the building's DEC operational rating, was three times larger than its design estimate. This was not only due to fundamental differences in the rating metrics (such as the inclusion of unregulated loads in the operational rating) but also to significant underestimation of specific energy end-uses. This underestimation was the result of factors not considered at design stage, such as operating patterns, and technical problems within individual sub-systems. Trends in end-use consumption that contribute to this discrepancy are considered in this chapter. Two important sub-systems; space heating and domestic hot water, are investigated in detail in subsequent chapters. This chapter also describes the application of the TM22 Energy Assessment and Reporting Methodology to the assessment of energy performance.

4.2 Design Energy Performance

The building's energy performance was estimated at two stages in the design process. The first estimate was made at concept design stage, shortly before the building design went out to tender. A later estimate was made at the end of the technical design stage, when the contractor was required to demonstrate compliance with building regulations. This compliance estimate was obtained from an energy model created with simulation software based on the National Calculation Methodology (NCM). This model was also used to generate the building's EPC asset rating.

4.2.1 Concept design stage

The building was designed to achieve a high level of energy efficiency and meet an annual emissions target of $15\,\mathrm{kgCO_2/(m^2{\cdot}yr)}$. The building's design stage performance targets were described in an energy strategy report prepared by the architect's environmental services consultant prior to tender in early 2009. It describes the energy saving measures proposed to meet the design target and illustrates the effect of the measures relative to two benchmarks; the good practice benchmark for natural ventilated buildings published in Energy Consumption Guide 19: Energy use in offices (ECON19) (Action Energy, 2003), and measured data from the Elizabeth Fry Building[1]. Although of similar size, the Elizabeth Fry Building is predominantly mechanically ventilated through hollowcore slabs, rather than the lightweight fabric and mixed-mode natural and mechanical ventilation strategy employed in the case study building. It is likely that the environmental services consultant chose the Elizabeth Fry Building on the basis of its energy performance, rather than any similarity in servicing strategy.

The energy saving measures included improved airtightness, heat recovery, enhanced U-values, phase change material (PCM), daylight-linked dimming, low resistance pipe and duct design and a ground source heat pump (GSHP) (Table 4.1). This combination of measures was estimated to achieve an annual carbon emission intensity of $12.3\,\mathrm{kgCO_2/(m^2{\cdot}yr)}$ relative to a good practice benchmark figure of about $30\,\mathrm{kgCO_2/(m^2{\cdot}yr)}$. The reduction in heating energy due to the use of PCMs incorporated in ceilings and walls was assumed to occur as a result of better storage of passive solar gains (Synergy, 2009). It was not possible, however, to obtain details of the calculations used to quantify the energy savings due to the proposed measures.

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[1] The Elizabeth Fry Building is a university building completed in 1995 and was considered exemplary for its energy performance (Bunn, 1995).

Option	**Description**
0	Base case
1	As option 0, but with improved airtightness (to reduce heating energy consumption)
2	As option 1, but with heat recovery (to reduce heating energy consumption)
3	As option 2, but with better u-values (to reduce heating energy consumption)
4	As option 3, but with PCMs (to reduce heating energy consumption)
5	As option 4, but with daylight-linked dimming (to reduce lighting energy consumption)
6	As option 5, but with low-velocity design (to reduce auxiliary energy consumption)
7	As option 6, but with heating and hot water provided by GSHP (to reduce heating and hot water energy consumption)

TABLE 4.1: Proposed energy saving measures

The estimated figure included regulated end-uses (such as heating, hot water and lighting) as well as some unregulated end-uses (such as small power electrical consumption, but not catering energy consumption). The fact that unregulated uses were considered and the fact that the benchmarks used are in-use figures suggests that the emissions target was interpreted as an in-use figure at this stage in the project.

Table 4.2 illustrates the predicted effect of combining successive energy saving measures. The most striking effect is an over thirtyfold reduction of heating energy from the good practice benchmark of 79 $\mathrm{kWh/m^2}$ to 2.3 $\mathrm{kWh/m^2}$ for the combination of heating and hot water provided by the ground source heat pump. Figure 4.1 shows the predicted effect of these design options in terms of CO_2 emissions.

4.2.2 Technical design stage

At the end of the technical design stage the contractor issued to Building Control a report prepared by a consultant to demonstrate Part L compliance. This report included an EPC certificate demonstrating that the building achieved an Asset Rating of 26 (a ‘B’ grade) with a Building Emission Rate of 12.18 $\mathrm{kgCO_2/(m^2{\cdot}yr)}$. This figure only includes regulated loads as the power and other electrical loads allowed for in the energy statement

	Heating	Hot Water	Fans & Pumps	Lighting	Power	Other Elec.	CO_2 Emissions
	(kWh/m^2)						(kgCO_2/m^2)
Type 1 Good Practice	79		2	14	12	3	28.1
Elizabeth Fry Building	37		18	26	8		29.0
Base case	85	7	6	14	12	3	32.3
Improved airtightness	55	7	6	14	12	3	26.6
Heat recovery	45	7	6	14	12	3	24.7
Better U-values	11	7	6	14	12	3	18.2
PCMs	5	7	6	14	12	3	17.1
Daylight-linked dimming	5	7	6	10	12	3	15.4
Low-velocity design	5	7	2	10	12	3	13.7
Ground source heat pump	1	1.3	2	10	12	3	12.3

TABLE 4.2: Estimated effect of energy saving measures (Synergy, 2009)

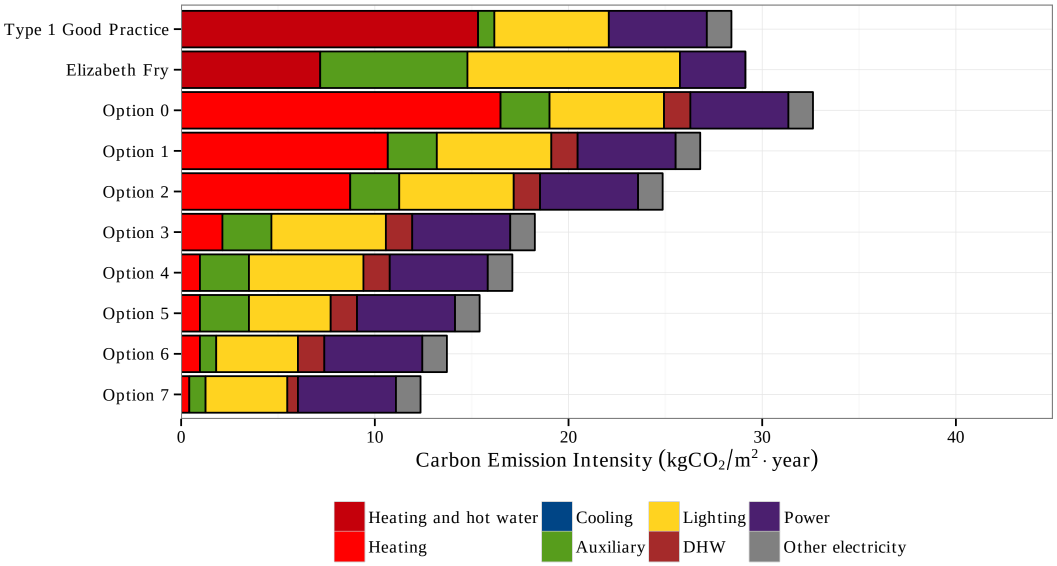


FIGURE 4.1: Concept stage energy statement - CO_2 emissions by end use

are not included in compliance and EPC calculations. Interpreted in this way, the design target is easier to meet than if it were an ‘in-use’ target that included unregulated loads. A copy of the building’s EPC is reproduced in Figure 2.7.

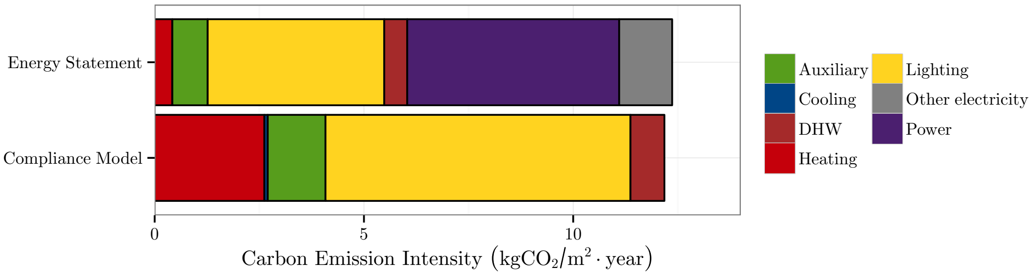


FIGURE 4.2: Concept and design model results

Figure 4.2 illustrates the difference between the energy performance estimates from the energy statement prepared at concept design stage and the compliance model created at technical design stage. These figures are based on on CO_2 emissions factors of 0.422 $\mathrm{kgCO_2/kWh}$ and 0.194 $\mathrm{kgCO_2/kWh}$ respectively for electricity and gas. The total figures are similar, however the design stage estimates of regulated loads obtained from the compliance model are roughly double those stated in the concept stage energy statement. Although the concept stage estimates do attempt to account for some unregulated loads (small power and other electricity), the estimates of regulated loads are clearly over optimistic. This is likely to be a general characteristic of early estimates based on limited information. Furthermore, at the concept state of a project the design team is at risk of abortive work should they not win the tender, therefore it does not make commercial sense to invest significant resources in developing more robust performance estimates. Similarly, while demonstrating regulatory compliance is a mandatory requirement at design stage, there is no requirement to develop performance estimates that account for unregulated loads and reflect realistic operating patterns.

4.3 Operational Performance

Operational performance was reviewed to determine whether there were significant differences between the design energy consumption and the operational energy consumption. The building’s sub-metering was used to identify the end-uses responsible for any differences. Energy consumption data is available in the form of manual sub-meter readings taken at approximately monthly intervals since July 2011. Automatic sub-meter readings taken at approximately ten minute intervals by the wireless monitoring system became available from late 2011 when most of the meters had been connected to the system. Whole-building half-hourly electricity consumption for the period April 2011 to August 2013 was obtained from the electricity supplier. The energy data used for the comparison in this section spans the year from the beginning of August 2012 to the end of July 2013. Operational CO_2 emissions figures are based on emissions factors of 0.55 $kgCO_2/kWh$ and 0.194 $kgCO_2/kWh$ respectively for electricity and gas.

4.3.1 Display Energy Certificates

Two DECs have been generated for the building; the first, dated June 2012 showed an operational rating of 48 (a 'B' grade), a year later the operational rating has risen to 60 (a 'C' grade). A copy of the building's current DEC certificate is reproduced in Figure 2.8. The change in operational rating is due partly to the increasing level of occupancy in the building. During the period covered by the first DEC, on average about 20% of the incubator units were let. This rose to about 60% during the period covered by the second DEC.

While it may be tempting to attempt a comparison of the EPC and DEC scores, it should be remembered that there is a fundamental difference between them. The EPC rating is an estimate of the theoretical performance of the building as a result of its fabric and fixed services (regulated loads such as heating and lighting). The DEC expresses the actual performance of the building, including, in addition to regulated loads, unregulated loads such as office equipment, catering and external lighting.

4.3.2 Disaggregation by end-use

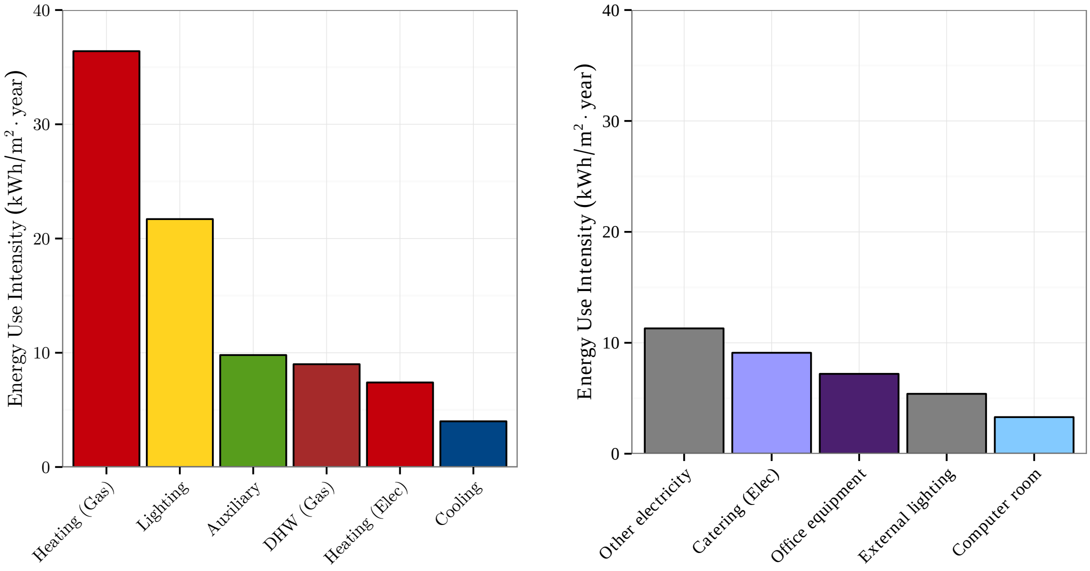
The building sub-metering has enabled the building's overall energy consumption to be partially disaggregated by end-use. Because some of the sub-meters serve a mixture of end-uses it has been necessary to make certain assumptions regarding the breakdown of loads. For example, the main sub-meter serving the incubator units also serves the comms room UPS. This was not separately metered until June 2013 however since then its load has been fairly stable at 1.5 kW. It was assumed that this was running constantly throughout the period under consideration. Each incubator unit has a pair of sub-meters recording total and small power consumption, lighting consumption is obtained from the difference of the two. In five units, one or other of these meters is faulty so the combined consumption measured by the individual meters is less than that obtained from the main sub-meter after subtracting the consumption due to the comms room UPS. The

End use item	**Heating**	**Cooling**	**Fans**
Auditorium AHU	33%	33%	33%
EAHP	90%	0%	10%
Comms Room AC	0%	67%	33%

Table 4.3: Estimated electricity consumption breakdown for individual plant items

small difference, less than 4% of the sub-metered total, cannot be assigned to a specific end-use and has therefore been added to an 'other electricity' end-use category. Further assumptions were necessary for other plant items such as the auditorium AHU, EAHP and comms room AC. Although these have their own electricity meters their electricity consumption falls into a number of end-use categories. This made it necessary to estimate the proportion of each item's consumption by end-use (Table 4.3). The proportion of electricity consumption due to fans was estimated from the equipment's operating current ratings. The split between heating and cooling operation of the auditorium AHU was based on an analysis of flow and return air temperatures.

Figure 4.3 illustrates the energy consumption of regulated and unregulated end-uses, measured over the year beginning August 2012.



(A) Regulated loads (B) Unregulated loads

Figure 4.3: Measured energy consumption by end-use

4.3.3 Design comparison

Figure 4.4 illustrates the overall difference in carbon emission intensity between the design compliance model figures and the measured in-use figures. The electrical component of the design figures has been recalculated using the same CO_2 emission factor used to calculate the in-use figures. In order to make a like-for-like comparison, the unregulated loads, which are absent from the design figure, must be subtracted from the in-use figure. The comparison is therefore between a design carbon emission intensity of 15.2 $kgCO_2/m^2 \cdot yr$ and an in-use carbon emission intensity for regulated loads of 32.4 $kgCO_2/m^2 \cdot yr$; a 113% difference from the design figure. Failing to account for the lack of unregulated loads in the design figures by using the total in-use carbon emission intensity of 52.4 $kgCO_2/m^2 \cdot yr$ would result in an apparent discrepancy of 244%.

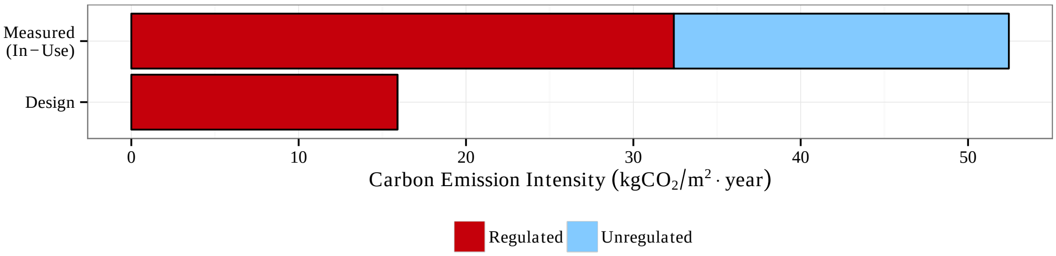


FIGURE 4.4: Measured and modelled carbon emission intensity (design vs. in-use performance gap)

In order to identify the origins of the difference in regulated loads, the design compliance model and measured in-use figures are compared by end-use (Figure 4.5). In terms of energy use intensity, heating represents the largest source of discrepancy between the compliance model and measured consumption, followed by auxiliary energy (fans, pumps and control equipment) and domestic hot water. Although the compliance model results obtained with the building documentation provide a breakdown by energy use intensity, they only provide a single figure for CO_2 emission intensity so it was not possible to create a breakdown by CO_2 emission intensity.

In order to verify the contractor's compliance model, which was created using the IES-VE simulation tool, an alternative model was created with virtually the same input data using the Tas simulation tool. This alternative model is described in Appendix D. Although the EPC asset ratings calculated by the tools are very similar (28 for the compliance model and 27 for the alternative model), their overall CO_2 emission intensities are slightly different (12.18 $kgCO_2/yr$ for the compliance model and 14.24 $kgCO_2/yr$ for the alternative model). The breakdown of energy use intensity by end-use is also different for the two models. The largest difference is in domestic hot water energy use, but lighting and, in percentage terms, cooling are also noticeably different.

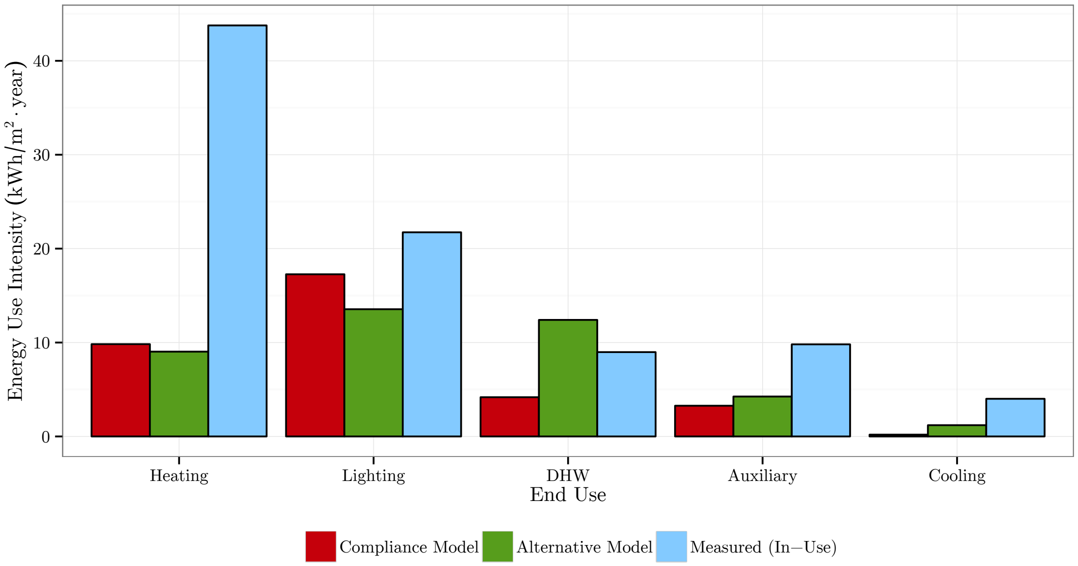


FIGURE 4.5: Measured and modelled energy use intensity by end-use

4.3.4 Benchmark comparison

Figure 4.6 expresses the consumption by end-use in terms of carbon emission intensity and compares the measured data with design and benchmark figures.

Since energy use for space heating is likely to be temperature dependent the benchmark and model figures have been adjusted to account for variation in annual degree days. This degree day normalisation of energy consumption allows for a fairer comparison between different years and models using different weather data (Day, 2006). The Type 1 benchmarks and the concept model's heating base case are taken directly from figures in ECON19, which are corrected to a national average of 2462 annual degree days (Action Energy, 2003). The compliance model was run with the CIBSE 2005 Birmingham TRY weather data, which has 2251 annual degree days. These figures are lower than the Midlands region degree days during the monitoring period (2758 annual degree days) so both benchmark and model figures have been adjusted upwards according to the method for adjusting DEC benchmarks (DCLG, 2008), which pro-rates a proportion of heating-related energy consumption. CIBSE TM46 provides details of the proportions of electricity and fossil-thermal benchmarks that can be pro-rated to degree days in different building types (CIBSE, 2008).

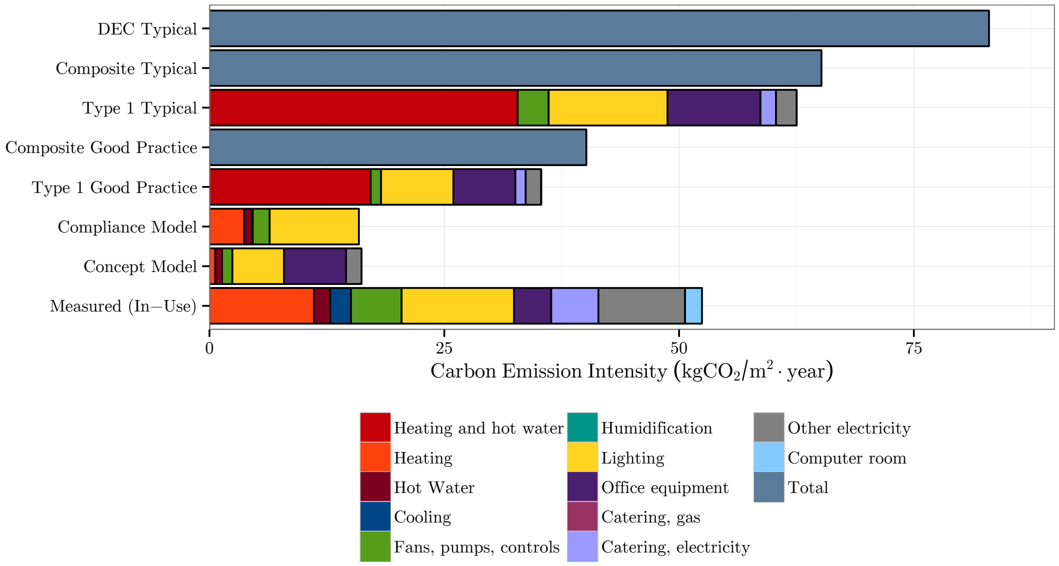


FIGURE 4.6: Measured, design and benchmark CO_2 emissions by end use

Although the in-use carbon emission intensity is much higher than the design estimates it is lower than the DEC typical figure and the Type 1 typical benchmark. The DEC figure is representative of offices in general, which would include a range of building ages and heating, ventilation and air conditioning systems. A more relevant comparison is against the Type 1 office benchmarks, which are applicable to naturally ventilated cellular offices. The building however includes a kitchen and café as well as an air conditioned auditorium. To account for these space types composite benchmarks were derived from an area weighted average of the relevant benchmarks listed in CIBSE Guide F (CIBSE, 2012). The building's in-use carbon emission intensity exceeds the composite good practice benchmark by 31%. Table 4.4 shows the components of the composite benchmark after degree day adjustment.

Although the composite benchmark, which more closely reflects the usage of the study building, is a more appropriate basis for comparison it still does not account for the mixed-mode operation of the offices, which uses an extract fan that runs when the building is in heating mode. Furthermore the composite benchmark cannot be disaggregated by end-use like the office benchmarks, which have therefore been used for the end-use comparison. In terms of CO_2 emissions (which allow a direct comparison of electricity and gas consumption), the measured energy consumption for heating and hot water is slightly lower than the good practice benchmark. This is encouraging since improvements to the control of the heating system are expected to reduce its consumption. Cooling and computer room energy consumption does not feature in the naturally ventilated

Category	**Floor Area** (m^2)	**Fossil fuels** ($kWh/m^2\cdot yr$)		**Electricity** ($kWh/m^2\cdot yr$)		**Total** ($kgCO_2/m^2\cdot yr$)	
		Good	Typ.	Good	Typ.	Good	Typ.
Education (further and higher)							
Catering, bar/restaurant	207.4	188.6	266.3	140.3	152.6	113.7	135.6
Lecture room, arts	271.3	106.6	127.9	67.9	76.0	57.5	66.6
Offices							
Naturally ventilated, cellular	3545.0	84.2	161.0	33.0	54.0	34.5	60.9
Area Weighted		91.1	164.2	40.8	60.6	40.1	65.2

Table 4.4: Composite benchmarks

building benchmarks so a direct comparison is not possible. Similarly, benchmark energy consumption due to fans in the 'fans, pumps and controls' category will be much smaller in completely naturally ventilated buildings. The auditorium air handling unit and office extract ventilation contribute to the measured figure for this building. Lighting energy consumption is comparable with the typical benchmark. Better control of lighting in communal areas could reduce this. Office equipment energy consumption is less than the good practice benchmark, however this may be a result of the occupancy level and intermittent usage of some of the office units. Catering energy consumption is significantly higher than the benchmark figures, which only assume the provision of tea-points rather than full kitchens. Furthermore, the kitchen in the study building is all-electric which could increase its relative CO_2 emissions. The 'other electricity' includes external lighting and electricity consumption that could not be assigned to any other category due to limitations of the sub-metering and sparse documentation of circuit schedules. About one third of this 'other electricity' is due to external lighting.

4.4 Consumption Trends

Figure 4.7 shows daily total electricity consumption calculated from the half-hourly data obtained from the electricity supplier. The daily consumption shows frequent variations due to the reduction in consumption during weekends. Applying a seven-day filter to the data makes the weekly variation clearer although there is still a wide variation in consumption during the monitoring period. The overall trend, calculated from the data, shows a steady increase during the first year of operation, followed by a levelling out during the second year. This is broadly consistent with the overall trend in occupancy, which rose slowly during the building's first year of operation to about 35% and then levelled off at about 70% from the middle of the second year (Figure 4.8). Not all the building's electrical loads however are occupancy related so much of the week to week variation is due to other factors discussed below.

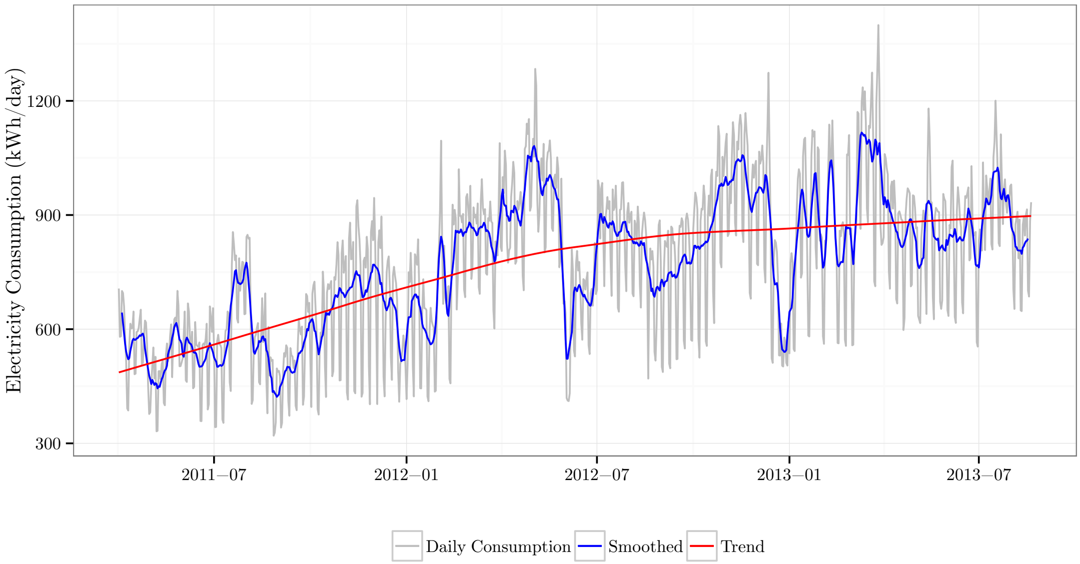


Figure 4.7: Daily total electricity consumption

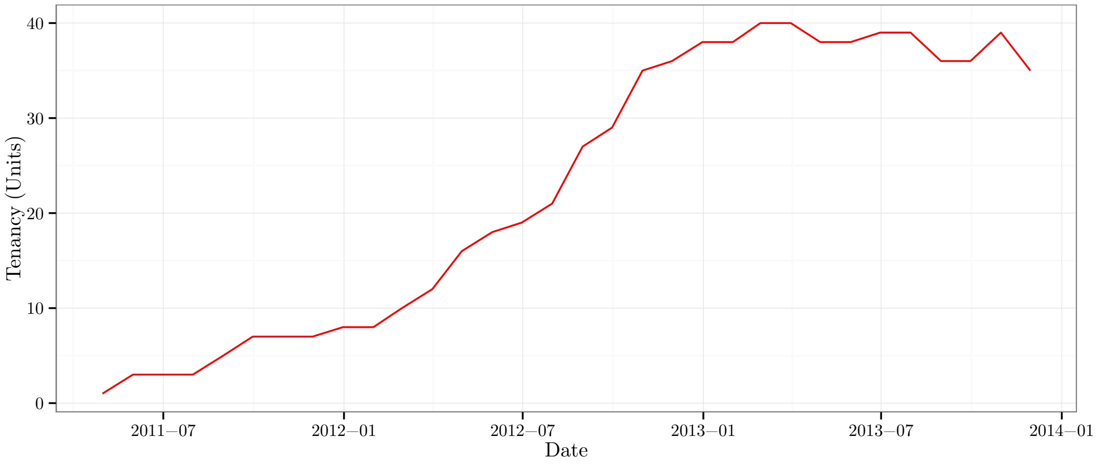


Figure 4.8: Building occupancy

Figure 4.9 shows the monthly average daily electricity consumption of the building's main sub-meter categories. These figures are further disaggregated below.

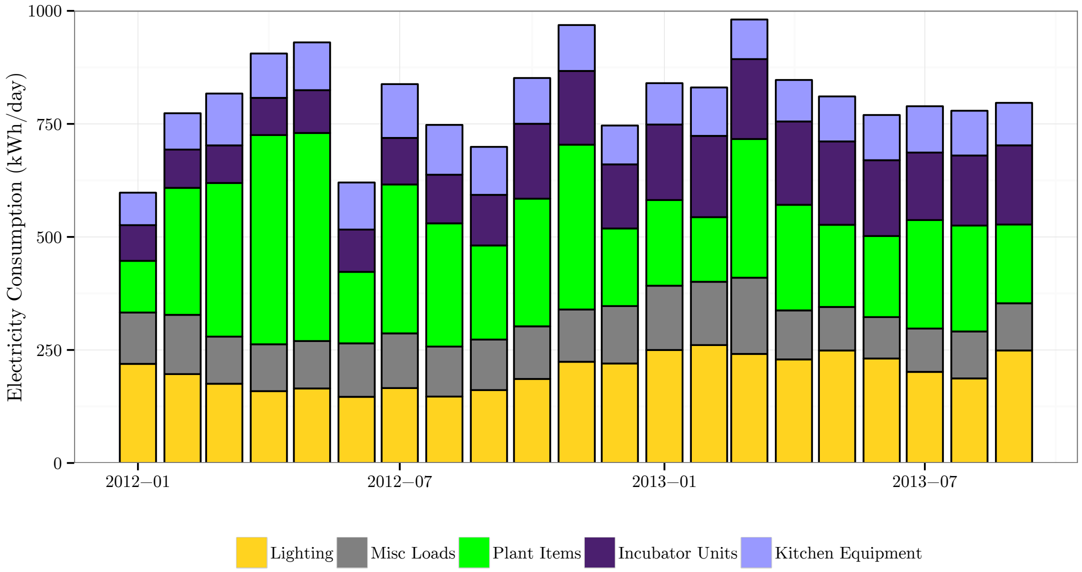


FIGURE 4.9: Monthly average sub-metered electricity consumption

4.4.1 Plant items

Figure 4.10 shows the monthly average daily electricity consumption of the individually metered plant items. Extract fans, pumps and controls are not individually metered but form the majority of the load on the mechanical services control panel. The greatest variations in plant power consumption are due to the intermittent operation of the auditorium AHU and the exhaust air heat pump, which are the building's two largest single consumers of electricity. At the beginning of 2012, the auditorium AHU was left running permanently as it was otherwise unable to maintain the auditorium at a satisfactory temperature in cold weather. This was due to a compressor fault that has since been rectified. Even in warm weather the unit was frequently left running either accidentally or intentionally because the building operators were concerned that the unit, which had proved unreliable, will fail to restart if turned off. The extract air source heat pump was not fully operational during either of the two winters during the evaluation period. It was however in operation during spring and autumn seasons and surprisingly during the summer as well. This was found to be due to the BMS control strategy, which activates the heating system when the ambient temperature is below a specified limit. Originally this was set to 18 °C, however it was later set to 10 °C and then as low as 5 °C

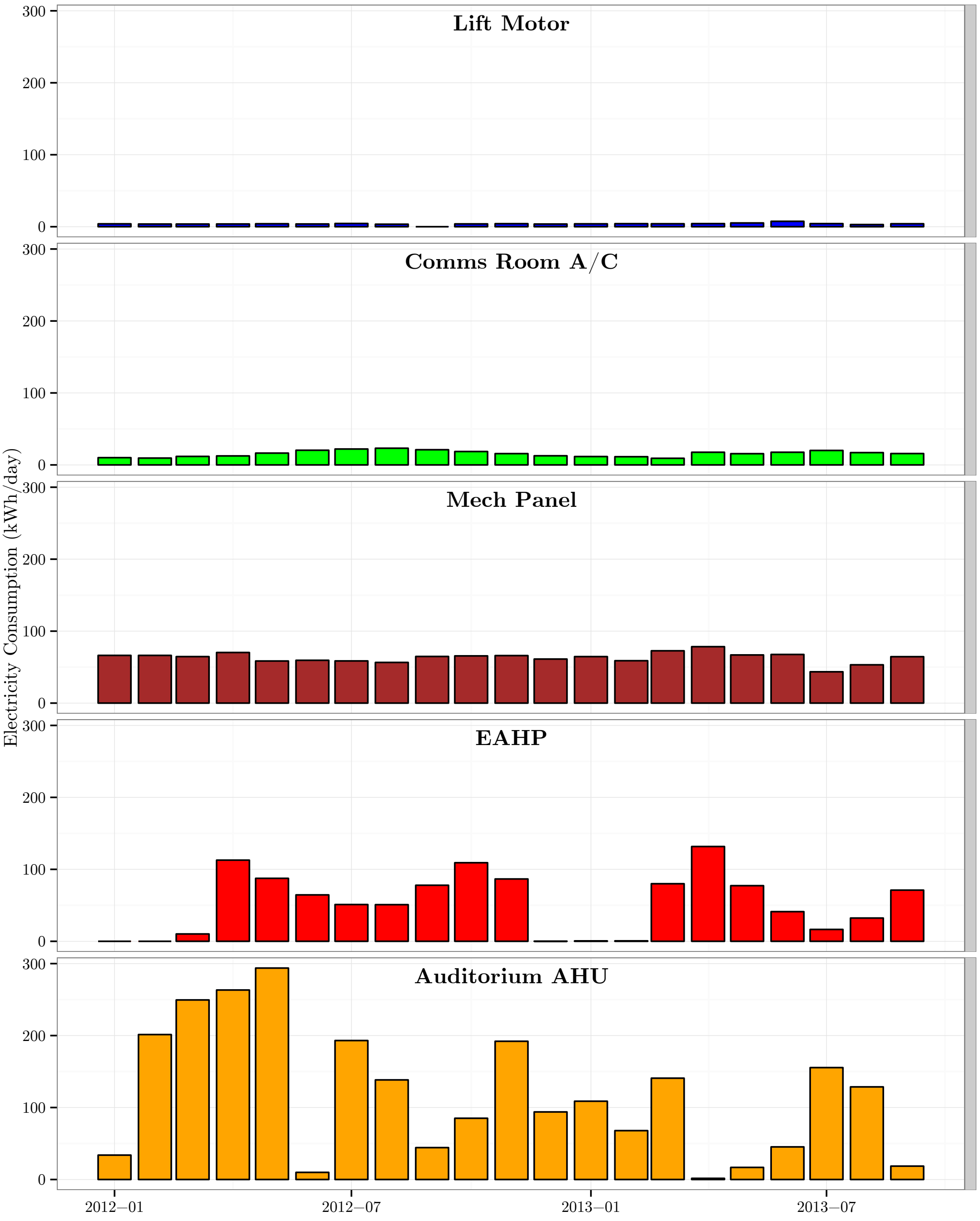


Figure 4.10: Electrical sub-metering - Plant items

before being reset to 20 °C. The reason for the adjustment is unclear but it could have been due to untrained building management staff attempting to address summertime overheating then subsequently reverting to what was believed to be an appropriate setting for winter operation.

4.4.2 Lighting

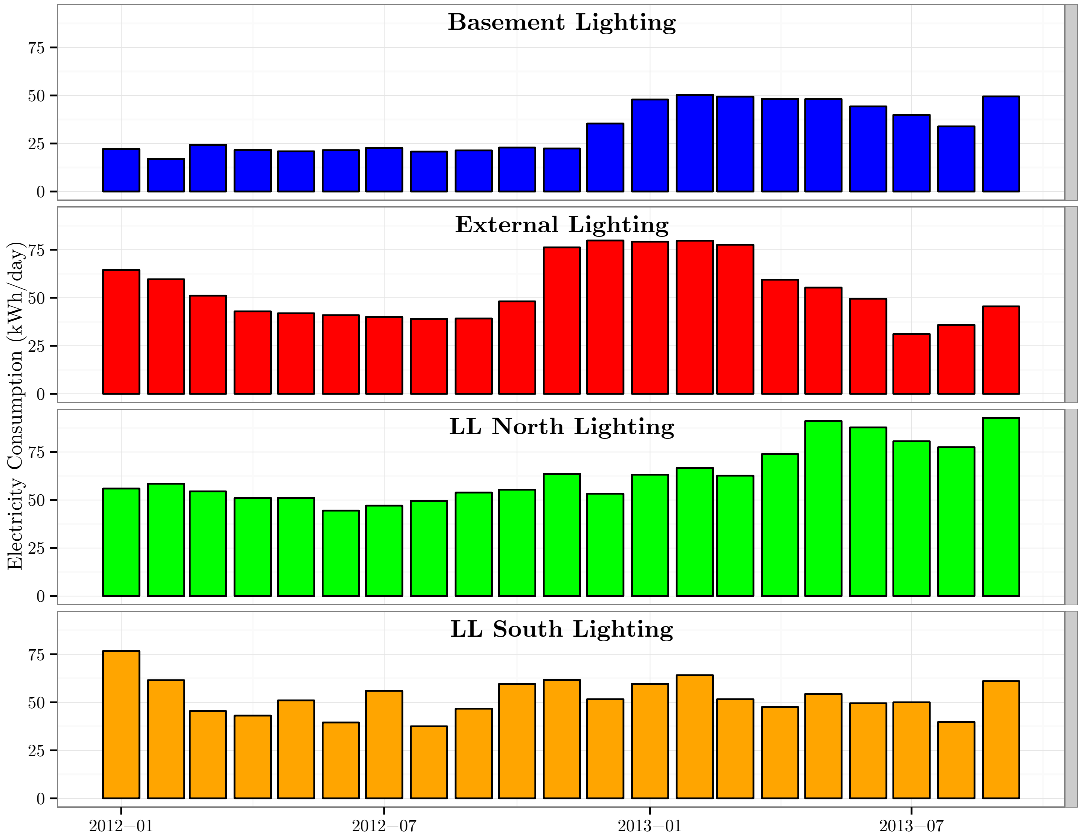


Figure 4.11: Electrical sub-metering - Lighting

Figure 4.11 shows the monthly average daily electricity consumption of building's four lighting distribution boards. There is a seasonal variation in lighting electricity consumption, much of this is due to the external lighting, which operates on a time switch that is periodically adjusted to account for daylight availability. Landlord north lighting electricity consumption increased dramatically between March and May 2013. This may be due to the fire exit stairs being increasingly used for general movement between office floors. The lighting in these stairwells is not controlled by PIR and is often left on overnight. The basement lighting electricity consumption has almost doubled since

November 2012. This may be the result of manual adjustment to extend the operating period.

4.4.3 Incubator units

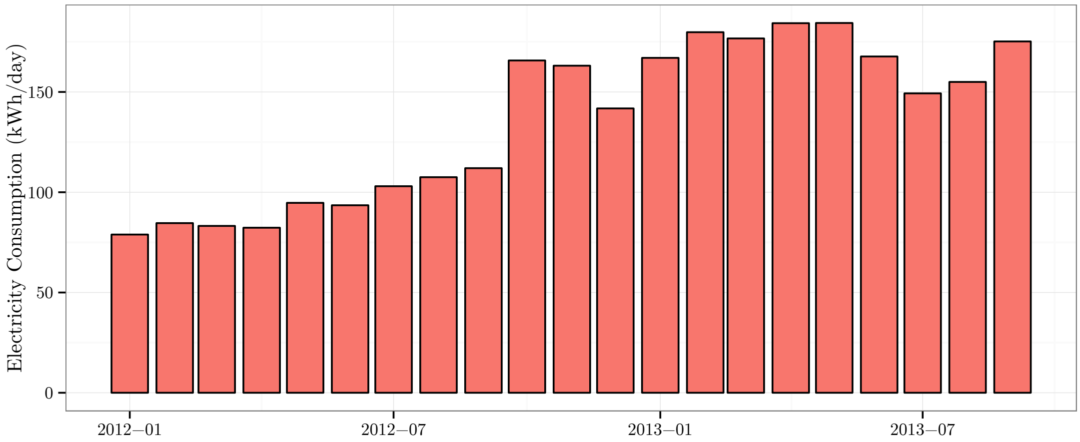


FIGURE 4.12: Electrical sub-metering - Incubator units

Figure 4.12 shows the incubator unit electricity consumption (less the Comms Room UPS) and the building's occupancy. The incubator unit consumption has increased, broadly in line with the increasing building occupancy shown in Figure 4.8. Tenants generally work core hours of 9-5 but part time occupancy is common, particularly in the smaller incubator units. Out-of-hours occupancy is infrequent. The amount of electrical equipment in the units is fairly light, typically including small office equipment such as laptops and personal printers, however one or two tenants run servers in their offices. Although desktop computers are usually turned off when tenants leave their office, other equipment like printers will be left on standby.

4.4.4 Kitchen equipment

Kitchen power has remained fairly constant (around 100 kWh/day) throughout the monitoring period. The kitchen was found to have a base load of about 2.5 kW due to fridges, freezers and possibly other equipment being left on. The café is open to the public, so the number of meals served is less closely related to building tenancy. On an average weekday, the café serves about 50 hot drinks, 25 cold meals and 10 hot meals. Assuming this is equivalent to about 40 meals the energy consumption per meal served is approximately 2.5 kWh/meal. This falls in the range of good practice benchmarks for coffee shops (approx 1.4 kWh/meal) and staff restaurants (approx 3.9 kWh/meal) (CIBSE, 2009b).

4.4.5 Miscellaneous loads

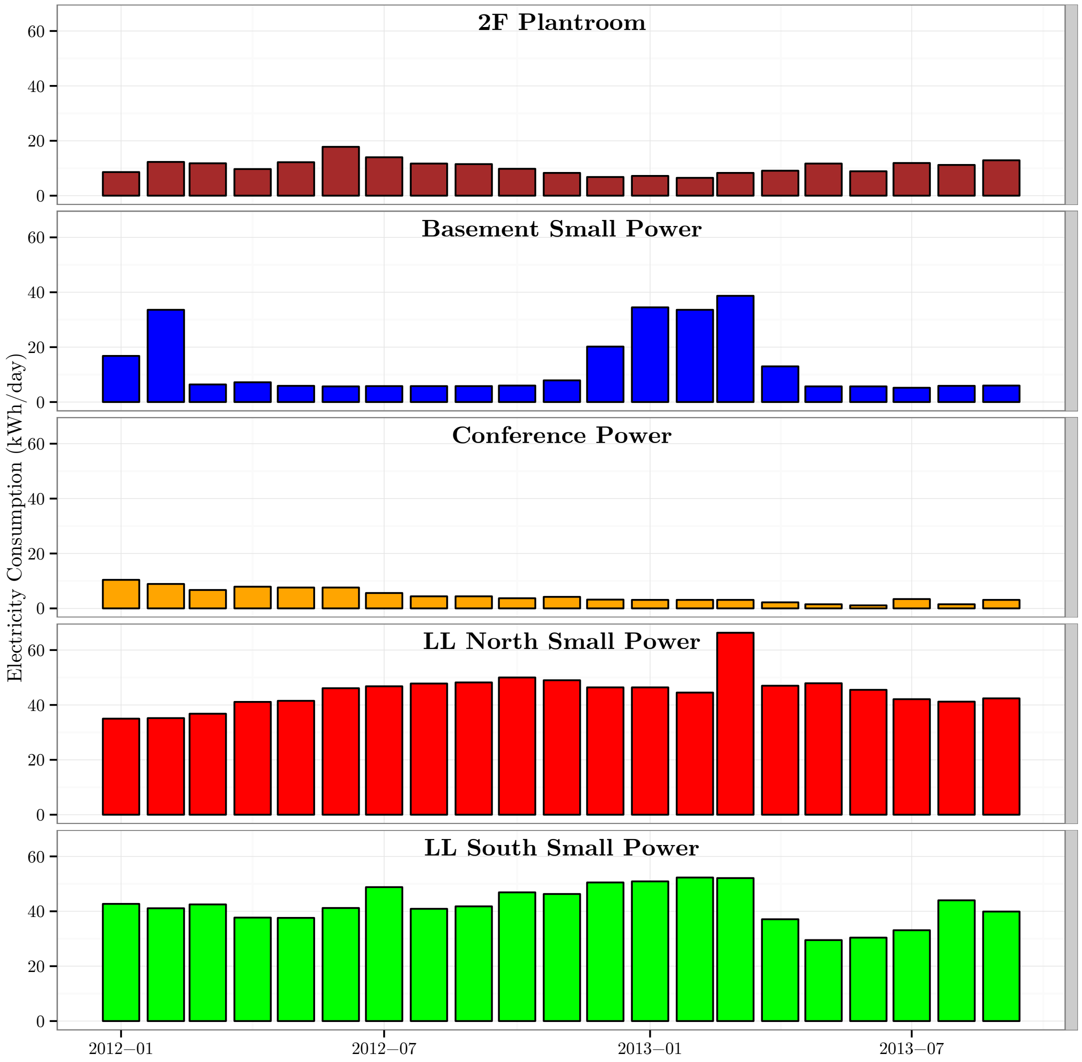
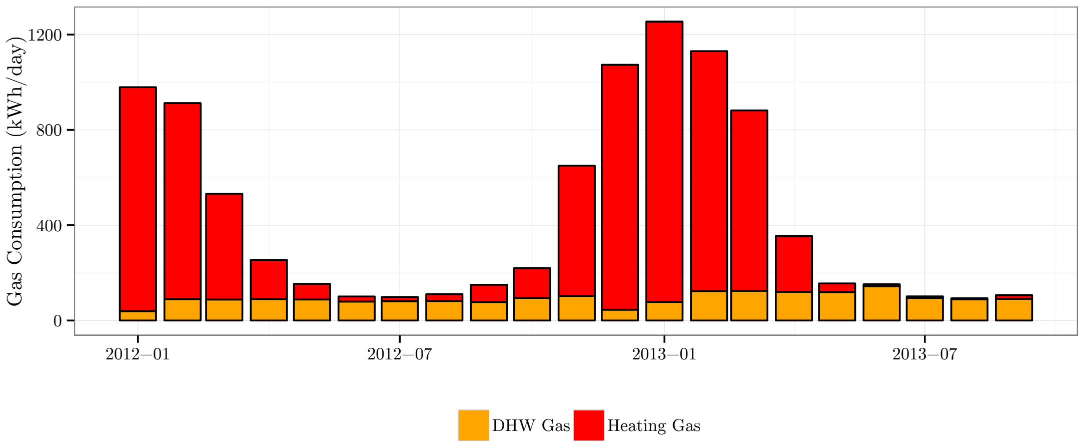
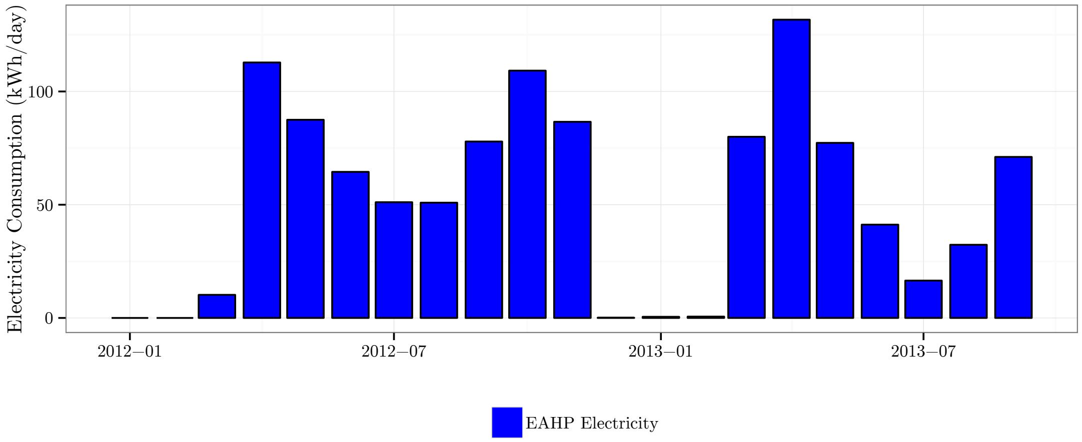


FIGURE 4.13: Electrical sub-metering - Miscellaneous Loads

Figure 4.13 shows the power consumption of miscellaneous load items. Much of the variation in consumption is due to the operation of trace heating for pipework in the undercroft car park during cold weather. The consumption figure for March 2013 is artificially elevated due to the EAHP electricity meter being offline (therefore it was not possible to subtract the EAHP consumption from the other loads on the landlord north small-power distribution board). There was a significant reduction in the landlord



(A) Gas consumption



(B) Heating electricity consumption

Figure 4.14: Electrical and gas sub-metering - Heating and hot water

south small-power consumption during spring 2013; however, since there is no record of connected loads it was not possible to identify the reason.

4.4.6 Heating & hot water (electricity and gas)

Figure 4.14 shows the energy consumption of electricity and gas used for heat generation. Gas consumption for domestic hot water is relatively stable. However, as discussed in more detail in Chapter 6, the system appears to be oversized for the level of demand so most of the energy used is to maintain storage and circulation temperatures. Gas consumption for heating shows clear wintertime peaks, which are likely to have been exacerbated by the EAHP not contributing to the building's heating during both winters as well as the switch in December 2012 to 24/7 operation of heating (due partly to concern that it would fail to restart if left to BMS control). The EAHP continues to operate during the summer. This is probably unnecessary and is due to the high ambient temperature at which the heating plant is deactivated (currently 20 °C). It must be noted that this comparison between kWh of gas and kWh of electricity does not take into account the greater efficiency of the heat pump, nor does it take into account the differences in primary energy[2] or carbon intensity between gas and electricity. Figure 4.15 expresses the space heating system's gas and electricity consumption in terms of CO_2. Although the EAHP was intended to satisfy the majority of the building's heating demand, the gas usage when the EAHP is operating is significant. This is partly as a consequence of the boiler's flow temperature being set to 80 °C, causing unnecessary cycling of both the boiler and EAHP. The flow temperature was subsequently reduced to 60 °C, which reduced the cycling and was hoped to allow the EAHP to operate more effectively. Despite this adjustment, the gas boiler was still observed to be running more often than expected. This may be because the control strategy is too sensitive to fluctuations in the heating flow temperature; the boiler is enabled to respond quickly, rather than allowing the heat pump to run steadily. When designing and commissioning systems such as this that use a combination of heat sources, their compatibility (for example flow temperatures) and the appropriateness of the control strategy must be considered.

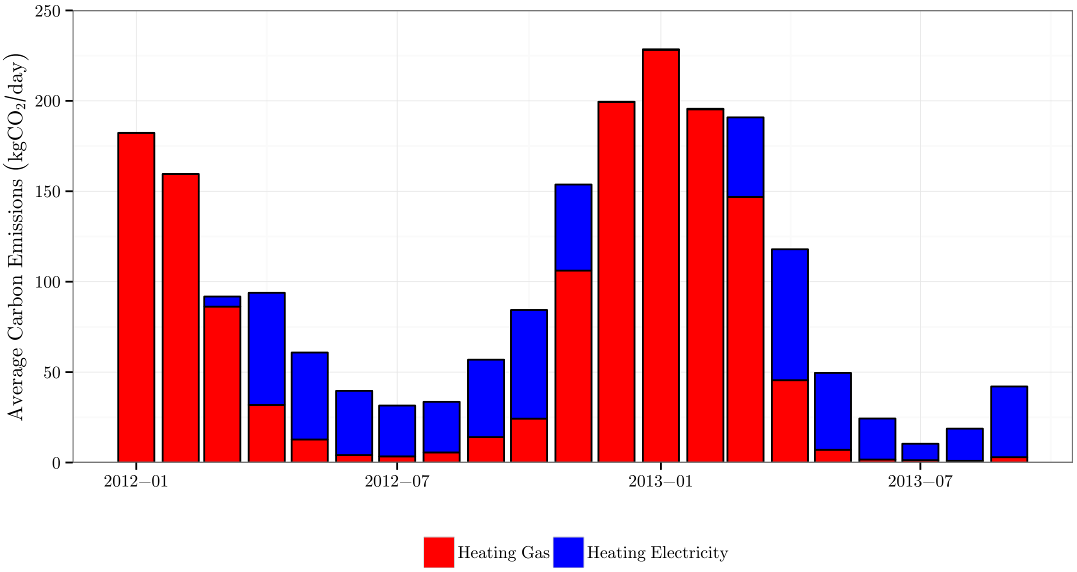


FIGURE 4.15: Building CO_2 emissions - Heating energy consumption

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[2] Primary energy is the energy required to supply one unit of delivered energy, taking into account the energy required in extraction, generation and distribution (prEN 15603:2013). The use of primary energy, rather than delivered energy, enables the direct comparison of energy from different sources.

4.5 TM22 Energy Assessment

CIBSE TM22 describes an established method for assessing the energy performance of an occupied building based on metered energy use (CIBSE, 2006b). The methodology is derived from work carried out by Field et al. (1997), which described a procedure called the Office Assessment Method. The procedure was used for the energy assessment part of the PROBE studies (Cohen et al., 2001).

The 2006 version of TM22 provides three levels of assessment, all of which have been implemented as a Microsoft Excel spreadsheet accompanying the CIBSE document. The first level is a simple whole-building electricity and fossil fuel benchmark comparison that can be carried out on a single worksheet. Benchmarking can be carried out on four categories of building (office, hotel, bank/agency and mixed use industrial building) and a range of sub-categories such as naturally ventilated, air conditioned etc. Results are presented relative to good practice and typical benchmark figures for whole building carbon emissions or energy cost. The second level is a slightly more detailed whole-building assessment that allows for multiple metered supplies and up to four zones of different usage type. This enables comparison against a composite benchmark that is tailored to the usages within the building, for example an industrial unit with adjacent office space. It can also adjust the metered consumption and benchmarks to account for differences in weather conditions (in terms of annual degree days relative to the benchmark degree days), hours of occupancy, small power load density and the percentage split of electrical and fossil-fuel heating and cooling loads. The second level also allows for CHP, on-site renewables and process energy use to provide a more detailed assessment of whole-building energy performance. The most detailed level of assessment allows evaluation of a building's sub-system energy performance. This provides estimates of end-use energy consumption that can be compared with end-use benchmarks (if available). The end-use estimates are built up from the estimated consumption of of individual items (e.g. chillers) or groups of items (e.g. lighting circuits) by end-use category. The estimates can then be compared with design or modelled data and sub-metered data.

In addition to the intention of the original Office Assessment Method to obtain estimates of end-use energy consumption, TM22 2006 was also intended to support energy labelling based on metered energy uses. This has been superseded by the methodology described in DCLG (2008) for calculating operational ratings for DEC certificates. The TM22 methodology however still serves its original purpose and caters for a variety of needs. These include use by estate and building managers to identify poorly performing buildings and sub-systems. Energy assessors and surveyors can use the methodology to identify opportunities for energy savings measures and provide a consistent template for energy reporting. Building designers can use it to develop design stage estimates that can be compared later with in-use figures. The methodology can also help designers to identify necessary sub-metering at the design stage.

One of the benefits of the procedure is its ability to generate estimates of energy consumption by end-use in existing buildings without relying on extensive sub-metering. In order to do so however detailed information on the building's end-use items must be available. This information would normally be obtained from as-built drawings, electrical circuit schedules, O&M documents or manufacturers' literature. Site surveys may also be necessary to verify or supplement documented information. If sub-metered data is available it can be used to validate the estimates by reconciling metered and estimated end-use consumption. This form of validation suffers from the same limitation as high-level validation or calibration of simulation models, in that it is quite possible to get the right answer for the wrong reason: A high degree of reconciliation, where metered end-use consumption closely matches estimated end-use consumption, could be the result of a chance combination or deliberate manipulation of input values.

Information on individual end-use items is used to arrive at an estimate of annual energy consumption for each end-use category. An end-use item's full load energy consumption is calculated by multiplying its nominal rated load by a load factor that relates its nominal rated load to its actual full load power. Resistive loads such as immersion heaters and incandescent lighting will typically have load factors of unity. Fluorescent lights will have slightly higher load factors due to the electricity consumption of their control gear. Office equipment such as computers are likely to operate at significantly below their nominal ratings and may have load factors of 10% to 25% (CIBSE, 2012). The item's annual energy consumption is then obtained by multiplying its full load energy consumption by its equivalent full load operating hours. This is obtained by summing daily, weekly and annual operating hours, which are then apportioned into day and night/weekend operation by multiplying by percentage usage factors.

While it is relatively straightforward to identify rated loads for lighting and large plant items it may be difficult to identify miscellaneous loads such as communication and security systems distributed around the building. Individually such loads may be small, but they may be numerous and typically operate continuously throughout the year. In multi-tenanted buildings commercial buildings there may be a wide range of small-power loads that are unlikely to be documented. In this situation estimates of installed loads will be uncertain unless a detailed site survey can be carried out.

In buildings where services systems are centrally controlled according to a fixed time schedule it should be possible to estimate annual operating hours with a degree of certainty. Most modern buildings however incorporate energy saving measures such as optimum heating start/stop control and occupancy or daylight sensing lighting control. These will operate autonomously within the constraints of a master time schedule so it is difficult to establish their actual operating hours. Similarly, unless office equipment is operated according to a fixed schedule occupants will be responsible for switching on and off as required. Even if computers are typically left running it is likely their inbuilt power-saving settings will automatically enable standby mode after a certain period of inactivity. For these reasons, estimates of annual operating hours are likely to be subject to significant uncertainty.

The estimates of annual energy consumption by end-use are therefore dependent on the product of a number of uncertain estimates about installed loads, load factors, operating hours and usage factors. The TM22 spreadsheet does provide a description field for each load item, which can be used to describe the basis for the estimates. It does not however facilitate sensitivity analysis or allow for uncertainty in the input data. Although uncertainty could be reduced by carrying out a detailed site survey the time requirement and therefore cost of obtaining the amount of data necessary for an accurate assessment may be prohibitive.

4.5.1 TM22 analysis

A TM22 analysis was carried out on the case study building to evaluate the application of a standardised method against the bespoke analysis described above. The calculations were carried out using a beta test version of the TM22 spreadsheet, issued in April 2012 to participants in the TSB's Building Performance Evaluation programme.

The energy consumption data used in the analysis ran from August 2012 to August 2013, to correspond to the period of half-hourly energy data obtained from the building's electricity supplier. Manual meter readings were used to obtain the data as the pulse output from the main electricity meter to the monitoring system was not connected until partway through the assessment period. The analysis was simplified somewhat by the fact that there are no on-site renewables. The building's gross internal area was entered as $4024\,\mathrm{m}^2$, the same as used for the building's DEC. Default CO_2 emissions factors were used (Table 4.5).

Fuel	**Emissions Factor** ($kgCO_2$)
Electricity (grid)	0.55
Natural gas	0.194

TABLE 4.5: CO_2 Emission Factors (CarbonBuzz, 2014)

Energy supplied		**Carbon dioxide emissions**		
Natural gas	Electricity	Natural Gas	Electricity	TOTAL
(kWh)		($kgCO_2$)		
189,833	318,499	36,828	175,174	212,002
(kWh/m^2)		($kgCO_2/m^2$)		
47.2	79.2	9.2	43.5	52.7

TABLE 4.6: TM22 Simple Assessment - Annual delivered energy and CO_2 emissions

Simple assessment

The results of the simple assessment (Table 4.6) are plotted by the spreadsheet to provide a comparison of supplied energy with a user specified benchmark and the benchmark from the building's DEC (Figure 4.16). The DEC benchmark is a composite benchmark that takes into account the different space categories within the building (general offices, auditorium and café). The benchmark also includes an adjustment to allow for the influence of ambient temperatures on heating energy consumption. The building's design energy consumption was entered as the user specified benchmark to highlight the difference between the building's asset rating (a design figure) and its actual energy consumption. The TM22 figures differ slightly from the operational energy consumption described previously in Section 4.3 due to a difference in the monitoring period.

In terms of energy consumption, the building's electricity use is similar to the benchmark figure while the heating energy is significantly lower. The DEC benchmarks are intended to be representative of the whole building stock so a recently constructed building complying with recent building regulations would be expected to use significantly less energy for heating provided it is operated in a reasonably efficient manner.

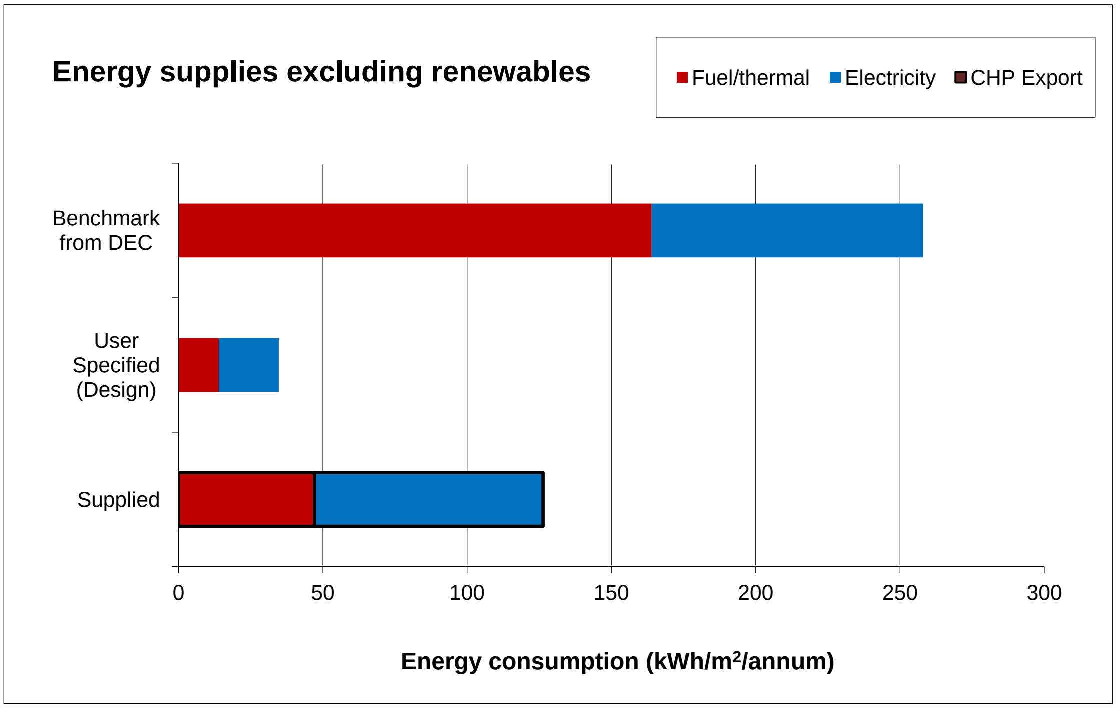


FIGURE 4.16: TM22 Simple Assessment

Sub-meter data

As sub-metered electricity consumption (Table 4.7) was available it was possible to attempt to reconcile the TM22 estimated energy consumption by end-use with the sub-metered consumption obtained from the monitoring system. There is a minor discrepancy between the metered energy supply and the sum of sub-metered consumption. This is because of the small difference in metering duration between the manual main meter readings and the automatic sub-meter readings. The main meter also serves the fire alarm panel directly so its (small) consumption will not be accounted for by the sub-meter readings.

Operating profiles

The TM22 spreadsheet uses hourly profiles to determine the operating period of each load item. This approach is straightforward and can provide an accurate estimate of operating periods when they are well defined, for example lighting and plant items operated according to a fixed schedule. The case study building contains multiple tenants, only some of which operate regular office hours (roughly 8am to 6pm during the week); the majority of the office units do not appear to be used so regularly. Rather than attempting

Sub-meter	**Annual consumption** (kWh)
Incubator Units + Comms UPS	73,406
Basement Lighting	14,084
Basement Small Power	5,559
External Services	21,848
Kitchen Power	36,536
Conference Power	1,052
LL South Lighting	19,534
LL South Small Power	15,803
LL North Lighting	25,436
LL North Small Power	44,230
2F Plantroom	35,680
Lift Motor	1,485
Mech Panel	23,751
Total	**318,404**
Main Meter	318,499

Table 4.7: TM22 Sub-metered electricity consumption

to estimate an hourly profile for each tenant it was considered more appropriate to capture this variation by applying an average usage factor to office lighting and small power loads. The spreadsheet also defines a seasonal split, which is used to apportion seasonal loads such as heating, cooling and external lighting. The split was left at its default values (30% winter, 30% summer, 40% spring and autumn).

In-use data

The in-use worksheet is the core of the TM22 detailed assessment. It is where the individual load items are entered, along with their rated loads, load factors, hourly profiles and usage factors. The worksheet provides a running total of the calculated annual energy consumption. For the case-study building, the worksheet was completed based on information from a range of sources, starting with the 'as-installed' information provided in the O&M manual. Because this information was found to be incomplete and inaccurate in some areas it has been supplemented with information from manufacturers' literature, site inspections and, where necessary, estimates and assumptions. The detailed monitoring carried out on the building enabled load factors, operating profiles, usage factors and seasonal factors to be based on patterns of use evident from observed load profiles and a general understanding of the building's usage.

Detailed assessment

The detailed assessment provides estimates of energy consumption disaggregated by end-use. The spreadsheet allows for reconciliation of sub-meter readings against the calculated end-use estimates as a form of verification. In the case study building the reconciliation process is complicated by the fact that many of the sub-meters serve multiple end-use categories. In these cases an attempt has been made to break the loads down by end use. In some cases a single item of equipment (such as the auditorium AHU) represents multiple end use categories (heating, cooling and fans) so it has been necessary to make assumptions in apportioning the overall load. Since the TM22 disaggregation is based on consumption figures obtained from installed loads and estimated adjustment factors for load duty, operating hours and seasonal variation it will produce slightly different results than the disaggregation approach used to obtain the figures in Sections 4.3.2 and 4.4, which are based on actual sub-metered consumption and assumptions regarding load breakdowns where multiple end-uses are served by a single sub-meter.

The results of the detailed assessment are shown in Table 4.8, which provides a comparison of benchmark energy demand with design and in-use figures. The design figures clearly don't include any unregulated loads such as offices appliances and catering. The in-use figures are larger than both the good practice and typical benchmarks. This is due partly to the inclusion of heating energy consumption, which is absent from the benchmarks because it is assumed to be provided by thermal fuel, and cooling and air movement energy consumption, due to the presence of a mixed-mode ventilation system and air conditioning in the auditorium, meeting and comms rooms.

The building's estimated heat demand for the categories space heating (gas) and domestic hot water (gas) are calculated by the spreadsheet from the metered fuel consumption used for the simple assessment. For the detailed assessment each fuel is assigned an average thermal efficiency, which is used to convert fuel consumption into heat demand. An estimated figure of 75% was used to account for the overall efficiency of heat generation for both space heating and hot water.

As well as the DEC benchmark, the detailed assessment includes a comparison with typical and good practice office benchmarks from ECON19. The benchmarks can be selected from one of the four office categories: naturally ventilated cellular, naturally ventilated open-plan, air-conditioned standard and air-conditioned prestige. The case study building most closely matches the naturally ventilated cellular, however the presence of an air conditioned auditorium and fully catered café reduces the relevance of the benchmark. The thermal fuel consumption components of both DEC and ECON19 benchmarks are converted to heat demand figures by the TM22 spreadsheet using a default thermal efficiency of 80%.

In terms of heat demand, domestic hot water is similar to the typical figure however the sum of electrical and thermal space heating demand is to be less than both typical and good practice benchmarks. While the spreadsheets converts the benchmarks and the space heating gas consumption into equivalent heat demand it does not convert the space heating electricity consumption. This appears to be a limitation of the TM22 spreadsheet in that it is unable to account for buildings with both electrical and fossil fuel heat sources. In terms of electrical load, the two most significant end-uses are internal lighting and small power, which are comparable to the type 1 typical office benchmark figures (23 kWh/m^2·yr and 18 kWh/m^2·yr respectively).

The result of the reconciliation between the TM22 in-use estimate and the metered data is shown at the bottom of Table 4.8. There is only 0.5 kWh difference between the two figures, however this is because many of the rated loads were derived from load profiles generated from sub-metered data.

Overall load profiles

Figure 4.17 shows average weekday and weekend electrical load profiles obtained by processing the supplier's half-hourly consumption data with the TM22 half-hour data analysis module. The error bars indicate the maximum and minimum values at each time interval. Both profiles feature a large variation in half-hourly loads from about 8am to 10pm. Outside of these hours there is less variation about what appears to be a baseline load of 25 kW, which doesn't change at weekends. Average weekday consumption increases between about 7 am and 9 am, corresponding to the beginning of the working day. Consumption beings to tail off in the afternoon. The rate at which consumption increases is greater than the rate at which it tails off. This is probably due to there being greater variation in occupant leaving times than arrival times. There is a slight increase in average consumption from 8 am to 10 pm on weekends, which is due to occasional weekend use of the building.

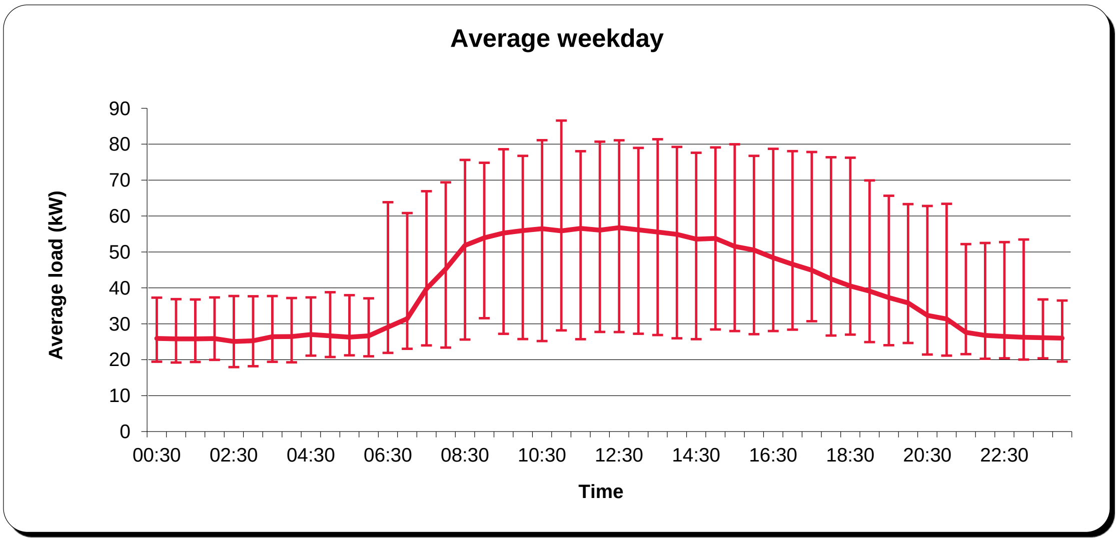
System	**Energy demand** (kWh/m^2·yr) Design estimate	In-use estimate	Typical benchmark	Good practice benchmark
Space Heating (electricity)	2.9	7.4	N/A	N/A
Space Heating (gas)	6.2	28.3	107.2	54.7
Domestic hot water (gas)	3.8	7.1	7.6	5.3
Space cooling	0.2	3.6	0.0	0.0
Air movement	2.1	7.2	0.0	0.0
Pumps and Controls	0.9	4.1	5.7	1.9
Lighting	15.9	21.7	21.9	13.3
Household/office appliances	0.0	19.3	17.1	11.4
ICT Equipment/computer room	0.0	2.4	2.4	2.4
Indoor transportation	0.0	0.3	N/A	N/A
Cooking	0.0	7.9	2.9	1.9
Cooled Storage	0.0	0.0	N/A	N/A
Other electricity	0.0	5.6	3.8	2.9
Total	**21.9**	**79.6**	**53.7**	**33.7**
Metered building energy use	79.2	79.2		
Variance TM22 vs. metered total	-57.2	0.5		
Variance TM22 vs. metered total	-72%	1%		

TABLE 4.8: TM22 Detailed assessment - Energy demand by end-use

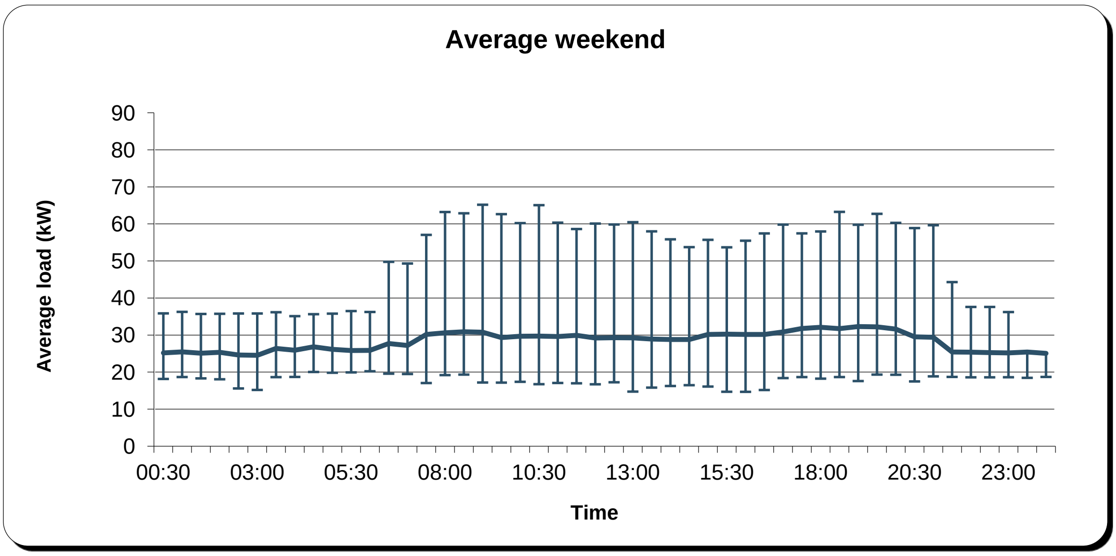
4.5.2 TM22 issues

A number of issues with the TM22 assessment were identified. Some of these, such as the difficulty in accounting for a combination of electrical and fossil fuel heating, are due to the design of the spreadsheet and its methodology, which is primarily concerned with electrical loads. Others are due to the difficulty in obtaining accurate information and making appropriate assumptions about the input data. There are several ways the TM22 tool can be used so it is important to clarify from the outset the purpose of the exercise as this will determine the nature of the loads and load profiles entered against each sub-meter. The following use cases have been identified:

- Development of metering strategy



(A) Average weekday



(B) Average weekend

FIGURE 4.17: TM22 Half-hourly electrical load profiles

- Development of design energy use estimates (for comparing against in-use)
- Comparison of in-use against design estimates
- Development of baseline consumption (for assessing impact of changes)
- Benchmarking actual consumption
- Identifying specific problem areas

The tool could be very useful when used in conjunction with designers at an early stage to develop an appropriate metering strategy and to ensure realistic assessment of the building's regulated (and possibly unregulated) load breakdown, provided sufficient information about the building's likely usage is available. In these cases, metered data would not yet be available.

Once the building is operational it may be possible to compare its performance against design estimates. The validity of this comparison will depend on the level of detail present in the design estimates and whether the building is being used as intended. It is also worth bearing in mind that buildings can need up to two years for systems and operators to settle-in and allow energy consumption to stabilise (Cohen et al., 2001).

If the tool is being used to develop baseline consumption figures (for ongoing performance monitoring or the assessment of changes to equipment and operating patterns) the availability of design estimates is less important, however it is crucial that the installed loads and load profiles entered in the tool correspond closely to the actual usage. In this case, detailed schedules of the building's equipment and usage will be necessary. These can be obtained from a variety of sources including as-installed documentation (if this is accurate), building surveys, interviews, metered data and load profiles. This calibration process is not a trivial task as although adjustments to either load or profile can yield the same result both values must be correct. Only when an accurately calibrated model of the building's performance has been obtained can the impact of changes be usefully assessed.

The use of the TM22 as a benchmarking tool is simpler, requiring only the sub-metered energy consumption, however the energy consumption must be broken down into the appropriate end use categories. A good sub-metering strategy will make this much easier, reducing the need for assumptions and guesstimates. Although an accurate breakdown of actual consumption is important, the calculated consumption is not necessary for a simple benchmarking exercise.

The tool could also be used to identify problem areas in more detail than provided by a simple benchmarking exercise. Here the actual consumption is reconciled against the calculated consumption to identify discrepancies at the sub-meter level. This is a more challenging task as it requires the installed loads and load profiles to accurately reflect the desired building operation rather than the actual operation (otherwise no discrepancies will be apparent). In a well managed building, with clearly defined loads and operating patterns it will be relatively straightforward, and discrepancies will identify potential problem areas such as inefficient services or unnecessary out-of-hours operation. When the building's loads are not clearly defined and operating patterns vary it is more difficult to determine the origins of the discrepancies. Uncertainties will be present in one or more of the rated power consumptions, load factors, operating profiles or usage factors.

Where small loads are used only occasionally, the equivalent continuous average load is practically insignificant in comparison to the uncertainty in the larger loads.

The presence of uncertainty reduces the value in the information that metered consumption differs from calculated consumption as it becomes harder to distinguish which is the 'wrong' value. For example, if the calculated values are 'right' (i.e. known to be accurate) then any discrepancy means the metered consumption must be 'wrong'. In this case 'wrong' could mean either the readings are incorrect or that there is a genuine difference in energy consumption, perhaps because the loads themselves have increased or are running for a longer period. On the other hand, if the actual loads are known accurately and correspond closely to the metered consumption any discrepancy would suggest that the calculated consumption is 'wrong'. This would imply that the design loads and/or the design load profiles are inaccurate.

In the case of inadequate design information and limited information on the actual installed loads and operating periods, there will be much uncertainty in the calculated consumption. If the metered consumption is believed to be fairly accurate, discrepancies could indicate problems with either the actual energy consumption or the calculated consumption or both, hence the possibility of getting the right answer (no apparent discrepancy) for the wrong reasons.

The usefulness of TM22 for developing baseline consumption models and identifying problem areas depends on the accuracy of the calculated consumption. This requires accurate data on loads and operating patterns, which may not be readily available. It is probably easier to use TM22 for design assessments, particularly if the metering strategy is specifically developed to current best practice standards with TM22 assessment in mind. The application of the TM22 to the case study building was made easier by the work carried out in conjunction with the bespoke energy analysis described earlier. In particular, benchmarking by end-use should be a fairly straightforward process; however, the building's sub-metering strategy made it necessary to make assumptions regarding the disaggregation of certain end-uses.

4.6 Discussion

There is a clear discrepancy between the building's design and operational energy consumption. There are many factors that contribute to this discrepancy however they can be considered in terms of two principal issues. The first issue relates to the nature of the design estimate of energy consumption which, in common with many buildings, is derived from the building's compliance modelling. As this modelling makes no attempt to account for unregulated energy use it is not surprising that the design figures underestimate operational energy consumption in the presence of significant external lighting loads and an all-electric kitchen. These differences clearly invalidate direct comparisons between figures from compliance modelling and energy monitoring. Nevertheless, such comparisons are often attempted (CarbonBuzz, 2014). Even if unregulated energy uses are excluded, the operational figures are still twice as large as the design model figures. This is partly due to modelling assumptions about the performance of building services plant such as the exhaust air heat pump, which was modelled with a COP of 5.4 and assumed to be the sole source of heat to the incubator offices. It is also due to the use of standardised occupancy and load densities in the compliance methodology and unanticipated factors such as continuous operating of the heating system, use of the auditorium AHU and poor control of lighting in communal areas. To address these issues both greater realism in design energy estimates and diligence in building energy management are necessary. Factors relating to variations in heating and domestic hot water sub-system performance are investigated in more detail in Chapters 5 and 6 respectively. Due to maintenance and communication issues it was not possible to determine exactly what and when changes were made to the system during the case study period. Since these changes may have had the potential to affect system efficiency and energy consumption a further question considered is whether it is possible to infer operational changes from building monitoring data.

The TM22 methodology provides a standardised and relatively simple means to assess a building's energy performance. The effectiveness of its approach to disaggregating in-use loads depends on the ability of its user to accurately estimate the magnitude and operating duration of load items. In practice this is often difficult due to lack of information about the building's systems and operating patterns. This uncertainty will reduce the accuracy of the end-use breakdowns and could result in inappropriate conclusions being made about the building's performance. The need for disaggregation techniques could be reduced by better end-use sub-metering. In new buildings this could be addressed by clarification and more effective enforcement of the requirement in Building Regulations Part L for sub-metering that enables at least 90% of estimated annual energy consumption of each fuel to be assigned to specific end-use categories (HM Government, 2010). In existing building however it may not be possible to increase the level of sub-metering. In either case, the TM22 methodology could benefit from the ability to account for uncertainty in its input data. An adaptation of the TM22 methodology that allows a probabilistic treatment of uncertainty is developed in Chapter 7.

4.7 Conclusions

The case study building's monitored carbon emission intensity ($52.4\,\mathrm{kgCO_2/m^2{\cdot}yr}$) is over three times larger than the design figure ($15.2\,\mathrm{kgCO_2/m^2{\cdot}yr}$). This discrepancy is partly due to the absence of unregulated loads in the design figure; however, subtracting unregulated loads gives a figure of $32.4\,\mathrm{kgCO_2/m^2{\cdot}yr}$, a fairer comparison but still more than twice the design figure. The review of energy performance at the whole-building level revealed the following broad areas of risk relating to this discrepancy.

- Performance targets
- Energy modelling
- Operating patterns

A lack of clarity regarding the brief's performance targets is evident from the difference between the energy consumption estimates prepared at concept stage and design stage. At concept stage, the target appears to have been interpreted as an operational energy consumption target, while at design stage the target was interpreted as a building regulations compliance target. Although the former represents a much more stringent target, an industry-wide adoption of operational energy targets would address a significant cause of apparent performance gaps and potentially reduce risks associated with energy performance contracts.

The level of detail in the energy modelling is a closely related issue. Industry standard compliance calculations omit unregulated loads and assume a number of standardised operating conditions, which do not necessarily correspond to the actual use of the building. In fact, it may not be possible to predict certain operating patterns. For example, the observed variation in plant operation was a result of maintenance issues and user behaviour as a consequence of poor reliability.

The TM22 methodology was found to be capable of benchmarking sub-system energy performance however its usability and usefulness is dependent on the accuracy of its input data.

Chapter 5

Sub-System Performance (Space Heating)

5.1 Introduction

This chapter considers the energy performance of the building's space heating sub-system. In this context space heating refers to the combination of gas boiler and exhaust air heat pump supplying heat to the buffer vessel that serves the building's radiators and underfloor heating. The chapter begins by considering performance in terms of annual energy use intensity benchmarks, rules of thumb for estimating heating loads and the calculation of energy consumption estimates. The system operating patterns are then identified and related to trends in the analysis of monitored energy consumption. The temperature dependency of energy consumption is also investigated and an attempt is made to ascertain the effect of changes to system settings. Finally, the efficiency of the exhaust air heat pump, as determined by a short period of temporary monitoring, is discussed.

5.2 Performance Estimates

This section considers space heating energy benchmarks, design estimates of heating load, and modelled estimates of energy consumption.

5.2.1 Energy benchmarks

Energy Consumption Guide 19: Energy use in offices (Action Energy, 2003) provides whole-building benchmarks for the energy consumption per unit treated floor area of principal end-uses. These benchmarks are still widely used despite their age. The heating and hot water energy benchmarks for good practice and typical naturally ventilated buildings are 79 kWh/m^2·yr and 151 kWh/m^2·yr respectively. Benchmarks for domestic hot water energy consumption for hand washing and catering are 12 kWh/m^2.yr good practice and 20 kWh/m^2·yr typical. These figures can be subtracted to obtain space heating benchmarks of 67 kWh/m^2·yr good practice and 131 kWh/m^2·yr typical. CIBSE Guide F (CIBSE, 2012) also provides similar space heating benchmarks of 72 kWh/m^2·yr good practice and 141 kWh/m^2·yr typical. The good practice benchmark is intended to be used as an upper limit for new buildings, while the typical benchmark represents a maximum for buildings of any age.

5.2.2 Heating load estimates

Design estimates of heating load can be compared with benchmarks and figures from similar buildings. The space heating benchmarks provided by CIBSE Guide F include figures for estimating installed heat generation capacity. For naturally ventilated offices the good practice figure is 80 W/m^2 (CIBSE, 2012). Guide F also provides figures for heating loads; for offices the figure is 70 W/m^2. These heating loads are reproduced from a series of BSRIA Rules of Thumb, which date back to at least 1995 (BSRIA, 1995). Despite the age of these benchmarks, they appear to remain relevant. For example, two relatively recently constructed and award winning buildings (Heelis, the National Trust head office in Swindon (BSRIA, 2007a) and The Hive, a library in Worcester (Pearson, 2013)) both have an installed heating capacity of about 100 W/m^2.

Based on the case study building's gross internal area of 4024 m^2 its installed heating capacity is only 24 W/m^2. The actual heated area, i.e. the total internal area of rooms provided with heat emitters served by the boiler and heat-pump system, is 2475 m^2. The difference is due to the presence of the unheated street and the auditorium, which is heated by its own self-contained air handling unit, and small rooms, such as cleaners' cupboards, that are not directly heated. These areas are covered by the definition of gross internal area (GIA), also known as total usable floor area (TUFA), and as they are conditioned spaces, are included in the floor area used for energy calculations (DCLG,

	Elizabeth Fry	**Case Study**
	Fabric U-Value (W/m^2·K)	
Wall	0.2	0.17
Floor	0.16	0.21
Roof	0.13	0.10
Glazing	1.3	1.76

TABLE 5.1: Comparison of fabric thermal performance

2008). Since different definitions of internal area can lead to large differences in energy use intensity, all floor areas in this research are expressed in terms of GIA.

Design heat loss figures were obtained from the building's mechanical and electrical services contractor however they were early-stage calculations, prepared before the building's design was finalised. After removing from the calculation zones that are actually unheated, the heat loss at a design ambient temperature of -4 °C is approximately 76 kW, or 19 W/m^2. Checking the design infiltration heat loss figures against room volumes reveals that an infiltration rate of 0.8 air changes per hour (ac/h) was used. Since the building actually achieved a post-construction air permeability of 5.5 m^3/m^2·hr @ 50 Pa, the peak infiltration rate is likely to be substantially less than 0.8 ac/h. Based on figures in CIBSE Guide A, which provides empirical values for air infiltration rates for buildings of different air permeability (CIBSE, 2006a), the design infiltration heat loss was recalculated with an infiltration rate of 0.2 ac/h. An updated design heat loss calculation accounting for unheated spaces, the reduced infiltration rate, and as-built information obtained from the building's O&M documents showed a steady-state heat loss of 38 kW at design conditions.

By comparison, the Elizabeth Fry building at the University of East Anglia has a gross internal area of 3250 m^2 and is heated by three 24 kW gas boilers, which corresponds to an installed heating capacity of approximately 25 W/m^2. The building's design heat loss was 45 kW (Bunn, 1995), which corresponds to a heating load of approximately 14 W/m^2. Table 5.1 compares the area weighted U-values of the Elizabeth Fry building with the case study building. The figures are generally similar, although the Elizabeth Fry glazing has a slightly lower U-value than the case study building. Its post-construction air permeability of 4.2 m^3/m^2·hr @ 50 Pa (Standeven et al., 1998) is also slightly lower than the case study building. This comparison suggests that the case study building has a lower margin between design heat loss and installed heating capacity than the Elizabeth Fry building.

5.2.3 Energy consumption estimates

Space heating was found to be the largest source of discrepancy between modelled and monitored energy consumption. Energy consumed by space heating is covered by the energy efficiency requirements of the Building Regulations (HM Government, 2010); it is a regulated energy use. Regulatory compliance may be demonstrated by meeting the whole-building carbon emission target and the minimum performance standards set out in the Non-Domestic Building Services Compliance Guide (DCLG, 2010a). This specifies minimum efficiencies for a variety of heat sources including gas boilers and heat pump systems. The whole-building carbon emissions are calculated using performance assessment tools based on the National Calculation Methodology (NCM) such as SBEM, IES-VE and Tas.

IES-VE and Tas are both dynamic models; IES-VE uses a finite-difference approach to model building heat transfer processes (IES, 2009) while Tas uses the response factor method (EDSL, 2001). Both approaches account for time-varying heat flow and thermal storage within the building fabric to calculate the thermal demand in each zone at discrete, usually hourly, time steps. Specific details of the calculation methods used to determine the building's overall fuel energy demand are not publicly available. Both tools have been accredited for use in demonstrating regulatory compliance and generating non-domestic EPCs. The accreditation process involves first testing the robustness of the software's calculation algorithms against CIBSE TM33: Tests for Software Accreditation and Verification (CIBSE, 2006c). These tests relate to properties such as annual heating and cooling loads, solar gain and overheating risk. Following these tests, a series of enhanced test models are used to verify that the software complies with the requirements of the NCM (Raslan and Davies, 2010). Details of these enhanced tests are not published, so it is not possible to determine how rigorously they evaluate the ability of the model to calculate annual energy demand from the building's thermal heating load. The variation in results identified by Schwartz and Raslan (2013) suggests that the accreditation process cannot guarantee consistency between tools.

Table 5.2 compares modelled and monitored annual heating energy use intensity. The compliance model was created by a consultant to the main contractor in order to demonstrate compliance with Building Regulations and to generate the building's on-construction EPC. The alternative model was created to verify the compliance model and is described in Appendix D. Figure 5.1 shows the monthly variation in modelled and monitored heating energy use intensity. Months from the monitoring period have been re-ordered to align with the model results. The modelled figures have been adjusted for variation in annual degree days, allowing a fairer comparison with the monitored figures. The energy use intensity figures combine both electricity and gas consumption. Ideally they should be converted to a metric that permits a fair comparison of the two fuel types, such as primary energy or equivalent CO_2 emissions. This was not possible as the disaggregated model output does not distinguish between fuel types.

Data	**Compliance Model (IES)**	**Alternative Model (Tas)**	**Monitored**
Energy Use Intensity (kWh/m^2·yr)	12.0	11.2	43.8
% of Monitored	27%	26%	100%

Table 5.2: Comparison of modelled and monitored data

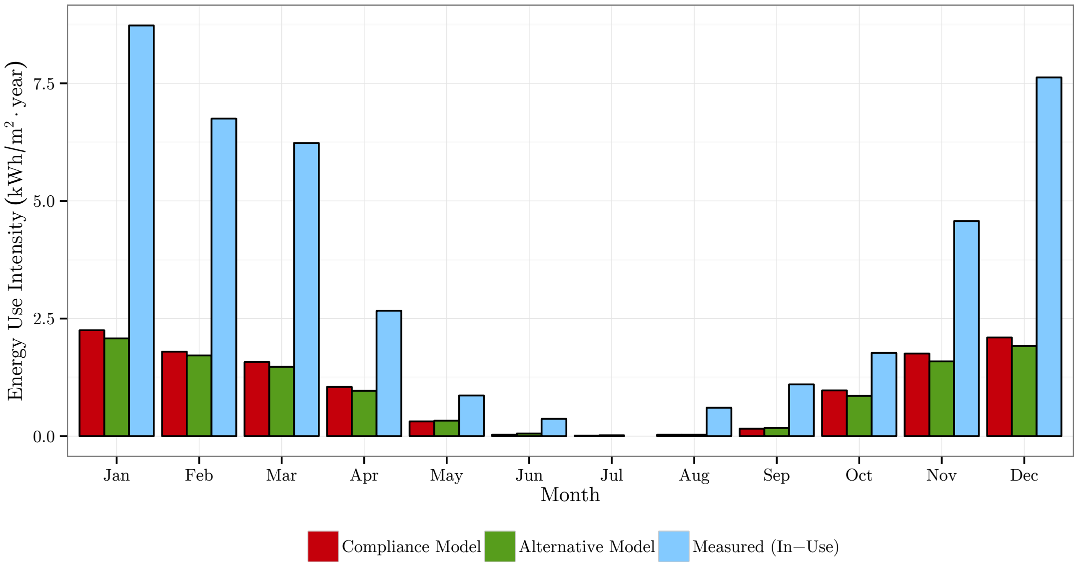


Figure 5.1: Monthly comparison of modelled and monitored data

There is a significant difference between the model estimates of heating energy consumption and the actual monitored consumption. However despite being much higher than the model estimates, the monitored consumption is still lower than the best practice space heating benchmark. The failure of the EAHP during the winter and the decision to run the heating system continuously both contributed to the high monitored consumption. These technical problems are described in detail in Appendix E.

5.3 Operating Patterns

The operating pattern of the space heating system is more complex than that of the domestic hot water system, which operates according to a simple time schedule. The operation of the space heating system is affected by the action of the optimum start-stop controller and an ambient temperature limit, above which the heating system is disabled. As a result, it was necessary to infer the operating pattern from the monitoring data. The most robust indication was found to be the temperature difference of the primary heating water supplied to the buffer vessel. System operation was inferred when the primary flow temperature exceeded the primary return temperature by more than 1 K. Similar logic was used to infer operation of boiler and heat-pump. Because of greater variation in flow temperatures a higher threshold of 2 K was used.

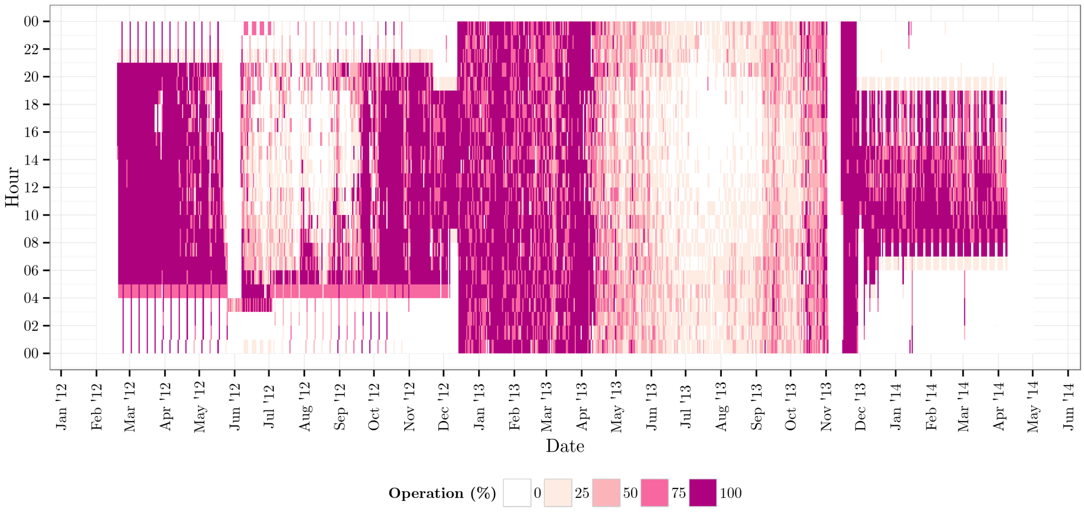


Figure 5.2: Space heating operating pattern

Figures 5.2, 5.3 and 5.4 illustrate the space heating, boiler and heat-pump operating patterns during the monitoring period. The colour scale represents the hourly percentage of 15-minute intervals each system was operating. Temperature data used to infer operation was available from mid February 2012. The space heating operating pattern shows three main operating regimes with different start and stop times. There are also several shorter periods of anomalous operation including two where the heating failed completely. The boiler operating pattern corresponds to the overall heating operating pattern, but with negligible operation during the summer and much of the mid-season. The heat-pump operating pattern shows periods of several months in both winters during which the heat-pump was not operating. Table 5.3 lists the main changes to the heating

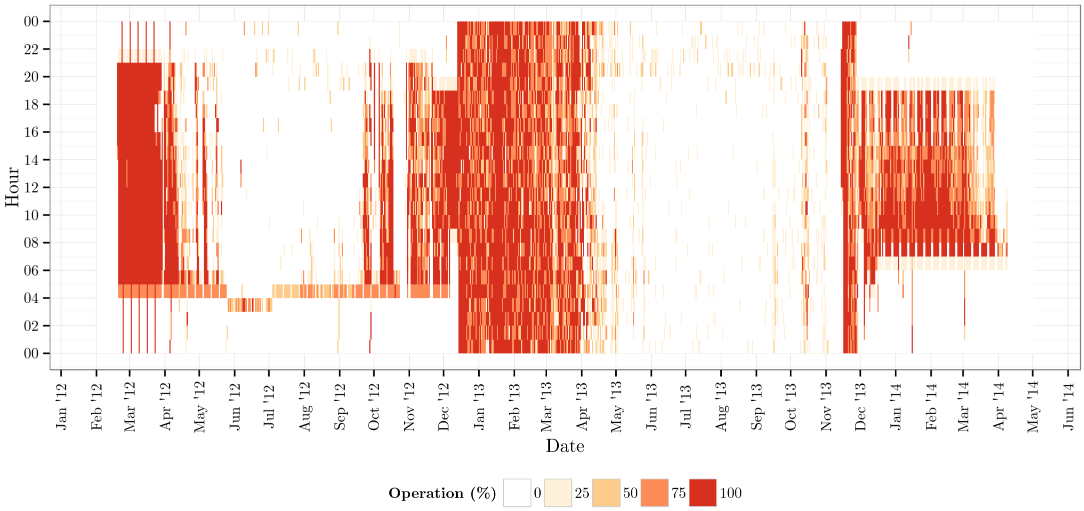


Figure 5.3: Boiler operating pattern

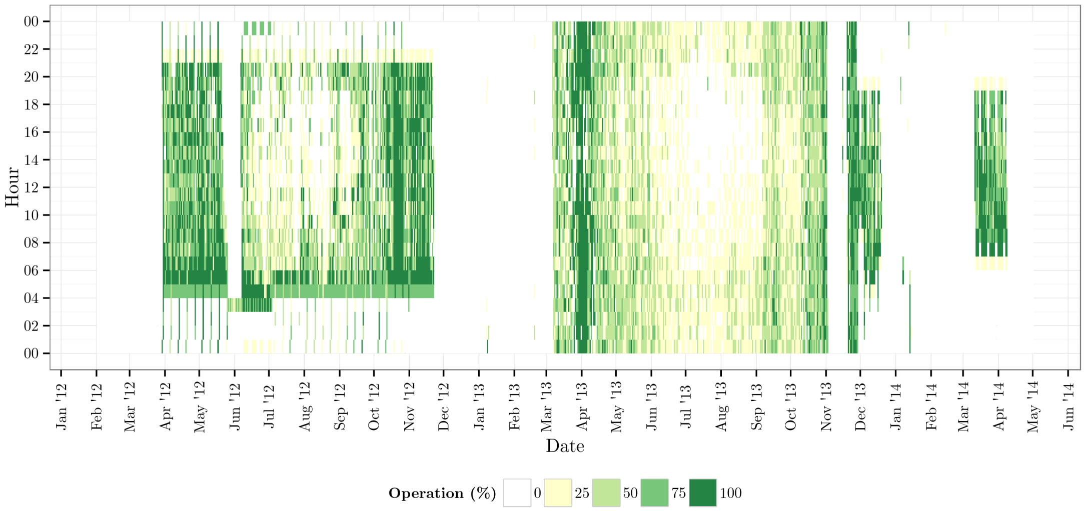


Figure 5.4: EAHP operating pattern

system's operating pattern. Other variations to system operation include adjustments to the boiler flow temperature and the compensated heating flow temperature. Together with the changes in operating pattern, these variations in system operation complicate the evaluation of sub-system performance.

Date	**Event Description**
2012-02-20	Operating period 04:00–21:00, overnight on Thursdays
2012-05-22	Heating virtually disabled by BMS adjustment
2012-06-07	Operation restored
2012-11-23	Heat-pump offline
2012-12-05	Heating failing to start automatically
2012-12-14	Heating set to continuous operation
2013-03-06	Heat-pump operation restored
2013-04-17	Primary circulation pump speed reset
2013-11-02	Heating failed due to boiler leak
2013-11-15	Heating restored (continuous operation)
2013-11-29	Beginning of trial adjustments to operating period
2013-12-19	Heat-pump offline
2013-12-20	Operating period now 06:30–19:00 M–F, 08:30–15:00 W/E
2014-03-11	Heat-pump operation restored

Table 5.3: Heating system operation changes

5.4 Analysis of Monitored Data

This section presents an analysis of data collected by the space heating sub-system monitoring described in Section 3.6.

5.4.1 Daily energy consumption trends

Figure 5.5 shows the variation in the heating system's daily primary energy consumption during the monitoring period. The heating boiler's gas consumption was not metered directly but obtained by subtracting the domestic hot water boiler's gas consumption from the consumption recorded by the main gas sub-meter. The boiler's electricity consumption, and the electricity consumption of auxiliary equipment such as control equipment and pumps was not included in this analysis. The electricity consumption of the exhaust air-source heat pump (EAHP) is measured by a dedicated sub-meter and includes all the equipment within the EAHP enclosure (compressor, exhaust air fan and control circuit). The heating gas and EAHP electricity consumption figures were multiplied by the primary energy factors for gas and electricity respectively.

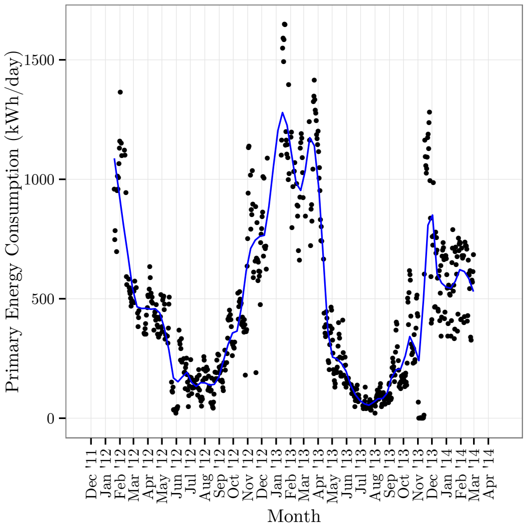


FIGURE 5.5: Daily primary energy consumption

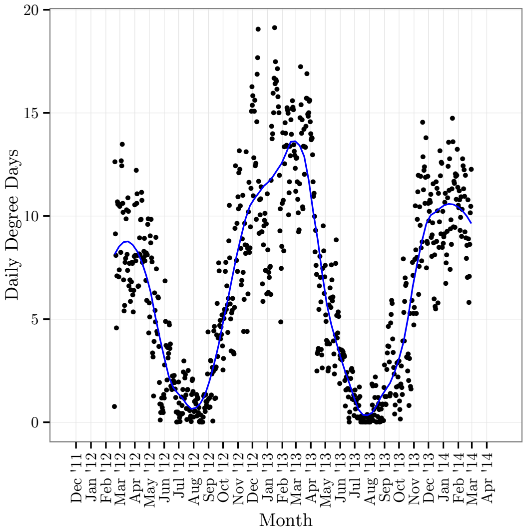


FIGURE 5.6: Daily degree days

The data shows an overall seasonal trend with much day-to-day variation. There are some periods of missing data, caused by interruptions to the monitoring system and a period where the pulse counter on one of the gas meters was dislodged during maintenance work. The need to maintain occupant comfort despite operational problems and equipment failures meant that adjustments to operating patterns and control strategy were made during the monitoring period. Some of these adjustments were made simultaneously and not all of the adjustments were documented by operation and maintenance staff, making it difficult to identify the impact of individual measures.

Energy use may be compared against degree days to provide a rough indication of temperature dependency. Degree days provide a measure of the severity and duration of outdoor temperatures. They are calculated as the summation over time of differences between ambient temperature and a specified base temperature (Carbon Trust, 2012). Although degree days can be calculated for both cooling and heating conditions, the term is used here to refer to heating degree days. The base temperature for heating degree days is defined as the ambient temperature below which the building will require heat input from its heating system. At temperatures between the base temperature and the desired indoor temperature, it is assumed that casual heat gains provide the necessary heat input. In the UK, the standard base temperature is 15.5 °C. This figure was developed in the 1930s based on a typical indoor temperature of 65 °F, and the assumption that casual heat gains provide a 5 °F rise in internal temperature (Day, 2006).

Figure 5.6 shows daily degree days calculated from BMS measurements of ambient temperature; it is evident from the plot that winter 2013 was milder than the previous winter. This may partly explain the difference in energy consumption between the two winters. Operational factors are also likely to have contributed. For example, the heating operation schedule was changed from continuous (24/7) operation to scheduled operation in December 2013. Other than a period in November 2013, when the heating system failed completely, it is interesting to note that the daily consumption remains above zero for virtually the whole monitoring period; the heating evidently continues to operate during the summer months. Compared with summer 2012 however, summer 2013 shows a reduction in daily variation. This is due to a lower variation in daily degree days, and also may be due to adjustments made to control settings in response to problems with the heating system.

Figure 5.7 shows the relationship between primary energy consumption and daily degree days. The plot also indicates the heating system's operating mode: boiler-only, EAHP and boiler and EAHP-only. Operating mode was inferred from the daily EAHP electricity and heating gas consumption. If the EAHP's electricity consumption was greater than 0.5 kWh it was deemed to be operating. Similarly, if the heating boiler's gas consumption was greater than 2.5 kWh it was deemed to be operating. The majority of boiler only-points correspond to the two winter periods where the EAHP failed to operate. The EAHP-only points occur during milder weather when the building's heating load is low enough that the boiler is not required.

The plot clearly shows a great deal of scatter, particularly in colder conditions, which suggests that the heating system becomes less weather dependant as load increases. The analysis is complicated by the operational problems and presence of different operating periods; however a number of other factors could contribute to the scatter. These include control issues, such as the size of the hysteresis band (the temperature difference between the controller's on-signal and its off-signal), occupant behaviour, such as the manual use of natural ventilation system, or high internal gains (Carbon Trust, 2012). Because of these issues, the standard base temperature of 15.5 °C will not necessarily correspond to the building's specific base temperature. Although the regression line is not a particularly good fit, the positive intercept suggests that the space heating continues to consume energy at ambient temperatures above 15.5 °C. This implies that the building's specific base temperature is, on average, higher than the standard base temperature.

Figure 5.8 shows the relationship between primary energy consumption and daily mean ambient temperature. This is known as the energy signature of a building's heating system

(Levermore and Chong, 1989). In buildings with clearly identifiable base temperatures the distribution of points will become horizontal when the mean ambient temperature ceases to influence heating energy consumption. This levelling-off is not evident in the case study building's energy signature; heating energy consumption continues even up to quite warm conditions, suggesting poor control or wasteful operation. The relationship between heating energy consumption and ambient temperature also appears to be somewhat non-linear.

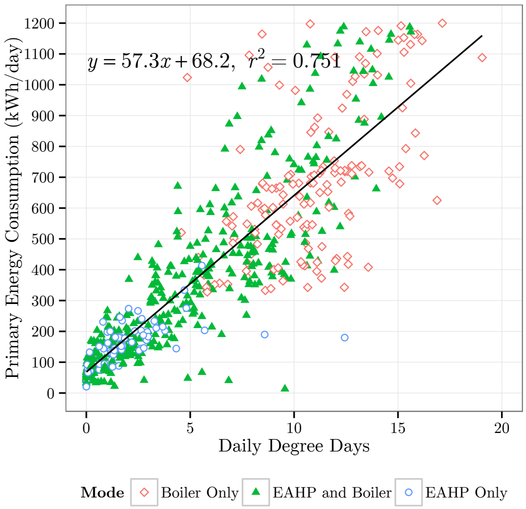


FIGURE 5.7: Daily primary energy consumption per degree day

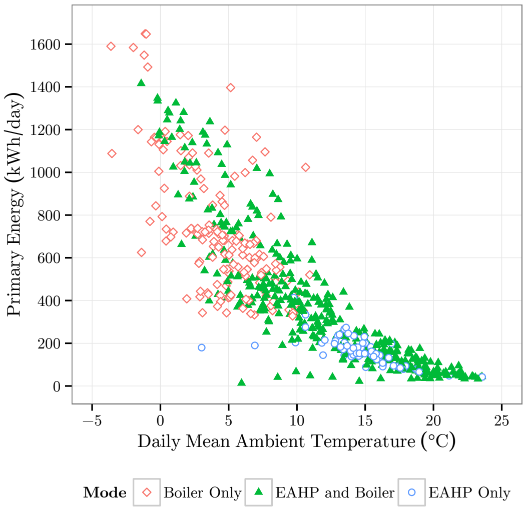


FIGURE 5.8: Primary energy consumption vs. ambient temperature

The reasons for the observed relationship between heating energy consumption and ambient temperature become more apparent when the energy consumption of the boiler and EAHP are considered separately. Figure 5.9 shows the heating gas consumption as a function of ambient temperature. A horizontal region occurs when the temperature exceeds about 13 °C; above this temperature the boiler hardly operates. Below this temperature the relationship between gas consumption and temperature is broadly linear but with much scatter. Figure 5.10 shows the corresponding relationship for the EAHP electricity consumption. This relationship is also broadly linear, but shows greater variation as temperature decreases. It is evident that the primary energy consumption in warm conditions is due to the EAHP. At lower temperatures, the increased scatter may be due to the increasing operation of the gas boiler, which causes rapid variation in flow temperatures that could affect the operation of the heat pump. It's also possible that operation of the natural ventilation openings, which occurs even in cold weather (to alleviate stuffiness), is affecting the operation of the heat pump by reducing the temperature of exhaust air. However this is impossible to verify without reliable monitoring of extract air temperatures.

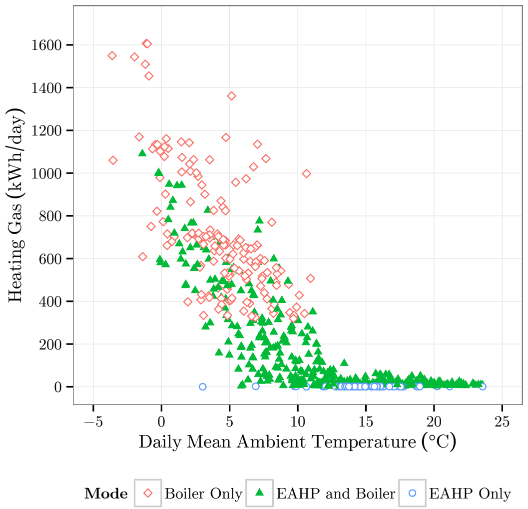


FIGURE 5.9: Heating gas consumption vs. ambient temperature

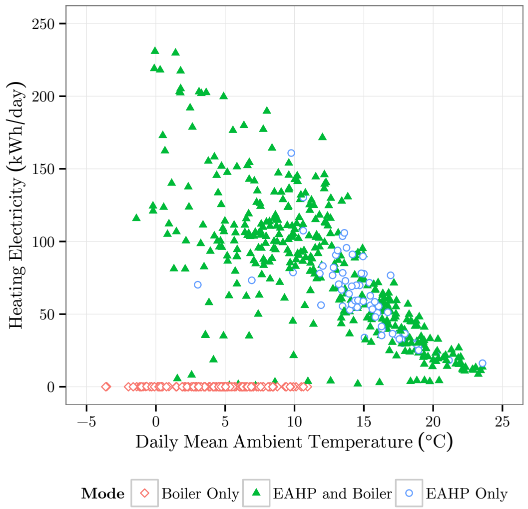


FIGURE 5.10: EAHP electricity consumption vs. ambient temperature

The use of monthly figures eliminates much of the variability due to day-to-day variations in conditions. A linear relationship between monthly energy consumption and monthly degree days, known as a performance line, is a widely used energy management technique (Day, 2006). In well controlled systems the residuals (i.e. the vertical scatter around the regression line) will be small, indicating a close relationship between the heating energy used and the number of degree days. Figures 5.11 and 5.12 show the performance lines for heating gas and electricity consumption. To correct for effect of months of different lengths, energy consumption and degree days are expressed in terms of each month's daily average. Months with average gas consumption of less than 50 kWh have been removed from the plot dataset, as these correspond largely to summer months where errors in obtaining heating gas consumption by difference between DHW gas consumption and overall gas consumption become significant.

The performance line's gradient reflects the temperature dependency of the heating energy consumption. The line's intercept relates to base-load energy consumption; a positive intercepts typically represent a non-temperature dependent base-load energy consumption. The validity of the base-load estimate depends on a correct estimation of degree day base temperature. Although the non-zero intercepts of the monthly performance lines shown could suggest a lack of temperature dependency, that are most likely to be due to mismatches in base temperature. The temperature at which the gas boiler ceases to

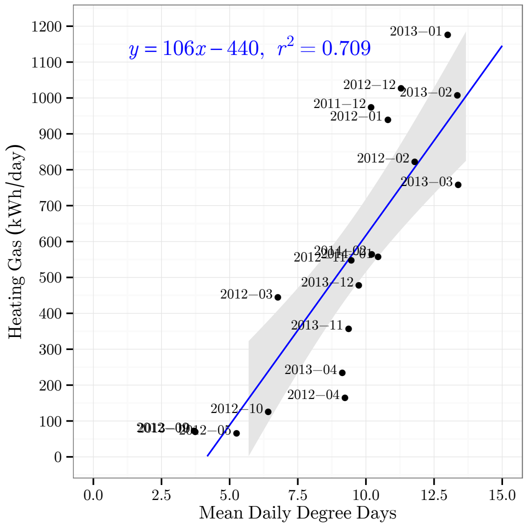


FIGURE 5.11: Monthly daily average heating gas consumption per degree day

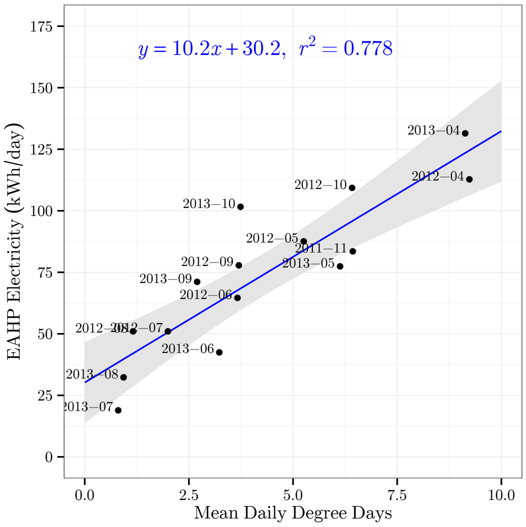


FIGURE 5.12: Monthly daily average EAHP electricity consumption per degree day

be required is below the standard base temperature of 15.5 °C, resulting in the negative intercept shown by the boiler's performance line. Conversely, the positive intercept shown by the EAHP's performance line is a consequence of the EAHP continuing to operate at ambient temperatures significantly higher than the standard base temperature. Because the boiler and EAHP have different temperature dependency relationships a single base temperature is not strictly appropriate; the boiler's consumption should be analysed with a lower base temperature and the EAHP's consumption with a higher base temperature. This would however make it difficult to compare the boiler's and EAHP's individual and combined energy consumption in terms of degree days. For the purposes of this analysis, the use of a single, standard, base temperature is sufficient. Since the EAHP is known to operate in warmer conditions, a base temperature of 18 °C was used.

5.4.2 Energy consumption distributions

The variation in system operation at different daily degree days is summarised using boxplots illustrating the median and interquartile range of daily primary energy consumption within 2.5 degree day bins. The data was restricted to the period following the pump speed change and has been filtered to exclude weekend operation, which would otherwise distort the distribution due to the change to a shorter weekend operating period in December 2013.

The data has been split into three figures according to operating mode; boiler only (Figure 5.13), EAHP only (Figure 5.15) and EAHP and boiler (Figure 5.17). The adjacent histograms (Figures 5.14, 5.16 and 5.18) illustrate the overall variation in daily primary energy per degree day.

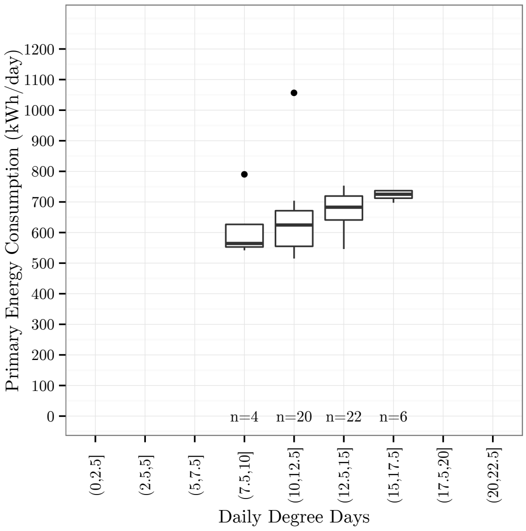


FIGURE 5.13: Primary energy consumption by degree day bin (boiler only)

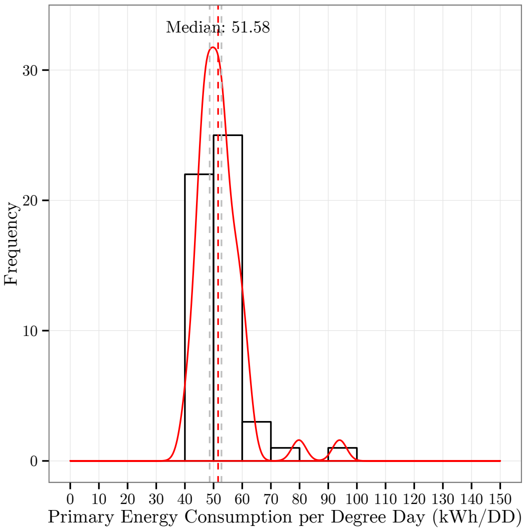


FIGURE 5.14: Distribution of daily primary energy consumption per degree day (boiler only)

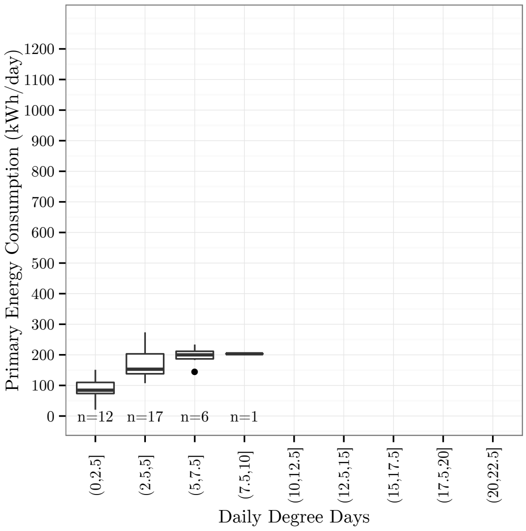


FIGURE 5.15: Primary energy consumption by degree day bin (heat pump only)

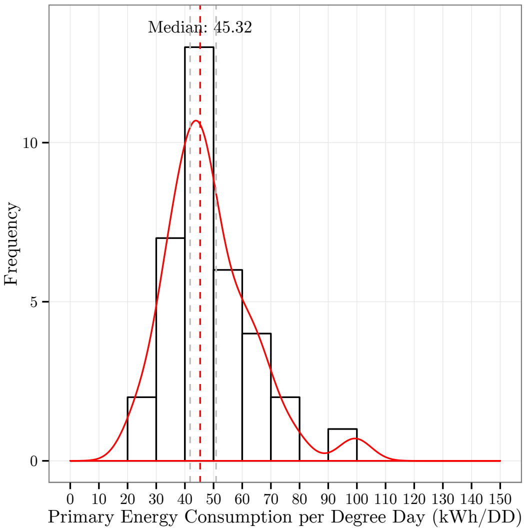


FIGURE 5.16: Distribution of daily primary energy consumption per degree day (heat pump only)

The boiler only operated on its own during colder conditions, corresponding to the periods in both winter 2012 and 2013 when the EAHP was out of service. With the

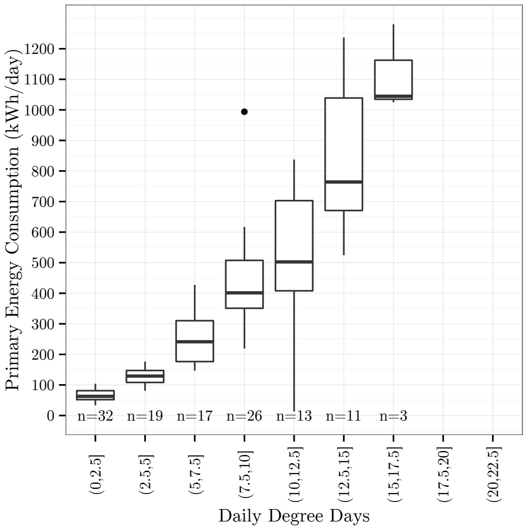


Figure 5.17: Primary energy consumption by degree day bin (boiler and heat pump)

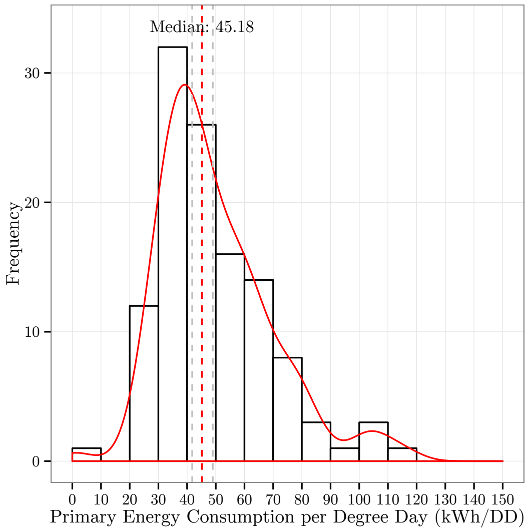


Figure 5.18: Distribution of daily primary energy consumption per degree day (boiler and heat pump)

exception of a few outliers, there was little spread in the boiler's binned primary energy consumption. There is correspondingly little spread in the histogram of daily primary energy consumption per degree day. The EAHP only operated on its own during warmer conditions, when its output alone was sufficient to maintain the heating flow temperature above its ambient temperature compensated set-point.

A comparison of the median primary energy consumption per degree day indicated on the histograms shows that the boiler operating independently consumes the most primary energy per degree day (51.6 kWh/DD). There was no significant difference between EAHP operation (45.3 kWh/DD) and combined operation (45.2 kWh/DD). The increase in spread when the EAHP is operating could reflect the fact that it is unable to modulate its output and is only controlled by a hysteresis band in the BMS control strategy. The boiler however is able to independently modulate its output according to flow and return temperature difference.

5.4.3 EAHP efficiency

Due to the problems with the EAHP heat meter discussed in Chapter 3, it was not possible to determine the actual efficiency of the EAHP throughout most of the monitoring period. The temporary monitoring discussed in Appendix C provided sufficient data to determine the EAHP efficiency for a short period on 9th April 2013. During this period, when the

EAHP was operating on its own, it achieved a measured COP of 2.1, based on measured heat input to the buffer vessel.

5.4.4 Changes to system settings

There were several changes made to the operation of the heating system that could affect the system's overall efficiency. The lack of reliable heat metering makes it impossible to estimate efficiency with any confidence. As a result, the following analysis discusses the effect of the changes in terms of the heating system's degree day normalised energy consumption, based on the assumption that the heating energy consumption is temperature dependent. The fact the building's heating energy signature (Figure 5.8) does not feature a horizontal region with significant energy consumption suggests that this is the case. A form of degree day normalisation (simply dividing the daily primary energy consumption by the daily degree days) has been used to attempt to remove the influence of ambient temperature from the heating energy consumption. This should make it possible to identify the impact of other variables. Figure 5.19 shows the relationship between normalised primary energy consumption and daily degree days. At degree days above one the relationship is reasonably flat, with scatter reflecting the variability in system operation. The relationship is not valid for degree days below one, as division will increase, rather than decrease, the result.

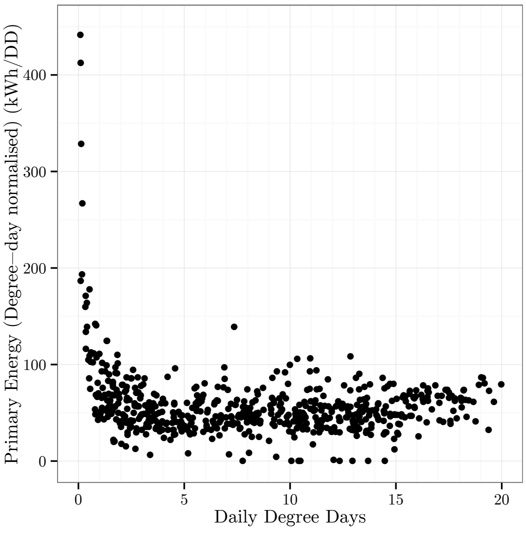


Figure 5.19: Energy consumption (degree day normalised) vs. daily degree days

The variable most likely to have a significant impact on energy consumption is the length of the daily operating period. Other variables could include the primary pump speed change, the failure of the EAHP, adjustments to boiler flow temperature limit, and changes to the temperature compensation settings. Disentangling the impact of these changes is complicated because many of them overlap in time. For example, the pump speed change occurred in spring 2013, during the period of continuous operation. As a result, its effects will be masked by the combination of seasonal variation and changes to and from scheduled operation. The heat pump has also never operated during the winter period of peak heating demand, so a comparison of system performance with and without the EAHP operating would be confounded by the difference in overall heating demand.

Operating period

Figure 5.20 illustrates the effect of operating period on normalised daily energy consumption (at daily degree days of one or more). The variability of the normalised energy consumption appears to decrease over time. This is partly a result of variation in the data collection periods; the period after continuous operation was shorter and only included the first four months of 2014. The reduction in variability may also be due to improvements in system control that took place towards the end of 2013. The period before and during continuous operation were of similar duration. There is hardly any difference in normalised energy consumption between these periods. Although the normalised energy consumption is slightly lower after the period of continuous operation there appears to be no significant difference between the normalised energy consumption in any of the three periods.

Pump speed

Figure 5.21 compares normalised daily energy consumption before and after the primary circulation pump speed was reset. Since this change occurred during the period of continuous operation the factors affecting consumption before and after continuous operation could also be responsible for the difference in consumption before and after the pump speed change.

EAHP operation

The EAHP failed for two extended periods during the monitoring. These failures, which resulted in boiler-only operation, occurred during the period of peak winter demand. Figure 5.22 shows the difference in terms of overall normalised primary energy

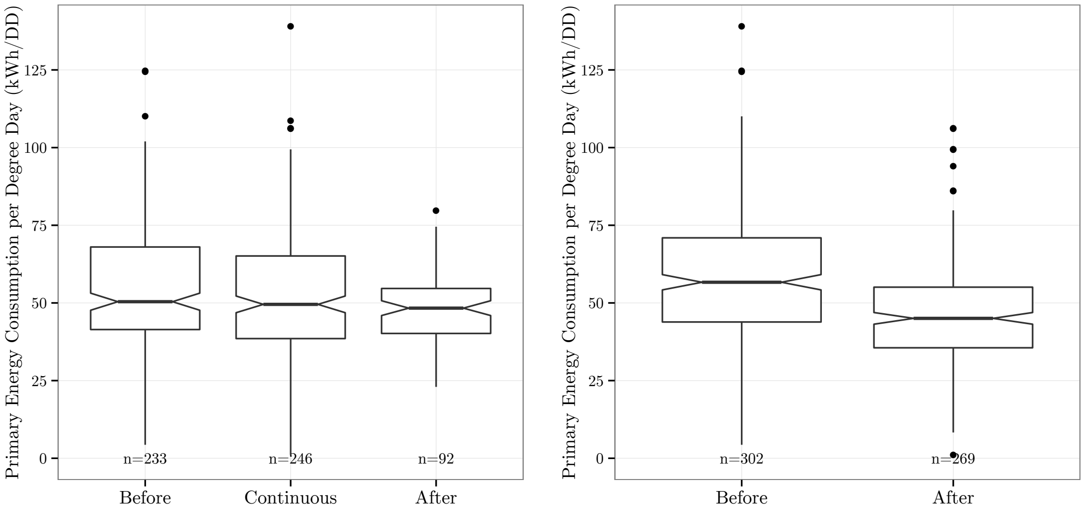


FIGURE 5.20: Energy consumption (degree day normalised) with respect to operating period

FIGURE 5.21: Energy consumption (degree day normalised) with respect to pump speed change

consumption. The boiler's capacity is much greater than that of the EAHP so its energy consumption is also much higher, even during periods when the EAHP is running. As a result, the failure of the EAHP does not have a significant effect on the normalised energy consumption.

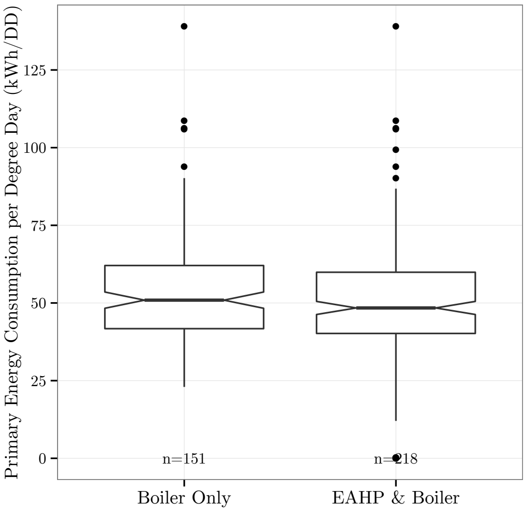


FIGURE 5.22: Energy consumption (degree day normalised) with respect to EAHP operation

Boiler flow temperatures

Figure 5.23 shows the adjustments to maximum boiler flow temperature. The boiler flow temperature limit was increased to 80 °C shortly before the switch to continuous operation. The limit remained at 80 °C for the majority of the period of continuous operation. As a result of this overlap it is not possible to isolate the effect of boiler flow temperature from the effect of the operation period.

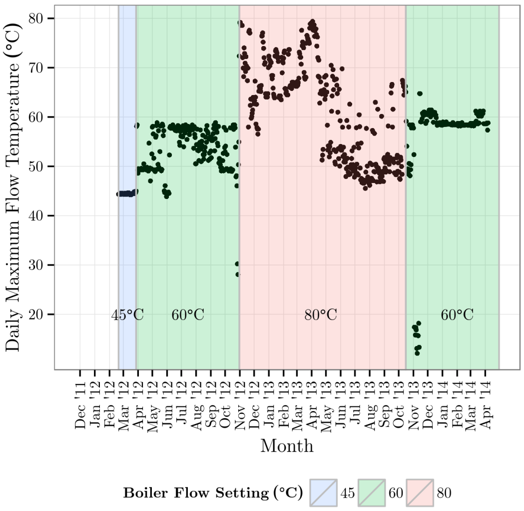


FIGURE 5.23: Boiler flow temperatures

Temperature compensation settings

The target heating flow temperature is compensated according to ambient temperature; as ambient temperature increases so the target flow temperature decreases. The relationship is linear between pre-set target flow temperatures at 0 °C and 20 °C ambient. These settings were changed several times during the monitoring period, as shown by Figure 5.24. There are six clearly identifiable linear relationships, corresponding to the compensated flow temperature settings shown in Table 5.4.

The adjustments to the temperature compensation settings were made during a relatively short period of time, which corresponded to the period of continuous operation with the EAHP offline. The adjustments were made progressively to test whether they affected the heating system's ability to maintain internal temperatures however there are insufficient data points to investigate the effect on energy consumption.

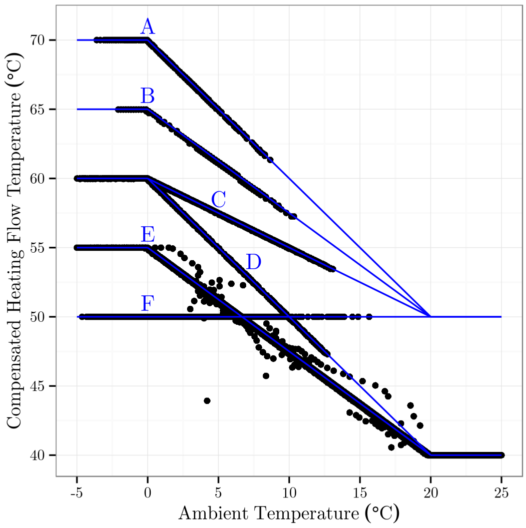


Figure 5.24: Temperature compensation relationships

Dates	$\mathbf{t_0}$	$\mathbf{t_{20}}$	**Label**
– 2012-11-22	60	50	C
2012-11-22 – 2012-12-06	60	40	D
2012-12-06 – 2012-12-11	70	50	A
2012-12-11 – 2012-12-13	60	50	C
2012-12-13 – 2012-12-21	65	50	B
2012-12-21 – 2013-02-13	60	50	C
2013-02-13 – 2013-03-06	50	50	F
2013-03-06 –	55	40	E

Table 5.4: Temperature compensation settings

5.5 Discussion

This chapter has investigated the energy performance of the case study building's space heating sub-system. The installed heating capacity is comparable to the Elizabeth Fry building, which was used as an exemplar by the design team. Interestingly it is less than the heating capacity in two other award winning buildings that were more recently constructed. This could be the result of more generous safety margins or to the inclusion of reserve capacity and DHW generation. The building's heating energy consumption is less than the good practice benchmark but significantly higher than the modelled estimate. The discrepancy would tend to suggest that the modelled estimate, at about 13% of the benchmark, was over optimistic. This is partly a result of the model assumption that the EAHP would be the only heat source serving the office units. In reality, due to the heating control strategy, the EAHP rarely operates as the sole heat source. The brief period of heat monitoring also suggests that the assumed seasonal COP of 5.4 is unlikely to be achieved in reality.

The heating energy consumption does not show a close temperature dependency; there is a great deal of scatter in both the daily degree day and ambient temperature relationships. This is partly due to variability in operating conditions and user behaviour. The temperature in each incubator unit is controlled locally by TRVs and will depend on the level of internal gains and the use of ventilation openings, which can be operated throughout the year (including during the heating season). The degree day relationships are complicated by the difference in appropriate base temperature for the boiler and the EAHP. The temperature dependency is also affected by the difference in operating characteristics between the two heat sources. The boiler is able to modulate its output according to flow and return temperature difference. The EAHP has much less ability to vary its output and its energy consumption will therefore be less temperature dependent.

Some of the fixes and adjustments made as a result of heating system failures and reliability problems are likely to have contributed to the discrepancy between modelled estimate and monitored consumption. For example, the model could not have anticipated the change to continuous operation. Because the case study building was occupied it was not possible to carry out controlled experiments to evaluate the effect of these changes, which could potentially affect the stability of internal comfort conditions. Furthermore some of the interventions carried out by building maintenance staff in response to problems were not documented so it was not possible to conclusively ascertain the effect of other changes such as pump speed and flow temperatures from the logging data. The study was useful from the point of view of understanding the issues that affect new buildings but did not provide a sufficient period of stable operating conditions to assess the performance and efficiency of the heating sub-system. This is more likely to be achieved in buildings that have had a longer period to settle into reliable operation.

Despite these issues, as well as the the limitations in measurement and calculation accuracy described in Appendix C, the results point towards the influence of specific factors and sub-system interaction on overall heating system performance. Heating energy consumption and its temperature dependency was found to vary due to interactions between the two heat sources. The effect of changes to system settings is difficult to ascertain due to the overlapping and ad-hoc nature of the changes made in response to system failures.

The results also provide a practical demonstration of the possibility of using typically available monitoring data (such as from the existing BMS and sub-metering installation) to make diagnostic inferences about a building's sub-system performance. The temporal raster plots (Figures 5.2, 5.3 and 5.4) of operating pattern make it possible to identify at a glance changes throughout the year such as system failures, changes to daily and weekly operating period, and the percentage hourly operation. Although in this analysis they were used to visualise duration of operation they could be used to visualise a range of other variables relating to building performance.

There is little research into the as-built fabric performance of non-domestic buildings, due partly to the diversity of building types and constructions. There are, however, some well-publicised investigations of domestic fabric performance. Bell et al. (2010) discuss the results of a study carried out at Elm Tree Mews, which found that measured whole house heat loss was 54% greater than predicted. This finding is supported by experimental research carried out by White (2014) into the effect of fabric performance on household energy consumption, which found that inaccurate calculation at the design-stage and poor attention to detail during construction could cause fabric under-performance of up to 50%.

Although the fabric performance of the case study building may have a significant influence on its heat demand, a rigorous investigation of fabric performance was outside the scope of the technical evaluation, which focussed on the performance of specific energy sub-systems. The post-completion air-tightness test results suggest that the integrity of the building's envelope is satisfactory. An exterior thermographic survey of the building envelope carried out during the research did not reveal any obvious defects, however the use of rain-screen cladding on a substantial proportion of the building limited its diagnostic value. It was not possible to obtain sufficient images for an interior thermographic survey due to difficulties in obtaining permission for unsupervised out-of-hours access to individual office units.

5.6 Conclusions

The monitored energy use intensity of the space heating system (43.8 kWh/m^2·yr) was nearly four times the weather-adjusted model estimate (12.0 kWh/m^2·yr). Although the case study considered a single building with some specific operational problems, the overall failure modes experienced are the result of causal risk factors that are likely to affect buildings in general. These factors include:

- Technology choice
- Design assumptions
- Handover and training
- Operation and maintenance

A significant design stage risk factor is the lack of understanding about the potential interactions between different heat sources. This contributed to the large variation in daily energy consumption when the heat pump and boiler were operating together. This risk could be mitigated to some extent by ensuring designers are using proven solutions; however this could stifle innovation if designers become reluctant to propose novel solutions on the grounds that they represent a greater performance risk.

Design stage assumptions have been shown to be overly optimistic. The EAHP's average COP is unlikely to be as high as 5.4; during a short period of monitoring it only achieved an average COP of 2.1. It is also unable to meet the majority of the building's space heating demand, with supplementary heating increasingly required at ambient temperatures below about 13 °C. These are design stage risk factors that could be mitigated by greater scrutiny of design and modelling assumptions. It must be remembered that NCM models were never intended to provide an accurate reflection of the building's actual usage. Although industry awareness of this problem is growing, Part L compliance or EPC calculations are still often the only source of modelled energy estimates. The limitations of the available energy estimates is therefore a further risk factor.

The level of commissioning and training provided during the handover process has an influence on whether the system operates correctly from the start (Mills, 2009). Adequate commissioning and user training can mitigate the risk of incorrect operation that may adversely affect system performance. Similarly, the training given to maintenance staff can mitigate the risk of maintenance being carried out without sufficient understanding of the implications on whole system operation.

Chapter 6

Sub-System Performance (Domestic Hot Water)

6.1 Introduction

This chapter considers the energy performance of the building's domestic hot water sub-system. In this context, domestic hot water (DHW) refers to potable water heated for uses other than space heating. In office buildings these will typically include hand washing, showers, washing-up and general cleaning purposes. The chapter begins by considering performance estimates in terms of energy benchmarks, demand estimates, and the calculation procedure for energy consumption estimates. The operating patterns in the case study building are outlined and data from the monitoring are then analysed in detail. The analysis considers energy and hot water consumption as well as factors that affect the efficiency of the sub-system. An energy balance is constructed for two typical days in order to investigate system energy losses.

6.2 Performance Prediction

6.2.1 Energy benchmarks

The whole-building benchmarks published in the widely used Energy Consumption Guide 19: Energy use in offices (Action Energy, 2003) provide a combined figure for energy used for space heating and energy used for domestic hot water. A supplementary table

Function	**Energy Source**	**kWh/m^2 TFA** Good Practice	Typical	**$kgCO_2/m^2$ TFA** Good Practice	Typical
Hand washing	Local electric	4	7	2.1	3.6
Hand washing	Central gas boiler	7	10	1.3	1.9
Hand washing and catering kitchen	Central gas boiler	12	20	2.3	3.8

Table 6.1: Benchmark DHW energy use and carbon emission intensities

provides benchmark figures per unit treated floor area (TFA) for on energy use and CO_2 emissions due to domestic hot water, these figures are reproduced in Table 6.1.

Considering hot water for hand washing only (excluding catering use), the good practice and typical energy consumption figures for local electric hot water generation are both 3 kWh/m^2 less than those for a central gas boiler system. This is due to local hot water generation largely eliminating the storage and distribution losses associated with central systems. The CO_2 emissions figures are however higher due to the greater carbon emission factor for grid supplied generation.

6.2.2 Hot water demand calculation

BS EN 15316-3-1:2007 provides methods for calculating the energy demand for domestic hot water generation in different installations (BSI, 2007b). The standard method for calculating energy demand (Q_W) is based on the heat content of the daily hot water requirement.

$$Q_W = \rho \times C_p \times V_{W,day} \times (\Theta_{W,del} - \Theta_{W,0}) \quad [\mathrm{MJ/day}]$$

Where ρ is the density of water at delivered temperature [983.2 kg/m^3], C_p is the specific heat capacity of water [4.1813 kJ/(kg·K)], $V_{W,day}$ is the volume of domestic hot water delivered per day at specified temperatures [m^3/day], $\Theta_{W,del}$ is the specified domestic hot water delivery temperature [°C], and $\Theta_{W,0}$ is the cold water supply temperature [°C].

Where measured data is unavailable, for example during the building's design, the volume of hot water delivered must be estimated. Although the standard provides guidance on estimating hot water requirements for single family dwellings it excludes education, offices, theatres and lecture theatres and shops. The requirements for domestic hot water

Type of building	**Daily (litres)**	**Daily (stored)**	**Unit**
Offices and general work places			
- with canteen	15	5	Person
- without canteen	10	5	Person

Table 6.2: DHW demand sizing

in commercial buildings such as these vary widely. In an office, the main use of domestic hot water will be for hand washing and occasional showers and washing-up at tea points. If catering is provided there will be additional hot water use in the kitchen however much of the washing-up will be done by commercial dishwashers, which have surprisingly low hot water consumption. The dishwasher in the case study kitchen for example uses 2.4 l per cycle (Winterhalter, 2009).

The Institute of Plumbing (IoP) provides recommended daily demand and stored volume figures for hot water demand sizing (IoP, 2002). The daily stored volume is the amount required to satisfy peak demand with a two hour re-heat period. Figures for offices are shown in Table 6.2.

As these are per person figures the supporting information accompanying the IoP figures states that an occupancy density of one person per 14 m^2 can be assumed if the actual number of occupants is unknown. Based on the IoP figures and the assumption of average occupancy density, the daily hot water demand of an office with canteen is approximately 1.07 l/m^2.day. Assuming five days per week operation, the annual heat requirement would be 58.3 MJ/m^2 or 16.2 kWh/m^2. After applying factors to account for a heat generation efficiency of 90% and a distribution efficiency of 90%, the total energy consumption is approximately 20 kWh/m^2, which corresponds to the typical energy benchmark given in Table 6.1. It is worth bearing in mind that the good practice benchmark is only 12 kWh/m^2 for hand washing and catering which, subject to the assumptions above, corresponds to a daily consumption of about 9 l/person. From this perspective it is clear that the IoP demand figures are rather generous and are in fact described as representative capacities which have not given rise to complaints of inadequacy.

Manufacturers' guidance for hot water demand estimation in offices is aimed at determining storage volumes and heating capacity and is usually expressed in terms of hourly rather than daily demand. For example, Hamworthy suggest an allowance of 1.5 litres/person for 1 hour peak load (Hamworthy, 2012), while Rycroft suggest 10 litres/hour maximum demand per public hand basin (Rycroft, 2002). It is also possible to derive daily demand figures from outlet flow rates and estimates of usage patterns.

For example, a typical flow rate of 0.15 l/s for a spray shower results in 45 litres per 5 minute shower. Assuming six showers during a peak hour, the additional hot water demand would be 270 l. Combining this with the estimate for hand basin use gives a peak hour demand of 510 l. The necessary storage volume is determined by the peak hour demand and the recovery period (the time taken for the hot water store to return to its temperature set-point), which is typically 2 hours (CIBSE, 2014). The case study building's DHW system has a storage capacity of 584 l with a recovery period of about 35 minutes, which would be capable of providing a continuous output of about 500 l/hour.

To reduce the risk of scalding, hot water is often mixed with cold water at the point of delivery using a thermostatic mixing valve to achieve a discharge temperature of about 40 °C. In this case, assuming a cold water temperature of 10 °C, only 60% of the delivered water volume will be from the domestic hot water system.

6.2.3 NCM energy consumption prediction

Energy consumed by DHW generation is covered by the energy efficiency requirements of the Building Regulations (HM Government, 2010); it is a regulated energy use. Regulatory compliance may be demonstrated by meeting the whole-building carbon emission target and the minimum performance standards set out in the Non-Domestic Building Services Compliance Guide (DCLG, 2010a). This specifies minimum seasonal gross efficiencies for boilers and water heaters and maximum daily heat losses from storage vessels. The whole-building carbon emissions are calculated using performance assessment tools based on the National Calculation Methodology (NCM) such as SBEM, IES-VE and Tas. These tools derive their performance estimates for DHW energy use from typical hot water demand figures in the NCM activity database. These demand figures are expressed in daily litres per unit floor area (l/m^2.day) but reflect occupancy density and nominal consumption per person for the specified activities. Table 6.3 shows the NCM demand figures and hours of use for the zone types in the case study building that have an associated hot water demand. The adjusted demand figure is obtained by multiplying the demand by annual hours of use then dividing by the daily hours of use and number of days in a year. The area weighted average represents the whole building's estimated hot water demand.

In SBEM, the overall energy consumption of the DHW system is calculated on a monthly basis from the estimated hot water demand, taking into account storage and distribution losses and the efficiency of the hot water generator. The calculation does not account

Zone Type	**Demand** (l/m^2.day)	**Annual Hours**	**Daily Hours**	**Adjusted Demand** (l/m^2.day)
Office	0.2	2277	9	0.14
Changing	76.15	2087	8.25	52.78
Lecture Theatre	0.13	4515	7.75	0.21
Food Preparation	0.33	3376	14	0.22
Eating & Drinking	5.69	5510	9.25	9.29
Area weighted average				0.75

Table 6.3: NCM hot water demand figures

for detailed draw-off patterns. Other NCM-based tools such as IES-VE and Tas take a similar approach. The following calculation adapts the NCM approach described in the SBEM Technical Manual (DCLG, 2011a) to provide annual estimates of DHW sub-system energy consumption. Two SBEM-type calculations were carried out using this approach; the first is based on an estimate of annual hot water demand using NCM demand figures, while the second is based on the actual monitored hot water consumption. In both cases, other inputs are based on manufacturer's data or default values if no other information is available.

Hot water demand

The monthly hot water demand is calculated by multiplying typical demand figures for different space types by the corresponding building floor area. The total hot water demand is then converted into an equivalent heat content. Based on the zone types and floor areas in the case study building, its average estimated hot water demand is 3413 l/d. Using the same assumptions as SBEM for specific heat capacity (4.18 kJ/kgK), density (1 kg/l) and temperature difference (50 K), the predicted daily heat demand is 198 kWh.

Dead-leg distribution loss

Dead-leg distribution losses (i.e. from residual hot water in outlet pipework) are calculated by SBEM for dead leg lengths greater than 3 metres by applying a factor of 0.17 to the monthly hot water heat demand. In the case study building the dead leg lengths in each zone are less than 3 metres so the dead leg distribution loss is assumed to be zero.

Secondary circulation loss

Daily distribution losses (for systems with secondary circulation) are calculated by multiplying the secondary pipework loop length by a heat loss per unit length and the daily hours of operation. These figures may be specified by the user, alternatively SBEM will use default values of 15 W/m heat loss per unit length and $4 \times \sqrt{\text{area served}}$ for secondary pipework length. For the case study building, the default values give a daily secondary circulation loss of 34 kWh, assuming a daily operating period of 8.5 hours.

Storage loss

Storage losses (for systems with storage) are calculated by multiplying the storage volume by a daily heat loss per unit volume. The storage volume is specified by the user or calculated by multiplying the daily demand (MJ/day) by a factor of 18, which represents the number of litres stored per MJ of daily demand. The daily heat loss is either specified by the user or is estimated automatically according to specified insulation type and thickness. If insulation type and thickness are also unknown, the software assumes an inefficient storage vessel and calculates storage losses accordingly. For the case study building, the storage volume is known to be 584 l and the daily heat loss, based on the calorifier manufacturer's literature, is 0.0082 kWh/l·day. The daily storage loss is therefore 4.8 kWh.

Energy consumption

The thermal total energy consumption of the domestic hot water system is obtained from the sum of the hot water demand, dead-leg losses, secondary circulation losses and storage losses. This figure is then divided by the seasonal efficiency of the DHW heat generator to obtain the total delivered energy consumption of the DHW system. For the case study building, the total average daily thermal energy consumption is 236.8 kWh. Based on the boiler manufacturer's quoted seasonal efficiency (SEDBUK) of 89%, the delivered energy consumption is 267 kWh/day, or 21 kWh/m^2·yr.

Data	**Compliance Model (IES)**	**Alternative Model (Tas)**	**SBEM NCM estimated demand**	**SBEM actual demand**	**Monitored**
Hot Water Demand (l/day)	297	2325	3413	255	255
Model Floor Area (m^2)	3702	3233	4565	4024	4024
Hot Water Demand ($l/m^2 \cdot day$)	0.08	0.72	0.75	0.06	0.06
Energy Use Intensity ($kWh/m^2 \cdot yr$)	4.2	12.4	21.3	5.3	9.8
% of Monitored	43%	127%	217%	54%	100%

Table 6.4: Comparison of modelled and monitored data

6.2.4 Model comparison

Table 6.4 compares the model estimates of hot water consumption and energy use with the SBEM-type calculations and the monitored data for a period of one year between March 2013 and February 2014. The compliance model was created by a consultant to the main contractor in order to demonstrate compliance with Building Regulations and to generate the building's on-construction EPC. The alternative model was created to verify the compliance model and is described in Appendix D. The hot water demand for the compliance and alternative models was deduced from the modelled zone areas and corresponding consumption figures for the relevant zone types in the NCM database. The alternative model and the SBEM estimated demand calculation result in hot water consumption estimates that are significantly larger than the actual consumption. This is due to assignment of the NCM's changing room zone type to the shower and changing rooms on the ground floor. The compliance model assigned the NCM's toilet zone type to these rooms, with a consequent reduction in hot water consumption estimate. The similarity between the compliance model's estimated water consumption and the monitored data suggests that the changing room zone type is inappropriate for changing rooms that are infrequently used. Despite the similar hot water consumption figures, the compliance model's energy estimate is less than half the monitored energy consumption.

Parameter	**Compliance Model**	**SBEM Calculation**
DHW Generator Efficiency	97.6%	89%
Generator Type	Using central heating boiler	
Fuel Type	Natural Gas	
Does the system have storage?	Yes	
Storage Volume (litres)	600	584
Storage Losses (kWh/l·day)	0.0033	0.0082
Does the system have secondary circulation?	Yes	
Circulation Losses (W/m)	10	15 (default value)
Loop length (m)	100	270 (default value)

Table 6.5: DHW system modelling assumptions

Although the water demand is similar, the monitored energy use intensity is more than double the compliance model's prediction. This will be due to assumptions regarding the system's operating period, thermal efficiency and distribution efficiency. The assumptions relating to thermal and distribution efficiency in the compliance model and the SBEM NCM calculation are shown in Table 6.5. The generator efficiency assumed in the compliance model actually higher than the manufacturer's specified efficiency of 89% for an average water temperature of 70 °C (Broag, 2009). Although the SBEM assumptions, described in Section 6.2.3, relating to thermal efficiency and storage losses are based on manufacturers figures, the assumptions regarding circulating losses are based on default values. The following analysis attempts to determine whether these assumptions are valid.

The monitored annual energy consumption is slightly less than the good practice benchmark however the building's actual occupancy density is about half the typical figure of 14m^2/person.

6.3 Operating Patterns

The system was originally configured to operate for 15 hours between 6 am and 9 pm from Monday to Friday. In December 2012 the schedule was changed to include operation for 11.5 hours between 8:30 am and 7 pm on Saturdays and Sundays. In June 2013, for a period of approximately six weeks the schedule was modified to operate constantly throughout the week. These variations are shown in Figure 6.1 and are discussed in more detail in Section 6.4.3.

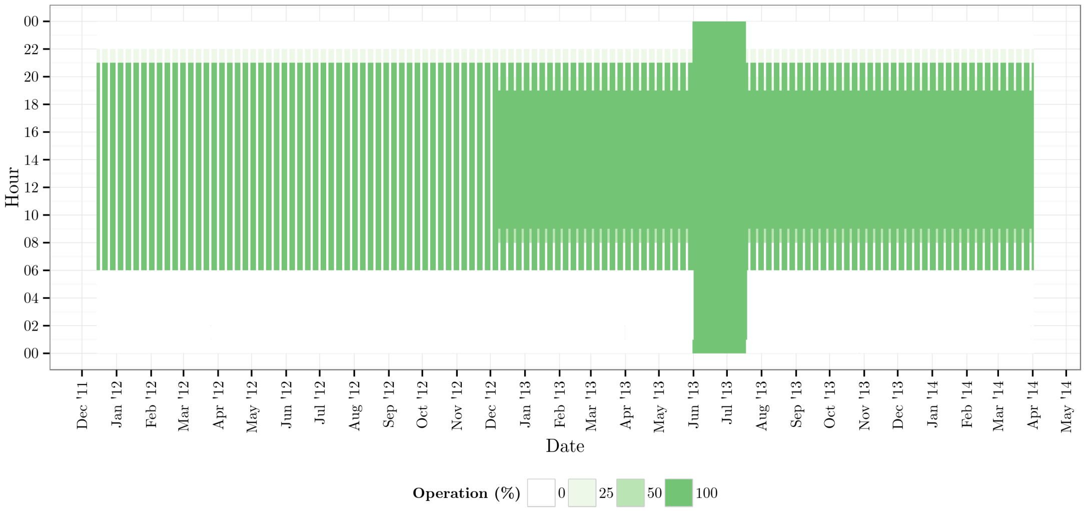


FIGURE 6.1: Domestic hot water heating operating pattern

6.4 Analysis of Monitored Data

This section presents an analysis of data collected by the domestic hot water sub-system monitoring described in Section 3.6. The overall data collection period ran from 21st November 2011 to 7th April 2014.

6.4.1 Daily energy and hot water consumption trends

Table 6.6 shows the comparison of the modelled and monitored DHW energy consumption during the year between March 2013 and February 2014. The modelled data is calculated according to the NCM, as used in SBEM and described above. Although the modelled data is only available by month there was no evidence of seasonal variation. There is a small variation in the daily averages obtained from the monthly figures; this is likely to be due to the presence of public holidays in the NCM occupancy profiles used in the calculation.

Figure 6.2 shows the daily DHW energy consumption during the complete monitoring period. While there is much day-to-day variation, the general trend can be attributed to

	Compliance Model	**Monitored**
Gas Consumption (kWh/day)	42.4	108.3
Primary Energy Consumption (kWh/day)	43.5	111.1
Carbon Emissions (kgCO$_2$/day)	8.2	21.0

Table 6.6: DHW annual average energy consumption

changes in operating schedule, such as the effect of including weekend operation from December 2012 and a short period of continuous operation in June 2013. The effect of these changes on system efficiency are explored below. The general trend in hot water consumption can be seen in Figure 6.3, which shows the daily cold water input to the hot water calorifiers. This is assumed to be equal to the volume of hot water drawn off. There is a fairly steady increase in hot water consumption, in line with the increasing occupancy of the building as more units were let over time. There are two noticeable dips that are due to reduced occupancy over the Christmas period.

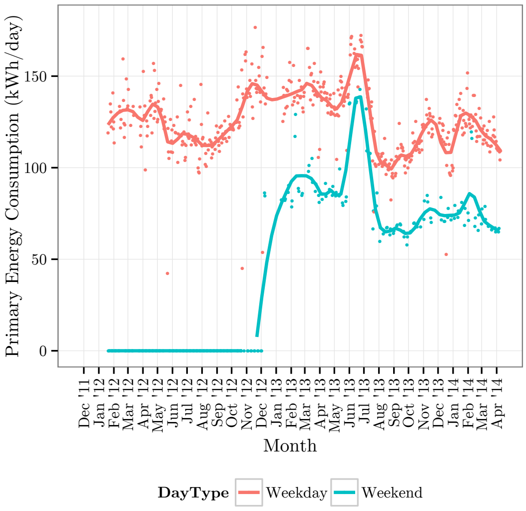


Figure 6.2: Daily DHW primary energy consumption

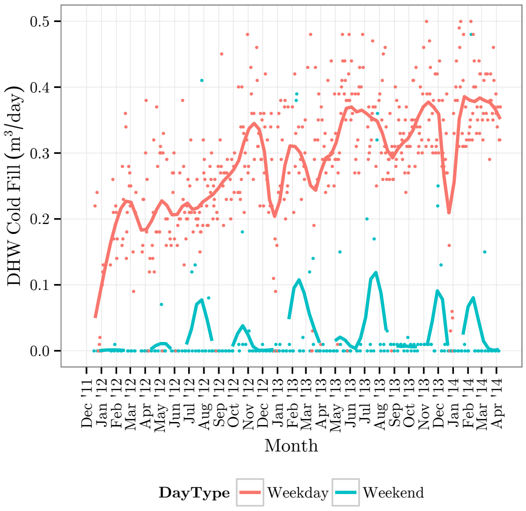


Figure 6.3: Daily DHW cold fill volume

6.4.2 Gas consumption and primary heat output

Figures 6.4 and 6.5 show the relationship between the boiler's gas consumption and its heat output using both 15-minute data and daily aggregate data. There are clearly more data points and a greater degree of scatter in the 15-minute plot. One reason for the greater scatter is the time lag between gas consumption and heat output as recorded by the respective meters, which results in increasing calculation error as the measurement interval decreases. For example, when the boiler starts firing after it has had time to cool there will be a lag in the heat entering the primary circuit as the flow temperature increases. Conversely when the boiler stops firing, gas consumption will cease immediately but residual heat will continue to enter the primary circuit until the flow and return temperatures equalise. Because of this, efficiencies calculated from 15-minute data will contain a large number of outlying values. Daily aggregates calculated from the 15-minute data will exhibit less variation as the errors are averaged out over the day's operating period. Both plots show clearly defined, linear relationships between gas consumption and primary heat output. The equations of both trend lines are similar and their gradients approximate the system's average primary efficiency. The presence of a negative y-axis intercept implies some gas consumption without a corresponding heat output. This could be a result of time lags between gas and heat measurement or the difference in pulse resolution between the gas and heat meters, which affects the temporal resolution (i.e. the interval between successive pulses) of the monitoring. It is possible that this is too low to reliably calculate efficiencies at 15 minute intervals due to the overestimates and underestimates that can occur when the boiler is only operating for part of the interval. For this reason, most of the following performance analysis has been carried out on the smoother daily aggregate data.

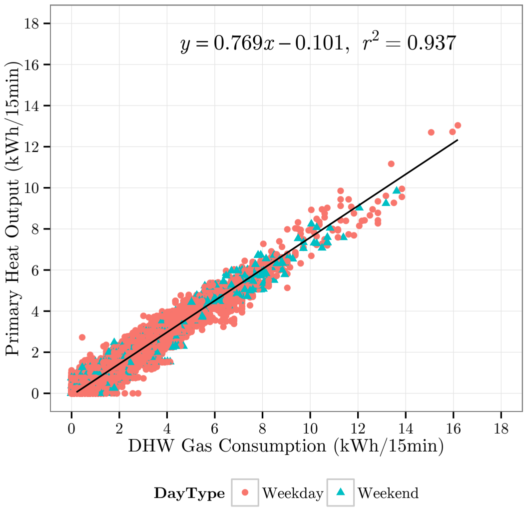


FIGURE 6.4: DHW gas consumption per unit heat output (15-min intervals)

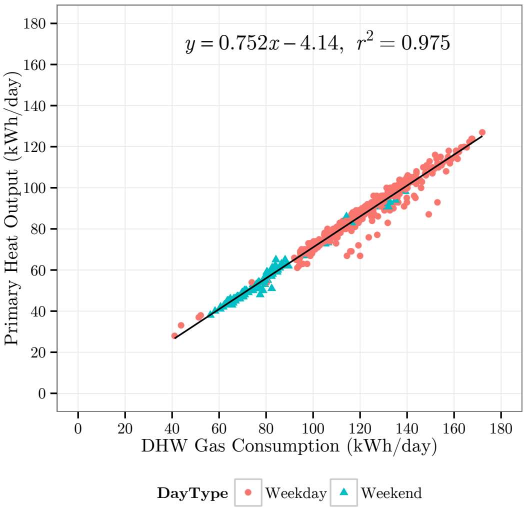


FIGURE 6.5: DHW gas consumption per unit heat output (daily intervals)

The frequency distributions of daily gas consumption and heat output are shown in Figures 6.6 and 6.7. The shape of these distributions is influenced by changes made to operating schedules (the introduction of weekend operation) and system settings (such as pump speed and boiler temperature setting) during the monitoring period.

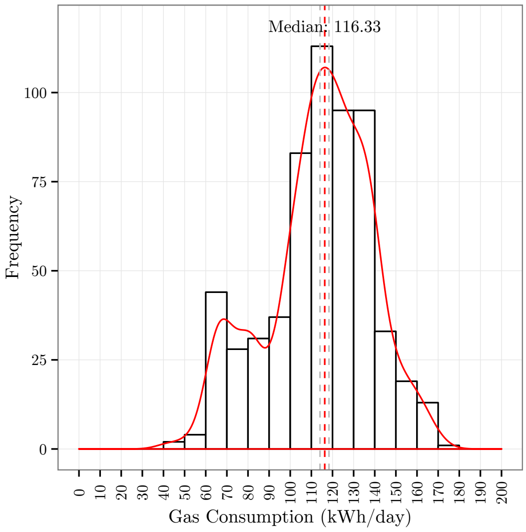


FIGURE 6.6: Daily DHW gas consumption

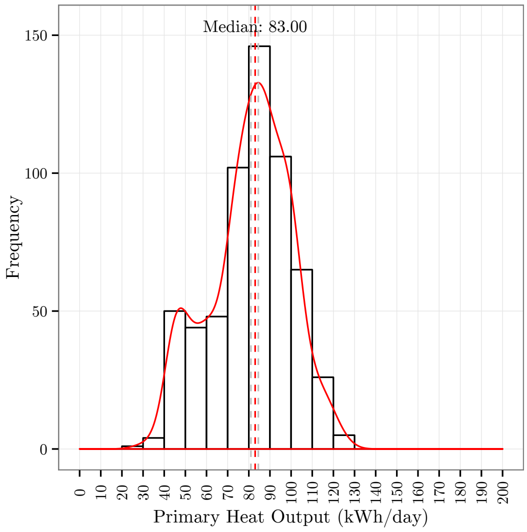


FIGURE 6.7: Daily DHW primary heat output

The distributions of calculated 15-minute and daily average efficiencies are shown in Figures 6.8 and 6.9. 15-minute average primary efficiencies were calculated for all 15-minute intervals with non-zero gas consumption and primary heat output. Daily average efficiencies were calculated for all days with scheduled system operation. The range of efficiencies calculated from the 15-minute data is extremely large and includes impossibly high values. This is due to the lack of synchronisation between gas consumption and heat output measurements. Despite this, the median value of the 15-minute efficiencies is within 5% of the median daily value.

6.4.3 Changes in operating schedules and system settings

Several changes to operating schedules and system settings occurred during the monitoring period. These changes are summarised in Table 6.7, and their nature and impact are discussed below.

Continuous monitoring of DHW primary heat and volume flow rate started at the beginning of April 2012. The observed operating pattern broadly follows the programmed operating schedule shown in Figure 6.1 with a few exceptions. These are most likely

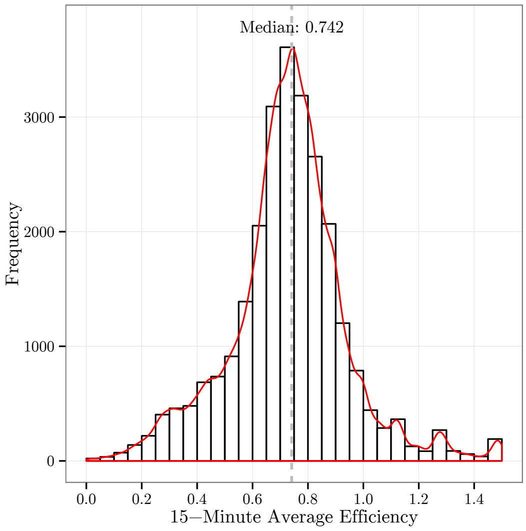


FIGURE 6.8: 15-minute average primary efficiency

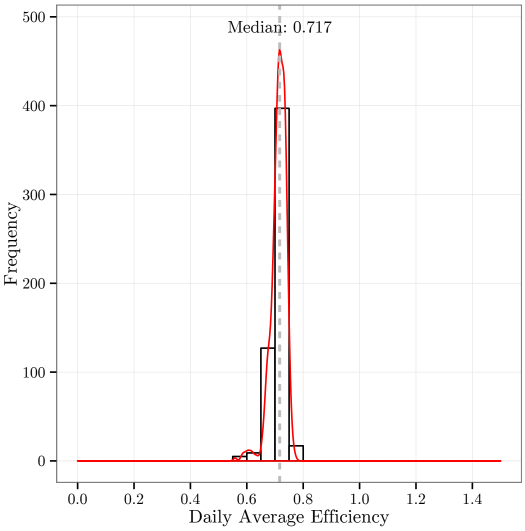


FIGURE 6.9: Daily average primary efficiency

Date	**Operating Days**	**Operating Times**	**Pump Speeds**	**Boiler Flow Temperature**
2012-04-03	Weekdays only	06:00 – 21:00 (M-F)	1.84 m^3/hr and 3.28 m^3/hr on alternate weeks	69 °C approx
2012-10-31				73 °C approx
2012-12-08	Weekdays and weekends	06:00 – 21:00 (M-F) 08:30 – 19:30 (S-S)		
2013-03-16			1.84 m^3/hr	
2013-05-10			2.55 m^3/hr	
2013-06-01	Continuous operation			
2013-07-19	Weekdays and weekends	06:00 – 21:00 (M-F) 08:30 – 19:00 (S-S)		

TABLE 6.7: DHW system operation changes

periods where an automatic frost protection function has run the primary circulation pump outside of the scheduled operating period. A comparison of primary pump operation (Figure 6.10) and boiler operation, based on the number of 15 minute intervals with non-zero volume flow or heat output (Figure 6.11), shows that during these periods of out-of-schedule pump operation the boiler itself is not operating.

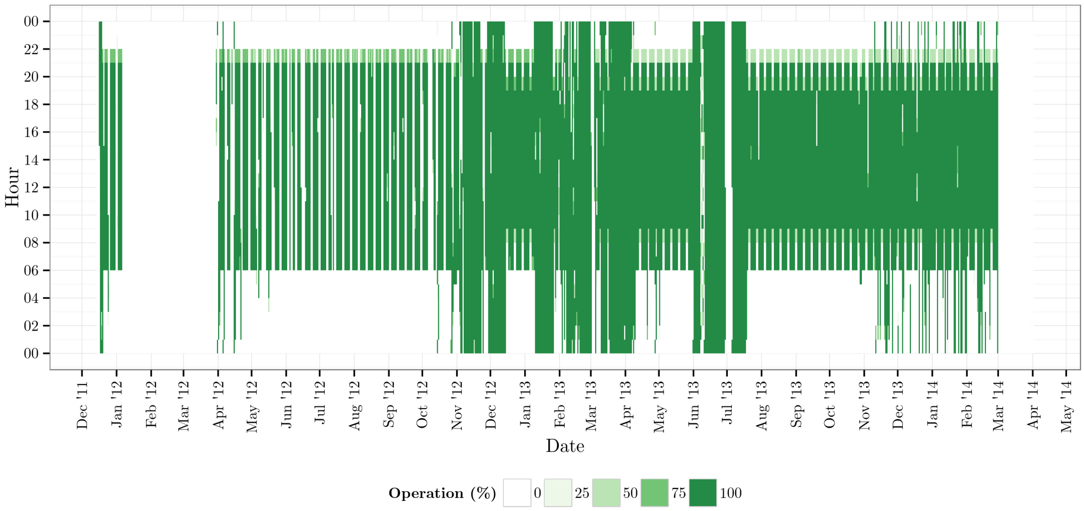


FIGURE 6.10: DHW primary pump operating pattern

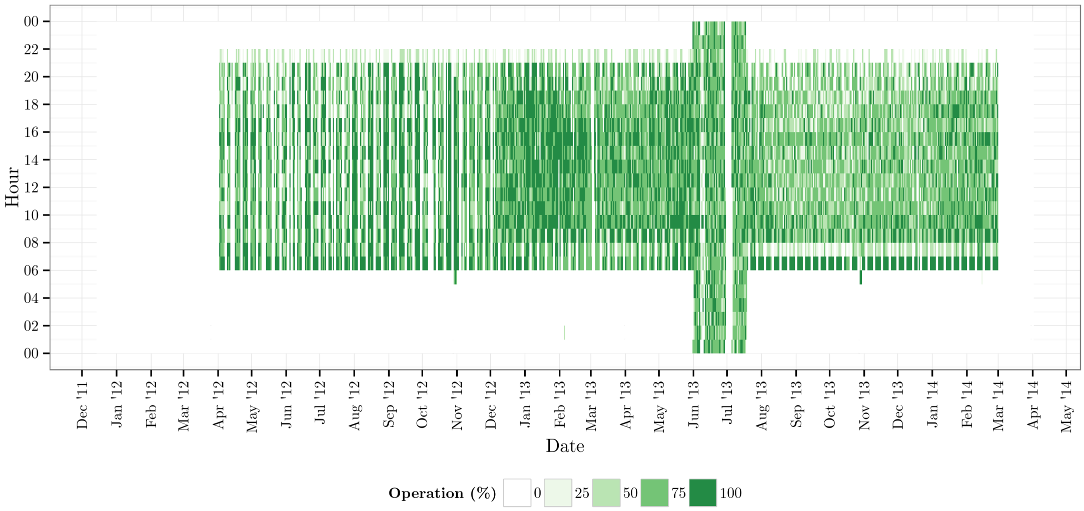


FIGURE 6.11: DHW boiler operating pattern

Weekend operation

Figure 6.12 shows the average daily primary efficiency for weekdays and weekends. Overall, the median daily average efficiency is 71.6% with an interquartile range of 3.1%. Weekend operation was included in the DHW operation schedule from 8th December 2012. The efficiency during weekend operation appears lower than during weekday operation. Notched box plots are used to compare the efficiency distributions for the different day types. The notches indicate an approximate 95% confidence interval around the median; a lack of overlap provides evidence that the medians differ (McGill et al., 1978). Figure 6.13 shows a small (about 2.5%) but noticeable difference in efficiency on weekdays and weekends. This reflects a significant[1] difference between the mean efficiency on weekdays and weekends. The lower efficiency at weekends could be due to a far lower hot water demand (the building is usually unoccupied at weekends) that may lead to higher return water temperatures. It is also possible that the shorter operating period at weekends means a greater proportion of the operating period is spent warming a cold boiler (which will also have been off for longer due to the later start on weekends).

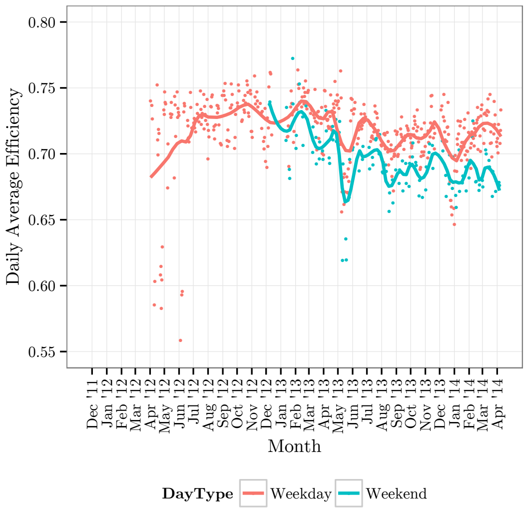


FIGURE 6.12: Daily average efficiency by month

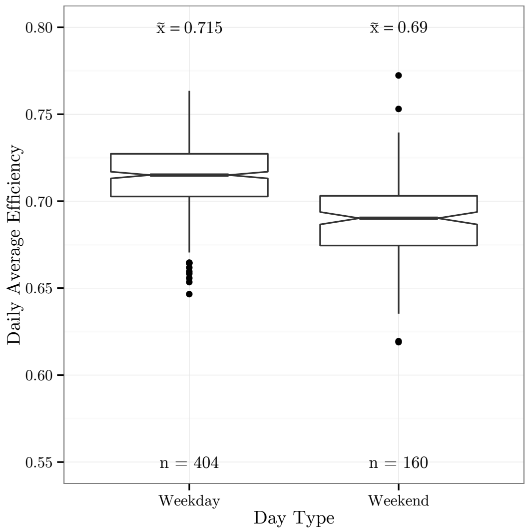


FIGURE 6.13: Daily average efficiency by day type

The temperature of the primary return can have an effect on the boiler's efficiency if it is too high for condensation to occur in the boiler's heat exchanger. In gas boilers, the temperature at which condensation begins to form is about 57 °C (CIBSE, 2010). Figure 6.14 shows the distribution of 15-minute return water temperatures. It is clear that for the vast majority of the time, the return temperature is outside the condensing

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[1] Welch Two Sample t-test, $p < 0.0001$

region. A comparison of return water temperatures during the operational period on weekdays and weekends is shown in Figure 6.15. The vertical dashed lines indicate the median return water temperatures, which at 67.6 °C on weekdays and 67.8 °C on weekends differ by only 0.2 °C. It is unlikely therefore that differences in return water temperature are responsible for the difference in daily efficiency between weekdays and weekends.

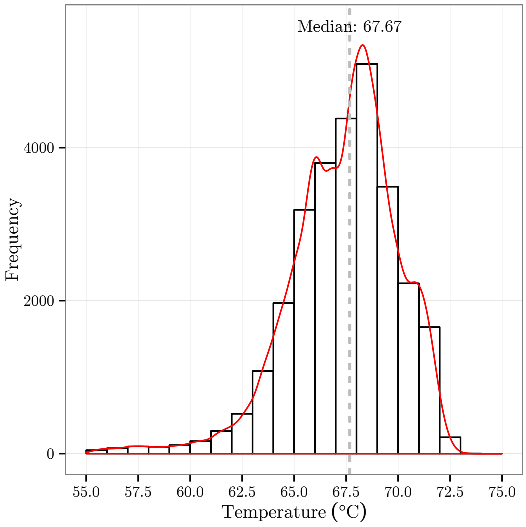

FIGURE 6.14: 15-minute primary return temperature

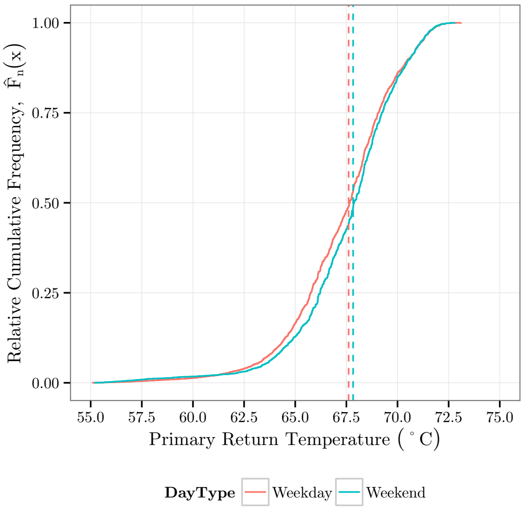

FIGURE 6.15: Cumulative distribution of 15-minute primary return temperatures

The relationship between primary return temperature and primary efficiency is shown in Figures 6.16 and 6.17. In order to capture the variation of primary return temperatures throughout the day it was necessary to plot 15-minute data (Figure 6.16), which contains a large amount of scatter. The presence of erroneously high and low efficiencies is due to differences in pulse resolution and lags between gas consumption and heat output, which result in mismatches between the 15-minute gas consumption and heat output figures. The general distribution is made clearer by plotting semi-transparent data points so the plot density represents the frequency of points. Although the plot shows a greater incidence of lower efficiencies at higher return temperatures it is not possible to infer any correlation, which suggests that return temperatures in the range observed do not have a significant influence on boiler efficiency. Constructing the plot with daily average data (Figure 6.17) smooths out the variation in primary return temperatures but gives more realistic efficiencies. This plot suggests a trend towards lower efficiencies at higher return temperatures, but again the correlation is poor and there is a great deal of scatter. It is likely that the range of return temperatures is too small to show a significant relationship with primary efficiency.

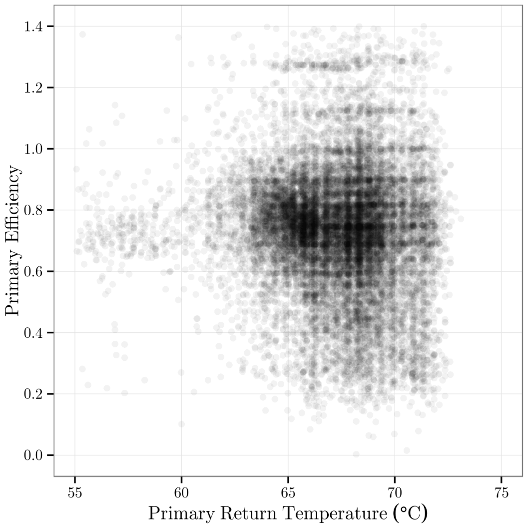

FIGURE 6.16: 15-minute primary efficiency and primary return temperature

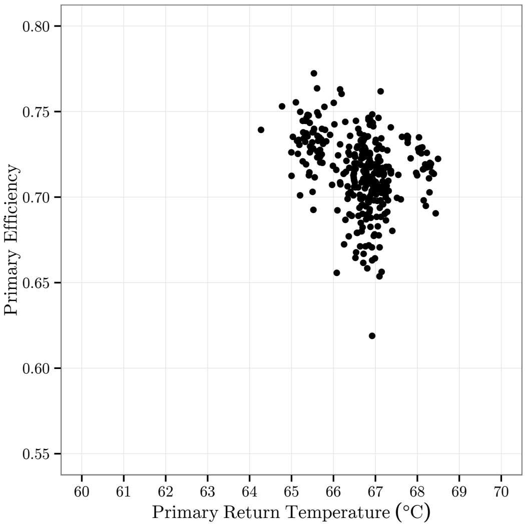

FIGURE 6.17: Daily primary efficiency and primary return temperature

The impact of operating period was investigated by comparing 15-minute average efficiencies at different intervals after the scheduled DHW start time. Figure 6.18 shows that average efficiencies within 15 minutes of schedule start are significantly lower than later intervals. This is likely to be the result of gas consumption being recorded before heat output is registered as well as the need to raise the temperature of a boiler that had previously been off overnight. The efficiency increases until about 45 minutes from schedule start as the boiler will be typically be operating continuously during this period to heat calorifiers that have cooled down overnight. Efficiency appears to drop slightly and the spread of values around the median increases at later intervals. This is because there will be greater uncertainty that the boiler was operating for a full 15-minute interval as the calorifiers reach their temperature set-points. The lower start-up efficiency could well be a reason for lower daily average weekend efficiency as the boiler operating period is shorter on weekends so the start-up period will make up a greater proportion of the total operating time.

Primary flow temperature

A larger change in return water temperature occurred as a result of an adjustment to the boiler's maximum flow temperature setting from approximately 70 °C to 73 °C on 31st October 2012. Figure 6.19 shows the effect of this adjustment on maximum daily primary return temperature. Figure 6.20 shows the difference in weekday primary efficiency at the two different primary return temperatures. The difference in mean efficiency is small

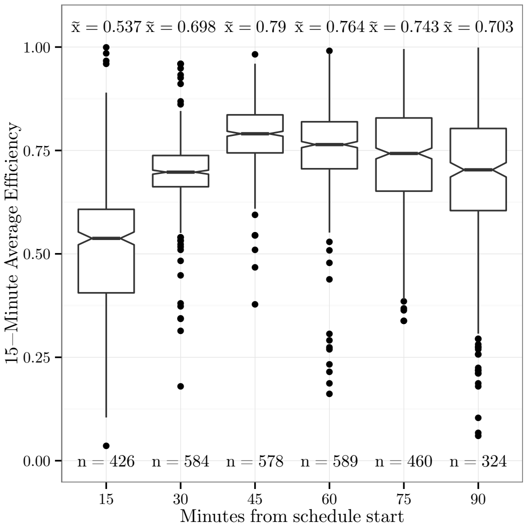

Figure 6.18: 15-minute average primary efficiency by operating time

but significant[2]. A larger change in efficiency may be expected with a larger change in return temperature, particularly if the temperature fell below the point at which the boiler begins to operate in condensing mode.

Pump speed

Daily average primary flow rates were calculated by dividing the daily cumulative volume flow (measured by the heat meter) by the daily duration of pump operation. Figure 6.21 shows the presence of three distinct daily average primary flow rates. Until the middle of March 2013 the flow rate was varying on alternate weeks, as a result of duty and standby pumps with different settings. This was rectified and from the beginning of May the pump speed was adjusted upwards to achieve a flow rate of 2.55 $\mathrm{m^3/hr}$, which was closer to the design flow rate of 2.75 $\mathrm{m^3/hr}$. Figure 6.22 shows weekday average primary efficiency at the three different flow rates. During the period of alternating weeks the median daily average primary efficiency was slightly (0.9%) higher when the pump was operating at the higher speed. Following the pump adjustment the median weekday average primary efficiency dropped to 71.4%, which suggests the influence of a factor other than pump speed.

Individually, the impact of these changes in operating schedule and system settings on daily efficiency is small. The largest difference observed was between weekend and weekday operation, possibly as a result of the differences in operating period. Overall the

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[2] Welch Two Sample t-test, $p < 0.01$

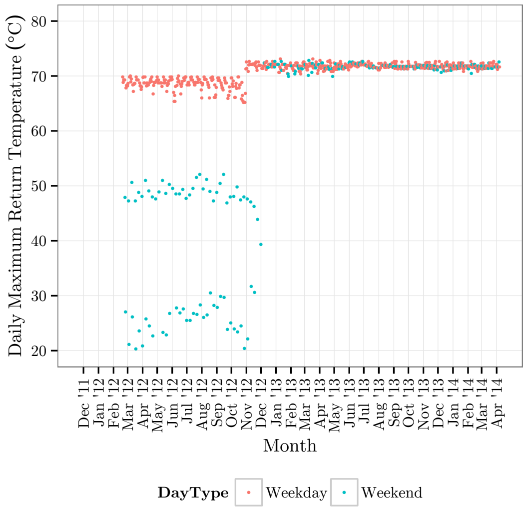


FIGURE 6.19: Maximum daily primary return temperature

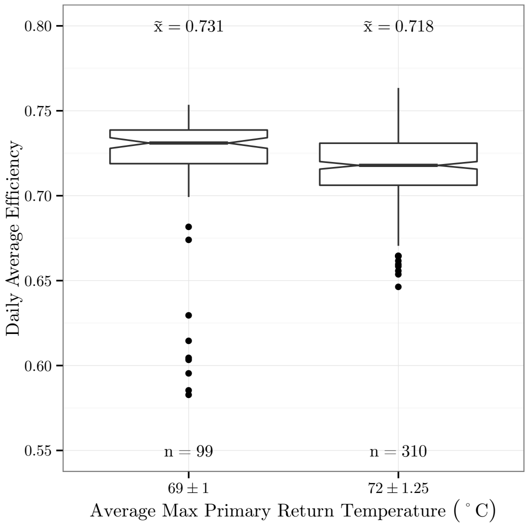


FIGURE 6.20: Daily average efficiency by maximum primary return temperature

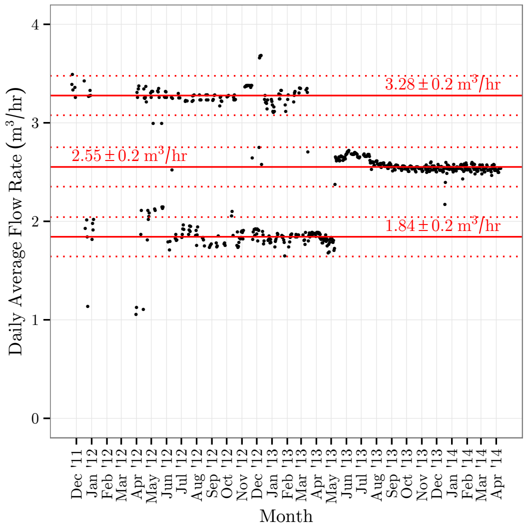


FIGURE 6.21: DHW primary daily average flow rate

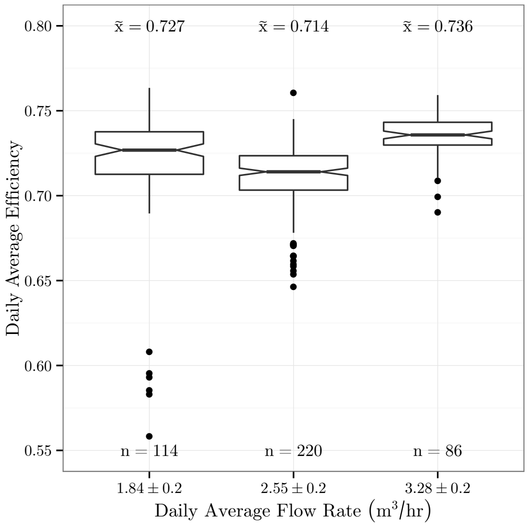


FIGURE 6.22: Daily average efficiency by primary flow rate

median daily primary efficiency was 71.7%, significantly lower than the boiler's primary efficiency assumed in the compliance model.

6.4.4 Ambient temperature

Although there is unlikely to be any significant correlation between ambient temperature and hot water consumption there may be some correlation between ambient temperature and gas consumption. This is illustrated by the trend in Figure 6.23. Not only will standing and distribution losses will increase in colder weather, but the temperature of the cold water supply will vary according to season. The amount of scatter in Figure 6.24 however, suggests that ambient temperature does not have an influence on boiler efficiency.

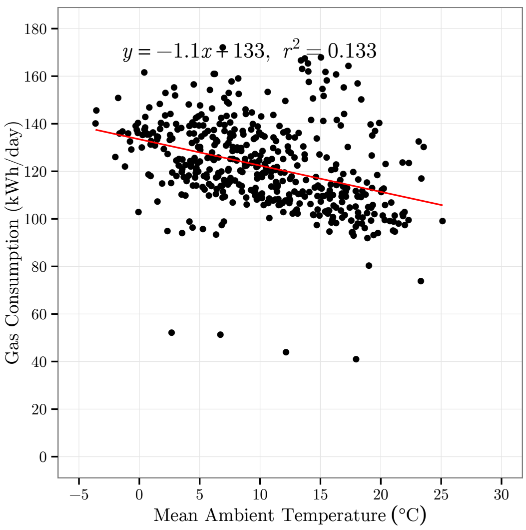


FIGURE 6.23: Daily gas consumption vs. ambient temperature

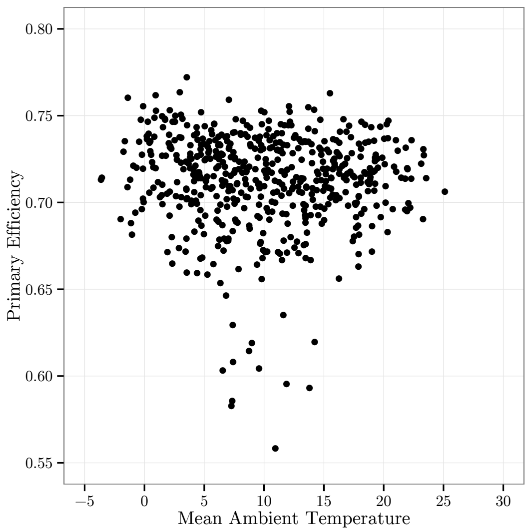


FIGURE 6.24: Daily primary efficiency vs. ambient temperature

6.4.5 Hot water consumption

The analysis in this sub-section is based on data recorded during the most recent stable operation period, i.e. without changes to the system's operation schedule and configuration, from 2013-07-19 onwards. Figure 6.25 shows a frequency distribution of hot water use excluding days of zero use. The median hot water use is $0.34\,\mathrm{m}^3$/day, however there is a noticeable secondary peak in the distribution at a very low water use that could be due to weekend occupancy or automatic urinal flushing. Figure 6.26 shows the corresponding gas consumption for each day's hot water use. The plot shows some correlation between gas consumption and hot water use but includes a large positive intercept of about 70 kWh/day at zero water use. This represents the gas consumption used to maintain calorifier temperatures at 60 °C against standing and distribution losses. Figure 6.27 shows the relationship between primary efficiency and hot water consumption. Weekends were excluded from this comparison because they were found to have typically lower primary efficiency than weekdays, the efficiency reduction was more likely to occur as a result of differences in operating schedule than hot water consumption. The plot does not appear to show a significant correlation between primary efficiency and weekday hot water consumption. Figure 6.28 shows the distribution of gas consumption on days with no hot water use; on these days the median gas consumption is approximately 68 kWh.

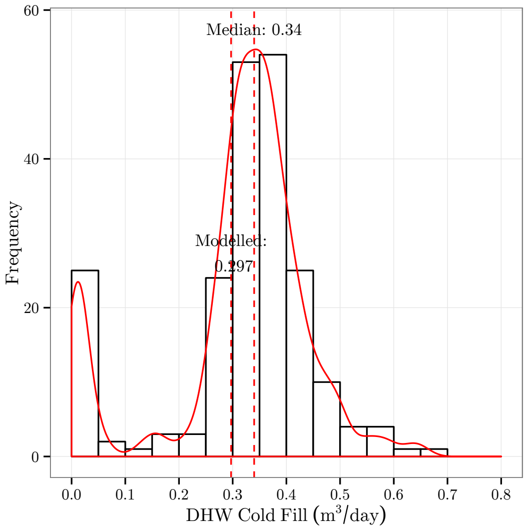


FIGURE 6.25: Daily hot water cold fill

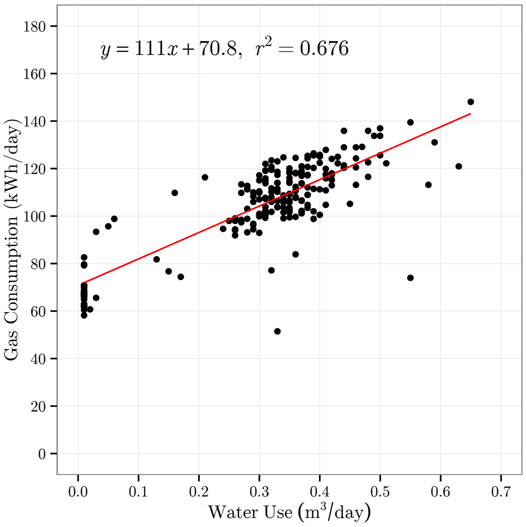


FIGURE 6.26: Daily gas consumption vs. hot water cold fill

6.4.6 Overall efficiency

The system's overall efficiency can be considered in terms of its fuel consumption per unit hot water consumption Figures 6.29 and 6.30 express the relationship between the boiler's heat output and hot water use and the boiler's gas consumption and hot water use as frequency distributions of the energy intensity of the delivered hot water, i.e. the amount of heat or fuel required to generate a unit volume of hot water. The relationship between primary heat demand and delivered hot water can be used to calculate the average distribution efficiency of the hot water system, while the relationship between gas consumption and delivered hot water can be used to calculate the system's overall efficiency. The average energy content of the generated hot water can be estimated from its temperature and the temperature of the cold water supply. If it is assumed that cold

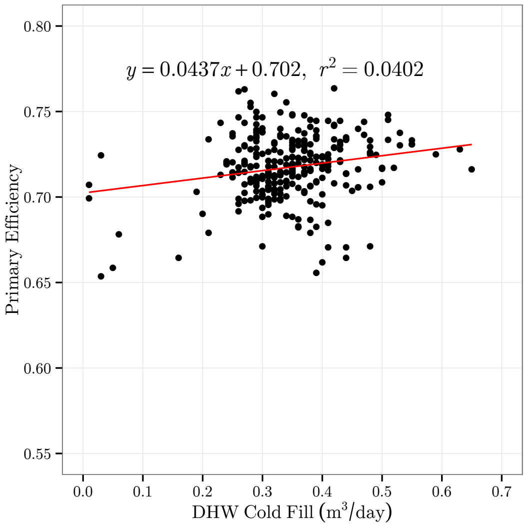


FIGURE 6.27: Daily efficiency vs. hot water consumption

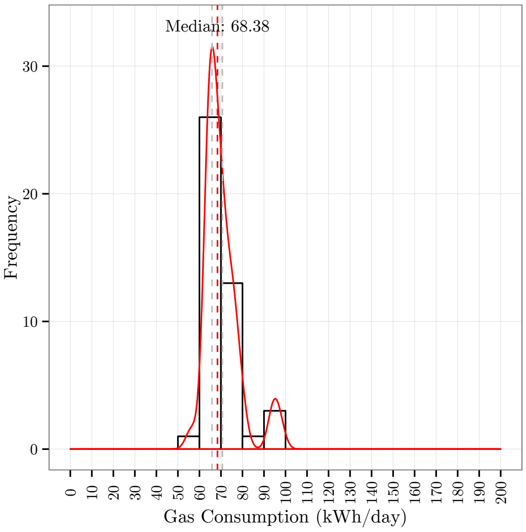


FIGURE 6.28: Daily gas consumption with no hot water use

water supplied via underground pipes will be near the ground temperature, which tends towards the annual average air temperature (Burch and Christensen, 2007), the average supply temperature is 12.5 °C. Assuming a hot water temperature of 60 °C the energy content of the generated hot water is approximately 54.2 kWh/m^3. Comparing this with the median primary heat intensity of hot water of 233.3 kWh/m^3 gives a distribution efficiency from primary heat output to hot water delivered at point of use of 23.2%. The overall system efficiency, based on a median fuel energy intensity of hot water of 327.1 kWh/m^3, is 16.6%.

6.4.7 Identification of 'Typical Days' energy balance

Although the preceding analysis captures the long-term behaviour of the system over the monitoring period, the variability in operating patterns makes it difficult to consider the system's energy balance in detail. By considering energy flows within the system on a single day with a known operating schedule it is possible to avoid some of the uncertainty present in the annual data and estimate the energy losses within the system. Figure 6.31 provides a schematic indication of the energy losses considered in this section.

A weekday and a weekend day with gas consumption, heat output and water consumption close to the median weekday and weekend values were chosen for further analysis. Table 6.8 compares the median values with the corresponding values for the selected days. In each case, the percentage difference from the median value is less than 2%.

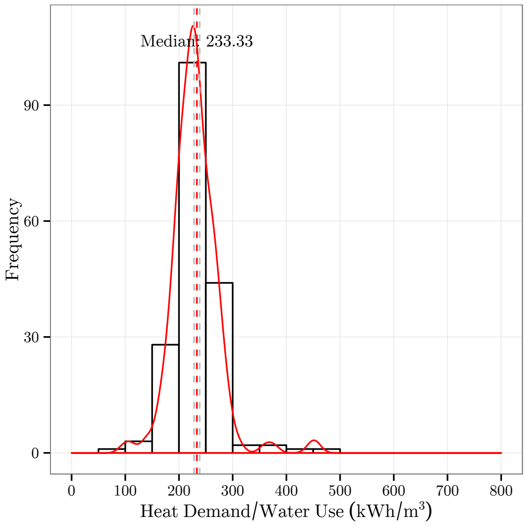


FIGURE 6.29: Primary heat intensity of delivered hot water (daily)

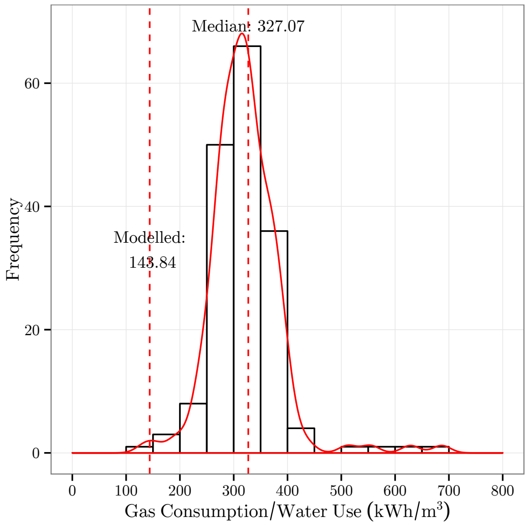


FIGURE 6.30: Energy intensity of delivered hot water (daily)

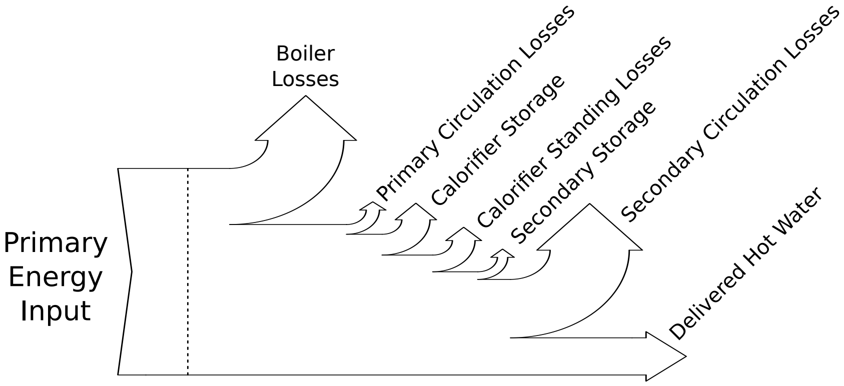


FIGURE 6.31: DHW system energy losses

	Median Weekday	**Friday 14/03/2014**	**% Difference**
Gas consumption (kWh)	111.20	109.29	1.7
Heat output (kWh)	80.00	80.00	0.0
Water used (m^3)	0.350	0.350	0.0
	Median Weekend	**Saturday 01/03/2014**	**% Difference**
Gas consumption (kWh)	67.26	67.65	0.6
Heat output (kWh)	46.50	46.00	1.1

TABLE 6.8: Typical days

The DHW system operates for 15 hours between 06:00 to 21:00 on the typical weekday and 10.5 hours between 08:30 to 19:00 on the typical weekend. Although there is no hot water use on the typical weekend the boiler does operate during the scheduled operating period, with an average heat output of 4.4 kW. This energy is used to bring the system up to temperature and to offset standing and distribution losses. On the typical weekday, the boiler operates during the scheduled period with an average heat output of 5.3 kW.

6.4.8 Boiler heat loss

The boiler heat loss is the difference between the energy content of the gas consumed and the boiler's usable heat output. Based on the measured gas consumption and heat output, the boiler's efficiency is 73.2% on the typical weekday and 68.0% on the typical weekend. These efficiencies correspond to heat losses of 29.29 kWh and 21.65 kWh respectively. Due to the location of the heat meter, approximately six metres from the boiler, the boiler's measured heat output will be slightly underestimated due to heat loss occurring between the boiler's flow and return connections and the heat meter.

6.4.9 Primary distribution heat loss

The primary distribution heat loss is the heat lost between the boiler's output and the primary coil in the calorifier. The pipework loop between the boiler and calorifier is approximately 24 m long. The pipework is insulated so heat losses will be relatively low, in the region of 14 W/m (KingspanTarec, 2012), however fittings such as pumps and valves are not insulated. Based on industry guidance, the heat emission from bare 50 mm pipework at a temperature of 50 K above an ambient temperature between 10 °C and 20 °C is 135 W/m (CIBSE, 2005). This figure can give a indication of the heat loss from bare fittings, which account for no more than 1.5 m of the pipework length. The total heat loss in the primary circuit is therefore approximately 500 W or 7.5 kWh during the weekday operating period and 5.25 kWh during the weekend operating period.

6.4.10 Calorifier storage

The calorifer storage represents residual heat stored in the calorifier at the end of the operating period. This stored heat is calculated from the difference between calorifier temperatures at the start and end of the operating period. On the typical weekend day these temperatures are 52.3 °C shortly after 08:30 when the system had switched on, and

60.0 °C at 19:00 when the system switched off (Figure 6.32). Based on a total calorifier storage volume of 584 l this temperature rise would require up to 5.2 kWh, depending on the amount of stratification in the tank. On the typical weekday the amount of heat stored at the end of the operating period is lower because the calorifier starts from a higher temperature, having had less time to cool down before the operating period.

6.4.11 Calorifier standing heat loss

The calorifier standing heat loss is estimated from the average rate of cooling outside of the operating period. The drop in average calorifier temperature between midnight and just before the start of the operating period was used to calculate a rate of cooling, which was extrapolated to the whole day. On the typical weekend day the standing loss calculated in this way was 10.9 kWh.

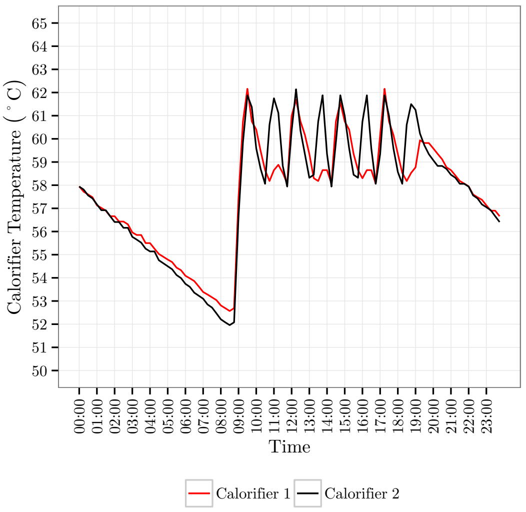


FIGURE 6.32: Calorifier temperatures (typical weekend day)

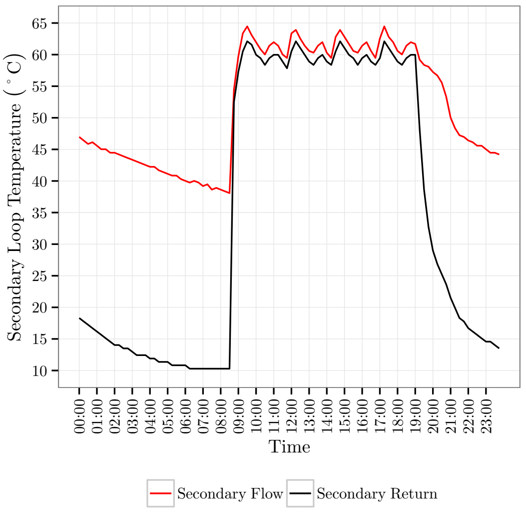


FIGURE 6.33: Secondary loop temperatures (typical weekend day)

According to the manufacturer's figures, the rate of heat loss from the two calorifiers is 200 W (i.e. 4.8 kWh per day) (Hamworthy, 2012). The heat loss estimated from the rate of cooling was significantly higher (454 W). The discrepancy with the manufacturer's figure could be the result of a higher rate of heat loss caused by thermal syphoning in the secondary circuit. The manufacturer's figure may also be an estimate based on theoretical insulation performance and a higher ambient temperature.

6.4.12 Secondary storage

The secondary storage represents residual heat stored in the water content of the secondary pipe loop at the end of the operating period. The average of the secondary flow and return temperature is assumed to be representative of the temperature in the whole loop, so the stored heat is calculated from the difference between the average temperatures at the start and end of the operating period. The temperature rise on the typical weekend is from 24.2 °C at 08:30 to 61.0 °C at 19:00 (Figure 6.33). The secondary loop is mainly 28 mm diameter pipework, with a water content of 0.56 l/m. Using the estimated loop length of 254 m, the volume of water in the system in 143 l, which will require 6.0 kWh to achieve the measured temperature rise.

6.4.13 Secondary distribution heat loss

The secondary distribution heat loss is the heat lost from the pumped secondary pipework that circulates hot water from the calorifier around the building. The secondary flow and return temperatures recorded at 15 minute intervals by the BMS could be used to estimate the average heat loss from the secondary circuit. To do so accurately would require flow rates to be measured at similar intervals. Due to the lack of heat or flow monitoring on the secondary circuit it was necessary to base estimates on the design flow rate of 0.11 l/s. There are no commissioning records to verify whether the design flow rate was achieved in practice. On the typical weekend day, the mean secondary flow and return temperature difference between 09:00 (after the temperatures had stabilised after switch-on) and 19:00 was 1.8 K. At the design flow rate the mean heat loss is therefore 0.8 kW, equivalent to 8.8 kWh over the course of the 10.5 hour operating period. Outside of the operating period the water in the secondary loop will cool. The rate of heat loss can be estimated in a similar way to the calorifier standing loss by estimating the average rate of cooling. Based on the drop in the average secondary flow and return temperature between midnight and just before the start of the operating period the mean heat loss outside the operating period is 2.3 kWh. The total secondary distribution heat loss for the typical weekend day is therefore 11.0 kWh.

6.4.14 Energy balance

Table 6.9 shows the energy balance for the typical days. The weekday figures were calculated in the same way as the weekend figures described above. The residuals

Typical Day	**Primary Energy Input**	**Boiler Losses**	**Primary Circulation Losses**	**Calorifier Storage**	**Calorifier Standing Losses**	**Secondary Storage**	**Secondary Circulation Losses**	**Delivered Hot Water**	**Residual**
Weekend	67.7	21.7	5.3	5.2	10.9	6.0	11.0	0	7.7
Weekday	109.29	29.3	7.5	2.5	11.3	5.3	17.4	20.2	15.8

TABLE 6.9: Energy balance (kWh) for typical days

represent the discrepancy between the primary energy input and the sum of energy losses including delivered hot water. Expressed as a percentage of the primary energy input (Figure 6.34), the residuals for the typical weekend and typical weekday are 11.4% and 14.4% respectively. This suggests there is additional heat loss that has not been accounted for, probably as a result of uncertainty in the estimated secondary circulation flow rate.

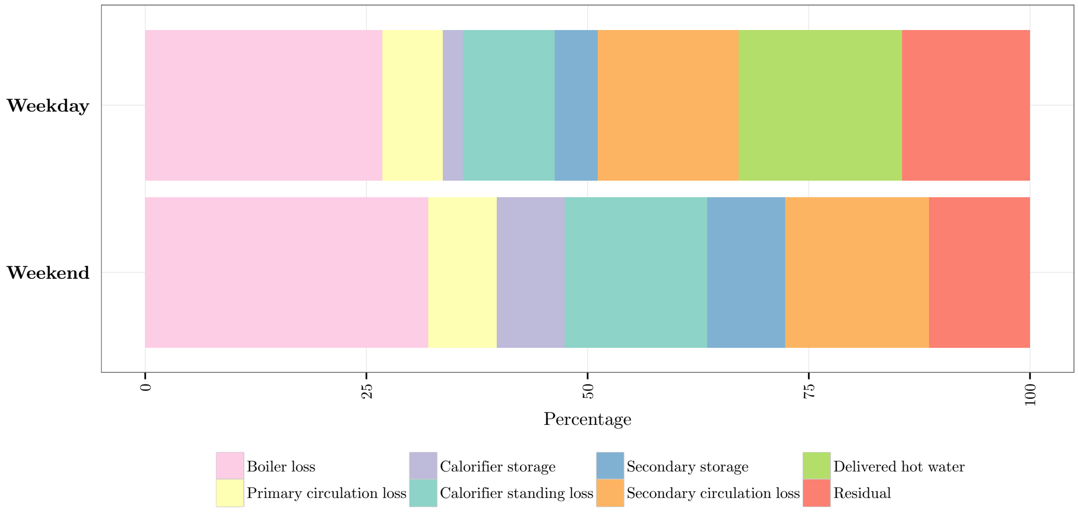


FIGURE 6.34: Percentage energy balance for typical days

6.5 Discussion

The energy used to generate domestic hot water is about 9% of the case study building's total energy consumption. The mean overall efficiency, in terms of energy consumed and hot water delivered is less than 20%. The mean boiler efficiency (disregarding heat lost from the short loop of pipe between the boiler and heat meter) is 72%. If a quarter of the primary distribution loss is assumed to take place before the heat meter, due to its distance from the boiler, this efficiency rises slightly to 75%. The mean distribution efficiency is much less however, under 25%, meaning that over three quarters of the boiler's heat output is wasted. The reason for this is the comparatively high storage and circulation losses relative to the actual hot water demand. This is a consequence of the system being over-sized; the result of typical design practice based on rules of thumb and safe assumptions regarding hot water demand. The issue of oversizing is a longstanding one; over thirty years ago, Jones (1982) noted that actual demand figures are significantly lower than design guidance. Had the actual level of hot water demand been estimated more accurately the designers might have opted for point-of-use electric water heaters, which are a more efficient alternative to a centralised storage system (CIBSE, 2012).

The hot water consumption predicted by NCM modelling tools is derived from standard figures in the NCM activity database. The result is highly dependant on the activity types assigned to the model zones. This is illustrated by the great difference in predicted water consumption between the compliance and alternative models. The difference is predominantly due to areas defined as changing rooms in the alternative model (these are male and female shower rooms, each with two shower cubicles), which in practice are rarely used. When modelling to estimate actual energy consumption, the NCM activity figures should be regarded with caution, and ideally only be used in the absence of more accurate estimates of usage patterns. Although the compliance model hot water demand is fairly close to the measured demand its annual estimate of energy use intensity is less than half of the monitored figure. This is the result of over-optimistic assumptions regarding boiler efficiency, storage losses and possibly secondary circulation losses, as well as a shorter operating period defined in the NCM activity database.

Although there is a variation in the daily DHW consumption that relates to the building's occupancy level, the relationship between daily DHW consumption and the energy consumption of the DHW system is less clear. Changes in operating schedules and system settings have a greater influence on the system's energy consumption than the actual hot water consumption. The changes also have relatively little effect on the boiler's daily average efficiency. The boiler may operate more efficiently if the return temperature were lower. This could be achieved through changes to the boiler control strategy such as increasing the hysteresis band and controlling according to calorifier temperature rather than primary flow temperature. This would reduce the frequency of boiler operation, allowing greater variability in the calorifier temperatures.

From a facilities management perspective, the need to avoid unnecessary operation is balanced by the need to maintain storage and distribution temperatures to satisfy health and safety legislation relating to Legionella. This would be less of an issue were the system not oversized, which leads to significant distribution and standing losses. The majority of the distribution losses are due to the secondary circulation loop, however this is necessary to ensure that the stored hot water is available within a short time at the point of use. The standing losses are the result of maintaining the stored water at 60 °C during the operating period, as per HSE recommendation (HSE, 2000). Storing water at this temperature explains why very few 15-minute boiler return temperatures during the DHW system's operation are below 60 °C, however this means the boiler will not achieve the higher levels of efficiency possible in condensing operation. In contrast to the HSE recommendation, Makin (2009) suggests it is only necessary to maintain a temperature of 60 °C for one hour a day, provided the temperature can be achieved throughout the whole storage vessel. Calorifier de-stratification pumps combined with a daily pasteurisation cycle to temporarily raise the storage and secondary circulation temperature would allow the usual operating temperature to be reduced.

6.6 Conclusions

The monitored energy use intensity of the DHW system (9.8 kWh/m^2·yr) was more than twice the model estimate (4.2 kWh/m^2·yr). Compared with the space heating system discussed in the previous chapter, the DHW system is of a much more conventional design. As a result, the specific technical issues identified in the case study are likely to be found in a range of broadly similar buildings. The issues will have occurred as a result of the following risk factors:

- Technology choice
- Design assumptions
- External constraints

The use of a centralised system has resulted in higher distribution losses than would have been likely with point-of-use water heaters; the mean distribution efficiency is less than 25%. The decision to use a centralised system was taken at the start of the project and was included in the environmental consultant's scheme design. At this stage however, the design was based on using heat directly recovered from the heat pump's refrigerant loop The contractor later opted to use heat from the primary circuit serving the building's heating system. Since the heating system operates at a low temperature (up to 50 °C) because of the heat pump it was necessary for the contractor to further change the design to provide a dedicated boiler to serve the DHW calorifiers. The choice of technology was therefore affected by design changes and an apparent lack of communication of design intent.

The mean boiler efficiency assumed in the compliance model was greater than the manufacturer's stated efficiency. Both figures were significantly greater than the measured daily average efficiency of 72%. Although the hot water consumption assumed in the compliance modelling is not dissimilar to the actual consumption, the size of the DHW installation suggests the design is based on the assumption of a much larger consumption. This could simply be due to the use of industry standard guidance rather than any specific risk aversion on the part of the designer. In this case, an appropriate mitigation would be to update industry guidance based on evidence of measured levels of hot water demand, and to provide the training necessary to actually change industry practice.

The need to adhere to design guidance relating to Legionella control represents an external constraint on system design and operating strategy. Although the HSE recommendation for maintaining water storage temperatures may be unnecessarily stringent, designers are unlikely to deviate from it for fear of potential liability. Again, the guidance could be updated if sufficient evidence exists to support lower storage temperatures with periodic pasteurisation cycles.

Chapter 7

Probabilistic Energy Performance Estimation

7.1 Introduction

This chapter describes a technique for evaluating building sub-system performance in probabilistic terms. It is based on the novel application of random sampling techniques to industry standard energy assessment methods such as the energy tree diagram described by Field et al. (1997), which forms the basis of CIBSE TM22 and TM54. It is therefore a combination of engineering-based (physical model) and statistical approaches. By assigning probability distributions rather than discrete values to model parameters, the model output will also take the form of a probability distribution. The spread of the distribution provides an indication of the uncertainty in the model output. Sensitivity analysis can then be used to determine the relative effect of the uncertainty in different parameters. The benefits of the technique are demonstrated by comparing the results of scenario-based calculations with those of the probabilistic calculations. Comparisons are carried out for two building sub-systems; an example lighting calculation drawn from TM54 and a domestic hot water calculation based on the case study building. An interactive web-based app has also been created to provide a further illustration of the principle. Finally, the input and output data obtained by random sampling is used to populate a simple Bayesian Network to permit diagnostic as well as prognostic reasoning.

7.2 Theoretical Background

7.2.1 The Law of Large Numbers

This law from probability theory underpins stochastic sampling approaches. It states that the mean outcome of a number of repeated trials will converge to the theoretical mean value as the number of trials goes to infinity (Ross, 2009).

$$\lim_{r\to\infty} \frac{Y_1 + \cdots + Y_r}{r} = E[Y_i]$$

In other words, the larger the sample size, the closer the sampled distribution will approximate the theoretical distribution (Vose, 1996). It is this ability to generalise population characteristics from random samples that makes Monte Carlo simulation possible.

7.2.2 The Central Limit Theorem

The central limit theorem states that as sample size increases a sampling distribution of a statistic will become normally distributed even if the population data is not normally distributed (Schumacker and Tomek, 2013). Mathematically, the central limit theorem can be expressed as follows: Let $X1, X2, \cdots, X_n$ be a sequence of independent and identically distributed (iid) random variables each having mean μ and variance σ^2. Then for n large, the distribution of

$$X_1 + \cdots + X_n$$

is approximately normal with mean $n\mu$ and variance $n\sigma^2$. It follows from the central limit theorem that

$$\frac{X_1 + \cdots + X_n - n\mu}{\sigma\sqrt{n}}$$

is approximately a standard normal random variable; thus, n large,

$$P\left\{\frac{X_1 + \cdots + X_n - n\mu}{\sigma\sqrt{n}} < x\right\} \approx P\left\{Z < x\right\}$$

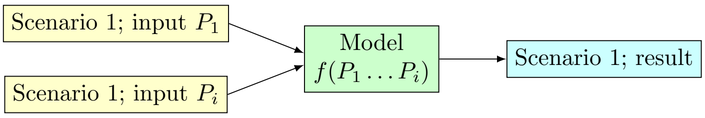
where Z is a standard normal random variable.

This means that the sum of independent random variables will have an approximately normal probability distribution and also explains why natural populations often follow a normal distribution (Ross, 2009).

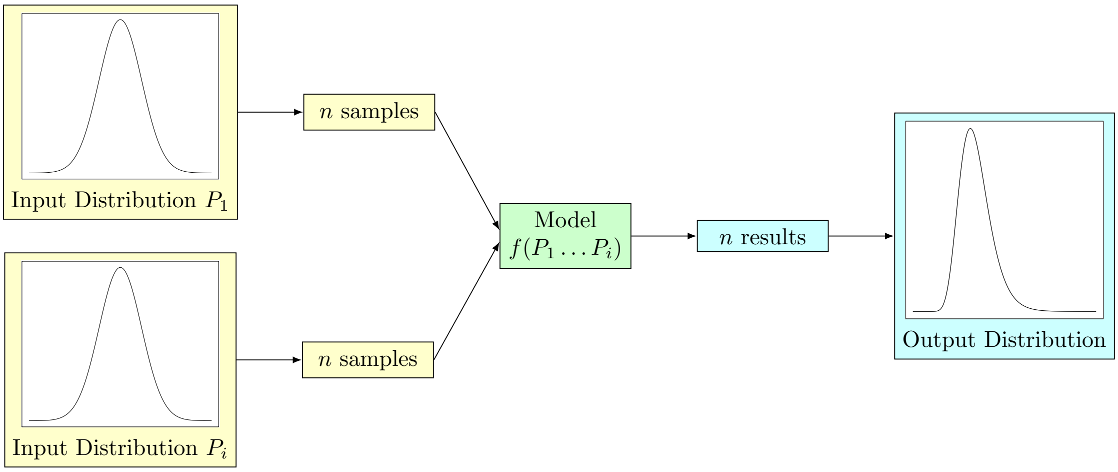
7.2.3 Monte Carlo simulation

Monte Carlo simulation is a technique that can be used to obtain probabilistic results from mathematical models. It is often used to determine output probability distributions that would be otherwise difficult or impossible to determine analytically. The results of the simulation may be used to evaluate the effect of uncertainties in model parameters and to determine likely outcomes based on these uncertainties. This is achieved by first describing uncertain model parameters in terms of probability distributions, then using random sampling techniques to generate sets of input values according to the characteristics of these distributions. A model output is then obtained for each set of parameter values. Repeating the process many times results in a distribution of model output values that may be used for further analysis and decision making (Raychaudhuri, 2008).

Figure 7.1 compares a scenario-based modelling approach with a Monte Carlo approach. The model used in both approaches is the same; it produces an output value based on a set of input values, $P_1 \ldots P_i$. The scenario-based approach can be run several times with different input values to generate results for different scenarios. The Monte Carlo approach repeatedly samples values of the input parameters from their probability distributions to obtain a corresponding number of output values.



(A) Scenario-based approach



(B) Monte Carlo approach

FIGURE 7.1: Modelling approaches compared

The output distribution represents the aggregated output values from n model runs using input data randomly sampled from the input distributions. By the law of large numbers, as the number of samples increases the probability density of the random sample values will approximate the probability density of the actual function. This may be demonstrated by comparing the following two histograms created in R from values randomly sampled from a triangular distribution of minimum 0, maximum 20 and mode 10. Figure 7.2 shows the distribution obtained by taking 100 samples from the source distribution.

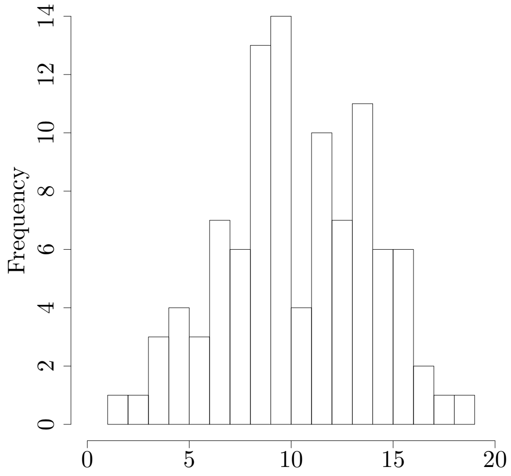


FIGURE 7.2: 100 random samples from a triangular distribution

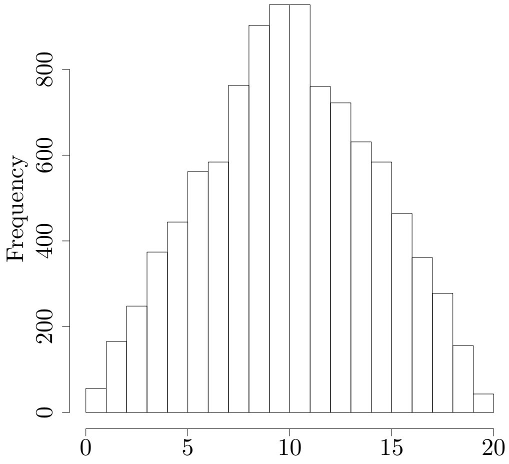


FIGURE 7.3: 10,000 random samples from a triangular distribution

Figure 7.3 shows the effect of increasing the number of random samples taken from the source distribution. The method is exactly the same, however this time 10,000 samples are taken from the same triangular distribution. The shape of the resulting distribution more clearly resembles the triangular shape of the theoretical distribution.

7.2.4 Latin Hypercube sampling

Latin Hypercube sampling is a stratified sampling technique whereby the probability distribution is split into intervals of equal probability which are then randomly sampled. This ensures that the resulting samples cover the full range of the distribution. The advantage of Latin Hypercube Sampling is its ability to reproduce input distributions with greater efficiency than an equivalent number of random samples (McKay et al., 1979). Figure 7.4 shows the distribution obtained by taking 100 Latin Hypercube samples from a triangular distribution with a minimum of 0, maximum of 20 and mode of 10. Compared with the distribution obtained from 100 random samples (Figure 7.2), the distribution obtained from 100 Latin Hypercube samples shows a much better match to the shape of the theoretical distribution.

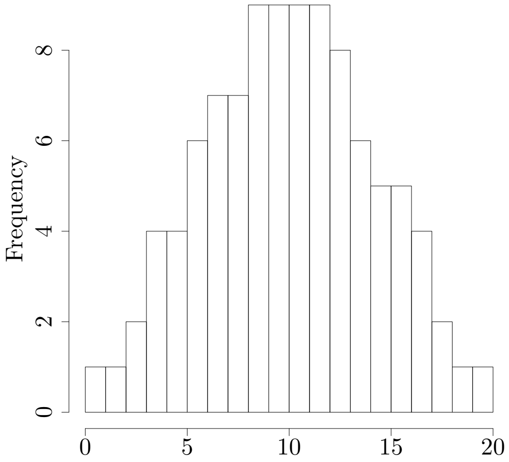


Figure 7.4: 100 Latin Hypercube samples from a triangular distribution

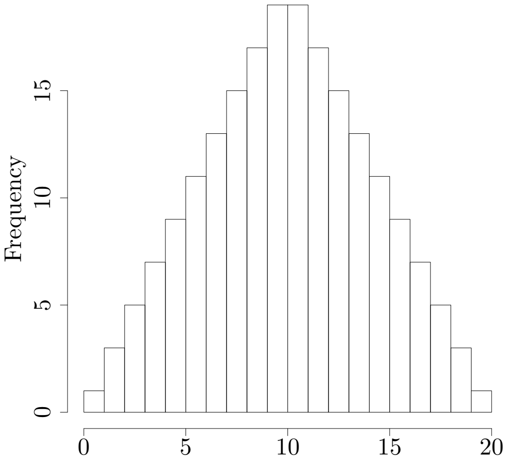


Figure 7.5: 200 Latin Hypercube samples from a triangular distribution

While at least 10,000 random samples were necessary to obtain a clearly defined output distribution, a similar result can be obtained with only 200 Latin Hypercube samples (Figure 7.5). A reduction in the number of samples needed to accurately capture input distributions will therefore reduce the number of iterations needed to achieve a robust output distribution. The fact that Latin Hypercube sampling can therefore provide a higher quality of analysis for a given sample size is an important consideration with complex models, however there is little benefit in using Latin Hypercube sampling for models of low computational cost (Helton and Davis, 2003).

7.2.5 Choice of input distributions

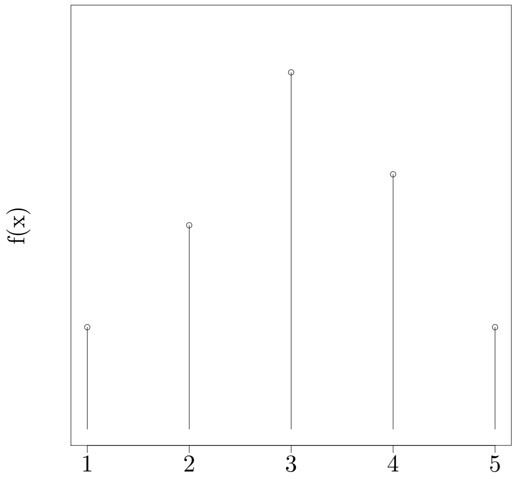
There is a wide range of statistical distributions that could be used to characterise the uncertainty in a model's input parameters. In practice however a small selection of distributions can model most uncertainty in building energy systems (Macdonald, 2002).

- Categorical distribution
- Uniform distribution

- Normal distribution
- Log-normal distribution
- Triangular distribution

Categorical

The categorical distribution (Figure 7.6) is a discrete, non-parametric distribution. It is used to model parameters that may take one of a finite set of alternative values. Each alternative value is assigned a probability, with the sum of the probabilities equal to one.



PMF:

$$f(x_i) = p_i$$

FIGURE 7.6: Categorical distribution

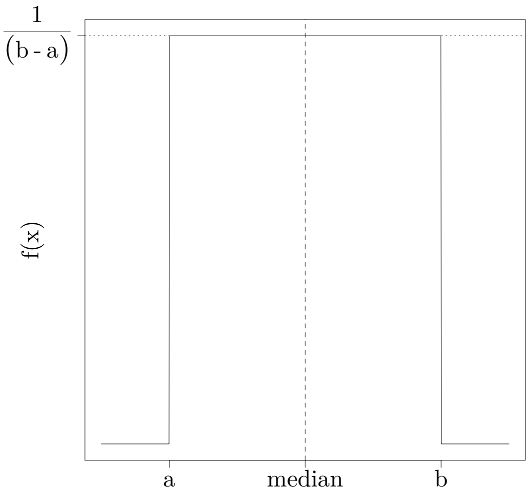
The following distributions are *continuous* distributions.

Uniform

The uniform distribution (Figure 7.7) is a continuous, non-parametric distribution. The distribution's bounds represent minimum and maximum values. The uniform distribution assigns equal probability values between these bounds. The uniform distribution is used if it is impossible to identify a most likely value.

Normal

The normal or Gaussian distribution (Figure 7.8) is a continuous, parametric distribution. It is unbounded, so may be inappropriate where negative values are impossible. The

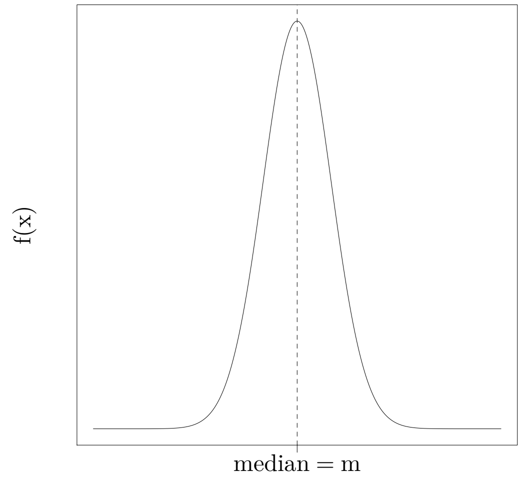


PDF:

$$f(x) = \begin{cases} \frac{1}{(b-a)} & \text{for } x \in [a, b] \\ 0 & \text{otherwise} \end{cases}$$

Figure 7.7: Uniform distribution

normal distribution often occurs in naturally occurring variables as a consequence of the Central Limit Theorem when adding independent random variables.



PDF:

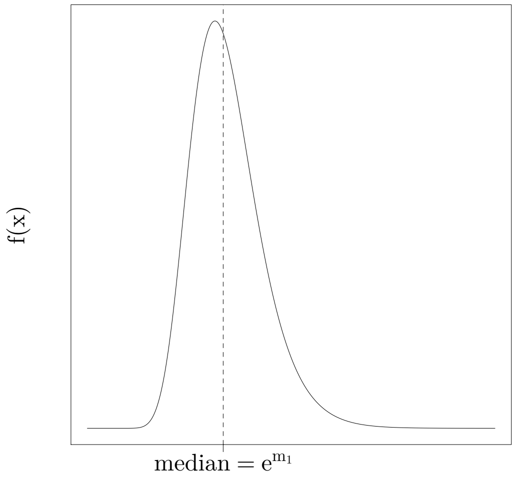
$$f(x) = \frac{1}{\sqrt{2\pi\sigma_1^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

Figure 7.8: Normal distribution

Log-normal

The log-normal distribution (Figure 7.9) is another continuous, parametric distribution. It is partially bounded and extends from zero to infinity. The log-normal distribution is well known and often occurs in naturally occurring variables as a consequence of the

Central Limit Theorem when multiplying independent random variables. A variable is Log-normally distributed when the natural log of the variable is Normally distributed.



PDF:

$$f(x) = \frac{1}{x\sqrt{2\pi\sigma_1^2}} \exp\left(-\frac{(\ln x - \mu_1)^2}{2\sigma_1^2}\right)$$

Where:

$$\mu_1 = \ln\left(\frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}}\right)$$

$$\sigma_1 = \sqrt{\ln\left(1 + \frac{\sigma^2}{\mu^2}\right)}$$

FIGURE 7.9: Log-normal distribution

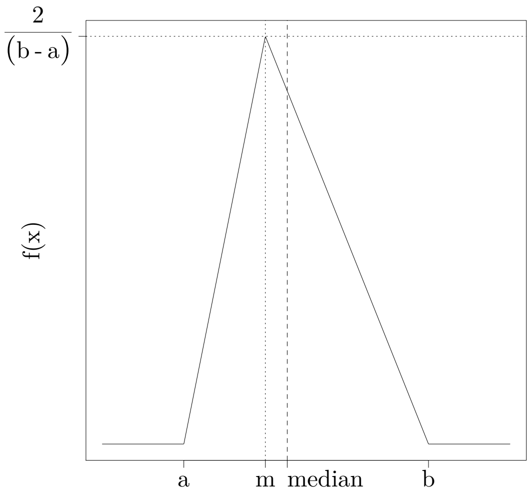
Triangular

The triangular distribution (Figure 7.10) is a continuous, non-parametric distribution. The distribution's bounds represent minimum and maximum values. The distribution is easy to define, being described in terms of minimum a, maximum b and most likely m values. It often used as a rough model based on values captured by expert elicitation in the absence of statistical information.

Triangular with quantile estimates

The standard triangular distribution is defined between its minimum and maximum parameters. The probability density at these limits is zero, therefore the maximum and minimum values have a zero likelihood of occurrence. Since it may be difficult to estimate these limiting values it may be preferable to estimate a 90% confidence interval for the variable's true value, i.e. to state a likely range of values.

Figure 7.11 shows a triangular distribution generated using a lower confidence interval c, upper confidence interval d and most likely value m, such that 90% of the probability mass falls between c and d.



PDF:

$$f(x) = \begin{cases} \frac{2(x-a)}{(b-a)(m-a)} & \text{for } a \leq x \leq m \\ \frac{2(b-x)}{(b-a)(b-m)} & \text{for } m \leq x \leq b \end{cases}$$

FIGURE 7.10: Triangular distribution

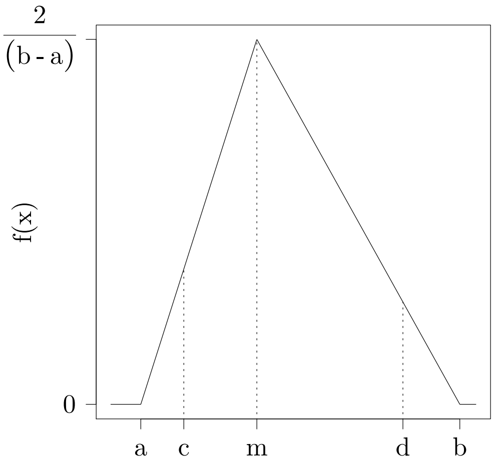


FIGURE 7.11: Triangular distribution from quantile estimates

Constructing a triangular distribution in this way presents some difficulty as the values of a and b must be calculated such that the small triangles bordered by ac and db are equal in area and correspond to the probability mass lying outside the confidence interval. Bateman (2013) discusses this issue and describes two iterative techniques using a Microsoft Excel spreadsheet with the Solver add-in for calculating the extremes of the distribution based on upper and lower quantiles corresponding to the desired confidence interval.

Kotz and van Dorp (2004) describe an alternative method for calculating the extremes of the distribution. This is based on solving a single equation to find q, the probability mass on the left hand side of the distribution.

$$q = \frac{m - a}{b - a}$$

The lower bound, a can be found as a function of q, given the lower percentile value c and the most likely value m.

$$a(q) = \frac{c - m\sqrt{\frac{p}{q}}}{1 - \sqrt{\frac{p}{q}}}$$

Similarly, the upper bound, b can be found as a function of q, given the upper percentile value d and the most likely value m.

$$b(q) = \frac{d - m\sqrt{\frac{1-r}{1-q}}}{1 - \sqrt{\frac{1-r}{1-q}}}$$

Substituting the equations for $a(q)$ and $b(q)$ into the equation for q gives an equation for $g(q)$ based on the percentile values c and d, the most likely value m and the left hand probability mass q.

$$g(q) = \frac{(m - c)\left(1 - \sqrt{\frac{1-r}{1-q}}\right)}{(d - m)\left(1 - \sqrt{\frac{p}{q}}\right) + (m - c)\left(1 - \sqrt{\frac{1-r}{1-q}}\right)}$$

The fact that value of $g(q)$ exists in the range $0 \leq g(q) \leq 1$ can be used to constrain an optimisation function used to find q. This method was implemented as a new R function that minimises the absolute difference between q and $g(q)$ using the *optimise* function to obtain the solution q^*, which is then used in the equations for $a(q)$ and $b(q)$ to find the appropriate minimum and maximum values of the standard triangular distribution.

In the examples that follow, uncertainty in input parameters was characterised using this function to generate triangular distributions based on 90% quantile estimates.

7.2.6 Sensitivity analysis

Sensitivity analysis provides a means to determine the relative effect of uncertainty in a model's input variables on the uncertainty in the model's output. It can therefore be used to identify the most important variables in models of building performance. Regression-based methods are widely used in sensitivity analysis of building energy and thermal load models (Tian, 2013). These methods are based on multiple regression analysis of the model's input distributions and corresponding output distribution. The method provides a form of 'global' sensitivity analysis, in which parameter sensitivity is dependent on the interaction of all other uncertain parameters (Hamby, 1994). The multiple regression model takes the form:

$$\hat{y} = \beta_0 + \sum_{j=1}^{k} \beta_j x_j$$

Where $\hat{y}$ is the estimated value of the true output resulting from the input values x_j. The values of the regression coefficients β are chosen to minimise the sum of squared differences between the true and estimated output values:

$$\sum_{i=1}^{N} (y_i - \hat{y}_i)^2 = \sum_{i=1}^{N} \left[y_i - \left(\beta_0 + \sum_{j=1}^{k} \beta_j x_j \right) \right]^2$$

The regression coefficients themselves are of limited use in sensitivity analysis because they will be influenced by the units of the input variables. Standardising the input and output variables by subtracting means ($\bar{y}$ and $\bar{x}_j$) and dividing by standard deviations (σ_y and σ_j) results in dimensionless coefficients that provide a comparative measure of variable importance (Helton et al., 2006).

$$\frac{\hat{y} - \bar{y}}{\sigma_y} = \sum_{j=1}^{k} \frac{\beta_j \sigma_j}{\sigma_y} \frac{x_j - \bar{x}_j}{\sigma_j}$$

Where $\beta_j \sigma_j / \sigma_y$ are referred to as the standardised regression coefficients (SRC).

Although standardised regression coefficients are commonly used (Silva and Ghisi, 2014; Hopfe and Hensen, 2011; Domínguez-Muñoz et al., 2010), they can perform poorly with non-linear models and are unsuitable for non-monotonic models. Where there is a possibility of non-linearity, standardised ranked regression coefficients (SRRC) can be calculated for rank transformed data. The rank transformation can convert a non-linear but monotonic relationship into a linear relationship (Helton et al., 2006). For complex non-monotonic models it is necessary to use selected screening or variance based techniques such as those described in Saltelli et al. (2004).

7.3 Application to industry practice

Industry standard energy estimation tools adopt calculation-based techniques such as dynamic simulation or steady-state methods (Wang et al., 2012). Since these techniques are based on deterministic relationships between their input and output variables they do not consider the effects of uncertainties in the input data. The effect of uncertainty may be incorporated in these tools through the use of probabilistic sampling techniques, in which input parameters are defined in terms of probability distributions rather than single values. The model's output will then also take the form of a probability distribution, the spread of which indicates the degree of uncertainty in the estimate. This can help define the level of risk associated with expecting a certain level of energy performance. It can also allow for progressive refinement in the modelling process, such as reducing the variance of particular input distributions as more information becomes available. The approach also facilitates sensitivity analysis to establish the effect of uncertainty in a particular input variable on the output distribution.

The uncertainty in input parameters is modelled by taking multiple samples from their probability distributions. This sampling generates many permutations of input parameters, each of which must be simulated. It is relatively straightforward to apply this approach with building simulation tools that accept plain text input files as these can be generated programmatically for each permutation of input parameters. Smith (2009) used a Monte Carlo simulation approach to investigate the impact of building fabric, air-tightness and solar access on heating and cooling loads at building stock level. The thermal modelling was carried out with ESP-r[1]. Another simulation tool often used with probabilistic techniques is EnergyPlus[2], which, like ESP-r, can also be controlled by plain text files. Within the UK construction industry, IES Virtual Environment[3] and EDSL Tas[4] are the most widely used dynamic simulation tools (Raslan, 2010). Along with Bentley Systems Hevacomp Simulator[5], these three are the only dynamic simulation tools accredited for

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[1] `http://www.esru.strath.ac.uk/Programs/ESP-r.htm`

[2] `http://www.eere.energy.gov/buildings/energyplus`

[3] `http://www.iesve.com/software`

[4] `http://www.edsl.net/main/Software.aspx`

[5] `http://www.bentley.com/en-GB/Products/Hevacomp+Dynamic+Simulation/`

calculation under the NCM (DCLG, 2013). As none of these tools offer a straightforward way of generating multiple input files for batch simulation it is difficult to integrate a full Monte Carlo simulation approach directly into current industry practice.

To address this issue, an indirect approach is proposed that adapts the procedure outlined in TM54 (CIBSE, 2013). The TM54 procedure supplements the calculations carried out within the dynamic simulation tool with steady state calculations for energy loads that are independent of the building's thermal demand. These include lighting, vertical transportation (e.g. lifts), small power, catering, server rooms and domestic hot water. The procedure partly addresses the lack of uncertainty analysis in current industry practice by recommending that best-case and worst-case scenarios are modelled in addition to a typical scenario. These scenarios are chosen based on the likely range of variability in input parameters. The modelling will therefore produce three results; a typical result and likely upper and lower limits. Sensitivity analysis is limited to evaluating the impact of manual one-by-one changes to the input parameters, an approach that can become unwieldy if it is necessary to investigate the effect of variations in a range of input parameters.

The probabilistic technique described below is based on random sampling, which requires multiple iterations of the model to produce an output in the form of a probability distribution. Although the sub-system models in TM54 have a relatively large number of input parameters, their steady-state algorithms are simple enough to allow probabilistic calculation to be carried out virtually instantaneously. This is different from probabilistic calculations involving dynamic thermal models where the complexity of the model and number of iterations required can make the analysis a time-consuming process. In those situations, Latin Hypercube sampling has been frequently used (Tian, 2013). Here, the computational overhead of generating Latin Hypercube samples is significantly greater than that of running the model so it provides no benefit over simple random sampling with a sufficiently large sample size.

The deterministic approach and its probabilistic alternative are demonstrated for two of the regulated end-uses; lighting and domestic hot water. For each of these end-uses, a tree diagram is used to show how the various input parameters contribute to the annual end-use energy consumption. Unregulated loads such as catering, small power, and vertical transportation can all be modelled using the same tree diagram approach.

7.4 Lighting Energy Consumption

The calculation of annual lighting energy consumption follows the example given in TM54. This is based on the method described in BS EN 15193: 2007 (BSI, 2007a), which calculates a building's *lighting energy numeric indicator* (LENI), the total annual lighting energy requirement per unit area.

$$LENI = W_L + W_{em} + W_{pc} \quad [\mathrm{kWh}/(\mathrm{m}^2 \cdot \mathrm{year})]$$

Where W_L is the lighting energy consumed to fulfil illumination requirements, W_{em} is the charging energy for emergency lighting, and W_{pc} is the standby energy for lighting controls. The lighting energy for illumination is calculated as follows.

$$W_L = \frac{F_C P_N \left(t_D F_D F_O + t_N F_O\right)}{1000} \quad [\mathrm{kWh}/(\mathrm{m}^2 \cdot \mathrm{year})]$$

Where P_N is the total installed lighting power (W), F_C is the *constant illuminance factor*, F_D is the *daylight dependency factor*, F_O is the *occupancy dependency factor*, t_D is the daylight operating time (hours), t_N is the non-daylight operating time (hours). The constant illuminance factor is used to account for control systems that attempt to maintain a constant illuminance level between cleaning and re-lamping. Without such control, illuminance levels will tend to diminish over time.

The charging energy for emergency lighting, and the standby energy for lighting controls may be calculated as follows.

$$W_{em} = \frac{P_{em} t_{em}}{1000} \qquad [\mathrm{kWh}/(\mathrm{m}^2 \cdot \mathrm{year})]$$

$$W_{pc} = \frac{P_{pc}(t_y - (t_D + t_N))}{1000} \quad [\mathrm{kWh}/(\mathrm{m}^2 \cdot \mathrm{year})]$$

Where P_{em} is the total installed charging power of the emergency lighting, t_{em} is the emergency lighting charge time (hours), P_{pc} is the total installed parasitic power of lighting controls when the lamps are not operating, t_y is the standard number of hours in the year (8760 hours). W_{em} and W_{pc} are frequently assigned benchmark values of 1 $\mathrm{kWh}/(\mathrm{m}^2 \cdot \mathrm{year})$ and 5 $\mathrm{kWh}/(\mathrm{m}^2 \cdot \mathrm{year})$ respectively.

The final figure for annual lighting energy consumption is obtained by multiplying the LENI value by a management factor, F_M. This is intended to represent how well energy use is managed during operation.

Although lighting energy consumption is treated as a steady-state calculation in TM54, it is usually possible to estimate lighting consumption within dynamic simulation software. In this case the calculation takes into account variation in daylight levels (derived from solar radiation data in the hourly weather file) and therefore the impact of daylight-linked lighting control. The effect of this dynamic behaviour is in fact accounted for in the LENI model through the factor F_D, values of which are provided in BS EN 15193 for different locations, window orientations, daylight factors and illuminance levels.

The relationship between parameters is illustrated by the tree diagram in figure 7.12.

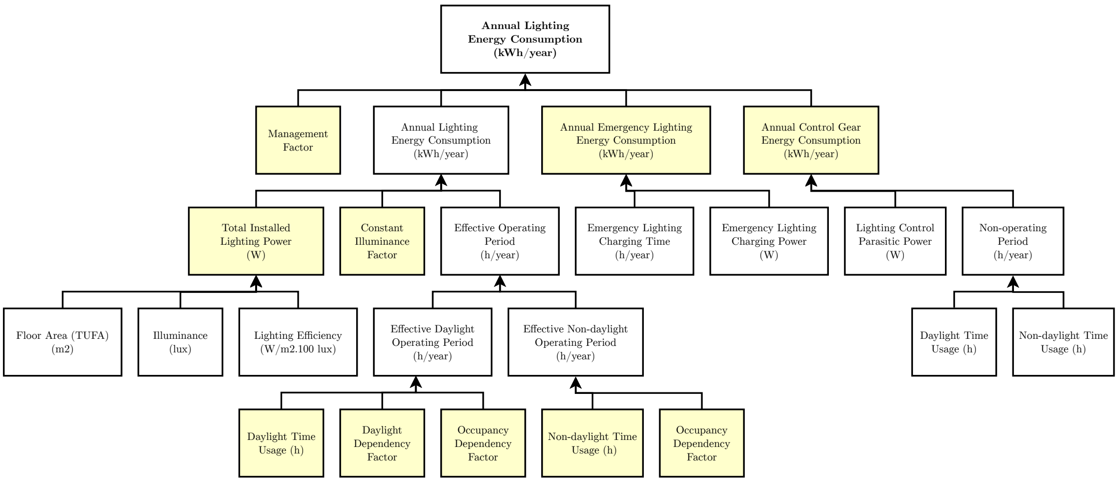

FIGURE 7.12: Lighting tree diagram

Note that it is not necessary to always begin calculating from the lowest level of the tree. The hierarchical structure can accommodate input data at different levels. In the example that follows, emergency lighting and control gear energy consumption are estimated directly, as is total installed lighting power.

7.4.1 Input data

The resulting deterministic model can be used to estimate annual lighting energy consumption as a function of the nine unique variables highlighted in figure 7.12. The following example, reproduced from TM54, illustrates the use of the model to obtain three scenario values, for low, mid and high energy consumption levels.

		Low-end	**Mid-range**	**High-end**
P_N	*Total installed power* (kW)	366	366	366
F_C	*Constant illuminance factor*	1.00	1.00	1.00
F_O	*Occupancy dependency factor*	0.90	0.95	1.00
F_D	*Daylight dependency factor*	0.90	0.95	1.00
t_D	*Daylight time usage* (h)	2620	3504	4346
t_N	*Non-daylight time usage* (h)	500	500	750
W_{pc}	*Parasitic control energy*	5.00	5.00	5.00
W_{em}	*Parasitic emergency energy*	1.00	1.00	1.00
F_M	*Management factor*	1.00	1.05	1.10

Table 7.1: TM54 lighting example scenarios

7.4.2 Scenario-based calculation

In this example, four of the variables remain constant and the remaining five can take three different values. As a result there are $3^5 = 243$ combinations possible. Rather than attempt to evaluate all combinations, TM54 simply calculates a lighting energy use for each of the three scenarios. The results of this example calculation are given in Table 7.2.

Scenario	**Annual Energy Density** (kWh/m^2)
Low-end	37.08
Mid-range	52.45
High-end	74.34

Table 7.2: Scenario-based lighting model results

7.4.3 Probabilistic calculation

The following example provides a probabilistic treatment of the annual lighting energy consumption calculation described above. The effect of variability and uncertainty in the input parameters is captured by assigning probability distributions instead of discrete values. This provides a more sophisticated analysis than either simply considering three separate scenarios or calculating all possible combinations of scenario inputs. The output distribution will reflect the probability of obtaining input values between the scenario limits rather than a series of discrete values.

The input parameters have been expressed as triangular distributions, which are useful when very little is known about the statistical characteristics of the data. If more information is available it may be possible to identify other underlying distributions that provide a more accurate representation of the variability in input parameters. Figure 7.13, for example, shows the empirical distribution obtained from 10^4 random samples of the management factor input distribution.

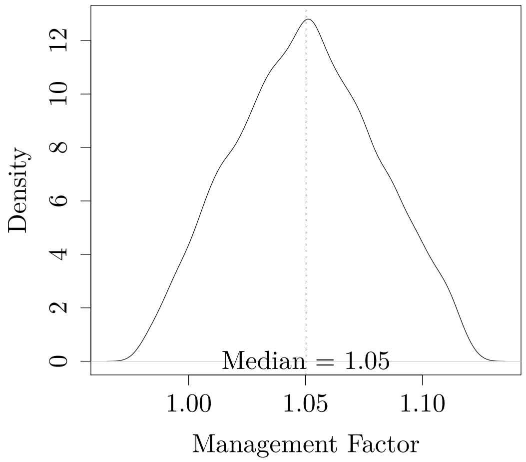

FIGURE 7.13: Example input distribution (lighting management factor)

Figure 7.14 shows the output distribution obtained from running the model with 10,000 samples from the input distributions. The shaded region represents the 90% confidence interval; 90% of the modelled results occur within this range. The median annual energy density will not necessarily equal the result of the mid-range scenario calculation because not all the input distributions are symmetrical. The range of the distribution is smaller than the range of the scenario results because the high and low scenarios were used to define 90% confidence intervals for the input distributions. As a result, the probability of obtaining all the input parameter values from the extremes of their distributions is very small. The probability of obtaining output values equal to or beyond the low-end and high-end scenario results shown in Table 7.2 is therefore 0.04% and 0.01% respectively. The advantage of the probabilistic calculation over the scenario-based calculation is that the probability density explicitly conveys the likelihood of different energy consumption figures.

7.4.4 Sensitivity analysis

Table 7.3 shows the results of the sensitivity analysis on the uncertain model parameters. Since the model function is simple and monotonic, standardised regression coefficients will give a reasonably reliable result. Robustness to non-linearity is increased by using

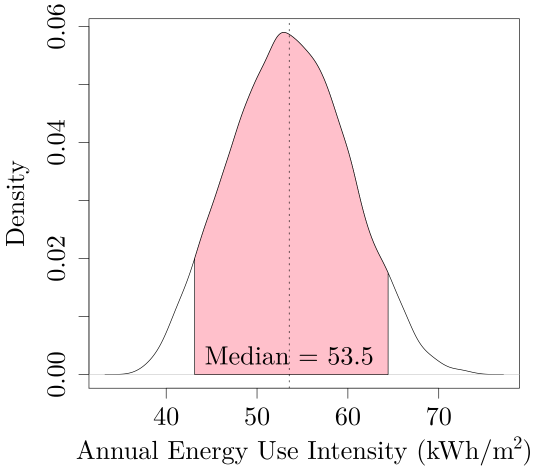

Figure 7.14: Annual lighting energy use intensity distribution

standardised ranked regression coefficients (SRRC). This rank transformation does not affect the relative sensitivities of the parameters.

Parameter	**Description**	**SRRC**
dtu	Daylight time usage	0.91
mf	Management factor	0.23
odf	Occupancy dependency factor	0.22
ddf	Daylight dependency factor	0.19
ntu	Non-daylight time usage	0.13

Table 7.3: Sensitivity analysis results

The high sensitivity of annual energy use intensity to daylight time usage results from the large range of uncertainty in this parameter. Conversely, there is less sensitivity to the other parameters on account of their smaller range. The results of the sensitivity analysis on this simple model are fairly trivial. However, the sensitivity of more complex models may be less intuitive if parameters with small ranges exert a disproportionate influence on the output value.

7.5 Domestic Hot Water Consumption

The calculation of annual DHW energy consumption follows the method described in chapter 6 and is illustrated schematically by the tree diagram in figure 7.15. The probabilistic calculation of total daily hot water consumption (at the bottom-left of the tree) is demonstrated by an interactive web-based app[6], which shows the effect of changing the range and most likely values of the input parameters. It also shows the effect of the sample size on the shape of the resulting distributions.

7.5.1 Input data

The input data for DHW model were based on empirical values from the case study building. The typical (most likely) values and 90% confidence minimum and maximum values are listed in Table 7.4. The data sources and assumptions used to obtain these values are described below.

	Minimum	**Typical**	**Maximum**
Specific occupancy (m^2/person)	30	60	84
Individual consumption (l/(person·day))	3	4.5	10
Average daily hours of operation (hours/day)	10.5	15	24
Average annual days of operation (days/year)	304	252	365
Hot water storage temperature (°C)	54	60	66
Cold water supply temperature (°C)	10	12.5	15
Primary loop length (m)	19	24	29
Primary loop loss per unit length (W/m)	17	21	25
Secondary loop length (m)	203	254	305
Secondary loop loss per unit length (W/m)	14	18	22
Calorifier standing loss (kWh/day)	4.8	10.9	12.0
Primary generation efficiency (%)	67	72	75

TABLE 7.4: DHW input data uncertainty

Specific occupancy

The term specific occupancy is used here to refer to the gross floor area per occupant (m^2/person). It is the inverse of occupancy density. The typical value was based on the assumption of 50% occupancy in 70% of the office units (the percentage let during the latter half of the monitoring period). The maximum value was based on full occupancy in 70% of the office units; the minimum was based on 50% occupancy in half of the office units.

It's worth noting that these values are much lower than those reported in a recent survey of UK office space (BCO, 2013), which stated a mean value of approximately 11 m^2 net internal area per person. Using a conversion factor of 76% net to gross (CIBSE, 2012)

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[6] Available at: `https://ndoylend.shinyapps.io/Coursera_DevDataProd/`

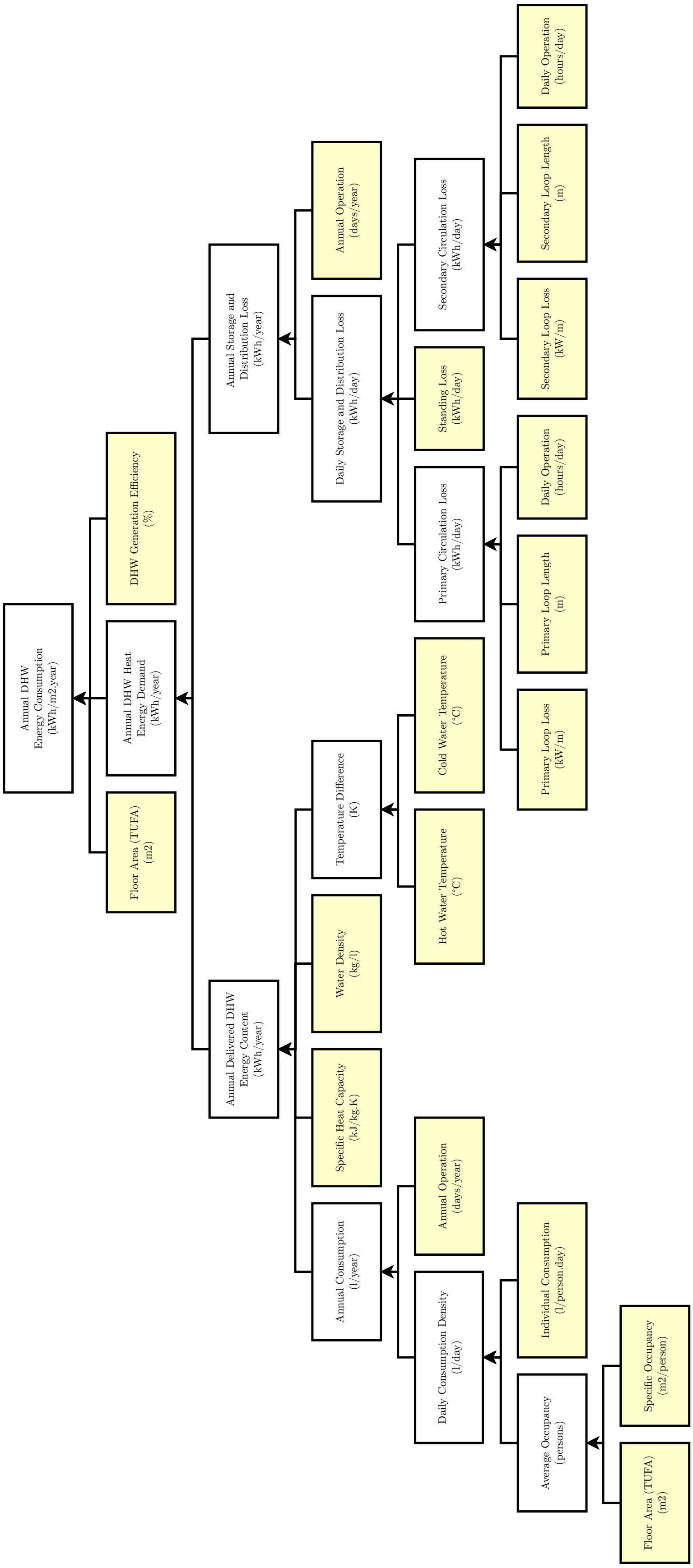


Figure 7.15: Domestic hot water tree diagram

gives a figure of 14.5 m^2 per person. The difference between this figure and that for the case study building is due to its relative low occupancy and the inclusion of spaces like the auditorium, street and café in the total area.

Individual consumption

The typical average daily hot water consumption (l/person) was obtained by dividing the measured average consumption by the estimated typical occupancy. Maximum and minimum values were obtained from published data (CIBSE, 2004).

Operating period

The typical daily hours of operation was based on the weekly average of weekday operating period (15 hours) and weekend operating period (10.5 hours). The maximum value was based on the weekday operating period; the minimum was based on the weekend operating period. The typical average annual days of operation was based on a six-day week less eight bank holidays. The maximum annual days of operation was base on year-round operation; the minimum was based on a five-day week less eight bank holidays.

Water temperatures

The typical hot water storage temperature was based on the documented BMS configuration and measured data. The maximum and minimum values of the hot water temperature were obtained from the typical values ±10%. The typical cold water supply temperature was based on the annual mean ambient temperature. The maximum and minimum values of the cold water temperature were obtained from the typical values ±20%.

Distribution losses

The typical primary loop length was estimated from site inspection. The typical secondary loop length was estimated according to the SBEM rule of thumb ($4 \times \sqrt{\text{area served}}$) The maximum and minimum values of these lengths were obtained from the typical values ±20%. The typical primary and secondary loop losses were estimated from measured data. The maximum and minimum values of these lengths were again obtained from the typical values ±20%.

Standing loss

The typical calorifier standing loss was estimated from measured data; the maximum value was obtained from the typical value plus 10%; the minimum value was obtained from the manufacturer's data (Hamworthy, 2012).

Generation efficiency

The typical DHW primary efficiency was calculated from measured data; The maximum and minimum values was obtained from the measured data's 90% confidence range.

Constant terms

The specific heat capacity and density of hot water were taken as constant values. It was also assumed that there is no uncertainty in the building floor area, which was taken as the total usable floor area (TUFA) from the building's Display Energy Certificate (DEC).

7.5.2 Scenario-based calculation

Table 7.5 gives the results of the three scenarios. The striking difference between the low-end and high-end results is due to the assumption that the input variables are at all at their best levels in the low-end scenario and their worst levels in the high-end scenario. In reality, the input variables are likely to occur within a range of values.

Scenario	**Annual Energy Density** ($\mathrm{kWh/m^2}$)
Low-end	3.72
Mid-range	10.20
High-end	28.59

Table 7.5: Scenario-based DHW model results

7.5.3 Probabilistic calculation

The output distribution of annual energy density is shown in Figure 7.16. The shaded area shows that 90% of the output values fall in the range 7.34 $\mathrm{kWh/m^2}$ to 15.10 $\mathrm{kWh/m^2}$, a much narrower interval than suggested by the scenario-based calculation. The median

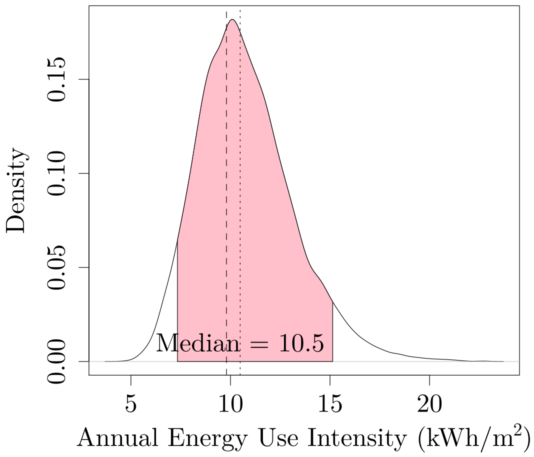


FIGURE 7.16: Annual DHW energy use intensity distribution

value, 10.49 kWh/m^2 is within 10% of the value obtained in the previous chapter from measured consumption data (9.8 kWh/m^2, indicated on the plot by the dashed line).

7.5.4 Sensitivity analysis

Parameter	**Description**	**SRRC**
annual_op	Average annual days of operation	0.50
ind_consump	Individual consumption	0.40
sl_loss	Secondary loop loss per unit length	0.35
sl_len	Secondary loop length	0.33
daily_op	Average daily hours of operation	0.32
st_loss	Calorifier standing loss	0.10
dhw_temp	Hot water storage temperature	0.08
pl_len	Primary loop length	0.04
pl_loss	Primary loop loss per unit length	0.04
cold_temp	Cold water supply temperature	-0.03
gen_eff	Primary generation efficiency	-0.15
spec_occ	Specific occupancy	-0.34

TABLE 7.6: Sensitivity analysis results

The results of the sensitivity analysis (Table 7.6) show that the annual days of operation and estimated daily hot water consumption (the combined effect of individual consumption and specific occupancy) are the greatest sources of uncertainty in the DHW model. Daily operating hours and heat losses from the secondary circulation loop are also significant. In general, the sensitivities of individual parameters will depend on the level of uncertainty in the parameter and the structure of the model.

7.6 Bayesian Networks

An interesting extension of the probabilistic approach described above is the development of Bayesian networks that reflect the structure of the energy tree diagrams. Training cases obtained by tabulating the randomly sampled input data with the corresponding output data can then be used to build the probability distributions within the network. The benefit of this approach is that once trained, the network can very easily be used to evaluate the impact of different combinations of input and output values. For example, if an actual energy use intensity is known, it can be entered in the network and the probability distributions of the input data will be updated accordingly. This form of diagnostic reasoning may be useful in energy audits of existing buildings. Figure 7.17 shows an example network for annual DHW demand.

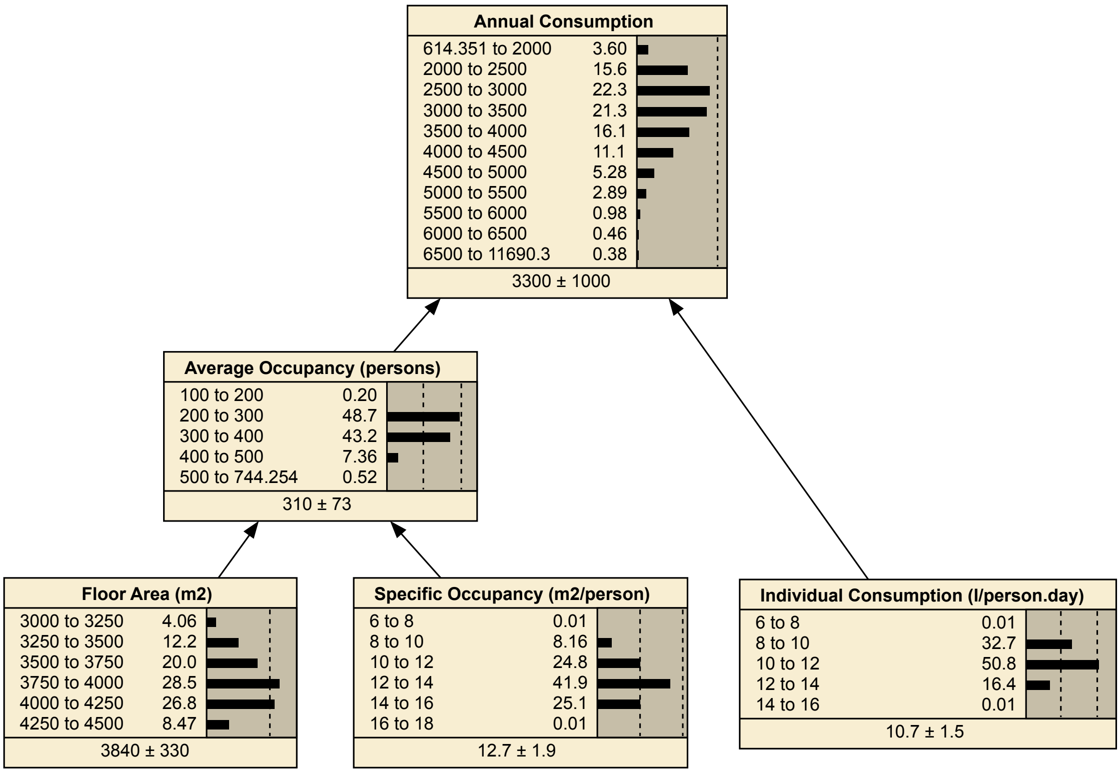


Figure 7.17: Bayesian Network for DHW Demand

7.7 Discussion

Similar analyses to those described above can be carried out for each of the building's principal energy sub-systems and the resulting probability distributions combined to obtain an overall probabilistic estimate of the building's energy use intensity. Although the model development work was carried out using R (R Core Team, 2014), the calculation algorithms are simple enough to be implemented as spreadsheet macros, making the approach widely accessible to industry. Both the probability distributions and sensitivity analysis results could then be presented in a more user-friendly form. For example, since the width of the distribution represents the level of uncertainty in the calculation results it could be colour coded to correspond to high, medium and low uncertainty. Similarly, the sensitivity analysis results could be colour coded to indicate the degree of sensitivity to each parameter.

One limitation of this approach is that the energy tree diagram calculations are not dynamic models, so they are only applicable to energy consumption obtained from steady-state calculations. Although it is possible to estimate annual energy consumption using steady-state models (Wang et al., 2012), particularly in simple buildings (Van der Veken et al., 2004; Carlos and Nepomuceno, 2012), a detailed calculation of thermal loads and plant behaviour is not possible. This is not necessarily a disadvantage, particularly when there is considerable uncertainty in input parameters. In these situations, the greater precision of the dynamic tools does not necessarily correspond to greater accuracy.

In theory, the probability distributions of the input parameters can be sampled to obtain sets of input data for Monte Carlo based runs using dynamic simulation software. The time required to carry out a large number of simulation runs and the difficulty in automating the process in currently accredited simulation tools are major drawbacks in applying probabilistic techniques to dynamic models. In practice, a hybrid approach could be used in which probabilistic calculations are carried out for parameters that can reliably be calculated outside of the dynamic model. The dynamic model is then used to run a small number of scenarios with input values chosen on the basis of the probabilistic calculations relating to input parameters. The resulting output values are then recombined with the probabilistic calculations relating to parameters not accounted for in the dynamic model (such as unregulated loads). Alternatively it may be sufficiently accurate, particularly at early design stages, to use energy tree diagram calculations with steady-state models of annual thermal demand based, for example, on peak heating load, monthly degree days or temperature bins and equivalent full-load hours. These could then be analysed using the probabilistic technique described above.

The procedure described in TM54 applies a management factor to each annual energy end use in order to account for differing levels of building management, maintenance and use of energy saving features. Unlike the majority of input parameters, the management factor is not objectively quantifiable. Birtles and Grigg (1997) explain that management factors are determined on the basis of experience and collective judgement. TM54 outlines a series of interview questions that can be used to develop estimates for management factors and states that *a management factor of 1.1 can be applied to represent a 10% increase in energy use due to poor management* (CIBSE, 2013). The subjective nature of the management factor is an apparent weakness in a methodology that attempts an objective quantification of uncertainty in performance estimates. Applying a probabilistic approach will help to manage the uncertainty associated with the management factor but further research is necessary to develop a robust means of assessing both the level and the impact of energy management in buildings.

7.8 Conclusions

This chapter has demonstrated the application of probabilistic methods to the steady-state calculations used in TM52. The advantage of this approach over a scenario-based approach is that the resulting probability distributions convey the likelihood of different energy consumption figures. Under a scenario-based approach, the best and worst case scenarios may have a very low probability of occurrence. Since these calculations are based on energy tree diagrams they are also readily applicable to the TM22 methodology. The underlying principle is that the uncertainty associated with each input parameter can be expressed in terms of a probability distribution. Carrying out multiple calculations with input parameter values randomly sampled from the input distributions will result in a probability distribution of output values. The most likely value and overall variability of the quantity of interest (typically annual energy use intensity) can be obtained from this output distribution.

The technique is applicable throughout the building lifecycle; albeit with different sources of information and levels of uncertainty. An advantage of the technique is its simplicity and computational efficiency, compared with constructing and running multiple dynamic simulation models. Early calculations can be based on typical design stage estimates or rules of thumb. In-use calculations can be based on guesswork, documentation or measured data, with uncertainty ranges corresponding to the degree of confidence in the input data. The sensitivity of the result to the variation in input data can highlight influential sources of uncertainty. This information can be used to identify the parameters that should be established with greater accuracy and those for which rough estimates will be sufficient.

Chapter 8

Energy Performance Risk Evaluation

8.1 Introduction

This chapter describes an approach to evaluating the risk of a building failing to meet design energy performance targets. The literature review identified a range of technical risk factors; here these factors are categorised and examples given. Since these factors may be the manifestation of lifecycle issues such as procurement and management, wider guidance relating to project performance as a whole is briefly reviewed. These factors are then combined as a taxonomy of risks relating to the potential failure to meet building energy performance targets. These risks may fall in the domain of a range of stakeholders and may be present at different stages in the project lifecycle. A mapping of taxonomy categories to key stakeholder group and lifecycle stage can help to identify where the main responsibility lies and at what project stage action should be taken. The taxonomy is then used in the development of causal maps of the risk factors. These could be used firstly as a communication tool to raise awareness of the interconnected nature of energy performance risk and also to guide construction review processes of feedback and continuous improvement. Two approaches to quantifying risk factors are proposed; the Lens model, which is used to calibrate expert judgement on the relative impact of risk factors, and Bayesian networks, which can be developed from causal maps to represent probabilistic relationships between factors. The development of these approaches into an analytic tool for the quantitative evaluation of risk impacts and likelihoods is then outlined. The chapter concludes by summarising the findings from the qualitative evaluation of the case study building and its procurement process. The evaluation was carried out through interviews with members of the design and construction team, building occupants and management staff. A post-occupancy evaluation using the Building Use Studies (BUS) questionnaire was also undertaken as part of the evaluation. Key risk factors are identified in the evaluation results.

8.2 Energy Performance Risk Factors

Existing literature was reviewed to categorise risk factors relating to building energy performance gaps. Table 8.1 lists the categories identified and provides relevant examples from the literature. These examples are intended to be illustrative of generic technical risks rather than provide a definitive catalogue of problems.

Category	Example
Commissioning	The lack of commissioning even on new "green" projects remains a major concern. Buildings are still being delivered with major commissioning flaws such as air handlers that never turn off and incorrect equipment installations (Bannister, 2009).
Usability	Operators and users may find it difficult to understand the control systems and operate them effectively (Bordass et al., 2004).
Reliability	Lowest-cost procurement provides a near guarantee that poorer quality equipment will be used throughout the building. As this equipment fails, it often causes energy consumption to rise by corrupting intended control regimes (Bannister, 2009).
Modelling Accuracy	Building energy simulation programs cannot possibly model all types of air conditioning systems . . . the designer must make the best of what options are available and use their skill and experience to approximate the actual system and its operation as best they can (Mason, 2004).
Design Intent	Changing requests from clients and/or value engineering exercises can result in significant deviations from what was originally specified (Bordass et al., 2004).

Category	Example
Communication	The lack of proper training of the workforce in combination with a poor liaison with the design team and system specialists resulted in significant construction faults, unplanned design solutions and wrong system commissioning (Gupta and Dantsiou, 2013). Failure to include operations staff in goal setting or accurately communicate the design intent to staff (Hinge et al., 2008).
Build Quality	It is not unusual for structures to cut into zones which had been intended for insulation, and to make air sealing measures very difficult to install; and for cladding systems not to be of the intended thermal integrity, especially at interfaces (Bordass et al., 2004).
Design Quality	Designers and developers [are often encouraged] to trim some of the basic good design or plant selections out of the design on the grounds that they are unnecessary to achieve the required level of efficiency (Bannister, 2009).
Occupant Behaviour	There may be emergent properties and unintended consequences, for example control systems which irritate the occupants and are therefore by-passed (Bordass et al., 2004). Tenants use ancillary equipment, such as heaters, fans and task lights, if proper air flow and services are not effectively delivered (Hinge et al., 2008).
Modelling Assumptions	Optimum control strategies and schedules are often assumed which do not occur in operation. For example, daylighting strategies would normally assume that artificial lighting is dimmed or turned off but operators or occupants often do not understand this and may not recognize if the controls are not working properly (Hinge et al., 2008).
Modelling Omissions	The designers may often have only reported the energy used by normal building services (heating, hot water, cooling, ventilation and lighting), not by anything else (Bordass et al., 2004).

Category	Example
Operation & Maintenance	Maintenance and energy management may not be up to standard (Bordass et al., 2004). The decision to adjust setpoints rather than correct problems, or the decision to run plant extra hours that are not needed, is often a key issue in the failure of a building to perform (Bannister, 2009).
Ongoing Monitoring	Careful testing and monitoring of system performance under actual loads is essential to identify and correct instabilities inherent in the systems as installed. Most complex buildings can easily take three years (or three seasonal cycles) to be brought up to optimal operation (Hinge et al., 2008).
Design Changes	What was actually specified to be built may have deviated from the design assumptions at the time the options were appraised and the estimates of energy use (Bordass et al., 2004).
Commissioning	In the buildings studied the excessive increase in heating consumption was mainly due to BMS commissioning shortfalls and lack of seasonal commissioning (Kimpian et al., 2014). . . . inspection revealed that most of the systems remained to be fully commissioned while for those that had undergone pre-commissioning there was no documented evidence on site (Gupta and Dantsiou, 2013). The systems may never be fine-tuned to suit changing occupancies and seasons (Bordass et al., 2004).
Handover	Most clients and users become 'crash test dummies': they are abandoned by the project team after handover just when they are likely to need the most help (Way and Bordass, 2005). Clients are hesitant to pay designers to return after occupancy, and designers have generally moved on to the next urgent project deadline (Hinge et al., 2008).

Table 8.1: Root causes of performance discrepancy

The technical risks identified in Table 8.1 are the manifestation of a wider range of issues. Bordass et al. (2001) describe factors identified in the PROBE study carried out on the University of East Anglia's Elizabeth Fry Building. They emphasised the importance of process and effective relationships within the design, construction and user teams.

More recently, Kimpian et al. (2014) identified the need to account for procurement and operational risks at the design stage. Since these additional factors are predominantly qualitative, their identification is a more subjective process.

The Commission for Architecture and the Built Environment (CABE), the Government's advisor on architecture, urban design and public space from 1999 to 2011, published guidance intended to help construction clients commission successful projects (CABE, 2003). This guidance included a number of 'watch points' which described a number of risk factors in the following areas:

- Client team
- Procurement
- Design
- Project team
- Approvals and context
- Site / construction

Similar guidance, published by the UK Office of Government Commerce (OGC) under the title 'Achieving Excellence in Construction' identified 'factors for success', the absence of which could increase the risk of unsatisfactory performance (OGC, 2007a). Although these documents addressed project performance in a more general sense, many of the factors are relevant to building energy performance.

Chan et al. (2004) conducted a study of project management literature and identified five main categories of factors that affect the success of construction projects, namely human-related factors, project-related factors, project procedures, project management actions, and external environment. Koutsikouri et al. (2008) used a process of expert elicitation including semi-structured interviews and facilitated workshops to identify critical success factors in multi-disciplinary design projects. Their four overall factor groups covered management issues, design team issues, competencies and resources, and project enablers. Two of these groups included factors that had not been identified in earlier work. These included the design team issues of inter-disciplinary team working and creativity and innovation, and the project enablers passion and enthusiasm and shared values.

8.3 Performance Risk Taxonomy

To facilitate the identification and evaluation of these risk factors, a taxonomic risk identification technique, developed by Carr et al. (1993), has been applied. This technique was developed to enhance the probability of success of software development projects by providing a systematic and repeatable identification of risks, based on a hierarchy of classes, elements and attributes. Classes, representing the highest taxonomic level, are divided into constituent elements, each associated with a set of attributes. For software development projects, three classes were defined: Project Engineering, Development Environment, and Program Constraints. Gallagher et al. (2005) applied the same technique to classify risks to a diverse range of operational missions including those of military units and customer service units. The three classes in the taxonomy of operational risks were: Mission, Work Processes and Constraints.

The taxonomic approach was used to categorise the energy performance risk factors identified in the literature. The risk factors were translated into elements and attributes and then assigned to four general classes, illustrated in Figure 8.1 and described below.

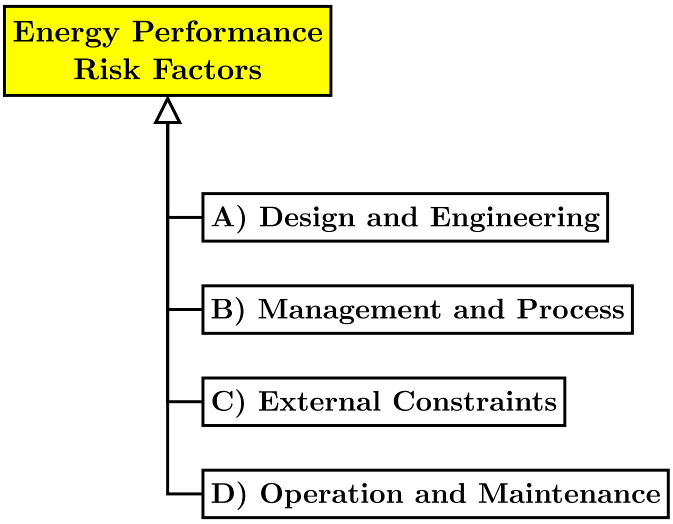


FIGURE 8.1: Classes of energy performance risk

8.3.1 Design and engineering risks

The Design and Engineering class encompasses the translation of requirements into a brief, the design development from brief to specification, including the assumptions made and the suitability of the technologies used. Figure 8.2 illustrates the elements and attributes of this class.

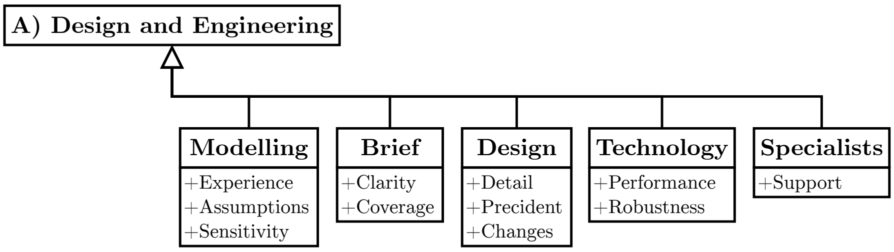


FIGURE 8.2: Class diagram for design and engineering risks

8.3.2 Management and process risks

The Management and Process class encompasses leadership, teamwork, contracts, procurement route and the quality of the construction itself. Figure 8.3 illustrates the elements and attributes of this class.

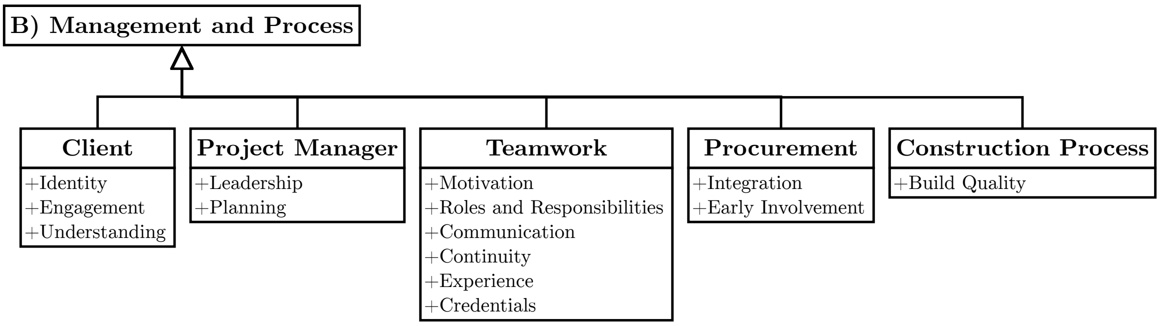


FIGURE 8.3: Class diagram for management and process risks

8.3.3 External constraints

The External Constraints class includes resources (such as schedule and funding), physical, technical and statutory constraints (such as planning and regulatory requirements). Figure 8.4 illustrates the elements and attributes of this class.

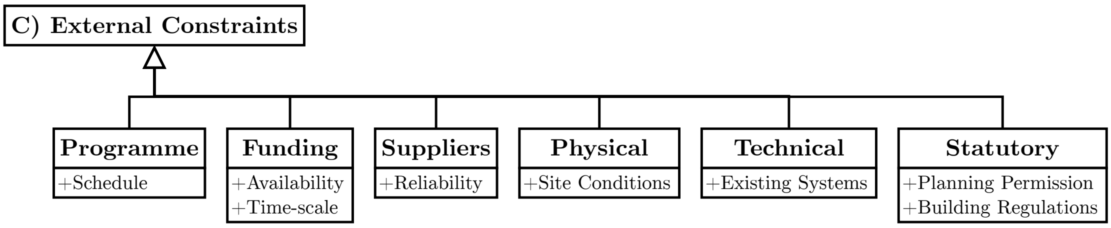


FIGURE 8.4: Class diagram for external constraints

8.3.4 Operation and maintenance risks

The Operation and Maintenance class encompasses the building users, facilities management and the commissioning and handover process. Figure 8.5 illustrates the elements and attributes of this class.

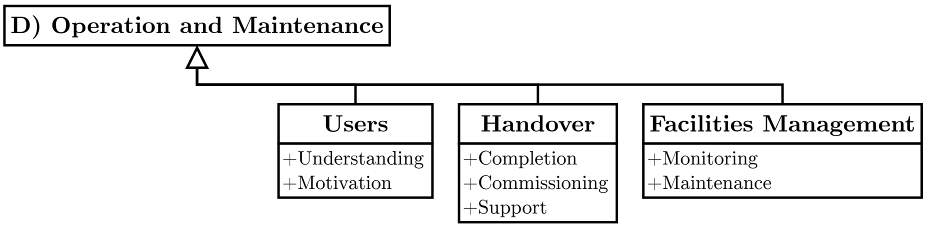


FIGURE 8.5: Class diagram for operation and maintenance risks

8.3.5 Taxonomy Based Questionnaire

In both Carr et al. and Gallagher et al. the taxonomy was used to create a taxonomy-based questionnaire (TBQ) that can be used to facilitate risk identification through a series of interviews. Na et al. (2007) applied the TBQ survey approach to evaluate both objective and subjective performance risks in software development.

A proposed adaptation of the TBQ survey is illustrated in Tables 8.2, 8.3, 8.4 and 8.5, which contain a series of questions intended to establish the presence of performance risks associated with each attribute. Currently, simple yes/no questions have been used to demonstrate the principle. A greater level of flexibility could be obtained by rewording the questions for use with anchored seven-point scales, in a similar fashion to the BUS questionnaire. The TBQ can be used as a risk management tool at various stages in the building project. It could be used in workshops and interviews with project participants to evaluate existing or proposed projects. When considering proposed projects, the questions would be reworded to elicit estimated probabilities that the risk factors occur.

Element	**Attribute**	**Example question**
Brief	Clarity	Is the brief clear and unambiguous?
	Coverage	Does the brief cover all areas of client requirements?
Design	Detail	Is the design complete to an appropriate level of detail e.g. technical requirements?
	Precedent	Is there any precedent for the design concept and its implementation?
	Late Changes	Is there a risk that significant design changes are made later in the project?
Technology	Performance	Is performance data available for similar applications of the proposed technology?
	Robustness	Is the proposed technology (including control strategy) sufficiently robust, given the building's procurement route and facilities management?
Modelling	Experience	Is the modelling work carried out by people with experience of similar projects?
	Assumptions	Is there significant uncertainty in modelling assumptions?
	Sensitivity	Has the modelling accounted for sensitivity of overall performance to variation in input parameters?
Specialists	Support	Has specialist support been adequate when required?

TABLE 8.2: Taxonomy questions for design and engineering risks

Element	**Attribute**	**Example question**
Client	Identity	Is there likely to be a clearly identified client for the duration of the project?
	Engagement	Is the client effectively engaged in project decision making?
	Understanding	Does the client have a good understanding of the design proposal?
Project Manager	Leadership	Is the project manager able to lead the project team?
	Planning	Is the project manager able to plan effectively?
Teamwork	Motivation	Do team members share a commitment to delivering a low-energy building?
	Roles and Responsibilities	Are project team members' roles and responsibilities clearly defined?
	Communication	Is there effective sharing of information along well defined lines of communication?
	Continuity	Is the project team stable throughout the project (i.e. without frequent staff changes)?
	Experience	Has the team successfully worked together on other projects?
	Credentials	Have individual team members contributed to the successful delivery of similar projects?
Procurement	Integration	Does the procurement route support integrated design to maintain design intent throughout the project? (e.g. retention of consultants to work with contractors)?
	Early Involvement	Are the team members (including contractors and building operators) involved early in the project?
Construction Process	Build Quality	Is there likely to be sufficient skill and supervision on site to deliver the required build quality?

Table 8.3: Taxonomy questions for Management and Process Risks

Element	**Attribute**	**Example question**
Programme	Schedule	Is the project schedule realistic for completing the project in the planned duration?
Funding	Availability	Is sufficient funding for the proposed design secured for the project?
	Time-scale	Are there any constraints on the timing of funding draw down?
Suppliers	Reliability	Is there a risk of external supplier or contractor reliability affecting the project?
Physical	Site Conditions	Are site conditions (e.g. existing utilities) likely to affect the construction process?
Technical	Existing Systems	Are compatibility issues with existing systems (e.g. district heating) likely to affect the project?
Statutory	Planning Permission	Is there a risk of refusal or delay in obtaining planning permission?
	Building Regulations	Is there a risk of refusal or delay in obtaining regulatory approval (e.g. Part L compliance)?

Table 8.4: Taxonomy questions for External Constraints

Element	**Attribute**	**Example question**
Users	Training	Will users be trained in appropriate use of the building?
	Motivation	Are users likely to be motivated to use the building appropriately?
Handover	Completion	Is there a risk that the project will be rushed to meet a completion deadline?
	Commissioning	Is there a risk that the building's technical systems may not be fully commissioned?
	Support	Is the project team committed to providing post-handover support?
Facilities Management	Monitoring	Will the building operator monitor the building's performance?
	Maintenance	Will the maintenance team have adequate skills and resources to maintain the building?

Table 8.5: Taxonomy questions for Operation & Maintenance Risks

8.4 Project Stakeholder and Lifecycle Stages

In addition to identifying the risks themselves, it is helpful to identify stakeholder groups having the greatest influence on the different risk factors. A list of typical project stakeholders was compiled and condensed into six main stakeholder groups (Table 8.6). The groups are defined fairly loosely as not all the stakeholders identified will be present on every project and some of the stakeholders may have multiple roles within a project.

It is also helpful to identify where in the project lifecycle the risk are likely to occur. The 2013 RIBA Plan of Work (RIBA, 2013) divides the construction project lifecycle into a sequence of eight stages (Figure 8.6).

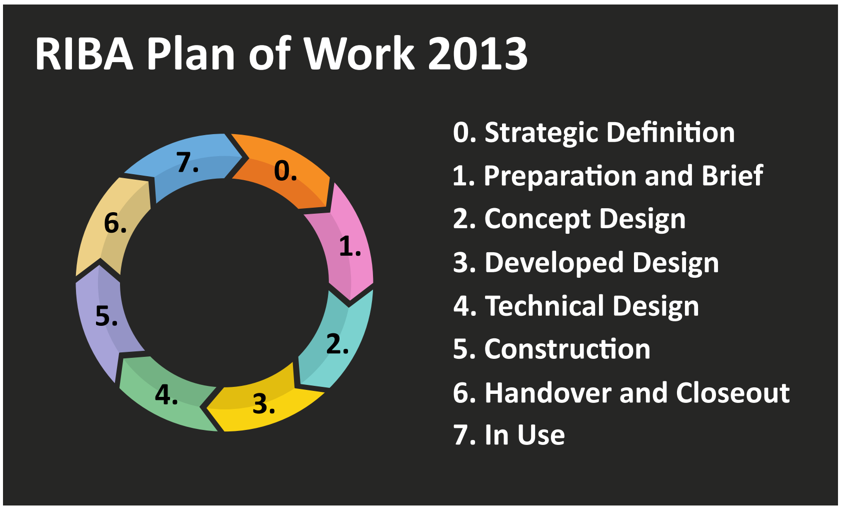


Figure 8.6: RIBA 2013 Plan of Work (after RIBA, 2013)

These stages can be simplified into five broad themes.

- Preparation
- Design
- Construction
- Handover
- Use

Zou et al. (2006) related a series of 20 project-related risks to their associated stakeholders and project lifecycle stages using a fish-bone diagram. Using a similar approach, the risk elements listed above have been mapped to the most relevant stakeholder group and project phase (Figure 8.7). This diagram could be used by project team members as part of a performance risk management process.

Stakeholder group	**Stakeholder**
Client Team	Client Developer Landlord Client representative
Design Team	Architect Mechanical engineer Electrical engineer Structural engineer Specialist consultants
Project Management	Project manager Cost consultant
Construction Team	Main contractor Mechanical contractor Electrical contractor Controls contractor Commissioning engineer Manufacturers and suppliers
Regulators	Building Control Planning Authority Central Government
Operators & Users	Facilities manager Maintenance team Tenant organisation Building occupants

Table 8.6: Stakeholder Groups

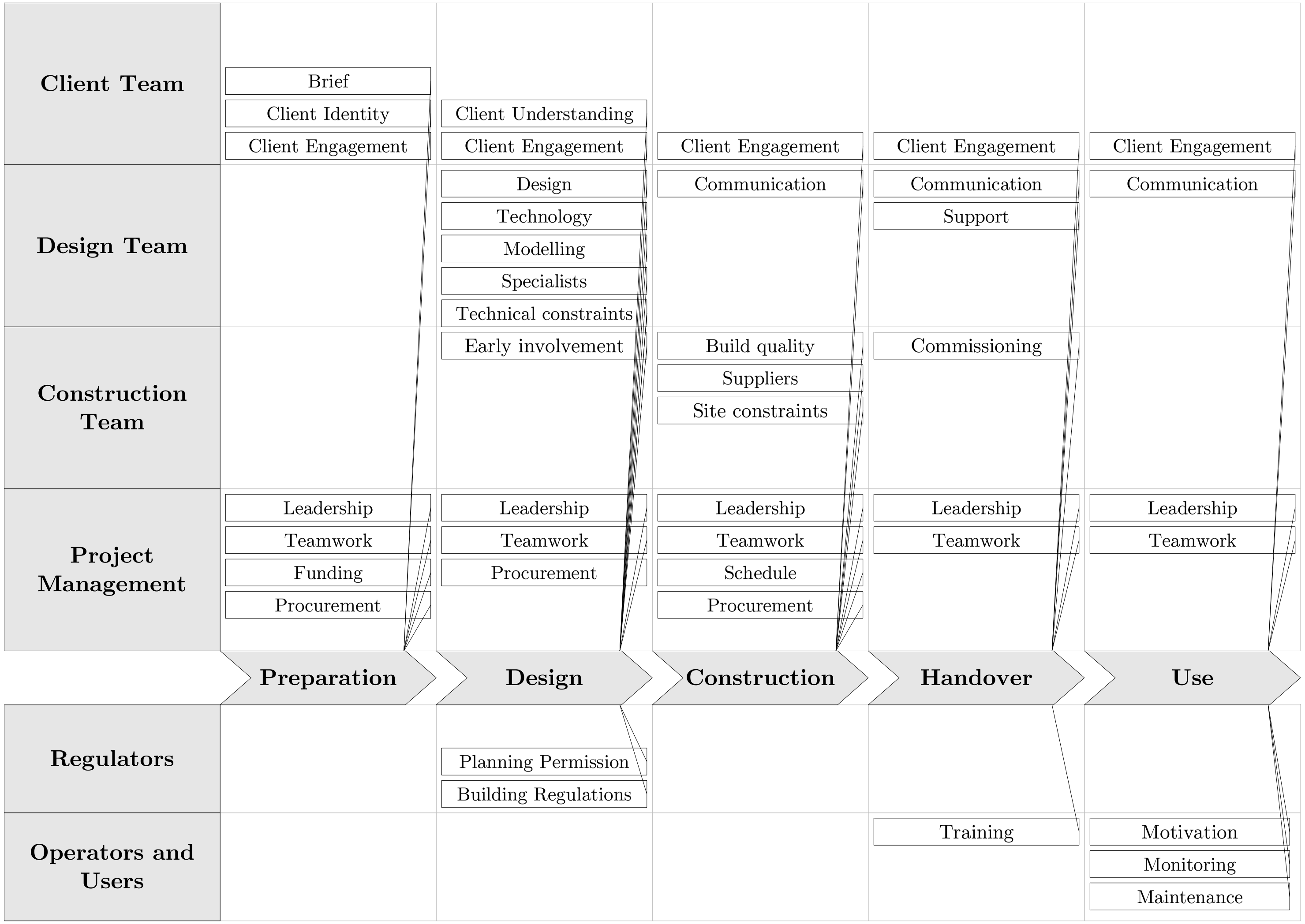


Figure 8.7: Performance risk elements by stakeholder and project phase

8.5 Mapping Risk Factors

The taxonomy provides a way of classifying and understanding the performance risks however it does not capture the interrelationship between the risk attributes of different elements. Koutsikouri et al. (2008) concluded that critical success factors are closely related to the socio-political dynamics of inter-disciplinary team work. Due to the interdependence of these factors, their identification and classification alone was considered insufficient to understand how to achieve project success. An approach is necessary that can consider the interrelationships of the factors involved. The risk taxonomy developed in this section provides the foundation from which such system models can be developed. Soetanto et al. (2011) describe a process of scenario development and causal mapping that could be applied to this task. Causal maps provide a graphical model of concepts and causal relationships, which can be used in risk mitigation to help anticipate unintended consequences (Al-Shehab et al., 2005). A robust technique for developing causal maps is described by Nadkarni and Shenoy (2004). This involves the use of structured methods (questionnaires and adjacency matrices) to elicit causal relationships from domain experts. The methods described facilitate the distinction between direct and indirect causes and the elimination of circular relations. Figure 8.8 shows part of a proposed questionnaire intended to identify cause and effect relationships in the operation and maintenance class.

Please tick one of the four alternatives provided to specify the type of direct relationship between the factors listed below. Also tick the sign associated with the relationship.

Relationship between factors							
Factor	Type of relationship				Sign		Factor
	None	→	←	↔	+	-	
1. Insufficient user training	☐	☐	☐	☐	☐	☐	2. Poor user motivation
1. Insufficient user training	☐	☐	☐	☐	☐	☐	3. Rushed completion
1. Insufficient user training	☐	☐	☐	☐	☐	☐	4. Incomplete commissioning
1. Insufficient user training	☐	☐	☐	☐	☐	☐	5. Lack of handover support
1. Insufficient user training	☐	☐	☐	☐	☐	☐	6. Poor FM vigilance
1. Insufficient user training	☐	☐	☐	☐	☐	☐	7. Poor FM maintenance
2. Poor user motivation	☐	☐	☐	☐	☐	☐	3. Rushed completion
2. Poor user motivation	☐	☐	☐	☐	☐	☐	4. Incomplete commissioning
2. Poor user motivation	☐	☐	☐	☐	☐	☐	5. Lack of handover support
2. Poor user motivation	☐	☐	☐	☐	☐	☐	6. Poor FM vigilance
2. Poor user motivation	☐	☐	☐	☐	☐	☐	7. Poor maintenance
3. Rushed completion	☐	☐	☐	☐	☐	☐	4. Incomplete commissioning

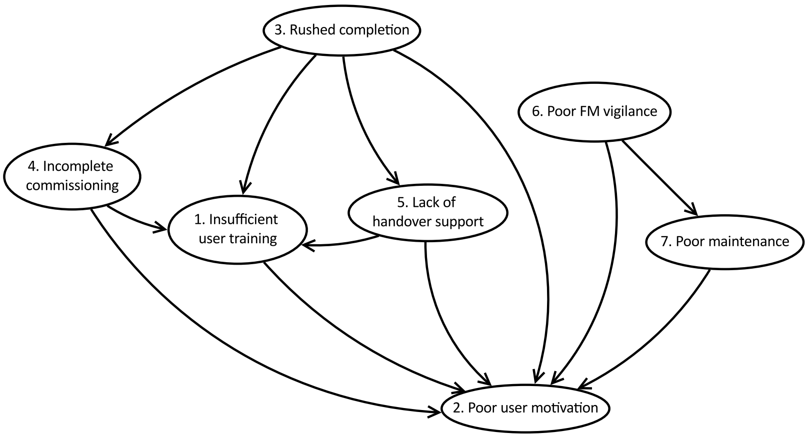
FIGURE 8.8: Structured interview to identify relationships

The number of factors that can be related using the questionnaire technique is limited; identifying pairwise relationships between 5 factors requires $\binom{5}{2} = 10$ questions. Increasing the number of factors to 10 increases the number of questions to 45. Once the relationships have been indicated on the questionnaire they can be transferred to an adjacency matrix such as in Figure 8.9. The matrix row and column numbers correspond to individual factors. The elements themselves define the relationships as positive (+), negative (-) or none (·). If the number of factors would make a questionnaire unwieldy it may be easier to enter the cause and effect relationship directly in the adjacency matrix.

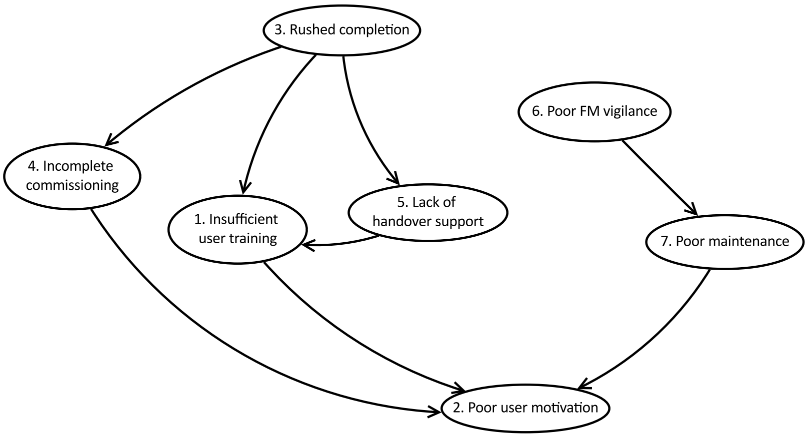
	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**
1.	■	·	+	+	+	·	·
2.	+	■	+	+	+	+	+
3.	·	·	■	·	·	·	·
4.	·	·	+	■	·	·	·
5.	·	·	+	·	■	·	·
6.	·	·	·	·	·	■	·
7.	·	·	·	·	·	+	■

FIGURE 8.9: Adjacency matrix

Once an adjacency matrix has been populated, drawing up the corresponding causal map is a straightforward task. Figure 8.10a shows a causal map of factors relating to the operation and maintenance class. This initial map may be simplified to clarify the relationships and facilitate subsequent conversion into a Bayesian network. The graphical nature of the map makes it easier to identify weak or redundant relationships that may be removed to simplify the map. This is illustrated in Figure 8.10b, where four links have been removed. The links between 4 and 1 (incomplete commissioning and insufficient user training), 3 and 2 (rushed completion and poor user motivation), 5 and 2 (lack of handover support and poor user motivation) and 6 and 2 (poor facilities management vigilance and poor user motivation) have been removed as they were judged unlikely to represent strong and direct causal relationships. For example, building occupants are unlikely to be poorly motivated as a direct consequence of rushed completion (particularly if they moved in some time after handover took place). Rushed completion could, however, have an indirect effect on occupant motivation if it resulted in incomplete commissioning (leading to erratic system performance) or insufficient training (due to incomplete or poorly presented user documentation).



(A) Initial causal map



(B) Simplified causal map

FIGURE 8.10: Causal maps derived from adjacency matrix

In order to link this causal map back to the operation and maintenance class and then to the root of the energy performance risk taxonomy some additional nodes are required. The factors ‘incomplete commissioning’ and ‘lack of handover support’ can be combined under ‘insufficient building readiness’. This additional node, combined with ‘poor user motivation’ and ‘poor maintenance’ (corresponding to the taxonomic elements Handover, Users and Facilities Management) are linked together as ‘poor operation and maintenance’, which is linked back to the root of the taxonomy (Figure 8.11).

Causal maps can be used as a risk management tool to develop a shared understanding among the project team. Additionally, identifying the relationships between risk factors can be seen as the first stage in developing a more powerful risk assessment methodology.

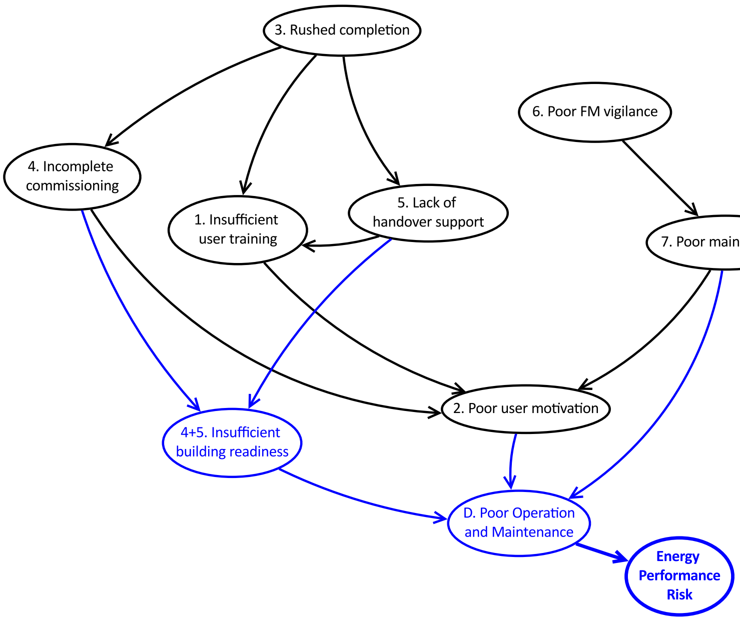


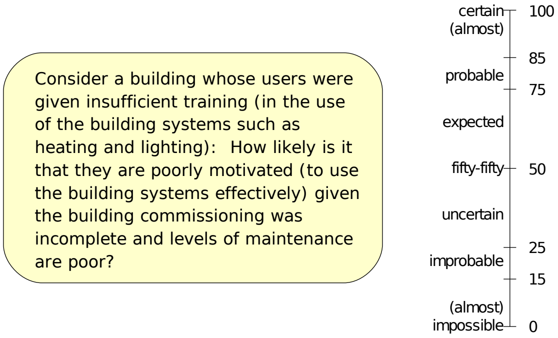
Figure 8.11: Causal map linked to root energy performance risk

8.6 Quantifying Risk Factors

The next stage involves developing a means of quantifying the effect of the risk factors. Currently, the data on the presence and impact of risk factors on energy performance is qualitative in nature. Published case studies such as PROBE do provide detailed information that permits identification of individual risk factors. However, despite the useful detail they provide, they are insufficient in number to provide the size of dataset required for reliable regression analysis or the training of neural networks. Qualitative data is also limited by a lack of metadata that would allow identification of risk factors. For example, although the DEC dataset (described in Chapter 2) contains energy use intensity data for several thousand buildings it does not provide sufficient information on the nature of the buildings themselves.

Based on the data available, quantifying the risk factors and their effects is likely to be a subjective process. However, there are techniques by which calibrated expert judgements can be used to quantify the relative importance of factors (Hubbard, 2010). Kempton et al. (2002) propose the use of one of these techniques, the Lens model, to normalise judgements of building condition by surveyors. The Lens model is based on applying multiple regression analysis to the results of expert elicitation surveys. In these surveys, judges are presented with values for a number of factors known as cues. Based on the cue profile presented, they are asked to give their opinion on the resulting outcome. Each judge repeats the process several times with different cue profiles. The results are used to construct a regression model with coefficients that reflect the relative impact of the factors.

While the Lens model is based on expert elicitation of factor impacts, Bayesian networks can provide an alternative approach based on elicitation of factor likelihoods. It is possible to develop network structure from causal maps, such as those described above, using the methodology described in Nadkarni and Shenoy (2004). The conditional probability tables underlying a Bayesian network can be derived from data, which may be in the form of probability distributions, or they can be obtained by expert elicitation. Expert elicitation of probabilities is useful where existing data is scarce or difficult to manipulate however it can be a extremely time-consuming process. Luu et al. (2009) carried out a literature review and workshop followed by three questionnaire surveys to develop a Bayesian network for modelling schedule risk in construction projects. The first two questionnaires, using a 5-point scale to evaluate the relative importance of risk factors and an adjacency matrix to elicit cause and effect relationships, were used to determine the network structure. The third questionnaire was used to obtain conditional probabilities for each variable. In order to reduce the time taken in expert elicitation, van der Gaag et al. (1999) developed a user-friendly technique for assessing conditional probabilities. This is based on the use of text fragments describing a particular situation, combined with verbal and numerical scales for indicating the probability of its occurrence. Although the preparation of text fragments can be time consuming, completed questionnaires have been used to elicit probabilities at a rate of between 150–200 probabilities per hour. Figure 8.12 shows a proposed example of a text fragment and probability scale.



Consider a building whose users were given insufficient training (in the use of the building systems such as heating and lighting): How likely is it that they are poorly motivated (to use the building systems effectively) given the building commissioning was incomplete and levels of maintenance are poor?

Figure 8.12: Example text fragment and probability scale

This form of questionnaire could be implemented on-line to provide a cost effective alternative to face-to-face elicitation techniques. Spaccasassi and Deleris (2011) demonstrate the use of a similar web-based tool for probability elicitation.

Once populated with probability information the Bayesian network can be used for diagnostic and prognostic reasoning about the causes and consequences of risk factors. For example, risk factors known to be present or absent can be assigned probabilities of 100% and 0% respectively. The network will then update the resulting change in probabilities of the other risk factors. This technique can aid project teams' early identification of likely risk factors and their potential consequences, leading to proactive rather than reactive mitigation measures.

8.7 Case Study Evaluation

This section describes the identification of energy performance risk factors present in the case study building project. The evaluation attempted to capture the viewpoints of the design and construction team, the operation and maintenance team and the building occupants. In addition, the development of the competition brief and performance targets are reviewed. The risk factors identified are shown in italics below the relevant paragraph.

8.7.1 Project origin and design brief

The project originated in a shared motivation of the University of Northampton (UoN), West Northamptonshire Development Corporation (WNDC) and Daventry District Council (DDC) to create a centre for sustainable construction. An opportunity to access matched funding provided by the European Regional Development Fund (ERDF) arose and a bid was prepared by WNDC and UoN. The University then led the development of a brief in conjunction with Building Research Establishment (BRE) and the funding bodies WNDC, DDC and the East Midlands Development Agency.

The design intent for the iCon building was to develop a sustainable 'Centre of Excellence' supporting education, training, conferences and business incubation in Daventry. A design competition invited entries for 'an iconic architectural example that showcases and complements innovative thinking and technology in a sustainable manner'. The accommodation to be provided included flexible start-up offices, conference facilities for 200 people, exhibition spaces, meeting rooms, break-out space, canteen and supporting facilities.

Competition

The design competition, run by BRE and RIBA (Royal Institute of British Architects) was announced in March 2008. Selection of the winning design was a two-stage process. The first stage was judged anonymously on the basis of two presentation boards and a short design and environmental statement submitted by each design team. A number of teams were short-listed and issued with a more detailed second stage brief. The winner was selected on the basis of the design's innovation and visual impression, contextual response to the site, adherence to the requirements of the brief and demonstration of sustainability and energy efficiency. Entries were also considered on their awareness of issues of practicality and financial feasibility involved in constructing an exemplar zero carbon building. There were 75 entries at the first competition stage. This was reduced to five short-listed entries, which were developed in more detail during the second competition stage. The judging panel did not include a clearly defined client, so the winning entry was chosen without input from the building operator or end-user. *Client: Identity*

Performance targets

The competition entries were required to demonstrate the practical aspects of energy efficiency and sustainability. One of the project's main criteria was the achievement of an innovative energy performance status, to be explored fundamentally by minimising the actual energy demand and therefore operational costs. The emphasis was placed firstly on incorporating appropriate design measures to minimise energy use and secondly on the use of suitable renewable energy technologies. The proposed design strategies were expected to reduce the energy demand whilst maintaining occupants' comfort throughout the year. The second stage of the competition required the designer to submit a carbon statement outlining targets, strategies and assumptions made to achieve best performance in several areas including CO_2 emissions, heating and electrical loads, thermal performance and air tightness. The building was developed with the clear aspiration of achieving a BREEAM 'Excellent' rating (the highest attainable at that time) and meeting a CO_2 emissions target of $15\,\mathrm{kgCO_2/m^2{\cdot}yr}$.

Discussion at the design and construction workshop revealed a lack of clarity regarding the nature and origin of the building's design CO_2 emission target. Although a target was clearly stated, it was not explicit whether it represented the building's actual energy consumption in-use, or merely the regulated energy consumption at design stage. During the project, the target shifted from an in-use target to a design target, for comparison with results of the building regulations compliance calculations. As a result it was not possible to use the target to verify the performance of the actual building in operation. *Brief: Clarity*

8.7.2 Design and construction perspective

A facilitated workshop was held in March 2012 with the aim of capturing and sharing lessons learnt by the project team. The workshop followed good practice guidance for post occupancy evaluation published by AUDE (2006). The architect, building services consultant, and main contractor were all represented, along with the project manager, building client and facilities management. Participants were asked for their opinion on whether the building had met key design aspirations. Figure 8.13 shows that the majority of participants considered the aspiration to include natural ventilation and passive cooling strategies was well met. The other aspirations were only considered to be partially met.

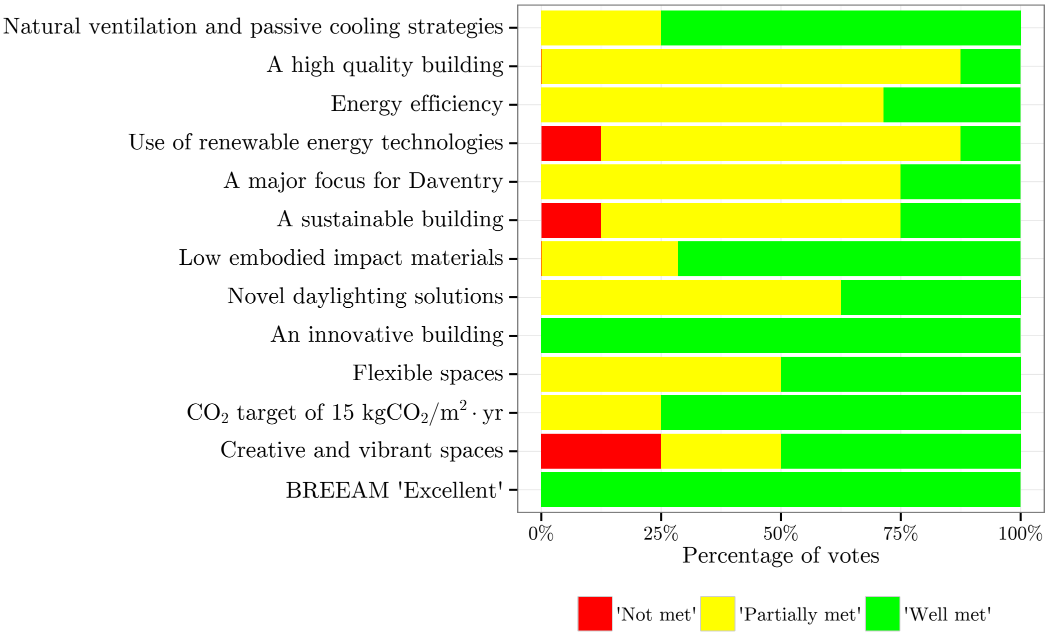


Figure 8.13: Design and construction team members' view of design aspirations

The workshop participants questioned whether the project requirements were actually developed in conjunction with the end-user. However, other than the ambiguity regarding the CO_2 emissions target, the brief was considered to be generally clear and comprehensive.

Although the brief represented an aspirational design, it was questioned whether the budget was sufficient to meet the aspiration.

The workshop was followed about a year later with individual interviews with the architect, building services consultant, main contractor and project manager. These open-ended semi-structured interviews were intended to pick up where the workshop left off and identify causal factors relating to issues affecting building performance.

Architectural design issues

The interview with the architect identified a number of factors that may have affected the performance of the finished building. The overall design was based on a decision to do something unusual and innovative that would appeal to the competition judges rather than a more traditional office design. Although there are some precedents for the general design concept, the specific combination of elements in the building's environmental strategy is unique. This compromise between winning the competition or choosing a 'safe' option is likely to have increased the risk of poor performance. *Design: Precedent*

Another factor related to the client's understanding of the design proposal and the designer's ability to communicate the impact of design decisions. For example, it was originally intended for the café and break-out areas to be open to the internal street. However it became apparent that the spaces would be cold in winter and could not be provided with a fixed heating system. The option of adding seasonal heating (such as infra-red heaters) was rejected as not fitting the building's low-energy image and not providing acceptable occupant comfort. As a result, the decision was made to enclose these areas within the envelope of the heated building. Despite the difficulty and structural implications of carrying out this change during the construction phase it was decided that the added cost was necessary. Fortunately there was sufficient leeway in terms of the building's design stage CO_2 performance to allow underfloor heating in the café without compromising the design CO_2 target. A clearer understanding by the client of their requirements could have prevented this late design change. Responsibility also lies with the designers as the implication of occupied areas being open to an unheated space should have been made clearer and understood by all members of the team prior to the design freeze. *Design: Changes; Client: Understanding; Teamwork: Communication*

Technical design issues

The interview with the building services designer provided more detail about the choice of environmental strategy, which was intended to be simple and robust. It is debatable however, whether the original proposal for a ground source heat pump with its ground loop pipework embedded in the building foundations would have satisfied this requirement. Ground source heat pump installations are subject to a number of factors that can adversely affect performance (DECC, 2012); furthermore, a ground loop embedded in the foundations would be difficult if not impossible to fix were it to fail after construction. The decision to use an air source heat pump was made on the grounds of cost and the contractor's concern about buildability and potential liability for defects. *Technology: Robustness*

The air source heat pump is a unit designed to supplement domestic hot water systems in flats and hotels (CIAT, 2009), but has not been widely used to provide space heating in offices. This project was the first time that the design and construction team had used the particular combination of envelope and services strategy. An untested application of the technology presents a risk to achieving design energy performance. *Design: Precedent*

It was acknowledged that overall performance is sensitive to the performance variation of individual components. Manufacturers' data sheets, often the only source of technical information on which to base performance estimates, are assumed to reflect actual performance (Maile et al., 2010). The information they contain is, however, typically based on bench testing individual components under standard conditions. To ensure appropriate assumptions are used to develop performance estimates it is suggested that manufacturers' data are supplemented with data from field trials and whole-system tests. *Technology: Performance*

The accuracy of building performance models is partly dependent on the user's knowledge and skill in application (Dwyer, 2013). Since the building performance modelling work was carried out by an external consultant it was not possible to review it in detail; however, the main contractor considered the work to be of a 'good standard'. Necessary assumptions were made on the basis of best available knowledge, given the limitations of manufacturers' data. Although the software used was an industry standard approved package, it was unable to take account of the PCM wall board used on the project. It was suggested by the services designer that modelling work should be carried out by people with a mechanical engineering background, which provides them with a common-sense understanding of the building plant items. It is believed that this was the case on this project however it should also be considered whether similar technical combinations have been modelled before, and whether there are any lessons to be drawn from previous experience. *Modelling: Experience; Modelling: Assumptions*

It was also pointed out that the output of the software does not allow for any deviation from input assumptions in actual operation. For example the size of ventilation openings was shown to be sufficient under design conditions but does not include any safety margin to allow for variation in occupancy or equipment density. This performance risk due to the inability to allow for uncertainty is the subject of the previous chapter; probabilistic calculations or even a simple scenario-based calculation could give an indication of the robustness to changes in boundary conditions. *Modelling: Sensitivity*

Some specialist support was provided, mostly limited to a review by BRE of the thermal modelling. This review questioned some of the assumptions built into the model, such as the efficiency of the exhaust air heat pump and the free area provided by ventilation openings. It was not evident that the points identified in the review were ever addressed. *Specialists: Support*

Procurement issues

The use of a design-and-build procurement route was specified in the brief. It was suggested that while this made it possible to meet the target budget it introduced additional constraints on the project. These include reducing the level of detail developed in the early design stages and contributing to a loss of knowledge of design intent when stakeholders changed after the project went to tender. At this stage, the role of the building services designer was reduced to a watching brief, with no design input. A traditional procurement route would have allowed greater involvement albeit at greater cost. From the contractor's point of view, design and build is capable of delivering the client's requirements and satisfying design intent provided the brief is sufficiently robust. *Procurement: Integration*

It was suggested that the client culture in public sector projects is very risk averse. Design and build projects are favoured as a way of reducing client liability. There is a trade-off however between liability and control that makes project success more sensitive to the contractor's ability to make cost and efficiency savings without compromising design intent, particularly in the technical design.

Value engineering

Value engineering is process of critical appraisal intended to determine whether project requirements can be met by alternatives with less cost and risk. Correctly applied, value engineering has the potential reduce waste and inefficiency in design, construction and maintenance (OGC, 2007b). However, the term is often used euphemistically to describe cost-cutting exercises that emphasise short-term savings over long-term benefits (Malina, 2013).

The case study building underwent a value engineering exercise towards the end of the design stage to realign the tendered budget with the cost plan. This resulted in a reduction in cladding cost and the removal of some features such as raised flooring and movable wall partitions from the design. There were however no changes considered to have significantly affected the environmental services and passive design strategy.

Project management

During the course of the project, several different project managers were involved at different times. In addition to this lack of continuity, the identity of the project client was often unclear. There were a number of client stakeholders with different requirements and a level of risk aversion that hindered decision making. This affected the team's ability to define appropriate requirements and make timely decisions during the project. *Teamwork: Continuity; Client: Identity*

There was greater continuity and a clearer definition of roles within the design and construction team. This is probably the result of greater experience of delivering projects. Both the main contractor and M&E sub-contractor have worked successfully together in the past. The architect and building services consultant are based in the same building and have also worked successfully together in the past. *Teamwork: Experience*

External constraints

External constraints have the potential to indirectly affect a building's energy performance. Programme delays can affect the time available for pre-handover activities such as snagging and commissioning. Funding issues can affect the level of detail produced at early design stages as well as the capital cost of building features. There was some suggestion among workshop participants that the target budget wasn't realistic given the aspirations contained in the brief. *Funding: Availability*

Shortly before construction was due to start it was discovered that the diversion of utility services crossing the site had not been carried out by the local authority as planned. This unexpected additional work had not been programmed or budgeted, resulting in a reduction in time and money available for the rest of the project. *Physical: Site Conditions*

The programme was affected by strict time-scales for draw-down of external funding. This limited the time available for preparing competition entries and tender documentation, which may have affected the amount of checking and refinement carried out at key project stages. The building's handover date was also fixed as a requirement of the funding. *Funding: Time-scale*

Planning permission and regulatory approval wasn't considered a problem but it was not clear whether building control actually had the ability to review the technical submission. In addition to building regulations approval, other certification such as BREEAM could result in delays if design changes were necessary to achieve specific credits.

Commissioning and handover

The combination of programme delays and a fixed handover date reduced the time available for the important tasks of commissioning and preparation of documentation. *Programme: Schedule; Handover: Completion*

In order to meet the completion deadline, only the minimum necessary commissioning work was carried out. Both the BMS control strategy and the auditorium AHU needed additional work after handover to rectify problems that should have been addressed as part of the commissioning process. The pre-handover inspection and snagging was driven by the architect and focussed on visual aspects such as finishes, rather than the technical details of the M&E installation. *Construction Process: Build Quality; Handover: Commissioning*

The O&M documentation was found to be incomplete and sometimes inaccurate. For example, the building log book, a document intended to help the building owner to operate the building in an energy efficient manner in accordance with the design intent (CIBSE, 2006d), appeared to have been copied from another project without updating any of the design estimates. Similar shortcomings have been found in projects reviewed by Kimpian et al. (2014). *Facilities Management: Training*

8.7.3 Operation and maintenance perspective

Meetings to review operational issues were held quarterly during the evaluation period. These meetings were usually attended by the building evaluator (the author), the building manager and the maintenance contract manager. The client representative and University of Northampton facilities management staff also attended on occasions. In addition to contributing to the building evaluation, the meetings were also an opportunity to develop and prioritise remedial actions. A further part of the evaluation process was a building walk-through, carried out with the building manager to identify general usability issues. This section describes key risk factors identified during the operational review process. Details of the technical issues encountered are given in Appendix E.

Post-handover support

There was no formal requirement in the building contract for the kind of post-handover support described in the Soft Landings framework (BSRIA, 2009). Members of the project team were involved with rectifying defects identified during the first twelve months of operation; however, their involvement was limited to specific issues rather than providing general support, would have had to have been paid for separately. *Handover: Support*

After handover, responsibility for the building's maintenance passed to the University of Northampton's facilities management team, however it was not clear who was responsible for day-to-day management of the building services systems. A short training session was provided after handover but it might not have been delivered to the right staff. No additional training was provided when new staff took over from the original building manager. As a result there appears to be a lack of understanding of how to best operate and maintain certain aspects of the building such as the heat pump and BMS control strategy. *Facilities Management: Training*

Maintenance issues

The building has presented challenges to its operators. The day-to-day management staff are on site, and are able to respond quickly to reported problems. Progressing from the initial response to a resolution of technical problems takes longer as there are no on-site maintenance staff. The building is part of the University of Northampton estate but the estates department are not responsible for its maintenance. Instead, a large property maintenance service provider is directly contracted to provide planned and reactive maintenance. Although they cover the maintenance of the building's M&E plant, a further sub-contractor provides the maintenance of the BMS and controls. Between them they do take prompt action to fix reported problems however the recurrence of related problems (such as with the heating system) suggest that these fixes are not addressing root causes. In fact, it is possible that the cumulative effect of adjustments made in response to individual symptoms is an unreliable system that no longer matches the design intent. *Facilities Management: Maintenance*

Continuity of design knowledge

Insufficient communication of design intent and critical energy performance criteria is a potential cause of performance gaps (ZCH, 2014). Weakness in transferring design knowledge though to operation is a contributing factor to the technical issues identified in the case study. Although the original environmental concept is largely present in the delivered building, an understanding of the interaction of components and system controls is lacking. For example, the BMS configuration for the ventilation and heating systems has been established largely by trial and error. The novelty of certain aspects of the system, such as the interaction of heat pump, boiler and ventilation system has made the process difficult for maintenance staff used to more traditional installations. Adjustments made without understanding sub-system interactions risk causing further problems (e.g. simultaneous heating and ventilation, boiler and heat pump cycling and excessive flow temperatures in the heat pump circuit). A lack of thorough understanding of the system's operation and design intent is therefore a serious obstacle to achieving satisfactory performance. *Teamwork: Communication*

8.7.4 End-user perspective

Considering building performance from the point of view of end-users is important not only terms of occupant satisfaction (Leaman and Bordass, 2000), but also in terms of energy consumption; Junnila (2007), for example, identified opportunities for a 20% saving in overall electricity consumption by improving end-user energy management of office equipment and lighting.

The case study evaluation was conducted using semi-structured interviews and a standard questionnaire. A selection of tenants who had been in the building for about a year took part in settling-in interviews. The Building Use Studies (BUS) questionnaire was issued to all tenants, and a small sample of the tenants who had completed the BUS questionnaire took part in follow-up interviews.

Settling-in interviews

These interviews were intended to investigate tenants' experiences moving into the building, the level of support they received during the settling-in period and their general experience and usage of the building. The interviews were carried out in September and October 2012. By this time the building had been open for over a year and was about 65% occupied with 27 different businesses. Most of the tenants interviewed had moved into the building between May and September 2011.

A number of issues relevant to the building's energy performance were raised in the settling-in interviews. Although tenants were generally satisfied with the building induction, the information provided on the building's environmental strategy and control systems did not explain how to set radiator TRVs and ventilation opening setpoints appropriately, or how to dim the lights as required. Simple user instructions should explain how best to operate systems and controls interfaces (CIBSE, 2012). They could also help to raise awareness of what to expect from the building's environment strategy. *Users: Education*

Training however does not guarantee that the users will be motivated to adopt energy efficient behaviour. For example, although each incubator unit has its own electricity meter, tenants are not billed for their electricity usage so there is no incentive for tenants to minimise their electricity consumption. Interestingly, the tenants interviewed felt that the environmental ethos was not as strong as it should be. Attitudes towards environmental impact varied; some tenants reported that they did try to ensure heating, lighting, etc. are not used unnecessarily while others expected the building to provide comfort regardless of user behaviour. Building management could take the lead in motivating tenants by placing greater emphasis on the building's environmental concept and encouraging user engagement. *Users: Motivation*

In the first few months of operation, tenants felt that the building management team were somewhat overwhelmed by the operational challenges of the building but by the time of the interviews building management was responding more quickly. Tenants appreciated being kept informed of progress in dealing with problems. *Facilities Management: Maintenance*

The tenants were asked to rate the building's performance against its design aspirations in the same way the design and construction team members were asked in the workshop session. They were also asked to rate the importance of each of the design aspirations expressed in the brief. Figure 8.14 lists the design aspirations in order of their rated importance. It is clear that the users' priorities are rather different from those of the design and construction team. Comfort and overall quality were the most important aspects of the building; problems with overheating are likely to have increased the average importance rank of 'natural ventilation and passive cooling strategies'. Other aspects such as energy efficiency may be important in a general sense but are in effect hidden from the users, particularly as they are not billed directly for energy use.

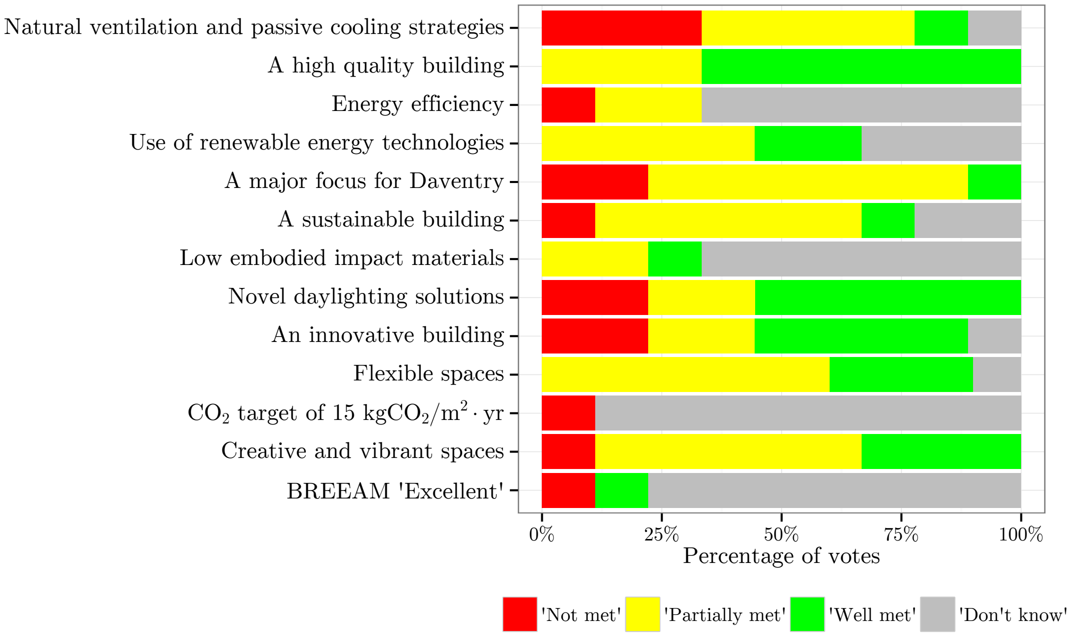


FIGURE 8.14: Building users' view of design aspirations

BUS questionnaire

The BUS questionnaire is aimed at identifying the strengths and weaknesses of how well the building meets the needs of its users (BUS Methodology, 2013a). The three-page questionnaire, available to licensees, includes tick-box questions for rating specific aspects of the building and text fields for more detailed comments. The survey was carried out in February 2013, nearly two years after the building opened. A total of 56 questionnaires were returned, mostly on the same day, which represents an excellent response rate (the exact number of questionnaires issued was not recorded but is thought to be about 60).

Due to the newness of the building and the relatively high turnover of tenants, only a quarter of the respondents had worked in the building for longer than a year. As the survey was carried out as part of the TSB study, the completed questionnaires were transcribed into a spreadsheet that was sent to Arup to be analysed and added to a database of results from other BUS surveys. This database includes results from a mix of non-domestic buildings including offices, schools, hospitals and museums. The majority of the buildings have been built or refurbished within the last 10 years and represent a wide range of constructions, environmental strategies and ventilation types (Fell, 2013).

The results of the BUS questionnaire survey were broadly consistent with the issues observed during the building evaluation study. In general, the building was rated well as a workspace that meets its users' needs. Figure 8.15, reproduced from the survey report, shows the building's aggregate occupant comfort and satisfaction score (indicated by the solid circle) was at the 80th percentile relative to the other buildings in the database.

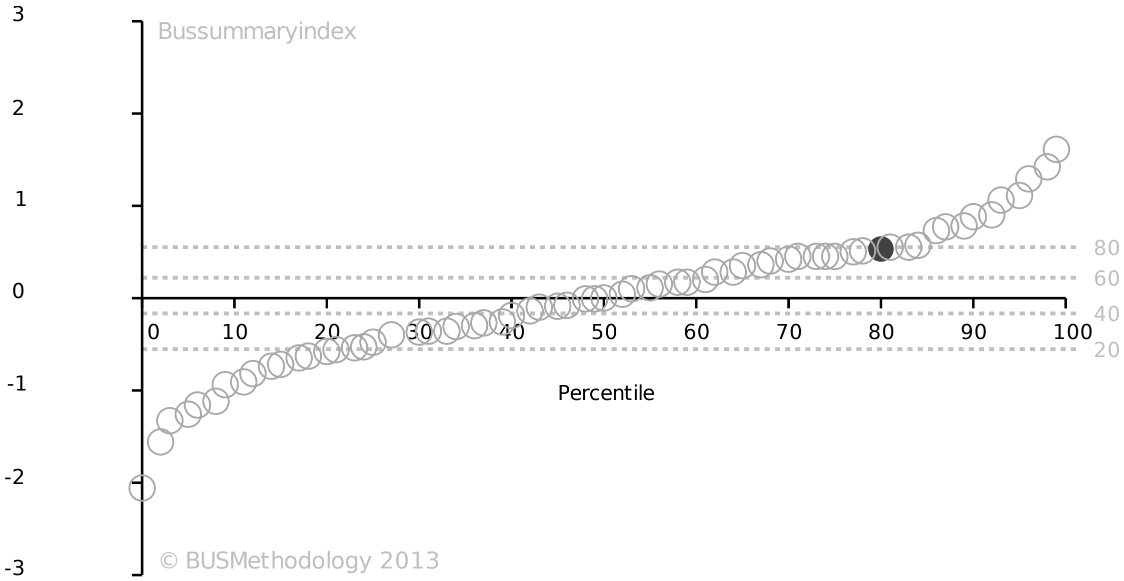


FIGURE 8.15: BUS summary score comparison (BUS Methodology, 2013b)

The problems with the building's natural ventilation and heating systems were reflected by the less satisfactory ratings for thermal comfort and air quality, particularly during summer. Figure 8.16 shows that the building's score for overall summer temperature was at the 25th percentile, and well below the scale mid-point score (indicated by the black cross). Despite this, the building's score for overall occupant comfort was at the 70th percentile, and significantly higher than the scale mid-point score (Figure 8.17). The levels of control over heating, cooling and ventilation were not significantly different from average, however these variables were rated as important by about a quarter of respondents. Lighting overall and lighting control also scored well; however, individual scores for artificial light and glare from lights were not significantly different from average. Improvements to the reliability of the heating system and the effectiveness of the natural ventilation system are likely to increase the scores for comfort in winter and summer.

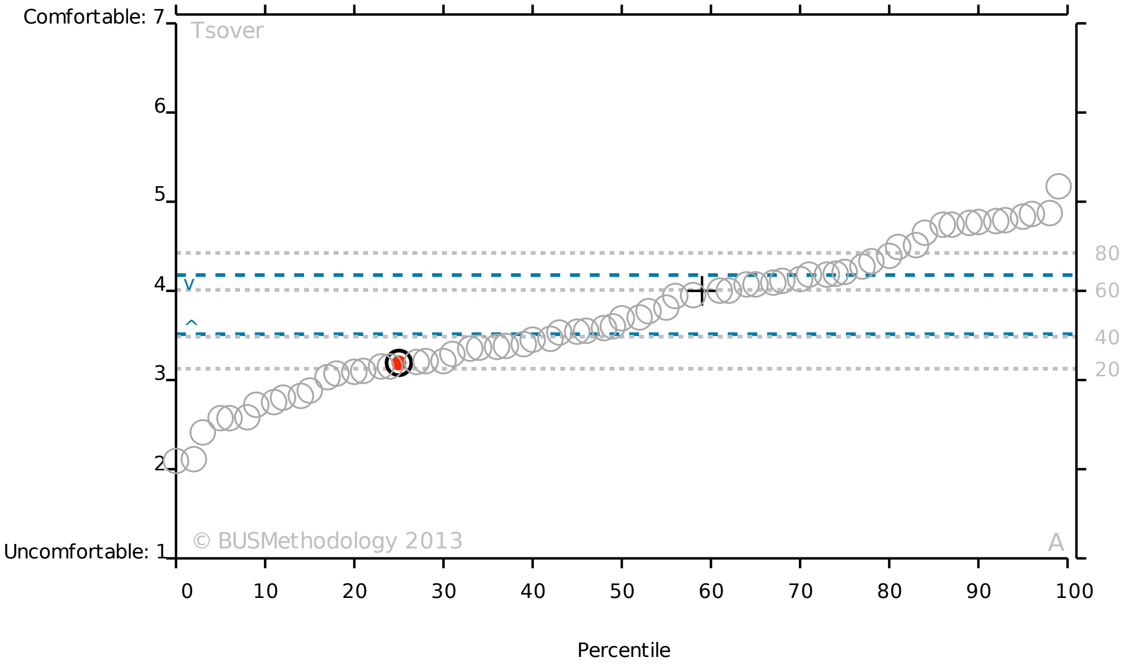


Figure 8.16: BUS temperature in summer: overall score (BUS Methodology, 2013b)

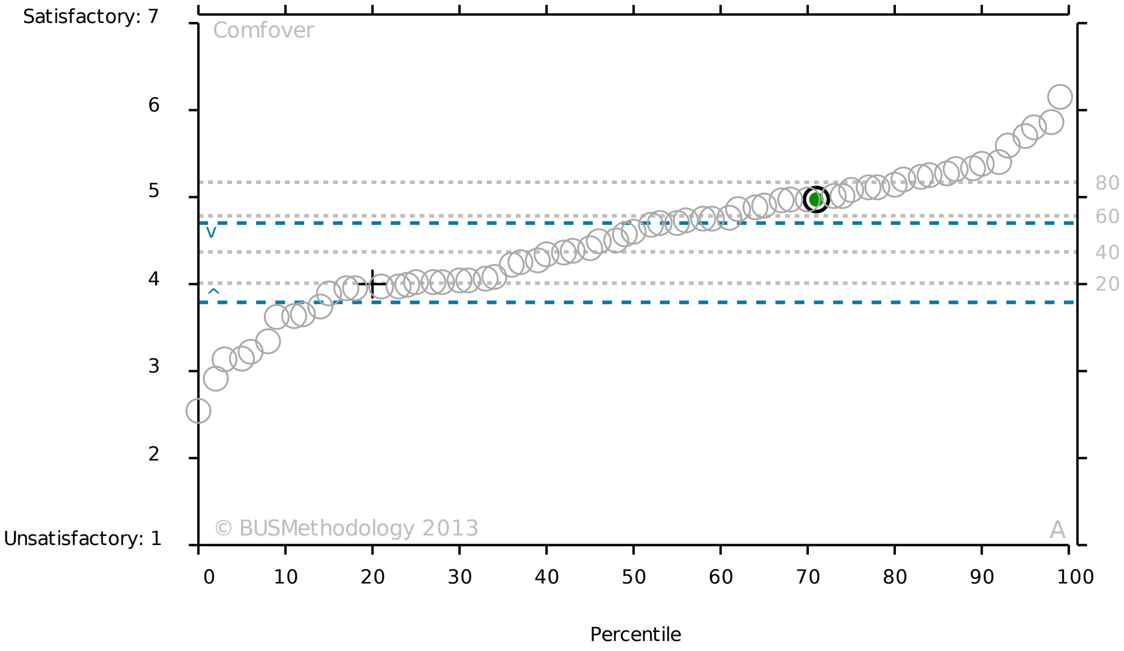


Figure 8.17: BUS comfort: overall score (BUS Methodology, 2013b)

Follow-up interviews

The follow-up interviews were carried out approximately six months after the BUS survey. A number of staff who had participated in the original survey were interviewed to investigate whether there had been any changes in the problem areas identified. Staff from eight offices were interviewed, four from the two-person offices on the top floor and four from the larger four or eight-person offices on the ground and first floors. In addition to the survey follow-up questions, occupants were asked about their occupancy patterns, use of electrical equipment and hot water consumption. These questions were intended to provide additional context for understanding variations in energy consumption between units.

From the tenants' point of view, the problems experienced with the heating system at the beginning of December 2012 appear to have been resolved. In one of the second floor offices the radiator is not used; due to the high levels of insulation and the level of internal gains no additional heating is required. In a different office the occupants mentioned that the unit tends to be cold in the morning, even with the heating running constantly. On occasions they have used a fan heater to get their office up to temperature. This office is adjacent to a unheated stairwell, which may explain why it is slightly colder than offices with heated spaces on either side.

Tenants are generally happy with the controllability of building services however some suggestions were made to improve the usability of the ventilation controls. The ability to adjust the pre-set light level was mentioned; this could be achieved with the use of a remote control to allow light levels to be pre-set as required. The ventilation control provides a manual open/close override; however this returns to automatic control after a pre-set delay, currently 5 minutes on the ground and first floors and 20 minutes on the second floor. Increasing the delay times could reduce the need for occupants to make frequent use of the override switch; however they would then have to wait longer before they could either open or close the vents again as it is not possible to make further manual overrides during the delay period. Buildings with good user controls are more likely to be energy efficient because systems will only operate when actually needed (BSRIA, 2007b). An improved control strategy should therefore reduce the amount of user intervention required whilst providing a manual override with an efficient default position.

The wide range of tenants in the building is responsible for the large variation in energy consumption between units. Seven out of the eight offices interviewed operate typical office hours however the smaller organisations may operate more variable hours. Electrical loads vary, mainly due to different levels of IT equipment use. Hot water use is also variable, some of the occupants interviewed use the showers from time to time, while others use very little hot water.

8.8 Discussion and Conclusions

This chapter has investigated a range of factors that can influence the discrepancy between a building's design and operational energy performance. Key risk factors were identified and used to develop a risk taxonomy, which was then related to stakeholders and project lifecycle stages. Summarising the range of risk factors in this way can help project teams focus on important issues at the appropriate time. A questionnaire based on the risk taxonomy was proposed as a way to quantify the presence of risk. The operation and maintenance section of the questionnaire could be used as the basis for establishing the management factor discussed in the previous chapter.

The use of causal mapping as a way to model the interrelationships among energy performance risk factors was introduced. The process of risk identification and causal mapping could be carried out as part of an expert elicitation workshop. The causal maps could then be combined with expert judgement to develop means of quantifying lifecycle risk factors using techniques such as the Lens model and Bayesian networks.

Taken together, the proposed techniques form a methodology for managing energy performance risk throughout the building lifecycle that has clear application in a number of areas: At the earliest stages of a project it could help to focus attention on the issue of building energy performance and identify opportunities for reducing risk. It could also be used in the due diligence process of risk assessment. As the project progresses it could form part of a programme of continuous quality control to ensure that focus on energy performance is not lost. It could also be used in building evaluation studies to identify areas that demonstrate good practice as well as areas for future improvement.

The performance issues identified in the case study building have their origins in risk factors occurring at various stages in the project. Early risk factors include the lack of a clearly identified client able to champion energy performance and the ambiguity of the CO_2 emission target. Design stage modelling assumptions, based on manufacturer's information, are partly responsible for over-optimistic performance estimates. The building's handover date was inflexible, due to constraints on funding availability. Combined with programme delays due to unexpected additional work, this reduced the time available for commissioning and preparation of O&M documentation. The end result was incomplete commissioning that was a significant factor in the building's performance in the early years of operation. The situation was exacerbated by a lack of understanding of design intent and system control strategy and a lack of coordination of remedial maintenance activity.

Chapter 9

Discussion and Conclusions

9.1 Introduction

This chapter summarises the key outcomes of the research in relation to the objectives stated in Chapter 1, discusses their significance and identifies areas for further work.

The research sought to tackle the issue of discrepancies between design and operational energy consumption. These discrepancies were found to occur as the result of a wide range of technical and lifecycle-related risk factors. A performance evaluation of a recently constructed building was carried out to construct a detailed case study. The evaluation identified specific technical risks at the whole-building level and at sub-system level for two principal energy end-uses; space heating and domestic hot water. In addition to identifying technical risks, the research also considered their origins in the building lifecycle. These risk factors were found to relate to a wide range of generic project performance issues. Finally, a methodology was proposed for identifying the presence of risk factors, quantifying their impacts and probabilities.

9.2 Key Outcomes

The first two objectives relate to the identification of significant causal factors resulting in performance discrepancies, and their origins in the project lifecycle. The building energy modelling carried out for the main contractor demonstrated that the building met its CO_2 emission target. However, due to a lack of clarity as to the nature of the target, the figure did not account for unregulated loads or realistic usage patterns. Although it would have been possible to make reasonable estimates it would not have been possible to predict system failures and the erratic operation of significant energy end-uses such as the auditorium air handling unit. The identification of these end-uses was made possible by the high level of sub-metering installed in the building. Modelling assumptions regarding sub-system performance are a further source of inaccuracy. The use of empirical data from similar buildings would be one way to verify these assumptions, potentially improving the accuracy of performance estimates.

The space heating sub-system used a novel combination of technologies. Its monitored energy consumption was found to be nearly four times larger than modelled estimates. The incorrect design-stage assumption that the exhaust air heat pump would meet the majority of the building's heating demand contributes significantly to this discrepancy. In reality the heating control strategy is not optimised for two different heat sources, with the result that the auxiliary boiler is frequently the lead heat source. Furthermore, technical problems caused partly by incomplete commissioning and poor training led to an extended period of continuous heating and the repeated failure of the exhaust air heat pump. Technology choice, design assumptions, handover and training, and operation and maintenance are therefore significant sources of risk relating to the performance of the space heating sub-system.

By contrast, the domestic hot water sub-system used a common technology; indirect gas-fired calorifiers and pumped secondary circulation. Despite this, its monitored energy consumption was over twice the modelled estimate. This is due to losses from the boiler, storage and secondary circulation being greater than originally assumed. It is likely that the choice of technology was driven by the design guidance on typical hot water demand, which is much greater than the monitored demand. This would have favoured the specification of a central storage system rather than point-of-use instantaneous water heaters that would have been more efficient for the relative small demand observed. A further issue is the boiler control strategy and extended operating time, intended to maintain calorifier temperatures above 60 °C due to concerns about Legionella. Technology choice, design assumptions and external constraints were therefore identified as sources of risk relating to the performance of the domestic hot water sub-system.

The third objective was the development of a technique for evaluating the effect of sub-system uncertainty on energy performance estimates. Despite the presence of considerable uncertainty at design stage, industry practice rarely incorporates the effect of uncertainty on performance predictions. A means of characterising building energy performance in terms of probabilities has been developed. This builds upon the deterministic calculations currently used by making explicit the uncertainty in performance estimates through the use of Monte Carlo simulation. This provides a way of generating probabilistic energy performance estimates. Instead of using discrete values, input data can be expressed as a probability distribution based on 90% confidence range. The output of the simulation will therefore reflect the level of uncertainty in the input data. A probabilistic adaptation of the tree diagram approach used as the basis of TM22 and TM54 was demonstrated. The resulting probability distribution for domestic hot water energy use intensity had a median value within 10% of the monitored value. More importantly, it indicated that given the specified uncertainty in input data, there is effectively a 90% chance that monitored value will fall in the range from about $7\,\mathrm{kWh/m^2}$ to $15\,\mathrm{kWh/m^2}$. Greater uncertainty in input data will result in a wider range of output values. Sensitivity analysis can be used to rank uncertain input variables according to their impact. This could lead to a clearer understanding among the design team of significant sources of uncertainty. This probabilistic approach is easily implemented and is therefore widely accessible to industry.

The final objective was to propose a methodology for lifecycle performance risk mitigation. Uncertainty in model input parameters is an aspect of performance risk that may be the result of a wider range of risk factors. A risk taxonomy was developed to categorise and facilitate the identification of these factors, many of which are related to process and management related issues occurring throughout the building lifecycle. The use of a taxonomy-based questionnaire during the building design process could help project stakeholders to develop a greater understanding of the factors that affect building energy performance. This understanding is an essential step towards risk reduction. A technique was then proposed for mapping the relationships between risk factors and quantifying their impacts and probabilities. The case study evaluation included a detailed consultation with key project stakeholders within the construction supply chain in order to support the identification of specific lifecycle risks. This identified the presence of risks within four taxonomy classes: Risks within the design and engineering class related to the clarity of the project brief, the choice of technology, assumptions made in the energy modelling and the use of specialist support. Risks within the management and process class related to client identity, teamwork, support for design integration under the chosen procurement method and quality control within the construction process. Risks due to external constraints related to programme timescale, availability of funding and physical site issues. Risks within the operation and maintenance class related to rushed handover, user education and training of facilities management and maintenance staff.

9.3 Discussion

This work has demonstrated the use of practical building evaluation techniques including the use of both quantitative monitoring data and qualitative data obtained from the design and construction team, facilities management staff and building users.

The monitored data contained a great deal of variability, as shown by the energy consumption frequency distributions and the temporal raster plots that provide a clear indication of the building's sub-system operating patterns. This variability illustrates a fundamental difference between the theoretical design models of buildings and practical reality of buildings in operation.

If the industry were to move towards the adoption of operational energy targets there would be a strong incentive for more reliable performance predictions. There are, however, significant factors affecting operational energy consumption that are difficult to predict. Designers and building operators alike may be unaware of future changes of use and operating patterns. In this situation, probabilistic predictions that produce a likely range of energy consumption values may be helpful to evaluate the impact of such changes.

Current industry-wide energy estimation techniques are based on evaluation of physical quantities. Where qualitative factors are considered, they are typically accounted for by applying 'management factors' to end-use energy consumption estimates. The risk management methodology developed in this work should facilitate a more robust, quantitative, evaluation of non-technical factors. As performance evaluation becomes more common, it is hoped that the detailed sub-metering necessary for understanding technical factors affecting energy consumption by end-use will also become more common.

The Soft Landings framework, described in Chapter 2, attempts to address some of the lifecycle factors identified in this research. It does not, however, provide a means of evaluating performance risk. The methodology proposed here could be incorporated within the existing framework to increase understanding of performance risk and lead to more realistic expectations of operational performance. The methodology is applicable throughout the project lifecycle and could be used for risk management in the early design stages, for investigating effect of design assumptions and for evaluating buildings in operation.

9.3.1 Limitations

Despite a number of technical issues with the monitoring system, it has still produced a great deal of useful data. The monitoring PC represents a single point of failure in an otherwise robust network of sensors. A more sophisticated wireless network capable of storing several days worth of data in the individual nodes would be less affected by failure of the monitoring PC. If nodes were provided with their own real-time clocks they would be able to make synchronised readings, eliminating the need to interpolate data to obtain a consistent time base. The lack of reliable heat meter readings from the space heating primary was disappointing. In future projects, the installation and commissioning of metering equipment should be part of a formal contract. Alternatively, non-invasive heat metering could be installed for a much longer period of post-completion monitoring.

The Monte Carlo approach to probabilistic energy performance estimates is extremely fast using even modest computing capability, provided the calculations are relatively straightforward. While this is the case for the examples given and most unregulated energy end-uses, it is not the case for detailed modelling of heating and cooling energy use. Although there are tools that facilitate Monte Carlo simulation using detailed energy models (Zhang and Korolija, 2010), they are typically time consuming to run and incompatible with industry practice accredited simulation tools. As an alternative, it would be possible to generate a small number of scenarios for detailed simulation, which would then be combined with the probabilistic estimates, or a simpler calculation of heating and cooling energy could be used.

Practical application of the energy performance risk management methodology would rely heavily on expert elicitation. The proposed methodology includes techniques to increase the speed and reliability of the elicitation; however, developing the elicitation questionnaires is still a time consuming process.

9.4 Further Work

This research is situated within a wider context of developing data-driven tools in support of smart sustainable communities (Rowley et al., 2013). It forms a key contribution to the development of a tool-set for risk management, decision-making and optimisation of environmental and socio-economic indicators at a range of physical and temporal scales.

An important extension of this research would be the validation of the proposed risk management methodology with further case study buildings at an early stage in their design process. The probabilistic energy performance estimation described in Chapter 7 could be used to demonstrate the uncertainty in typical design-stage energy estimates. Monitoring data from completed buildings could subsequently be used to improve the range estimates of uncertain input parameters. The techniques described in Chapter 8 could be used to evaluate the presence of performance risk factors at design stage. Evaluation of completed buildings could reveal whether performance risks had been successfully mitigated and identify additional risk factors not included in the existing taxonomy. Carrying out this work in conjunction with an industrial partner would be useful in verifying its practicality and scalability. Although the techniques were developed from the point of view of risk management in individual buildings, they could be adapted for application to a portfolio of existing buildings either to learn from experience, or to evaluate performance risks associated with retrofit projects. The approach described by Lee et al. (2013) could be used retrospectively to build up a database of risk probabilities similar to the development of actuarial tables described by Mathew et al. (2005) that also includes the effects of non-technical factors. This could be used to develop a Bayesian network model that integrates both technical and non-technical factors to predict energy performance risk. Training data relating to technical factors could be generated using the probabilistic models of energy performance, while data relating to non-technical factors would be obtained from the expert elicitation process.

Another area for further work would be the incorporation of more sophisticated sub-system models. Richardson et al. (2010) showed that their domestic electrical demand model was able to provide a good representation of measured consumption patterns. Electrical demand in non-domestic buildings will exhibit greater variability than in domestic buildings due to the wide range of building uses. Despite this it may be possible to use a similar activity-profile approach to characterise electricity demand within specific uses classes, such as retail or commercial offices. This could improve the accuracy of small power and lighting electricity consumption modelled by the probabilistic approach.

In addition to energy consumption data, the monitoring system has produced a large volume of environmental data including temperature, humidity, CO_2 and lux levels for each of the office units. A detailed analysis of this data was beyond the scope of the present research but presents a great opportunity for future projects.

Appendix A

Architectural Drawings

A.1 Plans

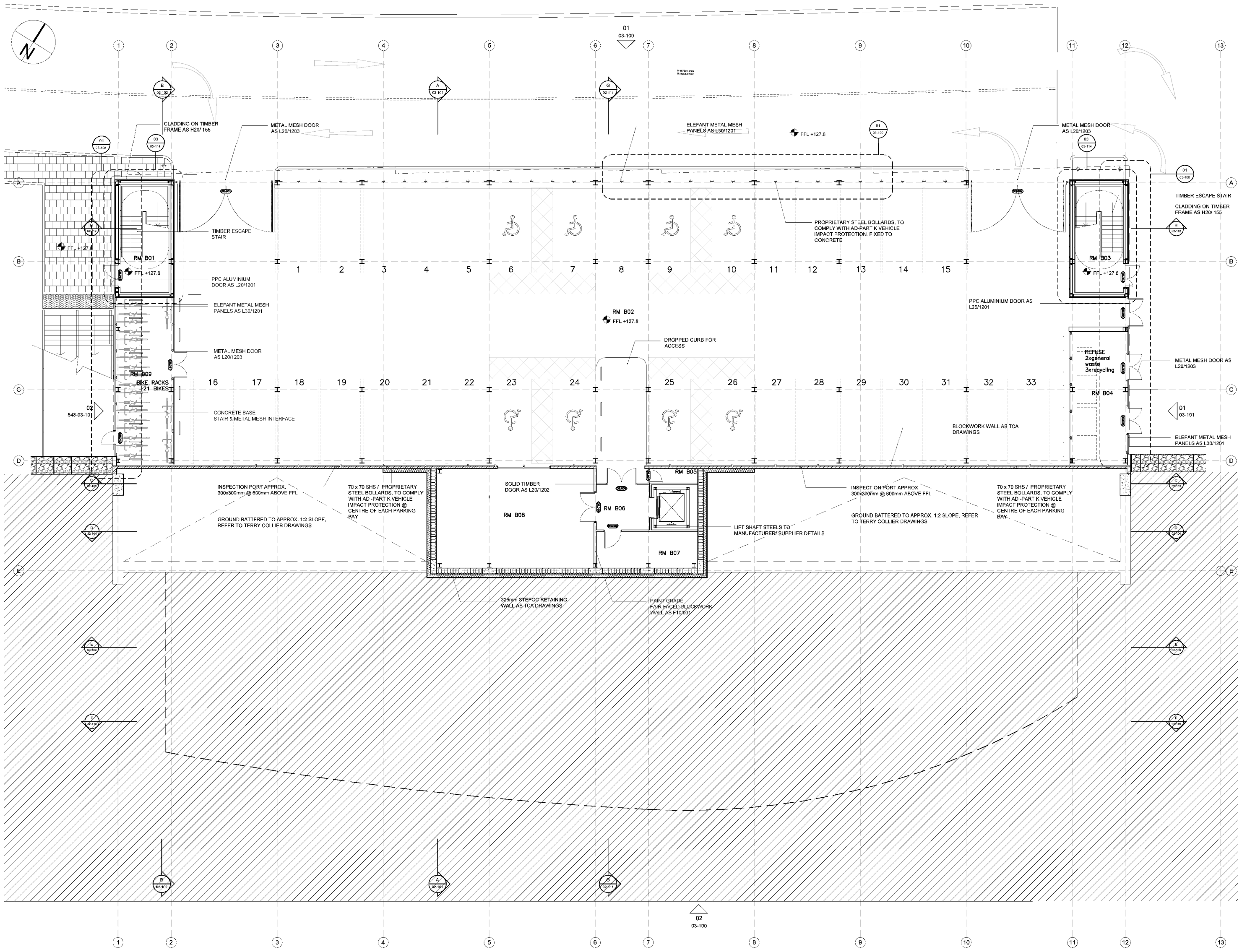


Figure A.1: Lower Ground Floor Plan (Consarc, 2011)

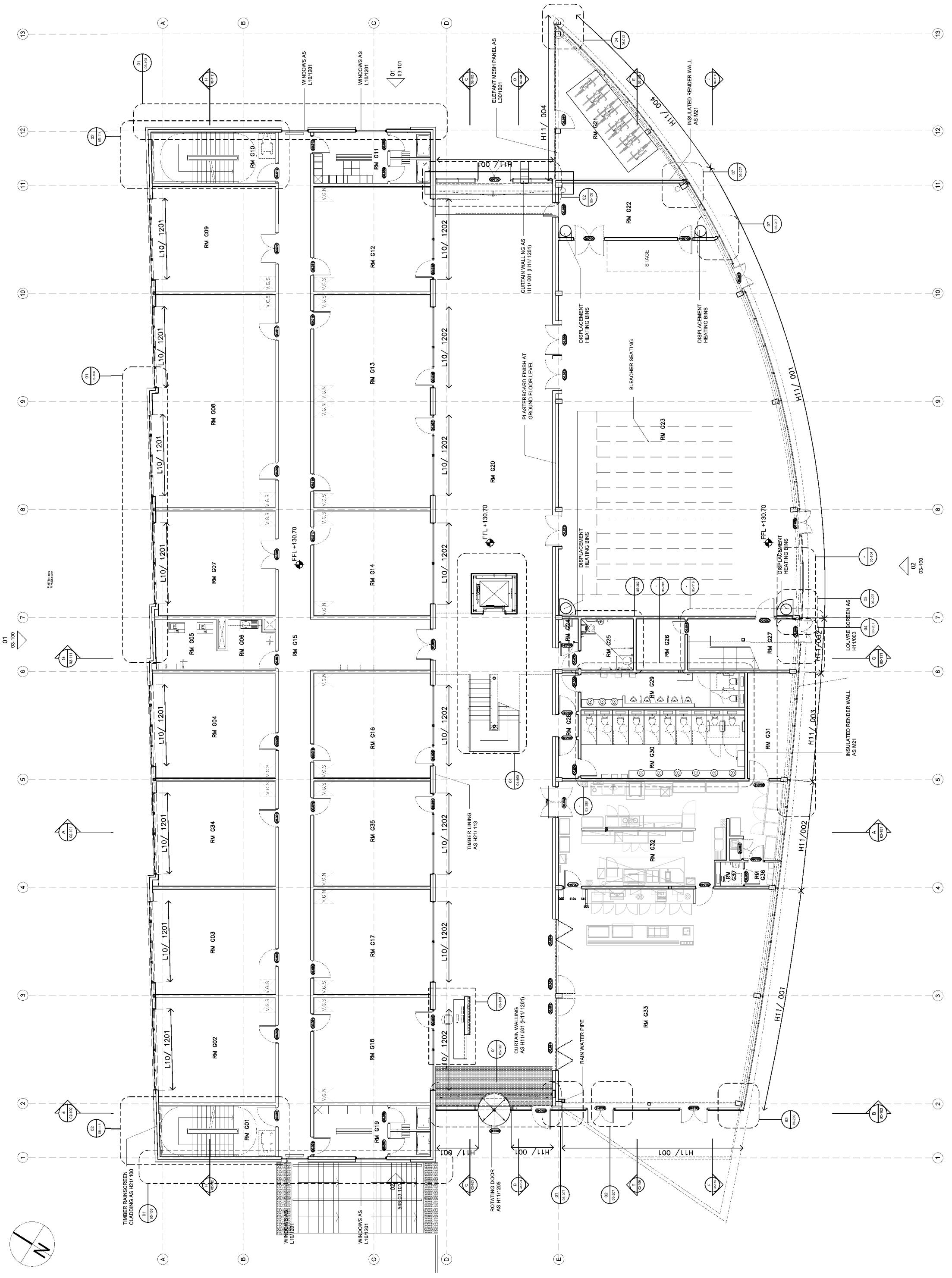


Figure A.2: Ground Floor Plan (Consarc, 2011)

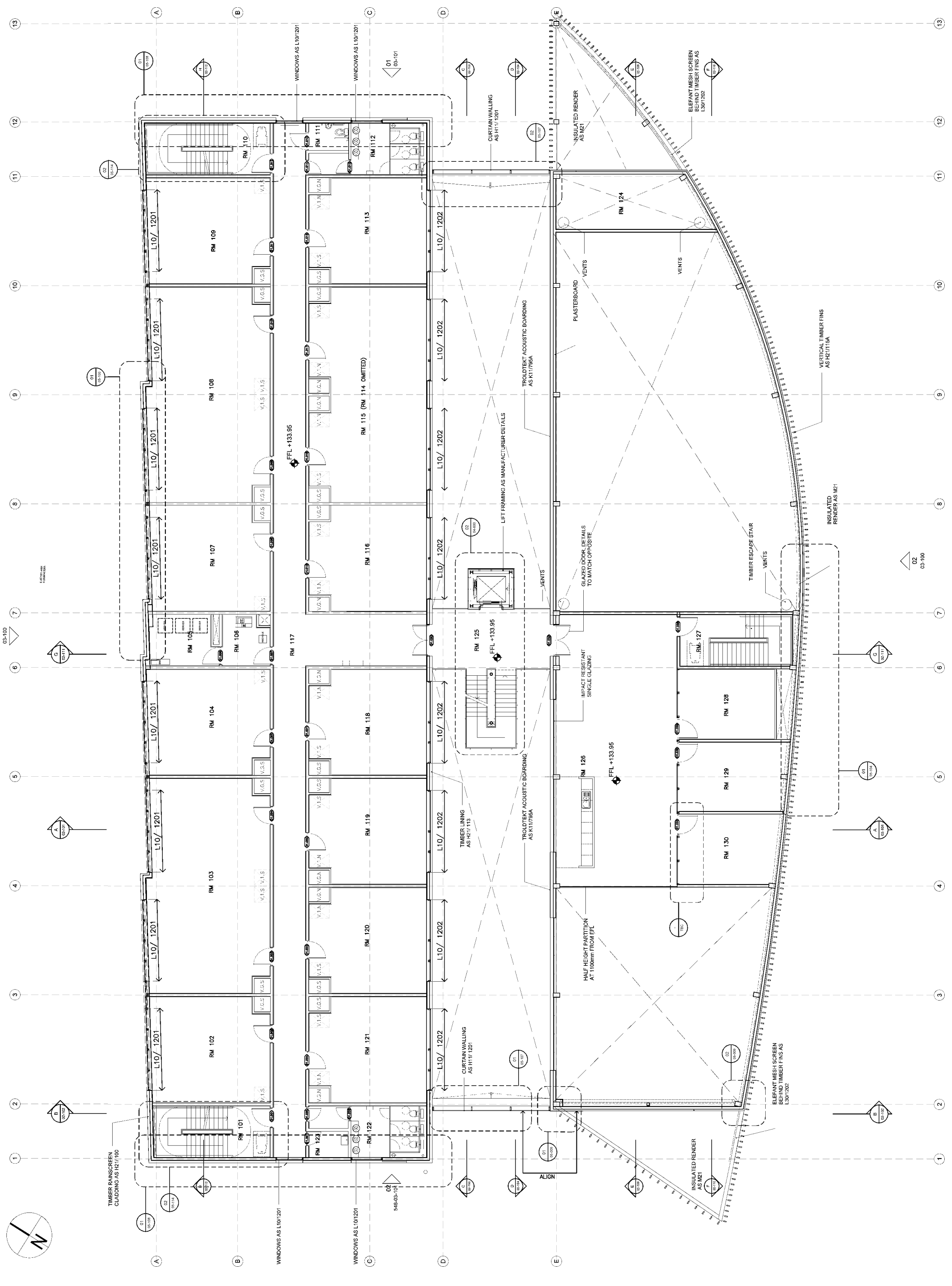


Figure A.3: First Floor Plan (Consarc, 2011)

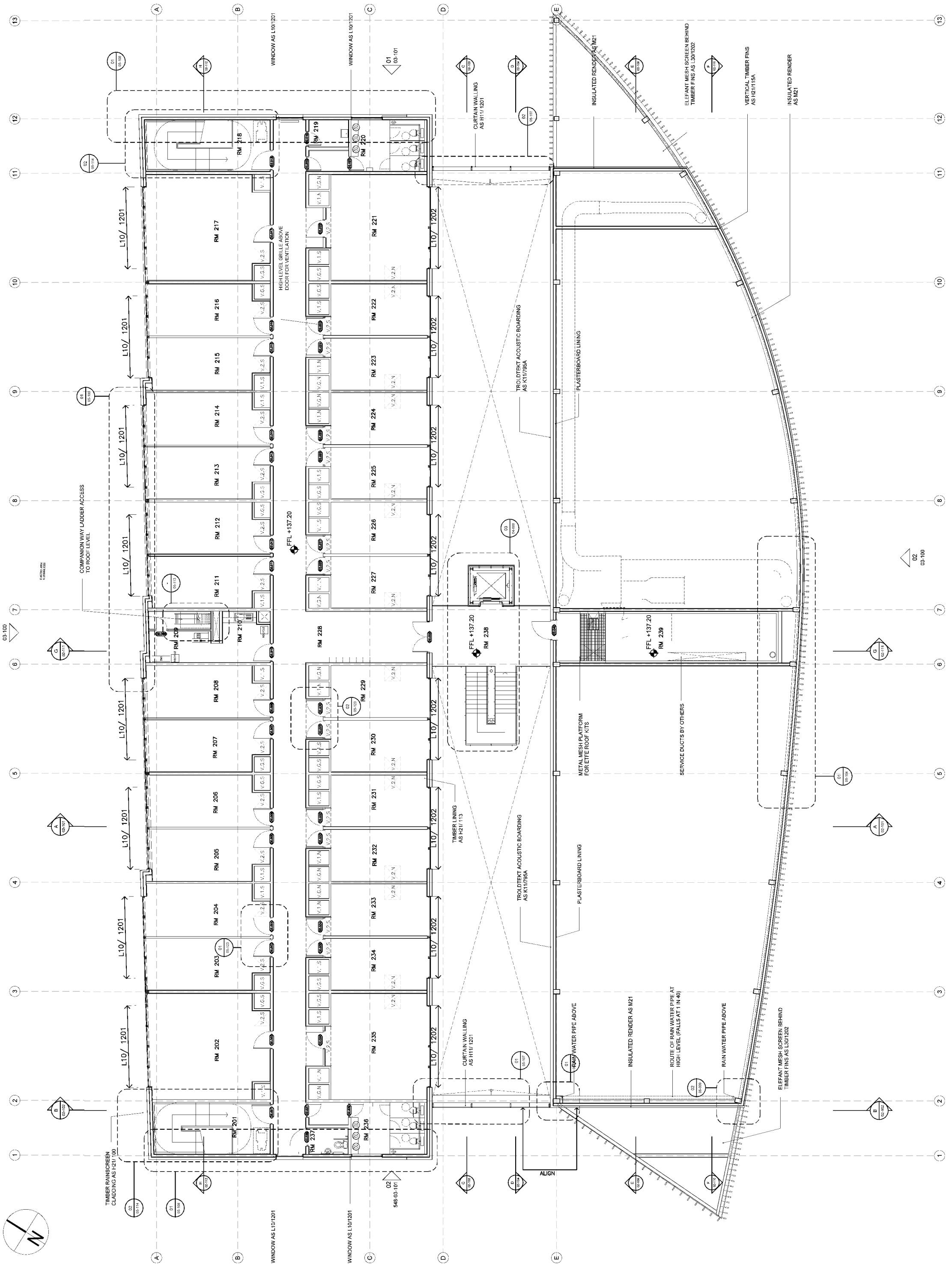


Figure A.4: Second Floor Plan (Consarc, 2011)

A.2 Sections

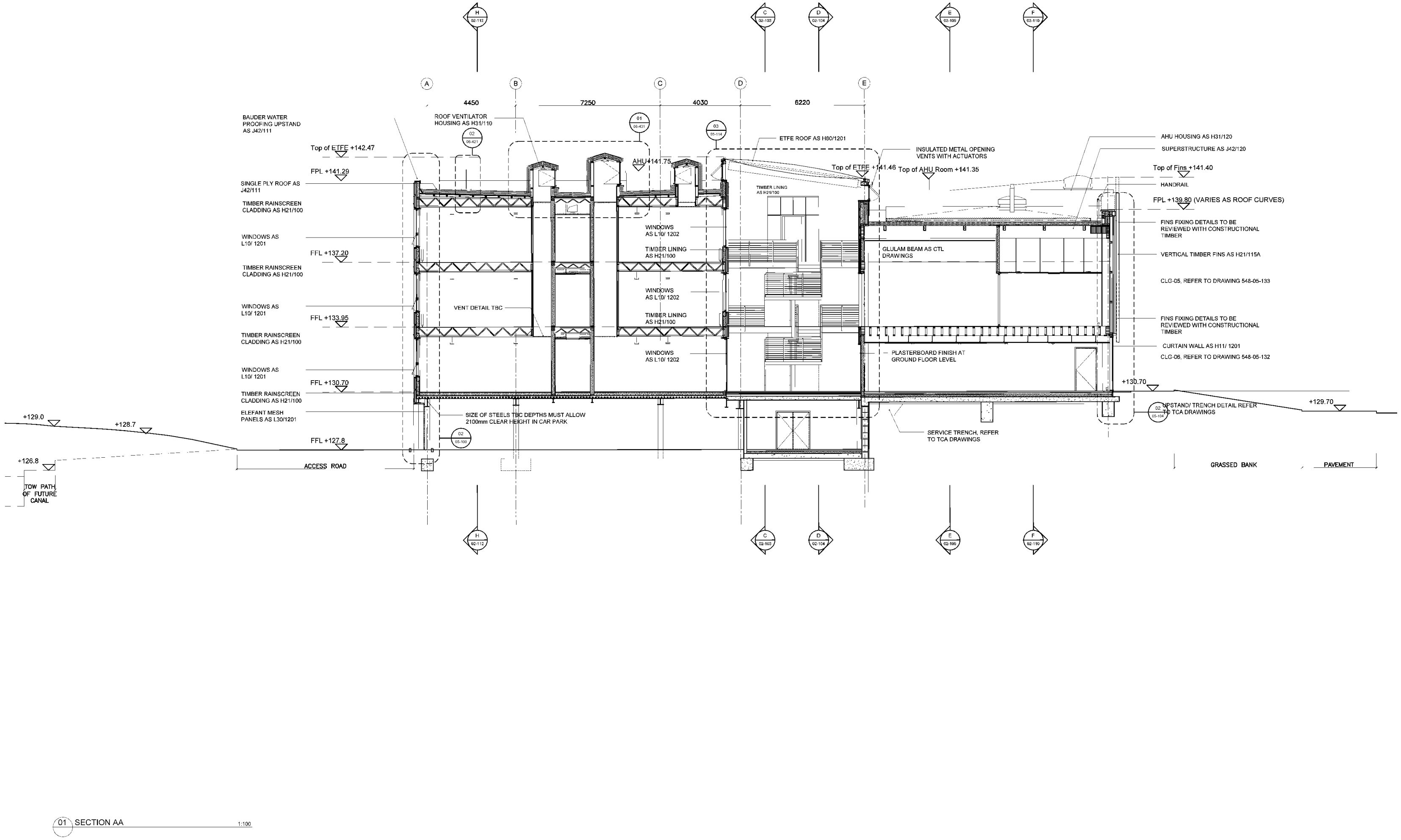


Figure A.5: Section AA (Consarc, 2011)

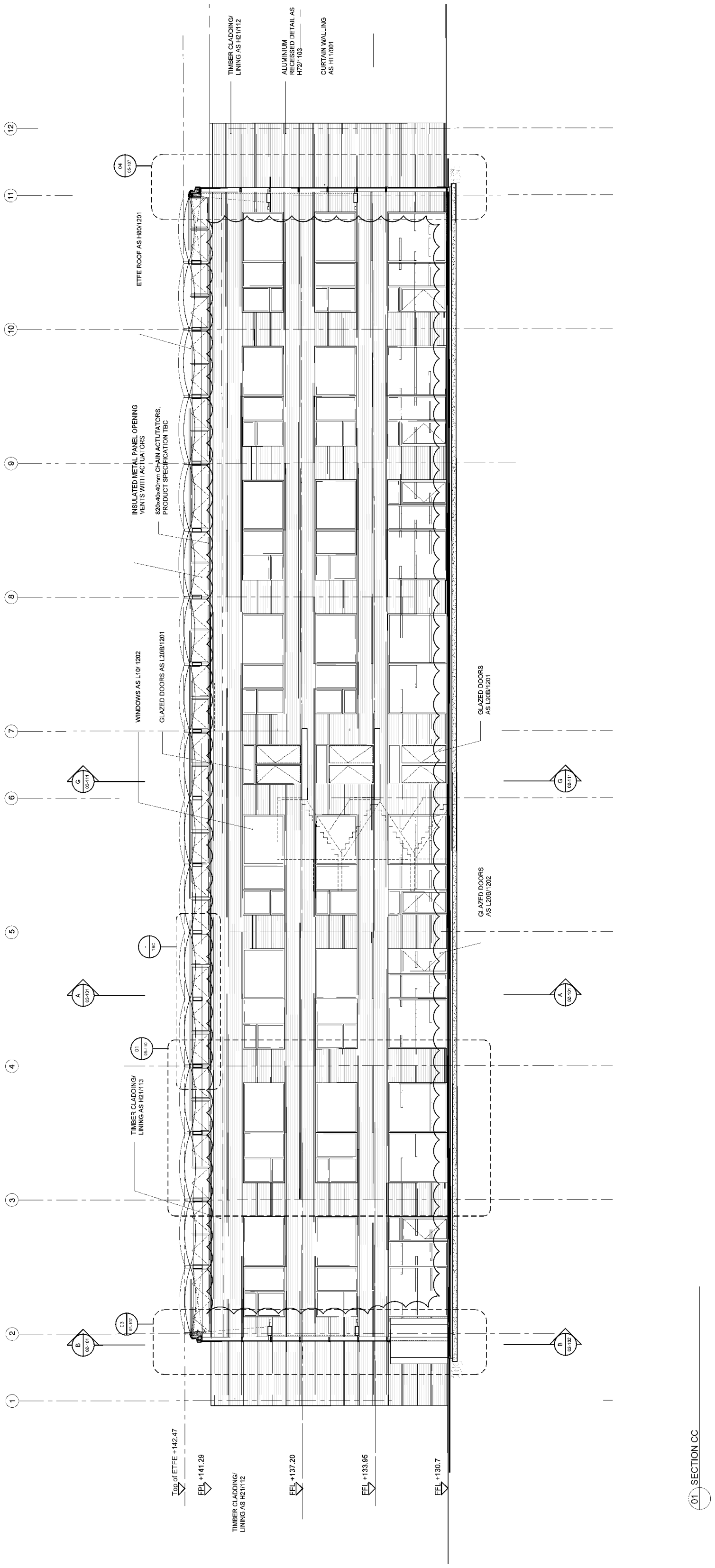


Figure A.6: Section CC (Consarc, 2011)

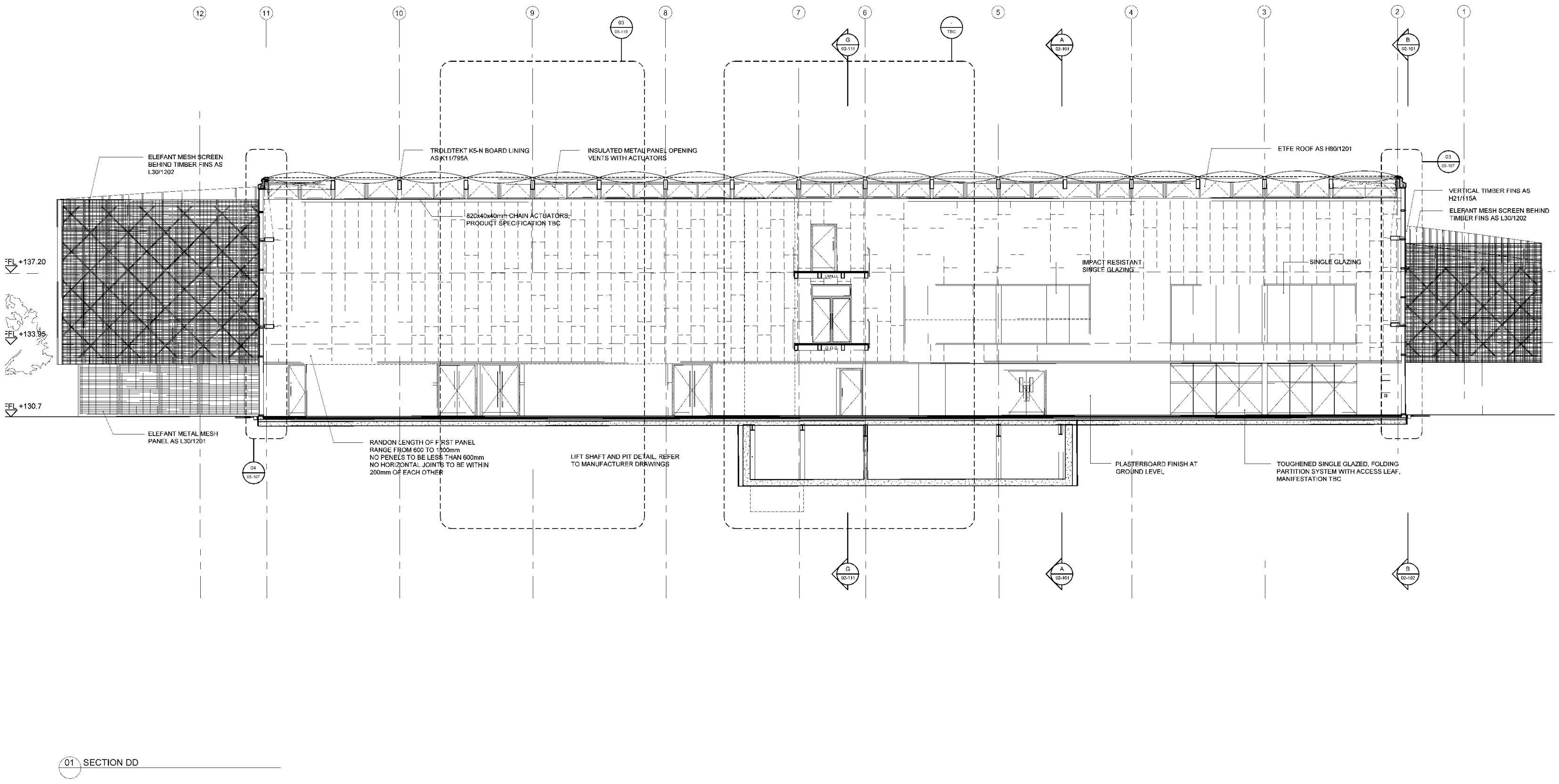


Figure A.7: Section DD (Consarc, 2011)

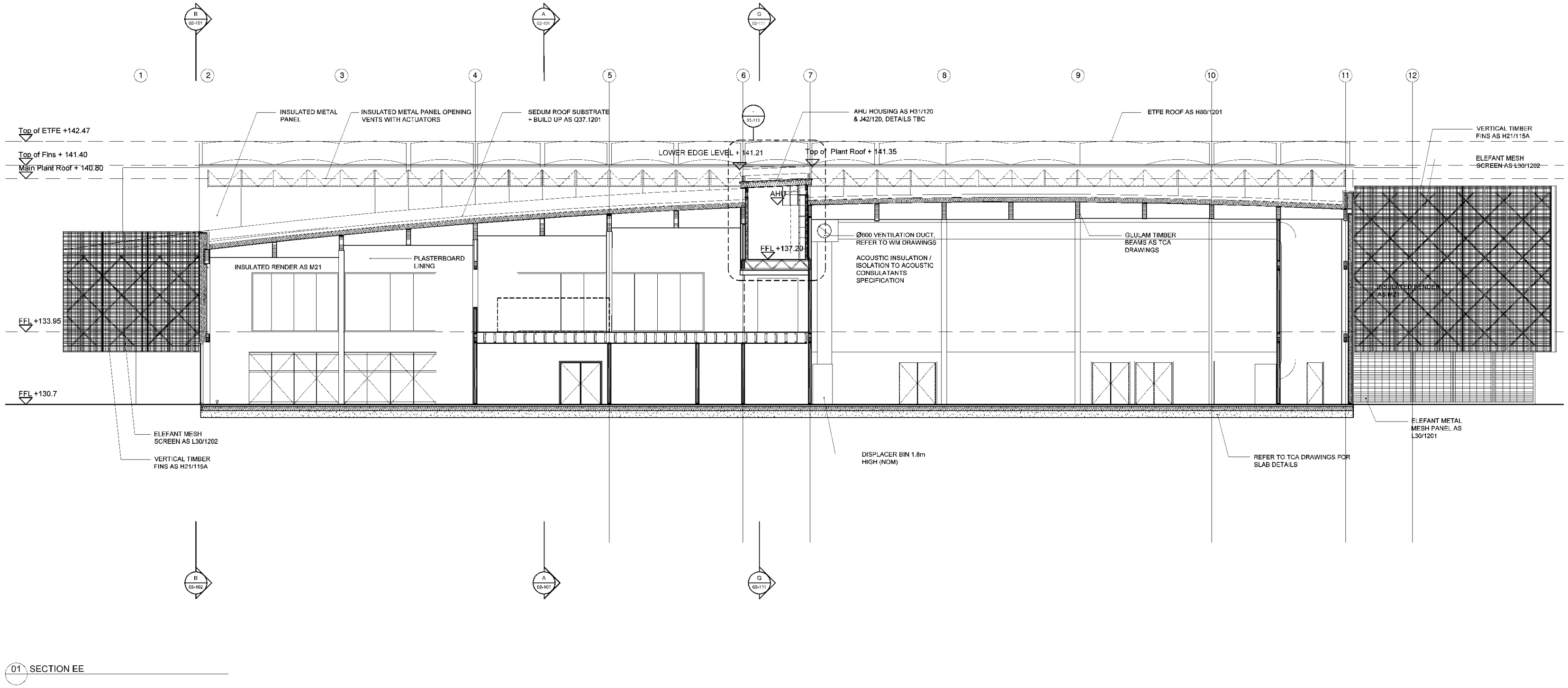


Figure A.8: Section EE (Consarc, 2011)

A.3 Elevations

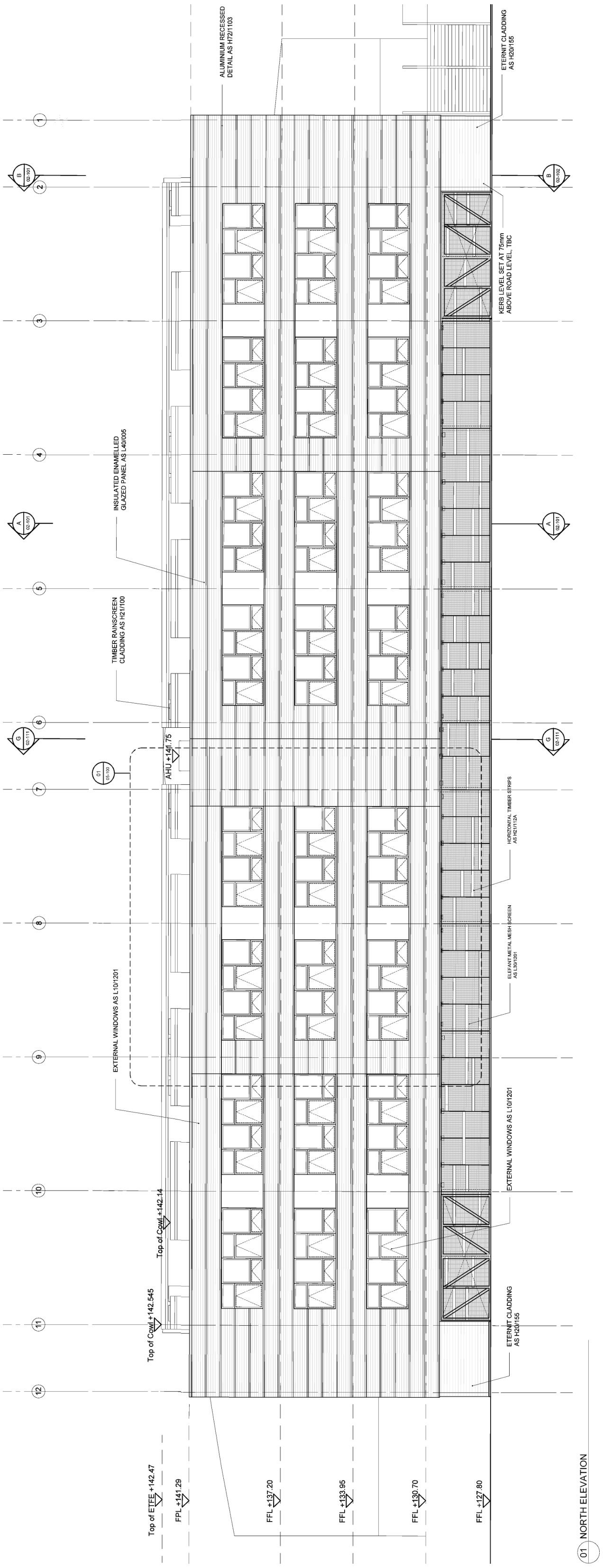


Figure A.9: North Elevation (Consarc, 2011)

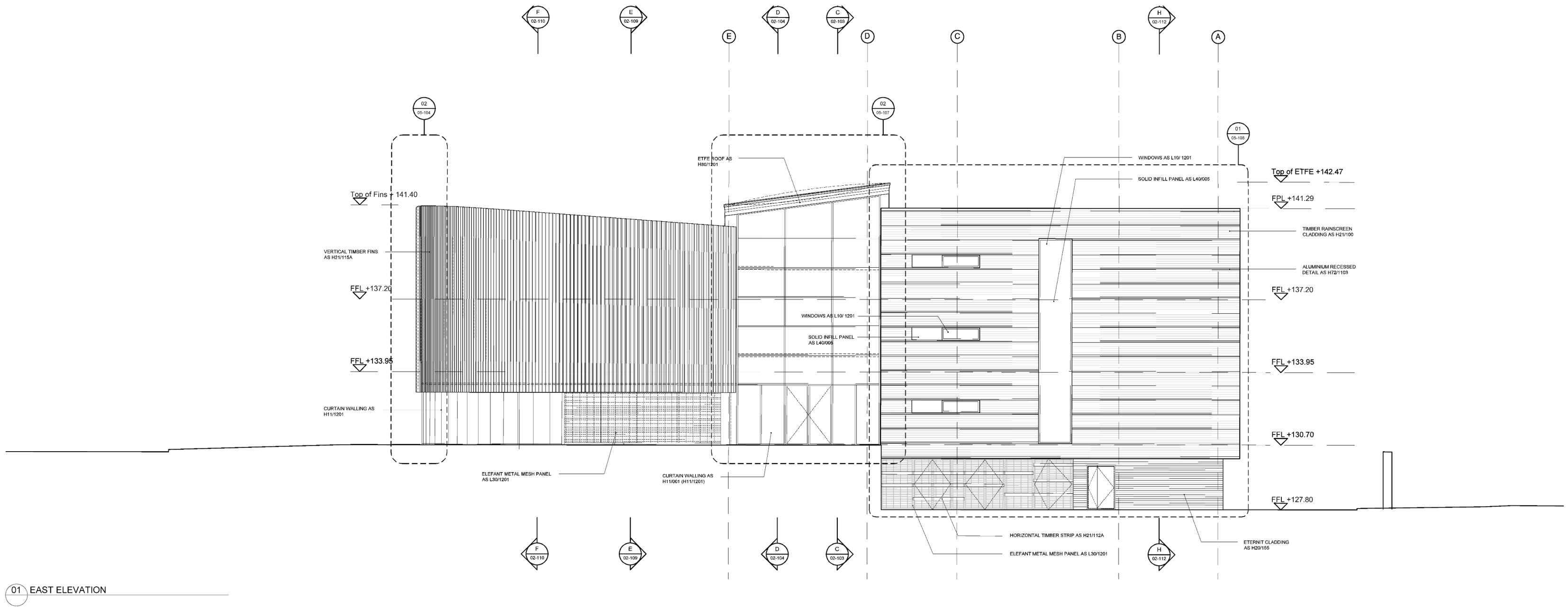


Figure A.10: East Elevation (Consarc, 2011)

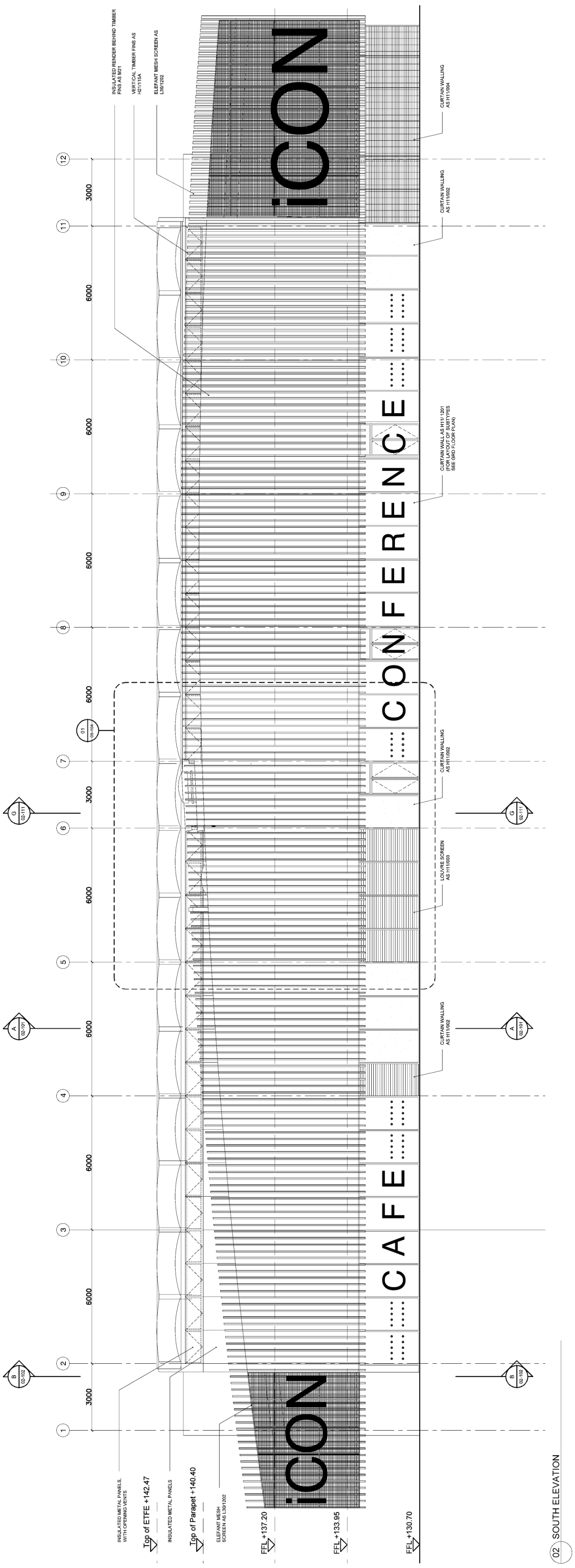


Figure A.11: South Elevation (Consarc, 2011)

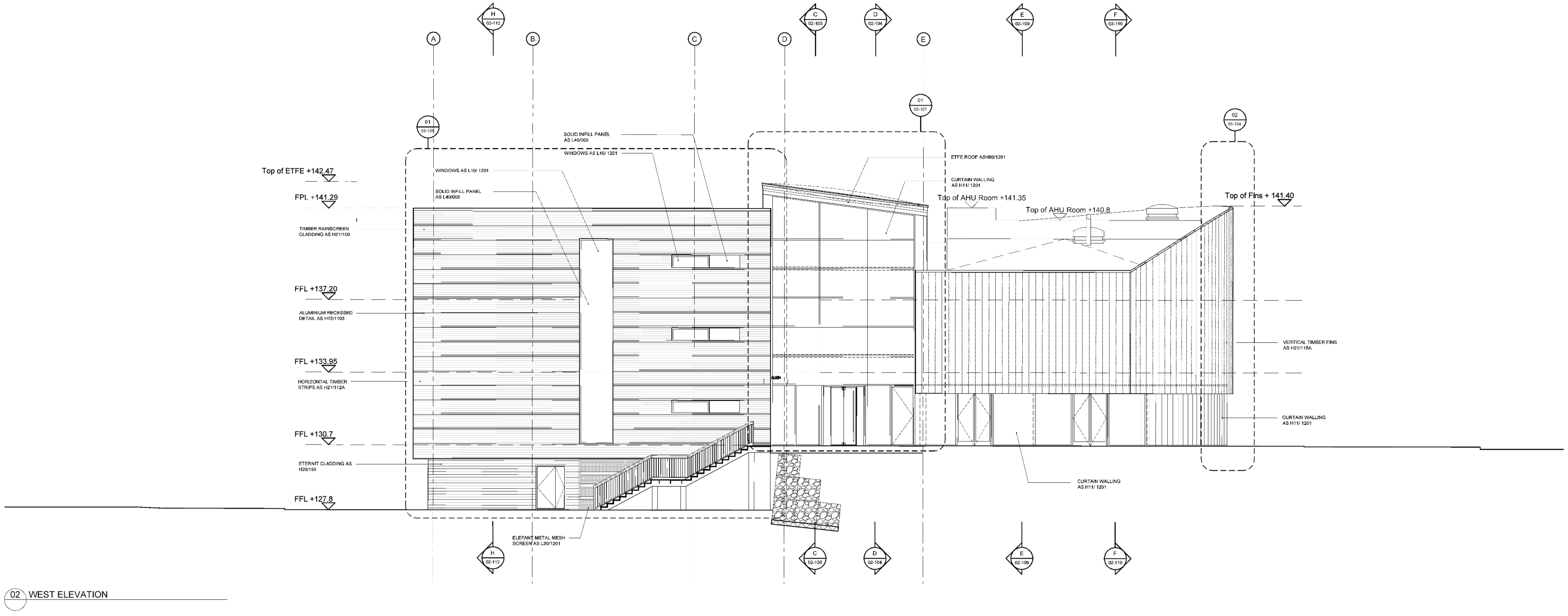


Figure A.12: West Elevation (Consarc, 2011)

Appendix B

Monitoring Equipment Datasheets

This appendix includes datasheets for the following monitoring equipment:

- Seamless Sensing Wireless Sensing Module
- Electrical Sub-Meter (ADM1TE)
- CO_2, Relative Humidity and Temperature Sensor (EE80)
- Light Sensor (LL-SC)
- Heat Meter (Superstatic, Supercal)
- Thermistor Sensor (TB/TI)

Wireless Sensing Solutions

Seamless Sensing's patent pending technology provides live information about your buildings. Wireless Smart Sensing Modules are connected to equipment and appliances that transfer information to a web based platform allowing you to monitor and control your buildings.

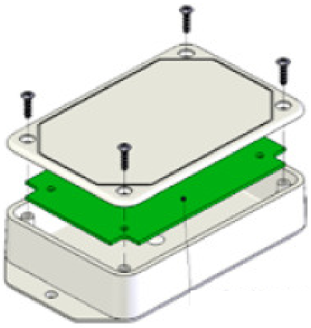
Wireless Sensing Module

Our wireless sensing module can be used to interface directly to a wide range of sensors and can also control your equipment. The wireless sensing module contains analogue, digital and serial interfaces allowing you to seamlessly integrate your buildings sensor infrastructure.

Features

Analogue Input Monitoring (voltage or current)

- Two channel analogue sensor inputs configurable as voltage or current.
- 12 bit analogue resolution.
- Analogue voltage range 0 - 5V or 0 - 10V.
- Analogue current range 0 – 20mA.

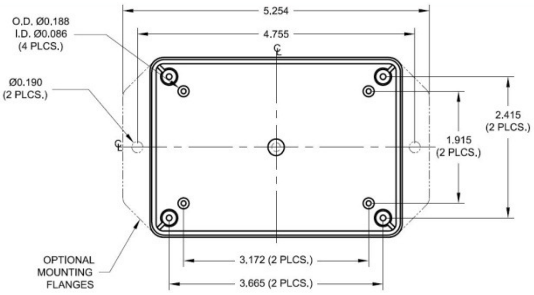


Energy Meter Monitoring (pulse counter)

- Two channel meter inputs.
- Interface to virtually any metering device (water, electric, oil, gas).
- Industry standard interface.

Serial Communications

- Serial port support baud rate up to 115200bps with full handshaking lines.
- Integrate more specialist sensing devices into your monitoring system.
- Custom serial command libraries can be developed for your requirements.

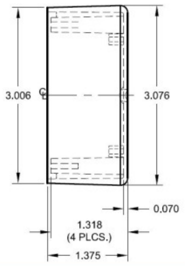


Relay Output Control

- Two channel relay output.
- Control equipment remotely.
- Configure alarms to automatically switch equipment / appliances.
- 240VAC, 16A rated switching load.

Special Purpose

- SPI serial interface header for off board sensors (for example, Sensirion SHT7x).



Power

- Wide range 12-28VDC or 240VAC powered.
- 24VDC 500mA output power (for powering sensor devices).

Communications

- True ZigBee mesh network providing :
    - Self healing and discovery for network stability.
    - Network coexistence with other2.4GHz devices.
    - Scalable network – simply add new modules with zero configuration (100's per network).
    - Self optimising wireless settings for the most robust communications.
    - No wireless configuration - out of the box wireless communications.
- ZigBee fully functional mesh router device.
- Range of up 100 meters indoors / 700 meters free space.
- 2 way communications.
- Multiple antenna options via externally mounted SMA connector.

Integration

- User-definable sampling intervals.
- Monitor and control equipment remotely.
- Web portal to manage data downloads, real time charting, alarming and intelligent trending functions.
- Optional Flash visualisations to display information to clients, building occupants.

Email: info@seamlesssensing.com
Web: www.seamlesssensing.com

ADM1TE DIN Rail Series Single Phase MID Approved

Introduction

The ADM1TE series are a 18mm wide electricity meter which is able to measure up to 30A. The ADM1TE is available in 4 different types. All meters are available for 120V or 230V and for 50Hz or 60Hz.

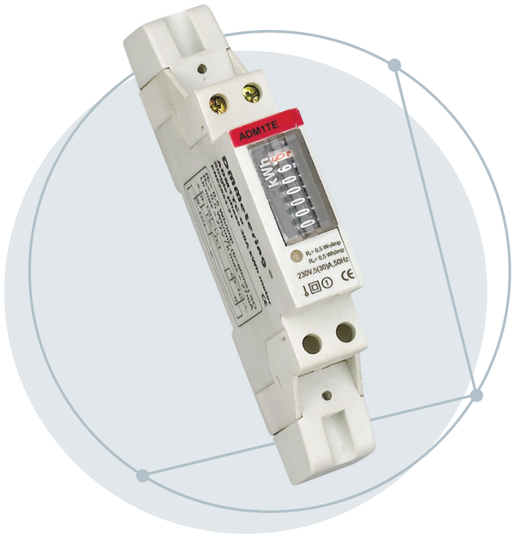
An MID approval is obtained for the ADM1TE with 6+1 motorstep counter. With this approval it is allowed to use the meter for billing purposes throughout Europe.

Functions and features

- ADM1TE Register. Contains a 6+1 motorstep counter and is MID, KEMA and CSA approved.
- ADM1LCD version 1. Contains an LCD display.
- ADM1LCD version 2. Contains an LCD display with possibility to connect an external voltage to read out the meter when there is no power.
- ADM1LCD version 3. Contains an LCD display with backlight and build in battery to read out the meter when there is no power.

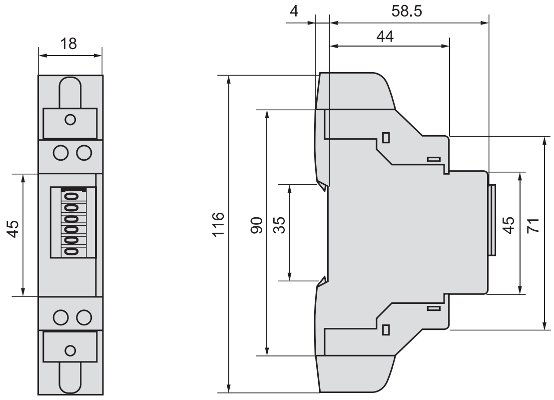
Technical specifications

Voltage	127 / 230V AC (-15%+10%)
Frequency	50Hz or 60Hz (±10%)
Current	5(20), 5(25), 5(30), 5(23)A
Power consumption	< 0,6W
AC voltage withstand	2KV for 1 minute
SO Output	SO according to DIN43864
Temperature range	-25°C ~ +55°C
Case	1 module DIN rail
Dimensions (wxhxd)	18x90x58,5mm without protection cover
Accuracy class	1 or 2
Packaging dimension	32x22x29.5cm - 12kgs (100pcs/ctn)



ADM1TE-s

Outline dimension



EE80 Series

HVAC Room Transmitter and Switches for CO$_2$, Relative Humidity and Temperature

EE80 series set new standards in CO$_2$ measurements for HVAC. The transmitters resp. switches combine CO$_2$, relative humidity (RH) and temperature (T) measurement in one modern and user-friendly housing.
The basic EE80 version for CO$_2$ and T can be easily extended with a RH plug-in module.
The CO$_2$ measerument is based on the infrared principle. A patented auto-calibration procedure compensates for the aging of the infrared source and ensures outstanding long term stability.
EE80 provides analogue outputs (in V or mA). The optional display indicates sequentially the actual measuring data.
As one more option a switching output with adjustable switching point and hysteresis is available.
A wide variety of models ensures an optimal adjustment for customised requirements.

Typical Applications

building management for residential and office areas
ventilation control

Features

CO$_2$ / RH / T measurement in one device
RH output with plug-in module
analogue or switching output
modern design
optional display
easiest installation
long-term stable

Technical Data

Measuring values

CO$_2$

Measurement principle	Non-Dispersive Infrared Technology (NDIR)	
Sensor	E+E Dual Source Infrared System	
Working range	0...2000 / 5000ppm	
Accuracy at 25°C (77°F)	0...2000ppm:	< ± (50ppm +2% of measuring value)
and 1013mbar	0...5000ppm:	< ± (50ppm +3% of measuring value)
Response time t_{63}	< 195s	
Temperature dependence	typ. 2ppm CO$_2$/°C	
Long term stability	typ. 20ppm / year	
Sample rate	approx. 15s	

Temperature

Accuracy at 20°C (68°F)	±0.3°C (±0.54°F)	version with current output 4 - 20mA: ±0.7°C (±1.26°F)

Relative Humidity

Measurement principle	capacitive	
Sensor element	HC103	
Working range1)	10...90% RH	
Accuracy at 20°C (68°F)	±3% RH (30...70% RH)	±5% (10...90% RH)

Outputs

Analogue Output

0...2000 / 5000ppm /	0 - 5V	-1mA < I_L < 1mA
0...100% RH / 0...50°C (32...122°F)	0 - 10V	-1mA < I_L < 1mA
	4 - 20mA	R_L < 500 Ohm

Switching Output

Max. switching voltage	50V AC / 60V DC	
Max. switching load	1A at 50V AC	1A at 30V DC
Min. switching load	1mA at 5V DC	
Contact material	Ag+Au clad	

General

Supply voltage	24V AC ±20%	15 - 35V DC
Current consumption	typ. 10mA + output current max. 0.5A for 0.3s	
Warm up time2)	< 5 min	

LL-SC

Internal light level transmitter ceiling mount

Technical Overview

The **LL-SC** is a light level transmitter designed for use in the active control of artificial lighting, both to optimise light levels and to achieve maximum energy efficiency.

The **LL-SC** transmitter uses a photo-diode cell to detect light levels in the 10-2000 lux range, providing a linear 0-10Vdc output signal.

The **LL-SC** is designed to be ceiling mounted for the measurement of all types of light levels.

Features

- Flush or surface mount options.
- 24Vac/dc supply
- 0-10Vdc output

Specification

Sensor reference	Photo-diode
Accuracy	±5% across range
Field of view	360°
Coverage	7 metres max.
Light range:	10 - 2000 Lux
Supply voltage	24Vac/dc
Dimensions	See Page 2
Temperature	–10 to +40C
Humidity	90%RH non–condensing
Material	Flame retardant ABS, polypropylene
Conformity	EMC, LVD, CE Marked
Country of Origin	UK

Product Codes

LL-SC/V

Ceiling light level sensor 0-10Vdc, output flush mount

LL-SC/V/S

Ceiling light level sensor 0-10Vdc, output surface mount

Page 1

Omni Instruments
Measurement > Control > Data Acquisition

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Superstatic
Static flow sensor
qp 1 - 400m^3/h

Flow measurement

Nominal flow	qp	1.0	1.5	2.5	3.5	6.0	10	15	25	40	60	100	150	250	400	m^3/h
Maximum flow	qs	2.0	3.0	5.0	7.0	12	20	30	50	80	120	200	300	500	800	m^3/h
Minimum flow	qi	10	15	25	35	60	100	150	250	800	1200	2000	3000	5000	8000	l/h
Starting point (50°C)		4	10	10	15	30	50	75	125	400	600	1000	1500	2500	4000	l/h
Plus value at qp		49.0	27.0	27.0	15.5	8.8	5.8 / 5.15	3.8	2.3	0.84	0.56	0.34	0.23	0.14	0.09	Imp/l
Pressure lost at qp		0.20	0.09	0.21	0.16	0.16	0.19	0.19	0.19	0.08	0.08	0.09	0.10	0.10	0.10	bar
Metrological class		EN 1434 Class 3														
Nominal pressure PN		16 / 25												10 / 16 / 25		bar

Mounting

Temperature continuously	130°C																				
Temp. sensor mounting place	Yes	Yes	Yes	Yes	Yes	Yes		Yes		Yes											
Mounting length	110	190	110	190	190	260	260	260	260	300	300	270	300	225*	300	250*	360	250	300	350	450	mm
Screwed connection	3/4"	1"	3/4"	1"	1"	1 1/4"		1 1/4"		2"												
Flanged connection							25		25		40	50	65	80	80	100	100	125	150	200	250	DN
Weight	1.8	2.3	1.8	2.3	2.3	1.96	2.9	1.96	2.9	6.1	7.0	12.2	12.8	11.5	12.2	14.0	14.6	16.0	23.0	30.0	57.0	kg

*upon request

Supercal Integrator 531

Temperature measurement	**Pt500 / Pt100**	two or four wire technique
Temperature range	0...200°C	
Temperature difference	(0.2) 2...150K	
Starting point	0.2K	

SPECIFICATIONS

Sensing element :Thermistor 10 kΩ at 25 °C
Thermistor accuracy
 -10 °C to +40 °C :±0.43 °C (14 °F to +104 °F, ±0.77 °F)
 - 30 °C to +50 °C :±0.59 °C (-22 °F to +122 °F, ±1.06 °F)
 - 30 °C to +100 °C :±1.11 °C (-22 °F to +212 °F, ±2.0 °F)
 - 30 °C to +110 °C :±1.28 °C (-22 °F to +230 °F, ±2.30 °F)
Ambient limits
 box :-40 °C to +50 °C (-40 °F to +122 °F)
 /TC probe :-40 °C to +100 °C (-40 °F to +212 °F)
 /TI probe :-40 °C to +110 °C (-40 °F to +230 °F)
Humidity :0 to 95 %RH
Measurement ranges
 /TO :-30 °C to +50 °C (-22 °F to +122 °F)
 /TC :-30 °C to +100 °C (-22 °F to +212 °F)
 /TI :-30 °C to +110 °C (-22 °F to +230 °F)
Cable entry :M20 conduit with M16 cable gland
Connections :1 part screw terminals for 0.5 to 2.5 mm^2 cross section (14 to 20 AWG) cable
Dimensions
 /TC :57 mm (2.24") x 117 mm (4.61") max diameter, cable 2 m (6'6")
 /TO :57 mm (2.24") x 102 mm (4.02") max diameter
 /TI :(box)57 mm (2.24") x 105 mm (4.13"), /S probe 150 mm (5.91") x 6 mm (0.24") /L probe 400 mm (15.75") x 6 mm (0.24")
Material
 Enclosure :Impact resistant ABS
 /TI, /TO probes :Brass
 /TC probe :Plated copper
 POC/SS/6 :pocket, 316 stainless steel/silver solder
 POC/B/6 :pocket, brass/silver solder
Environmental Protection:IP67 (NEMA6)

Input channels and sensor scaling

For IQ controllers link input channel for thermistor, T and set up the sensor type scaling; the recommended method of setting the sensor type scaling is to use SET.

For all IQ2 series controllers with firmware of version 2.1 or greater, or IQ3 series controllers, one of the following SET Unique Sensor References should be used:

Thermistor TBTO	(-10 °C to +40 °C)
Thermistor TBTO F	(+14°F to +104 °F)
Thermistor TBTC	(-30 °C to +100 °C)
Thermistor TBTC F	(-22°F to +212 °F)
Thermistor TBTI	(-30 °C to +110 °C)
Thermistor TBTI F	(-22°F to +230 °F)

Alternatively use sensor scaling mode 5, characterise, and enter the scaling manually as defined in the tables shown. Note that for IQ3 the scaling mode and exponent (E) don't need to be set up.

For all other IQ controllers see the Sensor Scaling Reference Card, TB100521A.

-30 °C to +110 °C
(-22 °F to +230 °F)

Units:		°C	°F
Y	Input type	1 (therm V)	
E	Exponent	3	
U	Upper	115	239
L	Lower	-35	-31
P	Points	20	
x	**Ix**	**Ox**	
1	0.480	110	230
2	0.549	105	220
3	0.630	100	212
4	0.724	95	203
5	0.833	90	194
6	0.961	85	185
7	1.110	80	176
8	1.484	70	158
9	1.985	60	140
10	2.641	50	122
11	3.470	40	104
12	4.460	30	86
13	6.663	10	50
14	7.668	0	32
15	8.102	-5	23
16	8.482	-10	14
17	8.807	-15	5
18	9.078	-20	-4
19	9.299	-25	-13
20	9.476	-30	-22

-30 °C to +100 °C
(-22 °F to +212 °F)

Units:		°C	°F
Y	Input type	1 (therm V)	
E	Exponent	3	
U	Upper	105	221
L	Lower	-35	-31
P	Points	18	
x	**Ix**	**Ox**	
1	0.630	100	212
2	0.724	95	203
3	0.833	90	194
4	0.961	85	185
5	1.110	80	176
6	1.484	70	158
7	1.985	60	140
8	2.641	50	122
9	3.470	40	104
10	4.460	30	86
11	6.663	10	50
12	7.668	0	32
13	8.102	-5	23
14	8.482	-10	14
15	8.807	-15	5
16	9.078	-20	-4
17	9.299	-25	-13
18	9.476	-30	-22

-30 °C to +50 °C
(-22 °F to +122 °F)

Units:		°C	°F
Y	Input type	1 (therm V)	
E	Exponent	3	
U	Upper	55	131
L	Lower	-35	-31
P	Points	11	
x	**Ix**	**Ox**	
1	2.641	50	122
2	3.470	40	104
3	4.460	30	86
4	6.663	10	50
5	7.668	0	32
6	8.102	-5	23
7	8.482	-10	14
8	8.807	-15	5
9	9.078	-20	-4
10	9.299	-25	-13
11	9.476	-30	-22

-10 °C to +40 °C
(14 °F to +104 °F)

Units:		°C	°F
Y	Input type	1 (therm V)	
E	Exponent	3	
U	Upper	45	113
L	Lower	-15	-5
P	Points	6	
x	**Ix**	**Ox**	
1	3.470	40	104
2	4.460	30	86
3	6.663	10	50
4	7.668	0	32
5	8.102	-5	23
6	8.482	-10	14

Manufactured for and on behalf of the Environmental and Combustion Controls Division of Honeywell Technologies Sàrl, Ecublens, Route du Bois 37,Switzerland by its Authorized Representative, Trend Control Systems Limited.

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Appendix C

Temporary Heat Metering

C.1 Introduction

This appendix discusses the results of a period of temporary metering installed with the aim of verifying the volume flow rate in the heating primary circuit. The findings have a significant implication for the validity of calculated heat flow and derived parameters such as efficiency and COP. The investigation also revealed issues relating to the sampling interval and interpolation of temperature measurements.

C.2 Metering Issues

The monitoring system installed in the case study building included a heat meter to monitor the exhaust air heat pump. It was intended to be used for calculating the heat pump's average COP based on monitored heat output and electricity consumption. Between the end of April 2012, when the heat meter was commissioned, and the end of November 2012, when the heat pump first failed, the average COP was 0.97. This is not only much lower than the manufacturer's performance figures of between 3.5 and 4 under design conditions but also lower than the system efficiency of the worst performing air source heat pump in the EST field trial (DECC, 2012). Figure C.1 shows the calculated daily average COPs for the heat pump's operation in 2012. It is clear that the daily COP frequently drops below 1.

Such poor performance was surprising, as a COP of less than 1 would indicate that electricity consumption was greater than the heat output and therefore that a significant

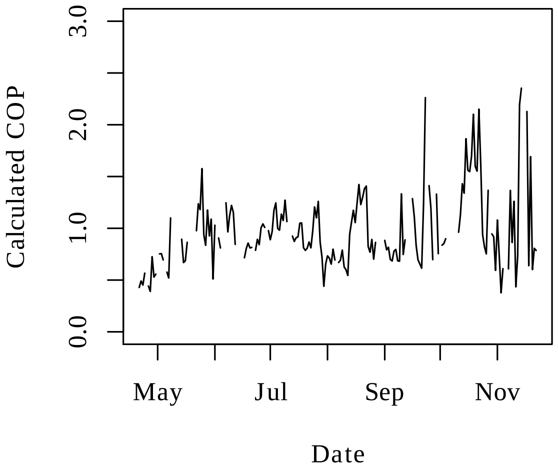


FIGURE C.1: EAHP calculated daily average COP

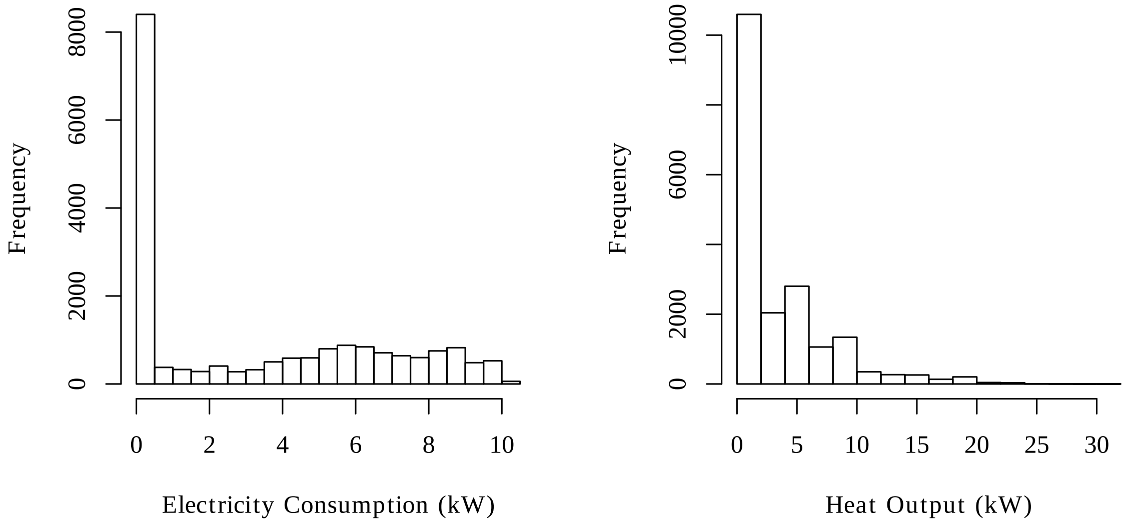


FIGURE C.2: EAHP measured 15-minute electricity consumption and heat output

proportion of heat was being dissipated from the unit instead of passing into the water flow. Since a visual inspection of the unit failed to reveal any obvious problems it was suspected that either the electricity or heat measurements were incorrect.

Figure C.2 shows the distribution of electricity consumption and heat output calculated at 15-minute intervals. Although there are many intervals when the unit is not operating, the spread of values during operation can be seen. The measured electricity consumption figures fall in the range of 0 to 10 kW. The majority of the measured heat output also falls in the range of 0 to 10 kW. While the electricity figures are consistent with the unit's rated maximum power input of 9 kW, the heat figures are much less than the unit's rated maximum power output of 32 kW (CIAT, 2009). This suggests that low heat output, rather than high electricity consumption, is responsible for the low average COP.

	Flow Temperature	Return Temperature
Heat Meter	48.4 °C	43.8 °C
BMS	48.3 °C	44.2 °C

TABLE C.1: Comparison of heat meter and BMS temperature measurement

The heat meter calculates heat flow using measured flow and return temperatures and volume flow rate. These are all measured close to the outlet from the EAHP. The temperature sensors are installed in sensor pockets in the pipework, and the flow meter is installed in-line with the flow pipe leaving the EAHP. The heat meter logs both cumulative volume flow and heat output at 15-minute intervals via the wireless monitoring system. It also displays, but not logs, the flow and return temperatures. On 27th September 2012, the flow and return temperatures displayed by the heat meter were compared with corresponding values from the BMS logs (Table C.1). These found to be reasonably close, which further suggests that unreliable flow measurement, rather than temperature measurement, is responsible for the low measured heat output.

In order to obtain flow rate values that could be compared with the design flow rate it was necessary to convert the cumulative volume flow logged by the heat meter into equivalent instantaneous values. This was done by multiplying the 15-minute cumulative flow by 4 (i.e. 60 minutes per hour / 15 minutes per interval) and dividing by 3.6 (to convert m^3/hour to l/s) to obtain average flow rates for each 15-minute interval. These values are plotted in Figure C.3, which shows a wide variation between a minimum flow rate of about 0.15 l/s and a maximum of about 0.4 l/s, at least until mid-September, when the maximum flow rate increased noticeably. During this period, the majority of the peak values were significantly lower than the design flow rate of 1.12 l/s. This was surprising, because the heating primary circuit was intended to operate with a constant volume flow rate. The apparent poor performance of the EAHP was therefore likely to be due to unreliable volume flow measurement by the heat meter. In order to verify the heat meter's operation it was necessary to independently measure the volume flow rates in the system.

C.3 Flow Measurement

Independent measurement of volume flow rates was achieved by temporarily installing a non-invasive ultrasonic flow meter (Flexim Fluxus F601) capable of logging measurements. The meter also included clamp-on temperature probes, which enabled its use as a heat meter. The meter was installed on 28th March 2013 and removed on 9th April. The only

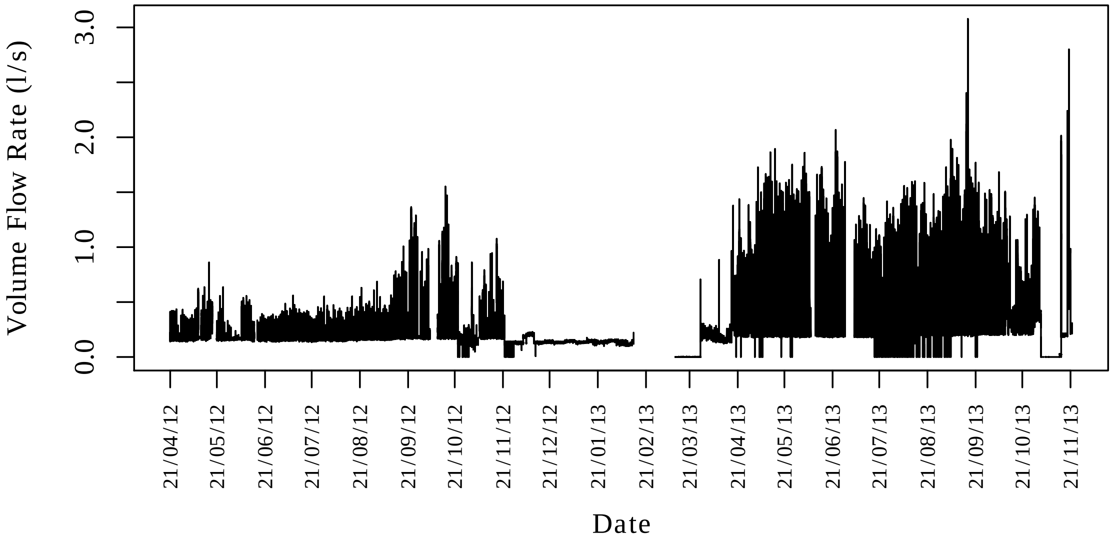


FIGURE C.3: EAHP heat meter measured 15-minute volume flow rate

convenient location for mounting the temporary heat meter was in the primary flow and return pipework to the buffer vessel. This pipe loop circulated water from the buffer vessel in the ground floor plant room up to the heat pump installed on the roof and back down to the plant room where it passed via the boiler header back into the buffer vessel (see Figure 3.11). Although the flow rate may be measured at any point of the loop it was not possible to measure the heat output of the heat pump alone. The location of the heat meter between the boiler and the heat pump meant it measured the heat input of both sources into the buffer vessel.

The initial objective of the temporary metering was simply to verify the flow rates measured by the original heat meter. Figure C.4 compares the distribution of measured flow rates during the period of temporary measurement. The measurements from the Flexim temporary metering are evenly distributed around a mean of about 0.6 l/s. By contrast, the measurements from the original heat meter are more widely spread around a much lower mean value. This differences are illustrated in Figure C.5. The flow rates were also checked just over a week after the temporary monitoring period using a Grundfos R100 pump remote control. This reported an estimated flow rate of 0.67 l/s, slightly higher than the temporary metering. The R100 however is not intended for accurate measurements and reports estimated flow rate based on the pump's settings (unless an optional flow sensor is fitted to the pump).

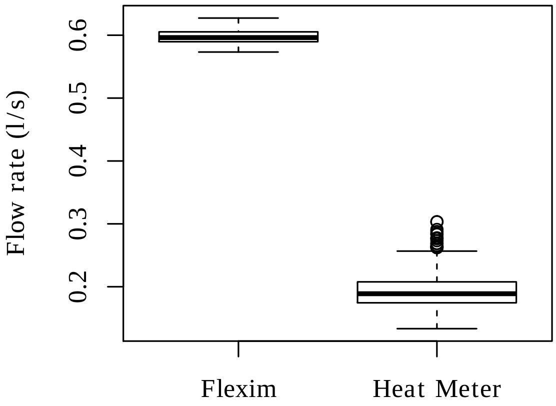


Figure C.4: Summary of measured flow rates

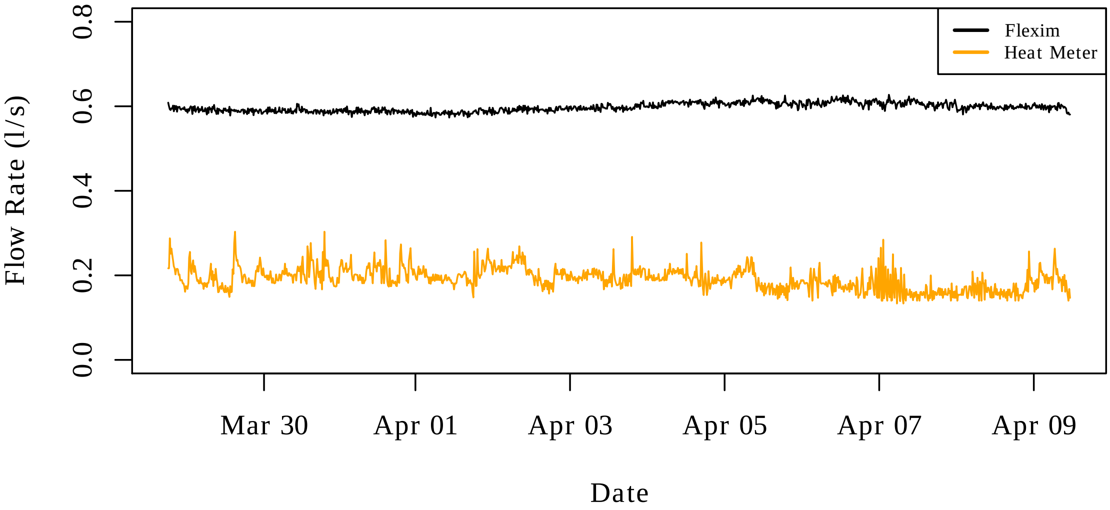


Figure C.5: Comparison of measured flow rates

C.4 Heat Measurement

Two sets of measurements were collected during the temporary monitoring period; one with both boiler and EAHP operating simultaneously, and another, shorter, set with measurements of the EAHP operating on its own. The period of combined operation contains 11.67 days of measurements at 10 minute intervals. The period of EAHP-only operation contains approximately 4.63 hours of measurements at 1 minute intervals. The buffer heat input, primary flow rate and flow and return temperatures for both periods are summarised in Tables C.2 and C.3 respectively. It is clear from the summaries that the buffer heat input is larger in combined operation, as the boiler has a higher heat output and is able to produce higher flow temperatures than the EAHP. In both periods, the primary flow rate was virtually the same (the higher maximum flow rate during the EAHP-only period was due to a brief adjustment to check pump operation).

	Buff_Q (kW)	Pri_Flow (l/s)	Buff_F (°C)	Buff_R (°C)
Min.	-2.02	0.57	41.05	40.21
1st Qu.	18.73	0.59	53.93	44.97
Median	25.87	0.60	56.71	46.06
Mean	27.72	0.60	57.20	45.91
3rd Qu.	35.00	0.61	60.76	47.14
Max.	66.69	0.63	70.82	48.53

Table C.2: Summary statistics (EAHP and boiler)

	Buff_Q (kW)	Pri_Flow (l/s)	Buff_F (°C)	Buff_R (°C)
Min.	1.68	0.58	43.75	41.88
1st Qu.	16.03	0.58	49.23	42.85
Median	19.03	0.58	50.49	43.37
Mean	16.18	0.61	49.70	43.19
3rd Qu.	19.19	0.58	51.37	43.50
Max.	20.66	0.89	51.66	44.18

Table C.3: Summary statistics (EAHP-only)

C.4.1 Combined efficiency (EAHP and boiler)

The presence of two heat sources operating simultaneously makes it impossible to determine their individual efficiencies unless their combined heat output can be disaggregated. The system's overall efficiency can be expressed in terms of primary energy or equivalent CO_2 emissions. Both of these quantities account for the primary conversion efficiencies of different fuel sources, with grid supplied electricity having higher primary energy and CO_2 emission factors than natural gas. The primary energy efficiency, expressed as the ratio of thermal energy produced to primary energy consumed, is $0.65\,\mathrm{kWh_{(t)}/kWh_{(p)}}$. The CO_2 emission factor for the thermal energy produced is $0.31\,\mathrm{kgCO_2/kWh_{(t)}}$.

C.4.2 EAHP efficiency

Since the EAHP was the only heat source operating during the second monitoring period it is possible to calculate its average COP based on the heat measurement from the temporary heat meter and the metered electricity consumption. The average COP during the monitoring period was 2.08, with the variation shown in Figure C.6. The peaks at the beginning and end of the monitoring period are due to non-alignment of the heat and electricity measurement intervals. The kink in the middle of the period occurred when the heat pump cycled off for a short time. Due to the non-alignment of measurement intervals electricity consumption and corresponding heat output may have fallen into

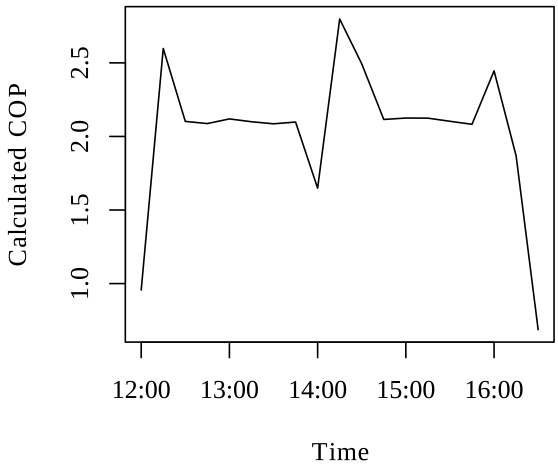


FIGURE C.6: EAHP calculated 15-min average COP (Flexim heat measurement)

adjacent intervals, resulting in the COP being underestimated in the first interval and overestimated in the following interval. These variations should average out over the course of a day.

The performance of the EAHP can be compared with the combined performance of the EAHP and gas boiler. With the EAHP operating on its own, the primary energy ratio is $0.81\,\mathrm{kWh_{(t)}/kWh_{(p)}}$ and the thermal energy CO_2 emission factor is $0.26\,\mathrm{kgCO_2/kWh_{(t)}}$. The primary energy ratio is higher when the EAHP is operating on its own, as its efficiency is greater than that of the gas boiler. Similarly, the thermal energy CO_2 emission factor is lower; the higher efficiency of the heat pump offsetting the higher CO_2 emission factor of grid supplied electricity.

By way of comparison, a heat pump operating with a COP of 3.0 will have a primary energy ratio of $1.17\,\mathrm{kWh_{(t)}/kWh_{(p)}}$ and a thermal energy CO_2 emission factor of $0.18\,\mathrm{kgCO_2/kWh_{(t)}}$. A gas boiler operating at an efficiency of 90% will have have a primary energy ratio of $0.88\,\mathrm{kWh_{(t)}/kWh_{(p)}}$ and a thermal energy CO_2 emission factor of $0.22\,\mathrm{kgCO_2/kWh_{(t)}}$.

C.5 Temperature Measurement

The heat meter measurements could be disaggregated if flow and return temperatures were known at different parts of the primary circuit, for example before and after the heat pump and before and after the boiler. This would allow calculation of heat inputs based on the assumption of constant volume flow rate around the primary circuit. This is a reasonable assumption as the volume flow into and out of a closed loop must be the same.

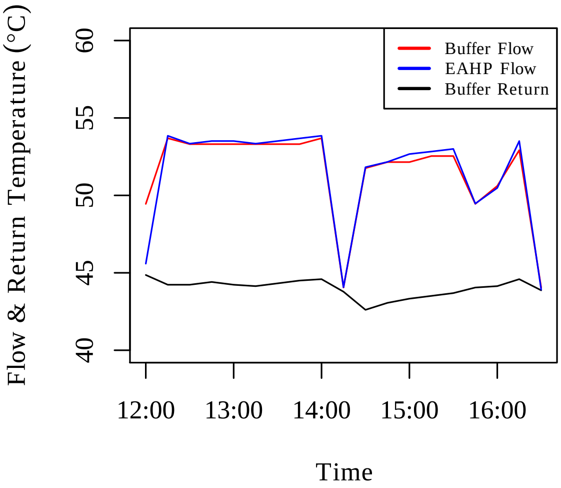


Figure C.7: BMS temperature measurements (EAHP-only)

A spot measurement of volume flow rate was taken when the pumps were recommissioned in April 2013. At this time the pumps were set to a constant speed and the controls locked to prevent further adjustment. Since the heating primary is a constant volume circuit (there being no TRVs or similar to cause variations in head and friction losses) it would be reasonable to assume this flow rate has since remained constant.

Although the temporary heat meter only measured temperatures entering and leaving the buffer vessel the BMS also measures these temperatures as well as the temperature leaving the EAHP. From these three temperatures it is possible to calculate the following heat flows:

- Heat input into the buffer vessel *(Buffer Flow - Buffer Return)*
- Heat output from the EAHP *(EAHP Flow - Buffer Return)*
- Heat output from the boiler *(Buffer Flow - EAHP Flow)*

Figure C.7 shows the circuit temperatures when only the EAHP is operating. In this case, the difference in temperature between water leaving the EAHP (EAHP Flow) and entering the buffer vessel (Buffer Flow) is negligible as there is no heat input from the boiler. Figure C.8 shows the circuit temperatures on a day when both the EAHP and boiler were operating. In addition to the difference between the buffer return and EAHP flow temperatures, due to the heat input from the EAHP, there are differences between the EAHP flow and buffer flow temperatures, which are due to the heat input from the boiler.

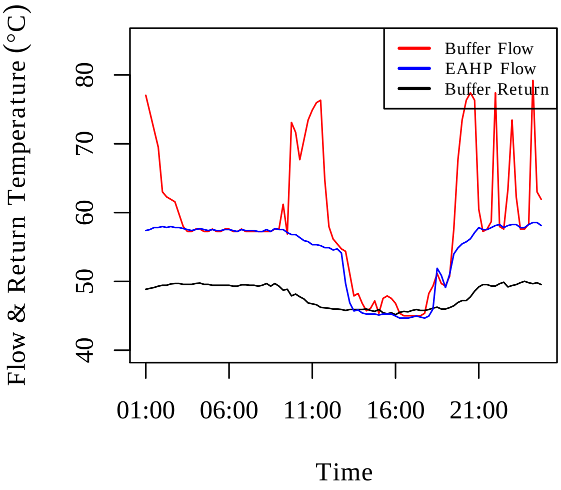


FIGURE C.8: BMS temperature measurements (EAHP and boiler)

C.5.1 Disaggregated heat and efficiency measurement

On the basis of the calculated temperature differences described above it should be possible to disaggregate the heat output and therefore determine the individual efficiencies of both heat pump and boiler in combined operation. To verify the approach, three sets of temperature measurement were compared: the temporary metering; the BMS sensors; and the wireless monitoring system. All three sets contained measured flow and return temperatures at or near to the buffer vessel.

Figure C.9 shows the temperature measurements during the period of EAHP-only operation. Although the measurements from different sensors follow the same profile there is a consistent offset between them. These differences result in different COPs for the same measurement period. Table C.4 compares the COPs obtained from the temporary heat metering with those obtained from the BMS temperature and wireless sensor temperature measurements. Since only the EAHP was operating, the temperature difference measured by the BMS at the buffer vessel should be the same as that measured by the BMS before and after the heat pump. Heat loss around the primary circuit or differences in sensor calibration could be responsible for the resulting difference in BMS COPs. The wireless sensing COP is somewhat higher than those obtained from the BMS temperatures, which is possibly the result of a scaling error caused by non-linearity in the wireless system's temperature conversion process. The COP assumed in the design compliance modelling, included here for comparison purposes, is much higher than any of the measured values.

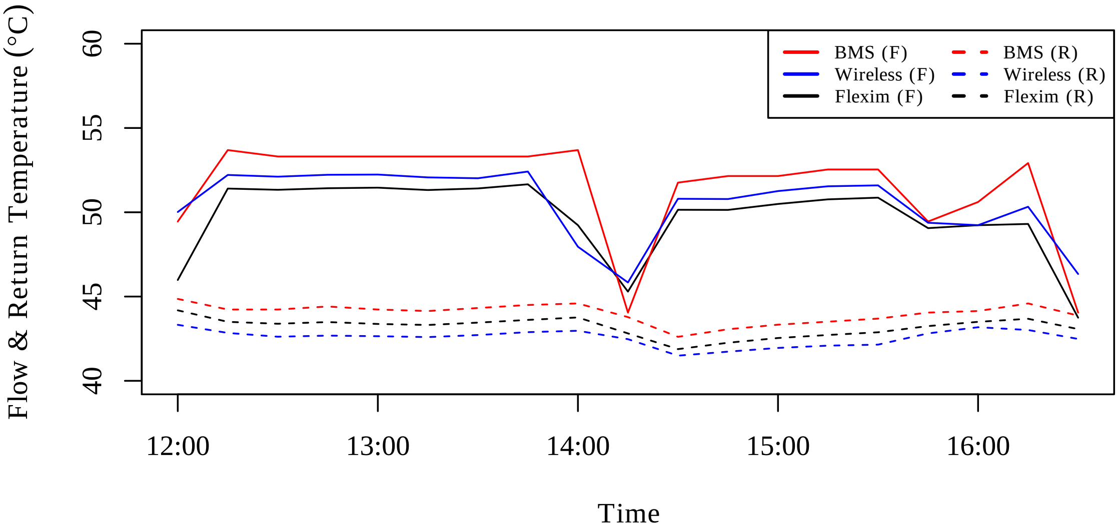


FIGURE C.9: Comparison of buffer temperature measurements (EAHP-only)

	COP	Percentage
Modelled	5.40	266
Flexim	2.03	100
BMS (Buffer DT)	2.25	111
BMS (EAHP DT)	2.19	107
Wireless	2.69	132
Heat Meter	0.88	43

TABLE C.4: Comparison of average COPs (EAHP-only)

Figure C.10 shows the temperature measurements during the period of combined EAHP and boiler operation. Here the difference in flow temperature measurements is striking, to the extent that the BMS temperature measurements bear little resemblance to the Flexim or wireless measurements. These two are also different, with an offset and significant variation in peaks.

C.6 Conclusion

The comparison of flow measurements obtained from the temporary heat metering with those from the EAHP heat meter strongly suggest that the EAHP heat meter is defective. The EAHP's COP, obtained during a short measurement period, was calculated to be 2.1. This is significantly less than the figure of 5.4 assumed in the compliance modelling. It is theoretically possible to derive heat flows from measured temperature differences and a spot measurement of volume flow rate. However, the differences between temperature

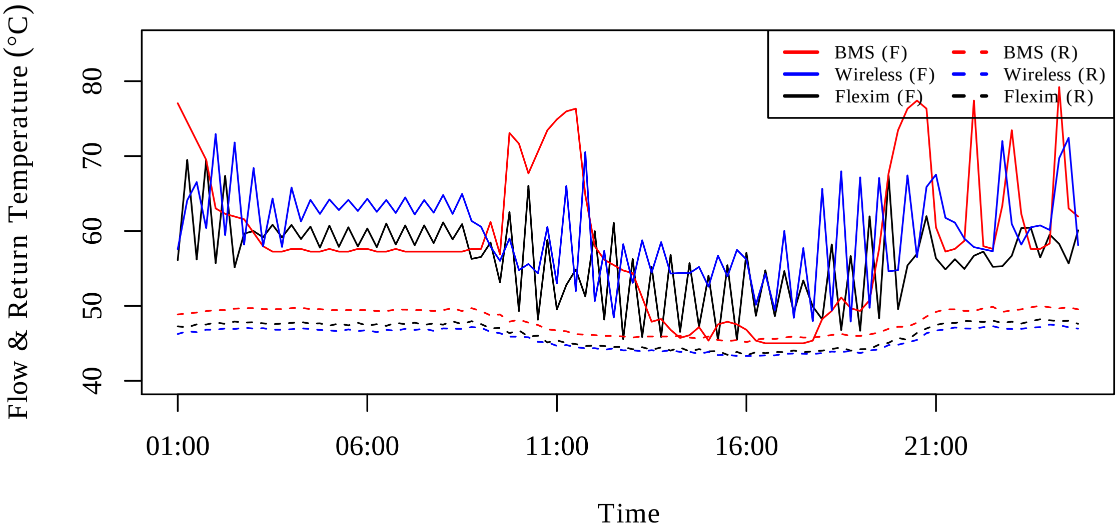


Figure C.10: Comparison of buffer temperature measurements (EAHP and boiler)

measurements shown in Figure C.10 are such that it would not be possible to have confidence in heat flows calculated from these measurements.

Appendix D

Alternative Model

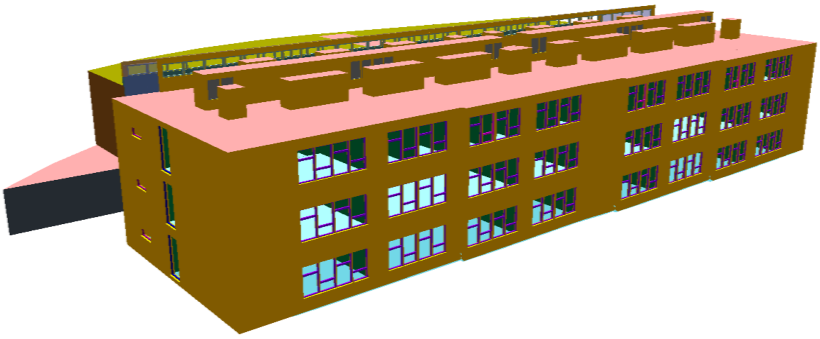
This appendix provides a detailed description of the alternative model created by the author to verify the contractor's compliance model.

1 Model Description

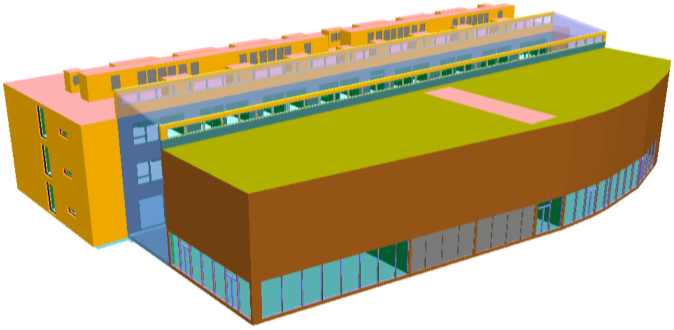
The alternative model was created using EDSL Tas 9.1.4[1], a dynamic thermal simulation package approved for the purposes of undertaking Part L and EPC Level 5 calculations. The 3D model was constructed in the Tas 3D Modeller with reference to the 2D plans, sections and elevations listed below.

Drawing Number	Title	Revision
548-01-099	Lower Ground Floor Level	K
548-01-100	Ground Floor Level	K
548-01-101	First Floor Level	L
548-01-102	Second Floor Level	K
548-01-103	Lower Roof Level	J
548-02-101	Building Section AA	N
548-02-103	Building Section CC	G
548-02-104	Building Section DD	G
548-01-109	Building Section EE	H
548-03-100	North & South Elevation	K
548-03-101	East & West Elevation	L

Architectural drawings used



3D view of Tas model, north perspective



3D view of Tas model, south perspective

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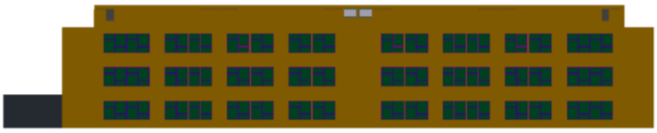
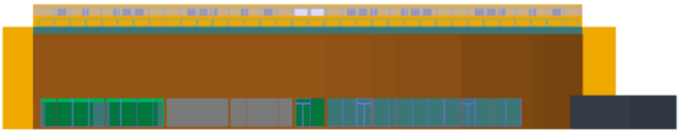
[1] EDSL website http://www.edsl.net/



North elevation

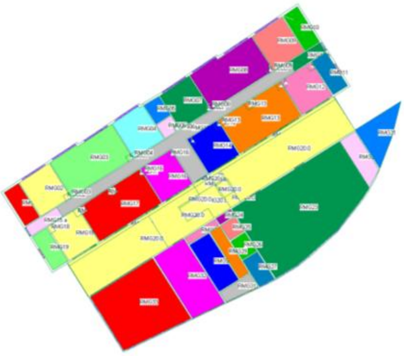
East elevation



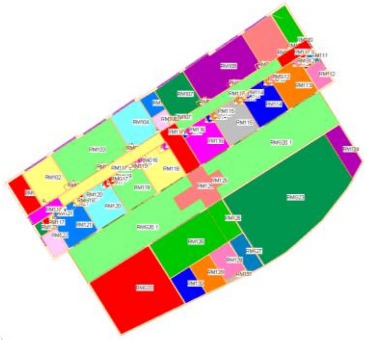
South elevation

West elevation

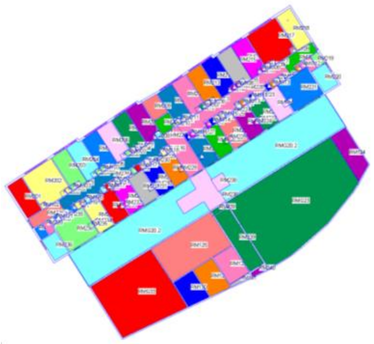
The model was zoned in accordance with the NCM guidance based on internal condition, servicing strategy, solar orientation and daylight access. Daylit spaces were divided into two sub-zones; the first representing the daylit space within 6m of the building façade, the second representing the non-daylit space beyond 6m from the façade. A full list of model zones and floor areas is included in Section 2, below.



Ground Floor Zones

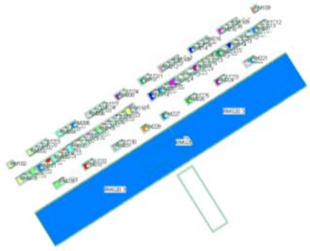


First Floor Zones



Second Floor Zones

Basement Floor Zones



Roof Level Zones

Detailed information about the building's construction elements, occupancy and operating conditions (described below) were applied within Tas Building Simulator. The corresponding notional (for the Part L compliance calculation), reference and typical building models (for the EPC calculation) were created and then simulated over the course of an hourly weather year.

1.1 Weather Data

Hourly weather data for simulation is provided by CIBSE for 14 sites in the UK. For annual energy analyses such as Part L2 studies an 'average' weather year, known as a Test Reference Year (TRY) must be used. There is no CIBSE weather data available for Daventry so Birmingham was chosen as the nearest site.

1.2 Construction Elements

The constructions proposed for the building and included in the model were significantly improved over the limiting area weighted maximum values specified in building regulations approved document L2A.

Element	**U-Value (W/m^{2}K)**
Ground Floor	0.14
Incubator Unit External Roof	0.10
Internal Floor	0.29
Internal Partition	0.29
Showcase External Wall	0.16
Showcase Green Roof	0.10
Internal Street Partitions	0.18
Suspended Ground Floor	0.12
Timber Rainscreen Cladding	0.18

Opaque Construction U-Values

Element	**U-Value (W/m^{2}K)**	**G-Value**
ETFE Atrium Roof	2.55	0.29
External Glazing	1.51	0.69
Internal Glazing	2.61	0.71
Window Frame	1.20	0

Transparent Construction U and G Values

1.3 Air Tightness

The original building was assumed to be constructed to provide the minimum standard of air tightness specified by building regulations approved document L2A (10m^3/m^2.hr@50Pa). An additional scenario considered the impact of increasing the air tightness to achieve an air permeability of 5m^3/m^2.hr@50Pa. The table below shows the resulting infiltration rates at different air permeability under test conditions stated in CIBSE Guide A Table 4.14 (obtained by interpolation where necessary).

Scenario	**Infiltration rate (ac/hr)**		
	Notional	**Design**	**Typical**
Base Building	0.30 (10m^3/m^2.hr @ 50Pa)	0.30 (10m^3/m^2.hr @ 50Pa)	0.425 (15m^3/m^2.hr @ 50Pa)
Improved Air Tightness	0.30 (10m^3/m^2.hr @ 50Pa)	0.15 (5m^3/m^2.hr @ 50Pa)	0.425 (15m^3/m^2.hr @ 50Pa)

Infiltration rates at specified air permeabilities

1.4 Internal Conditions

Internal conditions were assigned according to room function. The current National Calculation Methodology (NCM v3.5) database of standard internal conditions was used to specify internal load densities, occupancy periods and temperature set-points. The NCM internal conditions used in the model are summarised below.

NCM Zone Type	Sensible Gains (W/m^2)			Occupied Hours	Heating (°C)	Setback (°C)	Cooling (°C)
	Lighting	People	Equipment				
LibMusGal_EatDrink	7.8	13.4	20.0	2530	23	12	25
LibMusGal_FoodPrep	26.0	6.9	27.2	2530	17	12	21
LibMusGall_Lecture	15.6	17.1	2.0	1518	20	12	23
Misc24Hr_ITEquip	3.8	9.4	50.0	2555	20	N/A	23
Office_CellOff	18.8	5.1	10.0	3036	22	12	24
Office_Changing	5.2	9.1	5.0	3289	22	12	25
Office_Circulation	5.2	7.7	2.0	3036	20	12	13
Office_MeetRm	11.3	14.6	11.6	2024	22	12	24
Office_Reception	19.4	9.4	5.0	2530	20	12	23
Office_Store	1.9	7.7	2.0	2530	20	12	23
Office_Toilet	10.4	7.7	5.0	2783	20	12	23

NCM Internal Conditions

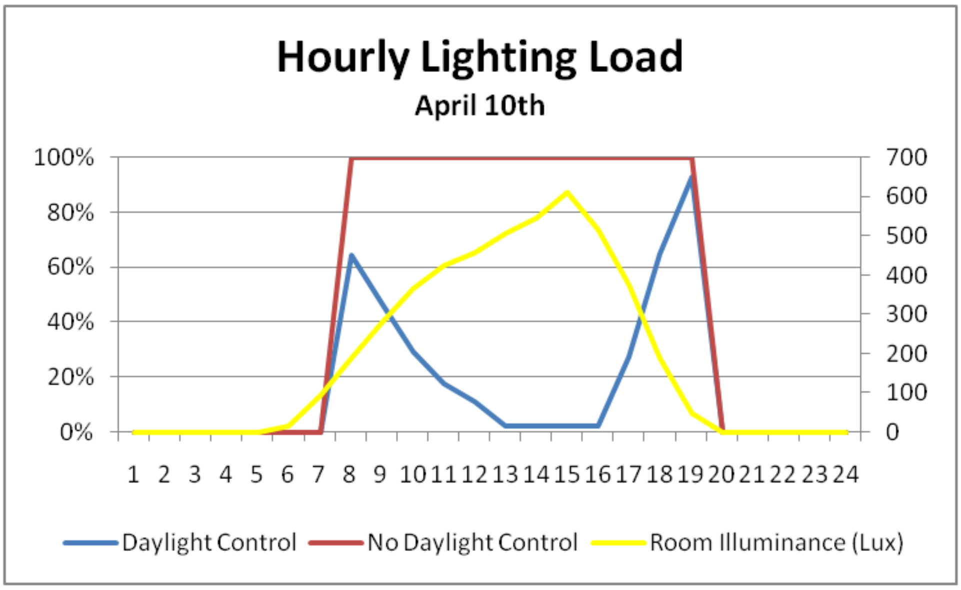
1.5 Regulated Building Services

System parameters and performance estimates are described in the following section.

1.5.1 Lighting

The design building includes several lighting efficiency measures including the use of high efficiency lighting, automatic presence detection and daylight-linked dimming. The benefit of daylight-linked photocell control dimming is calculated according to the hourly external illuminance (derived from hourly solar radiation data) and each zone's average daylight factor. Tas calculates the reduction in artificial light required to meet the zone's target illuminance based on the illumination provided by daylight.

The graph below illustrates the effect of daylight linked lighting control in a typical office. Without daylight control the lighting load is 100% throughout the day. With daylight control, the lighting load drops in proportion to the room illuminance provided by daylight. The lighting load reaches a minimum (related to the energy consumption of the control gear, assumed to be 0.3W/m^2) when the daylight provides all the required illuminance (500 lux in this example).



Effect of daylight linked lighting control

In this case the average daylight factors (over the floor area of the whole zone or the daylit zone when subdivided) were calculated for a representative sample of incubator units using LBNL Radiance 3.8[2], a physically accurate backward-raytracing tool. The surface and glazing properties used in the calculation are listed below.

Opaque Surface Light Reflectance		**Transparent Surface Light Transmittance**	
Floor	20%	External Glazing	70% (less 10% dirt factor)
Wall	50%	Internal Glazing	80% (less 10% dirt factor)
Ceiling	70%	ETFE Roof	20% (less 10% dirt factor)

Surface and glazing optical properties

The Radiance calculated daylight factors are indicated by green text in the table below. Where other zones are similar in size and location the daylight factors have been estimated based on the Radiance calculations, these values are indicated by red text in the table. The daylight factors in other zones were calculated by Tas according to the BRE simplified method. These values are indicated by blue text in the table.

All north facing incubator offices achieve average daylight factors in excess of 3%. The offices facing the internal street however do not achieve good daylight factors, particularly in the central offices, where the daylight access is obstructed by the lift shaft and atrium stairwell. It was assumed that the ETFE roof covering the atrium was a translucent material providing reasonable shading to avoid solar overheating, with a corresponding low 20% light transmittance. Increasing the light transmittance of the ETFE roof would have a direct impact on the daylight factors in the street-facing offices.

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[2] Radiance website: http://radsite.lbl.gov/radiance/

The table below lists each zone's lighting control strategy, average daylight factor (ADF), where applicable, and lighting power density in W/m^2 per 100 Lux.

Zone Name	Description	Lighting Control	Power Density (W/m2.100Lx)	ADF (%)
RMG23	Conference Room	Manual	3.2	2.0
RM111	Disabled WC	Manual	5.6	N/A
RM112	WC	PIR + Photocell	12.3	0.5
RM122	WC	PIR + Photocell	3.7	0.5
RM123	Cleaner's	Manual	8.1	N/A
RM219	Disabled WC	Manual	5.6	N/A
RM220	WC	PIR + Photocell	4.7	0.5
RM236	WC	PIR + Photocell	12.2	0.5
RM237	Cleaner's	Door	8.1	N/A
RMG11	Showers/Changing E	Manual	8.0	0.4
RMG19	Showers/Changing W	Manual	7.9	0.4
RM105	Comms	Manual	7.3	N/A
RM128	Meeting	Manual	2.9	N/A
RM129	Meeting	Manual	2.7	N/A
RM130	Meeting	Manual	3.0	N/A
RM209	Comms	Manual	7.3	N/A
RMG05	Comms	Manual	7.3	N/A
RMG32	Kitchen	Manual	5.6	N/A
RMG24	Cleaner's	Manual	7.6	N/A
RMG25	Disabled WC	PIR + Photocell	6.1	N/A
RMG28	Lobby	PIR + Photocell	7.5	N/A
RMG29	Male WC	PIR	4.6	N/A
RMG30	Female WC	PIR	5.6	N/A
RM102	1F Unit N Medium	PIR + Photocell	1.5	3.8
RM103	1F Unit N Large	PIR + Photocell	1.5	3.8
RM104	1F Unit N Medium	PIR + Photocell	1.5	3.6
RM107	1F Unit N Medium	PIR + Photocell	1.5	3.6
RM108	1F Unit N Large	PIR + Photocell	1.5	3.8
RM109	1F Unit N Medium	PIR + Photocell	1.5	3.8
RM113	1F Unit S Medium	PIR + Photocell	1.6	1.1
RM114	1F Unit S Medium	PIR + Photocell	1.5	0.8
RM115	1F Unit S Medium	PIR + Photocell	1.5	0.5
RM116	1F Unit S Medium	PIR + Photocell	1.5	0.5
RM118	1F Unit S Medium	PIR + Photocell	1.5	0.5
RM119	1F Unit S Medium	PIR + Photocell	1.5	0.5
RM120	1F Unit S Medium	PIR + Photocell	1.5	0.8
RM121	1F Unit S Medium	PIR + Photocell	1.6	1.1
RM202	2F Unit N Small	PIR + Photocell	1.5	4.0
RM203	2F Unit N Small	PIR + Photocell	1.5	3.2
RM204	2F Unit N Small	PIR + Photocell	1.5	3.2
RM205	2F Unit N Small	PIR + Photocell	1.6	3.2
RM206	2F Unit N Small	PIR + Photocell	1.5	3.2
RM207	2F Unit N Small	PIR + Photocell	1.5	3.2
RM208	2F Unit N Small	PIR + Photocell	1.5	3.2
RM211	2F Unit N Small	PIR + Photocell	1.6	3.2

RM212	2F Unit N Small	PIR + Photocell	1.6	3.2
RM213	2F Unit N Small	PIR + Photocell	1.5	3.2
RM214	2F Unit N Small	PIR + Photocell	1.5	3.2
RM215	2F Unit N Small	PIR + Photocell	1.6	3.2
RM216	2F Unit N Small	PIR + Photocell	1.6	3.2
RM217	2F Unit N Medium	PIR + Photocell	1.5	4.0
RM221	2F Unit S Medium	PIR + Photocell	1.7	1.1
RM222	2F Unit S Small	PIR + Photocell	1.7	0.7
RM223	2F Unit S Small	PIR + Photocell	1.7	0.7
RM224	2F Unit S Small	PIR + Photocell	1.7	0.7
RM225	2F Unit S Small	PIR + Photocell	1.7	0.7
RM226	2F Unit S Small	PIR + Photocell	1.7	0.7
RM227	2F Unit S Small	PIR + Photocell	1.7	0.7
RM229	2F Unit S Small	PIR + Photocell	1.7	0.7
RM230	2F Unit S Small	PIR + Photocell	1.7	0.7
RM231	2F Unit S Small	PIR + Photocell	1.7	0.7
RM232	2F Unit S Small	PIR + Photocell	1.7	0.7
RM233	2F Unit S Small	PIR + Photocell	1.7	0.7
RM234	2F Unit S Small	PIR + Photocell	1.7	0.7
RM235	2F Unit S Medium	PIR + Photocell	1.7	1.1
RMG02	GF Unit N Medium	PIR + Photocell	1.5	3.8
RMG03	GF Unit N Large	PIR + Photocell	1.4	3.8
RMG04	GF Unit N Medium	PIR + Photocell	1.4	3.6
RMG07	GF Unit N Medium	PIR + Photocell	1.5	3.6
RMG08	GF Unit N Large	PIR + Photocell	1.4	3.8
RMG09	GF Unit N Medium	PIR + Photocell	1.4	3.8
RMG12	GF Unit S Medium	PIR + Photocell	1.5	1.1
RMG13	GF Unit S Large	PIR + Photocell	1.4	0.6
RMG14	GF Unit S Medium	PIR + Photocell	1.5	0.2
RMG16	GF Unit S Medium	PIR + Photocell	1.5	0.2
RMG17	GF Unit S Large	PIR + Photocell	1.4	0.6
RMG18	GF Unit S Medium	PIR + Photocell	1.5	1.0
RM124	Void			N/A
RM131	Riser?			N/A
RM239	Plant?	Manual	3.7	N/A
RM240	Riser?			N/A
RMB02	Car Park	PIR	7.3	N/A
RMB04	Refuse	Manual	2.7	N/A
RMB05		Manual	12.3	N/A
RMB07		Manual	7.4	N/A
RMB08	Plant			N/A
RMB09	Bike Racks	PIR + Photocell	3.2	N/A
RMG21	Bike Store	Manual	9.4	N/A
RM101	Stair Core W	Manual	12.5	N/A
RM106	Repro?	Manual	10.2	N/A
RM110	Stair Core E	Manual	11.7	N/A
RM117	Corridor	PIR + Photocell	4.0	N/A
RM117.a	West end of corridor (6m daylit zone)			2.6
RM117.b	East end of corridor (6m daylit zone)			2.6
RM117.c	West end of corridor			0.0

RM117.d	East end of corridor			0.0
RM127	Stair Core S	Manual	10.2	0.0
RM201	Stair Core W	Manual	4.1	0.0
RM210	Repro?	Manual	10.2	0.0
RM218	Stair Core E	Manual	3.9	0.0
RM228	Corridor	PIR + Photocell	3.5	0.0
RM228.a	West end of corridor (6m daylit zone)			2.3
RM228.b	East end of corridor (6m daylit zone)			2.3
RM228.c	West end of corridor			0.0
RM228.d	East end of corridor			0.0
RMB01	Stair Core W	Manual	8.5	0.0
RMB03	Stair Core E	Manual	8.4	0.0
RMB06	Lobby	PIR + Photocell	2.8	0.0
RMG01	Stair Core W	Manual	12.2	0.0
RMG06	Repro?	Manual	10.2	0.0
RMG10	Stair Core E	Manual	11.7	0.0
RMG15	Corridor	PIR + Photocell	4.1	0.0
RMG15.a	West end of corridor (6m daylit zone)			2.5
RMG15.b	East end of corridor (6m daylit zone)			2.5
RMG22	Store?	Manual	5.5	0.0
RMG26	Store?	Manual	6.6	0.0
RMG27	Stair Core S	Manual	7.7	4.0
RMG31	Kitchen Store?	Manual	10.3	0.0
RM125	Stair/Lift Core Central	Manual	1.1	0.0
RM126	Break Out	Manual	1.4	0.0
RM238	Stair/Lift Core Central	Manual	2.1	0.0
RMG20.0	Internal Street (GF Level)	Manual	7.0	1.8
RMG20.1	Internal Street (FF Level)			1.9
RMG20.2	Internal Street (SF Level)			1.9
RMG20.3	Internal Street (RF Level)			16.5
RMG33	Cafe	Manual	3.4	3.8

Zone Lighting Control Strategy

1.5.2 Heating System

The building's primary heating system consists of an exhaust air heat pump serving an LTHW circuit, which feeds radiators throughout most of the building. The IT/comms rooms and meeting rooms are provided with multi-split VRF room units, which provide heating or cooling as required. Besides radiators, the perimeter convectors (in the café area) and underfloor heating (in the conference area) are also used. Their heat emission properties are listed below.

Heating Emitters

Emitter Type	Convective Fraction (percentage of total output)
Radiator	70%
Perimeter Convector	90%
Underfloor Heating	50%

Heating System Parameters: Exhaust air heat pump

Fuel	Full / Part Load Efficiency				% Load Served	CO_2 Factor
	25%	50%	75%	100%		
Electricity	350	350	350	350	100%	0.422

Distribution Efficiency	90%

Heating System Type (BRUKL Document)
Heat Pumps - all types except absorption and gas engine
Heat Source (BRUKL/EPC Document)
Heat pump (electric): air source
HVAC System Type (BRUKL/EPC Document)
Central heating using water: radiators

It has been assumed that the exhaust air heat pump has sufficient capacity to serve as the building's sole heat source. The design includes a back-up boiler to provide supplementary heating in periods of exceptional peak demand, or in case the heat pump is offline due to maintenance. If the gas boiler is intended to operate in parallel with the heat pump this must be accounted for in the calculations.

Heating System Parameters: Room units

Fuel	Full / Part Load Efficiency				% Load Served	CO_2 Factor
	25%	50%	75%	100%		
Electricity	350	350	350	350	100%	0.422

Distribution Efficiency	100%

Heating System Type (BRUKL Document)
Heat Pumps - all types except absorption and gas engine
Heat Source (BRUKL/EPC Document)
Heat pump (electric): air source
HVAC System Type (BRUKL/EPC Document)
Split or multi-split system

1.5.3 Cooling System

There are two cooling systems within the building, multi-split VRF room units in the IT/comms rooms, and a packaged AHU serving a displacement ventilation system in the conference hall.

Cooling System Parameters: Room units

Fuel	Full / Part Load Efficiency				% Load Served	CO_2 Factor
	25%	50%	75%	100%		
Electricity	350	350	350	350	100%	0.422

Distribution Efficiency	100%

Cooling System Type (BRUKL Document)
Split and multi-split air conditioners (including VRF)

Cooling System Parameters: Packaged AHU

Fuel	**Full / Part Load Efficiency**				**% Load Served**	**CO$_2$ Factor**
	25%	**50%**	**75%**	**100%**		
Electricity	350	350	350	350	100%	0.422

Distribution Efficiency	100%

Cooling System Type (BRUKL Document)
Packaged air conditioners – single duct types

1.5.4 Domestic Hot Water

The building's hot water demand was calculated by Tas using average demand figures included in the NCM database. This resulted in an overall figure of approximately 947 l/day which, assuming a 5 day week, results in an annual demand of about 246,000 l/year. Assuming the incoming cold water must be heated from approximately 10°C to 65°C, the annual heat energy requirement is in the region of 15,803 kWh. This hot water demand is served by two indirect fired gas calorifiers. The system efficiencies are listed below.

Fuel	**Seasonal Efficiency (%)**	**Distribution Efficiency (%)**	**CO$_2$ Factor**
Gas	90	90	0.194

DHW System Type (BRUKL Document)
Indirect fired (dedicated hot water boiler) - natural gas

1.5.5 Energy Management Features

It has been assumed that the building incorporates power factor correction to achieve a power factor of at least 0.90. It has also been assumed that automatic monitoring and targeting with alarms for out of range values is included in the base building.

1.5.6 Circulation Pumps

The building's primary heating system was assigned the following pump parameters.

Primary Circuit:	Constant Speed
Index Run Length:	25 m
Boiler/Coil Resistance:	40 kPa
Pump Efficiency:	50%

Primary heating circuit pump parameters

Secondary Circuit:	Variable Speed

Index Run Length:	150 m
Boiler/Coil Resistance:	40 kPa
Pump Efficiency:	50%

Secondary heating circuit pump parameters

1.5.7 Ventilation Systems

The ventilation systems were assigned according to room function and location. Offices within the incubator unit are provided with extract ventilation which operates in conjunction with the exhaust air heat pump in winter and naturally ventilated in summer. Natural ventilation is provided by a combination of openable room windows and automatically opening high-level stack vents. Rooms such as toilets, changing rooms and kitchens are provided with extract only or balanced supply/extract ventilation. Make-up air for the areas with extract only ventilation is assumed to bleed through from the adjacent zones. IT/comms rooms and meeting rooms are provided with fan coil units. The conference room is provided with displacement ventilation from a self-contained air handling unit. A schedule of room areas and system types is included in Section 2, below. The modelled system parameters are listed below.

Fan Coil Units

Air Supply:	Fancoil \ Radiant Cooling
Central AHU Fan System Type (BRUKL):	No fans
Local AHU Fan System Type (BRUKL):	New Buildings – other local units such as fan coil units (rating weighted average)
Duct Air Tightness:	Unknown
HEPA Filter:	HEPA filter usage determined by Activity
Supply Fan SFP:	1.3 W/l.s
Heat Recovery:	No Heat Recovery
Terminal Fan Type:	CAV
Terminal Fan SFP:	0.8 W/l.s
Terminal Fan ACH:	8
Extract Fan SFP:	0.5 W/l.s

Air system parameters – Fan Coil Units

Mechanical Ventilation

Air Supply:	Mech. Ventilation (Centralised Balanced)
Central AHU Fan System Type (BRUKL):	New Buildings – all other central systems
Local AHU Fan System Type (BRUKL):	No fans
Duct Air Tightness:	Unknown
HEPA Filter:	HEPA filter usage determined by activity
Fresh Air Supply Fan SFP:	1.3 W/l.s
Heat Recovery:	No Heat Recovery *(exhaust air heat pump considered separately)*
Terminal Fan Type:	None
Extract Fan SFP:	0.5 W/l.s

Air system parameters – Mechanical Vent

Extract Ventilation

Air Supply:	Mech. Ventilation (Extract only – Fan Remote from Zone)
Fan System Type (BRUKL):	New Buildings – all other central systems
Duct Air Tightness:	Unknown
Extract Fan SFP:	0.5 W/l.s

Air system parameters – Extract Vent

Displacement Ventilation

Air Supply:	CAV (all Fresh Air)
Fan System Type (BRUKL):	New Buildings – central mechanical ventilation with heating and cooling
Duct Air Tightness:	Unknown
HEPA Filter:	HEPA filter usage determined by activity
Supply Fan SFP:	1.5 W/l.s
Heat Recovery:	75% efficiency
Extract Fan SFP:	0.5 W/l.s

Air system parameters – Displacement Vent

Natural Ventilation

A simple window and roof ventilator opening strategy was modelled to simulate the temperature controlled natural ventilation system. As the zone air temperature rises above 23.5°C the apertures start to open, they are assumed to be fully open at temperatures of 24.5°C and above. The minimum opening temperature was specified to be higher than the heating set-point to ensure the window opening does not coincide with operation of the heating system. In the event of the external temperature exceeding the internal temperature the windows will be shut to minimise infiltration of warmer air. Windows within the offices were assumed provide a maximum 90% open aperture area, while roof ventilators were assumed to provide a maximum 60% open aperture area.

2 Zone and Room Type Data

Zone Name	Area (m^2)	Space Type	HVAC Strategy	NCM Internal Condition
RMG23	254.2	CONFERENCE	Displacement Vent	LibMusGall_Lecture_v3.5
RM111	3.1	SERVICE	Extract Vent	Office_Toilet_v3.5
RM112	11.6	SERVICE	Extract Vent	Office_Toilet_v3.5
RM122	11.7	SERVICE	Extract Vent	Office_Toilet_v3.5
RM123	3.1	SERVICE	Extract Vent	Office_Store_v3.5
RM219	3.1	SERVICE	Extract Vent	Office_Toilet_v3.5
RM220	11.6	SERVICE	Extract Vent	Office_Toilet_v3.5
RM236	11.7	SERVICE	Extract Vent	Office_Toilet_v3.5
RM237	3.1	SERVICE	Extract Vent	Office_Store_v3.5
RMG11	18.1	SERVICE	Extract Vent	Office_Changing_v3.5
RMG19	18.2	SERVICE	Extract Vent	Office_Changing_v3.5
RM105	10.4	SERVICE	Fan Coil Unit	Misc24Hr_ITEquip_v3.5
RM128	20.1	MEETING	Fan Coil Unit	Office_MeetRm_v3.5
RM129	21.3	MEETING	Fan Coil Unit	Office_MeetRm_v3.5
RM130	19.7	MEETING	Fan Coil Unit	Office_MeetRm_v3.5
RM209	10.4	SERVICE	Fan Coil Unit	Misc24Hr_ITEquip_v3.5
RMG05	10.4	SERVICE	Fan Coil Unit	Misc24Hr_ITEquip_v3.5
RMG32	70.3	KITCHEN	Kitchen Extract	LibMusGall_FoodPrep_v3.5
RMG24	3.3	SERVICE	Mech Vent	Office_Store_v3.5
RMG25	7.9	SERVICE	Mech Vent	Office_Toilet_v3.5
RMG28	7.0	CIRCULATION	Mech Vent	Office_Circulation_v3.5
RMG29	16.7	SERVICE	Mech Vent	Office_Toilet_v3.5
RMG30	33.9	SERVICE	Mech Vent	Office_Toilet_v3.5
RM102	37.6	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM103	76.8	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM104	38.3	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM107	37.2	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM108	76.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM109	38.3	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM113	36.1	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM114	36.2	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM115	36.2	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM116	36.2	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM118	36.2	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM119	36.2	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM120	36.2	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM121	36.1	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM202	36.7	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM203	18.4	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM204	18.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM205	18.0	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM206	18.1	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM207	18.4	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM208	18.4	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM211	17.6	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM212	18.0	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM213	18.2	OFFICE	Mixed Mode	Office_CellOff_v3.5

Zone Name	Area (m^2)	Space Type	HVAC Strategy	NCM Internal Condition
RM214	18.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM215	18.0	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM216	18.0	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM217	37.3	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM221	33.8	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM222	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM223	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM224	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM225	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM226	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM227	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM229	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM230	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM231	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM232	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM233	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM234	16.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM235	33.8	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG02	38.5	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG03	78.6	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG04	39.2	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG07	38.1	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG08	78.3	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG09	39.2	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG12	38.3	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG13	77.9	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG14	38.4	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG16	38.4	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG17	77.8	OFFICE	Mixed Mode	Office_CellOff_v3.5
RMG18	38.3	OFFICE	Mixed Mode	Office_CellOff_v3.5
RM124	47.6	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RM131	2.9	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RM239	34.1	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RM240	2.4	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RMB02	823.3	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RMB04	23.9	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RMB05	2.1	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RMB07	10.2	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RMB08	50.1	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RMB09	30.5	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RMG21	34.8	SERVICE	N/A	Unoccupied and Unconditioned_v3.5
RM101	18.0	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM106	7.4	SERVICE	Nat Vent	Office_Store_v3.5
RM110	18.9	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM117	30.0	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM117.a	10.8	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM117.b	10.8	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM117.c	37.5	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM117.d	37.5	CIRCULATION	Nat Vent	Office_Circulation_v3.5

Zone Name	Area (m^2)	Space Type	HVAC Strategy	NCM Internal Condition
RM127	18.0	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM201	18.0	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM210	7.4	SERVICE	Nat Vent	Office_Store_v3.5
RM218	18.9	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM228	30.0	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM228.a	11.9	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM228.b	11.9	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM228.c	44.8	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RM228.d	44.8	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMB01	17.3	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMB03	17.4	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMB06	8.9	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMG01	18.0	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMG06	7.4	SERVICE	Nat Vent	Office_Store_v3.5
RMG10	18.9	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMG15	99.8	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMG15.a	10.8	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMG15.b	10.8	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMG22	23.8	SERVICE	Nat Vent	Office_Store_v3.5
RMG26	9.9	SERVICE	Nat Vent	Office_Store_v3.5
RMG27	14.3	CIRCULATION	Nat Vent	Office_Circulation_v3.5
RMG31	12.7	SERVICE	Nat Vent	Office_Store_v3.5
RM125	115.7	CIRCULATION	Unconditioned	Office_Circulation_v3.5
RM126	99.4	SERVICE	Unconditioned	Office_CommStaff_v3.5
RM238	36.0	CIRCULATION	Unconditioned	Office_Circulation_v3.5
RMG20.0	334.3	CIRCULATION	Unconditioned	Office_Circulation_v3.5
RMG20.1	298.3	CIRCULATION	Unconditioned	Office_Circulation_v3.5
RMG20.2	298.3	CIRCULATION	Unconditioned	Office_Circulation_v3.5
RMG20.3	334.3	CIRCULATION	Unconditioned	Office_Circulation_v3.5
RMG33	133.2	CAFÉ	Unconditioned	LibMusGall_EatDrink_v3.5

3 Building Elements & Construction Materials

Layer	Material	Width (mm)	Thermal Conductivity (W/mK)	Convection Coefficient (W/m^2K)	Vapour Diffusion Factor	Density (kg/m^3)	Specific Heat (J/kgK)
Showcase External Wall							
1	Soundbloc (for walls)	25	0.25	0.001	8.6	1200	837
2	Cavity (horizontal flow)	50	0.01	1.25	1	0	0
3	Mineral Fibre Slab	200	0.035	0.001	1.6	30	1000
4	External Rendering	10	0.5	0.001	26.9	1300	1000
Timber Rainscreen Cladding							
1	Soundbloc (for walls)	25	0.25	0.001	8.6	1200	837
2	Mineral Wool	150	0.04	0.001	1.3	30	1000
3	Mineral Fibre Slab	50	0.035	0.001	1.3	30	1000
4	Cavity (horizontal flow)	50	0.01	1.25	1	0	0
5	Timber Board	13	0.165	0.001	181.9	650	1600
Street Partitions							
1	Soundbloc (for walls)	25	0.25	0.001	8.6	1200	837
2	Mineral Wool	150	0.04	0.001	1.3	30	1000
3	Timber Board	12.5	0.165	0.001	181.9	650	1600
4	Mineral Fibre Slab	50	0.035	0.001	1.3	30	1000
Internal Partition							
1	Lighweight Plaster	13	0.16	0.001	26.9	600	1000
2	Mineral Fibre Slab	105	0.035	0.001	1.3	30	1000
3	Lighweight Plaster	13	0.16	0.001	26.9	600	1000
Ground Floor							
1	Carpet	10	10	0.06	38.4	160	2500
2	Chipboard	22	22	0.15	86	800	2093
3	Cavity (downward flow)	50	50	0.01	1	0	0
4	Cast Concrete	200	200	1.13	107	2000	1000
5	Celotex XR3000	130	130	0.023	201.6	30	1500
6	London Clay	750	750	1.41	1920	1900	1000
Suspended Ground Floor							
1	Carpet	10	0.06	0.001	38.4	160	2500
2	Chipboard	22	0.15	0.001	86	800	2093
3	Cavity (downward flow)	50	0.01	0.5	1	0	0
4	Cement Screed	5	0.41	0.001	26.9	2100	650
5	Celotex XR3000	165	0.023	0.001	201.6	30	1500
6	Cast Concrete	200	1.13	0.001	107	2000	1000
Intermediate Floor							
1	Carpet	10	0.06	0.001	38.4	160	2500
2	Chipboard	22	0.15	0.001	86	800	2093
3	Cavity (upward flow)	350	0.01	1.95	1	0	0
4	Mineral Wool	100	0.04	0.001	1.3	30	1000
5	Soundbloc (for roof)	30	0.25	0.001	8.6	950	840
Incubator Unit External Roof							
1	Plywood	18	0.15	0.001	86	700	1420
2	Eshatherm TR26	220	0.023	0.001	201.6	30	1400
3	Cavity (upward flow)	450	0.01	1.95	1	0	0
4	Soundbloc (for roof)	30	0.25	0.001	8.6	950	840

Opaque Construction Element Layers

Layer	Material	Width (mm)	Thermal Conductivity (W/mK)	Convection Coefficient (W/m^{2}K)	Vapour Diffusion Factor	Density (kg/m^3)	Specific Heat (J/kgK)
Showcase Green-Roof							
1	Soundbloc (for roof)	30	0.25	0.001	8.6	950	840
2	Cavity (upward flow)	450	0.01	1.95	1	0	0
3	Plywood	18	0.15	0.001	86	700	1420
4	Eshatherm TR26	220	0.023	0.001	201.6	30	1400

Opaque Construction Element Layers (continued)

Layer	Material	Width (mm)	Thermal Conductivity (W/mK)	Convection Coefficient (W/m^{2}K)	Vapour Diffusion Factor	Solar Trans.	Emissivity	
							Int.	Ext.
ETFE Atrium Roof								
1	Texlon 150 (white)	0.15	0.23	0.001	9999	0.45	0.86	0.86
2	Cavity (Air-filled)	125	0.01	5.6	1			
3	Texlon 100 (clear)	0.1	0.23	0.001	9999	0.925	0.74	0.74
4	Cavity (Air-filled)	125	0.01	5.6	1			
5	Texlon 150 (white)	0.15	0.23	0.001	9999	0.45	0.86	0.86
External Glazing								
1	K Glass	6	1	0	9999	0.7	0.185	0.845
2	Cavity (Argon-filled)	16	0.01	1.16	1			
3	Optifloat (clear)	6	1	0	9999	0.78	0.845	0.845
Internal Glazing								
1	Optifloat (clear)	6	1	0	9999	0.78	0.845	0.845
2	Cavity (Argon-filled)	16	0.01	1.16	1			
3	Optifloat (clear)	6	1	0	9999	0.78	0.845	0.845
Window Frame								
1	Notional Frame	40	0.06	0.001	9999	0	0.85	0.85

Transparent Construction Element Layers

Appendix E

Operation and Maintenance Issues

This appendix provides a technical description of issues relating to the building's operation and maintenance that resulted in sub-optimal system operation during the case study evaluation.

E.1 Space Heating

The building's space heating system has been problematic since its first winter of operation in 2011. During November and early December there were complaints from tenants that the offices were unacceptably cold, particularly at the beginning of the week. The mechanical contractor and facilities management staff investigated and and made a number of adjustments including increasing the hot water system pressure and adjusting the temperature compensation settings to provide a flow temperature of 75 °C at 0 °C ambient and 45 °C at 25 °C ambient. In February 2012, after establishing that the heating system was operating reliably these settings were returned to their original values.

During autumn 2012 problems were experienced from the end of October. The system was apparently unable to maintain temperatures in the building when running or simply failed to start up in the morning. During December, as a result of these ongoing problems, the BMS schedule was changed to run the heating system constantly. Although this eliminated problems with system start-up it was not an ideal way to operate the system. The specific cause of the problems was not found; they may well have been due to a combination of factors rather than a single fault.

At one point it was suspected that the boiler shunt pump was either not running as intended or that the its operation was not being registered by the BMS. A current sensing switch, used to monitor the shunt pump's operation, was adjusted and then replaced but was never checked to establish whether it was actually defective. On subsequent occasions when the boiler shunt pump failed to start it was started by switching the pump to manual operation. On another occasion the heating system pressure was unusually low, which could have affected the system's operation or even prevented the boiler from running. As no leaks were found it was suspected that the pressurisation system wasn't working properly. The system was re-pressurised and appeared to run however it still failed a number of times to start in the morning. The controls maintenance contractor suggested that weekly fire alarm tests were causing the BMS to enter emergency shutdown, which was potential affecting its reliability. A key switch was added to the fire alarm panel so the BMS could be isolated from the fire alarm signal during tests.

The optimum start controller was discovered to have been set to respond to the minimum space temperature of a group of zones including the unheated street. The street was removed from the controlling set of zones but low temperatures in unoccupied offices where the heating had been switched off would have also reduced the effectiveness of the controller. Subsequently the controller was set to respond to the average space temperature rather than the minimum space temperature. This was a slight improvement however the unoccupied offices often bring the average temperature below the heating set point, causing the controller to start unnecessarily early.

During spring 2013 the heating system was generally reliable although still in continuous operation. The BMS alarm logs suggested that BMS was still not being isolated from the fire alarm when carrying out the weekly alarm test however there was no evidence that this was causing any problem. A temporary loss of heat to some of the radiators in one part of the ground floor was attributed to an air lock. The heating circuit pump was returned to automatic speed setting after being found set at maximum speed, possibly in an attempt to restore heat to the radiators. It was also possible that branch valves were adjusted in response to the problem but these changes were not logged.

At around this time, the University of Northampton commissioned an independent consultant to conduct a review of the plant and BMS operation, with the intention of realigning the building services system settings to design specifications and identifying opportunities for improvements to its reliability and efficiency. The consultant, working closely with the building evaluation team, reviewed and reset pump configuration and specified a simplification to the EAHP bypass damper. Since the consultant was not a controls specialist only a limited review of BMS strategy was made. No recommissioning was carried out, so it was not possible to check pipework and ductwork flow balancing.

By the beginning of summer 2013 the heating gas consumption was negligible and the EAHP electricity consumption less in magnitude and variability that the same quarter the previous year. However, the cumulative effect of individual adjustments and modifications made in immediate response to symptoms, possibly without understanding the effect these changes may have on the operation of the whole system, could be a system that no longer operates according to design specifications. For example, the heating was found to remain enabled up to ambient temperature threshold of 20 °C. This is likely to result in unnecessary operation of the EAHP during summer months, potentially contributing to overheating.

E.1.1 Exhaust Air Heat Pump

The EAHP is central to the building's low carbon heating strategy and is largely responsible for meeting the building's design CO_2 emission target. However, the unit failed to operate for a large part of the building's first two winters despite operating throughout the summer. The EAHP and boiler effectively operate in series, with the boiler supplying heat to the primary circuit via a small header. As a result, an EAHP failure is not immediately apparent because the boiler, which was intended to provide back-up and peak heating, is able to meet the building's full heat demand.

The first failure occurred in conjunction with the heating problems experienced in December 2011. In an attempt to get more heat into the building the heating system's flow temperatures were increased, despite being designed to operate at low temperatures. Under the increased temperature settings the target heating flow temperature would exceed 55 °C whenever ambient temperatures were below about 16 °C. This compromised the ability of the EAHP to contribute to the building's heating system, which was designed to operate at lower temperatures than a traditional gas boiler system; the heat pump is unable to operate at heating water temperatures above 55 °C. At the beginning of February 2012 the flow temperature was reduced back to its design value of 45 °C. Despite this the exhaust air heat pump remained offline due to a fault condition. The fault was eventually cleared and the heat pump was operational by the end of March. This episode is indicative of a lack of understanding of system operating strategy. Maintenance staff increased the flow temperature as an immediate response to heating problems without investigating further, as a result the system's efficiency was compromised and the underlying problems remained undiagnosed.

The EAHP then operated until the second failure occurred at the end of November 2012. At the time some maintenance work was being carried out in relation to another heating system failure but there was no indication of why the EAHP would have failed. The following spring, the problem was traced to incorrect control wiring. During the maintenance work in November it was discovered that a pair of control wires had become disconnected from the plant room control panel. No reason for the disconnection was documented so the wire was reconnected. Unfortunately this was responsible for disabling the heat pump, as its operation was incorrectly interlocked with an overspill damper intended to exhaust excess air from the office extract system. The BMS was configured to open the damper when the heat pump receives a run signal, however this also opened the auxiliary switch contacts on the actuator, which then prevented the heat pump from operating. The disconnected control wire was evidently a short term solution to allow the heat pump to run by preventing the damper from opening.

In March 2013, when this was realised to be the problem, the connections to the actuator's control relay were swapped from the normally-closed to the normally-open contact, reversing the operation of the damper. The damper now closed when the heat pump received a run signal, allowing the heat pump to start, and opened when the heat pump is not operating. In this configuration, the office extract air correctly vented to atmosphere via the overspill damper when the heat pump was not running but passed fully through the heat pump when running (at a volume slightly higher than the heat pump's maximum duty). Adjustments to the control strategy were proposed to interlock the damper with the office extract system, as it should have been originally designed. A more direct solution was recommended by heat pump manufacturer, which involved replacing the actuated damper with a spring loaded damper to allow excess air exhaust without any intervention from the control system. This work was carried out in December 2013 but the EAHP was not re-enabled afterwards, leading to a further inoperative period until March 2014.

The efficiency of the heat pump is affected by the temperatures of the heat source and heat sink (DECC, 2012). Since the heat source is the exhaust air from the offices, its temperature will be affected by the office temperature and extract volume flow rate. The temperature and flow rate of the extract air will also be affected by the opening and closing of ventilation openings if the natural ventilation system is simultaneously enabled with the heating system. The heat sink is the primary circuit serving the buffer vessel. Its temperature is affected by the building's heating load and the operation of the heat pump and gas boiler under the control of the BMS in response to the measured heating flow temperature. The control strategy, the interaction of the heat pump with the gas boiler and buffer tank, are therefore all factors that contribute to the heat pump's performance.

E.1.2 Pumps

Three of the building's water heating circuits are driven by twin-head pumps that are configured to alternate operation on a weekly basis. Flow measurement in the DHW calorifier primary circuit showed that flow rates were changing on a weekly basis because the two pumps were set to different operating modes. It was not possible to confirm the designed settings for any of the pumps however the calorifier pump operating at 60% constant pressure delivered a measured flow rate reasonably close to the design value.

As part of the external review, a representative from the pump manufacturer attended site to provide advice on the appropriate settings. On 17th April 2013, circulation pump settings were checked with a remote controller. The 'as found' settings were recorded and, where necessary, adjusted to be more consistent with the 'as commissioned' values. After checking that the pumps in the twin head units had been correctly set to the same flow and head (to prevent the weekly changes in volume flow rate), the control buttons on the pumps were then disabled to prevent further changes to the settings.

E.2 Natural Ventilation

The building's natural ventilation system relies on providing sufficient outdoor air to offset internal heat gains. Unlike systems incorporating passive cooling such as earth tubes or evaporative cooling, the air entering the offices is not tempered and can be no lower than ambient temperature. During particularly hot weather the system will cease to provide any cooling effect and providing outdoor air may become counterproductive. As the air movement is driven by a combination of wind and stack effect, warm and still conditions could also reduce the effectiveness of the system. Some of the incubator units do incorporate PCM boards but it has not been possible to establish their effectiveness.

There have been several reports of summertime overheating, particularly in the street-facing units. The outward-facing units are perceived to be more comfortable because the windows can be opened. Some of the occupants in these units have questioned the usefulness of the ventilation stacks, given that the windows alone appear to provide sufficient ventilation in warm weather and in hotter weather the vents make little difference (or in one instance reportedly made matters worse). The automatic operation of the vents was mentioned frequently, with tenants preferring a greater degree of manual control. The delay on manual opening and closing of vents is considered to be too long. The responsiveness of the vents to rain was also mentioned; it sometimes takes too long to close when it rains. Although occupants are generally aware the building is naturally ventilated there is still the expectation that the building should remain at a steady temperature. A better explanation of the building's ventilation strategy may be one way to manage occupants' expectations.

Although the design stage overheating modelling carried out to demonstrate Part L compliance showed a minimal risk of overheating in the offices, the model assumptions regarding internal heat gains may have been over optimistic. While the assumed lighting gains are appropriate for each office, the assumed occupancy and equipment gains are lower than those published in CIBSE Guide A.1 The actual equipment gains vary widely between offices, with some occupants running their own servers. Similarly, occupancy varies between offices, with some of the smaller 2-person offices occupied by up to four people. The overheating modelling does not provide any indication of the risk of overheating in situations like these where design assumptions are exceeded. If there is little or no safety margin in the design of the natural ventilation system some overheating will be inevitable.

Overheating has been exacerbated by the failure of several vent actuators which took some time to replace. During this time it was not possible to provide ventilation to the affected units. As a result some tenants were allowed to move into different office units. Some of the reports of cold offices in the winter may also have been linked to problems with vent actuators that had failed to close tightly or had jammed in an open position. All of the faulty actuators were eventually replaced, however their long-term reliability is questionable.

To alleviate some complaints of stuffiness and overheating during the winter the ventilation strategy set-points were adjusted to permit vent opening when the heating system is running. While this may have helped individual offices at times it may have had unintended consequences such as reducing the mechanical ventilation rate in other offices. The design intent was for the ventilation system to deactivate when the heating system is running. Allowing simultaneous operation could result in heating being provided to offices while the radiators are on, particularly if the immediate response to reduce office temperature is to open vents rather than reduce the TRV setting. Furthermore allowing vents to open when the mechanical extract system is running could unbalance the system, reducing the extract rate from offices with closed vents and instead drawing cold ambient air into the system via the open vents. This could affect the performance of the EAHP, since one of its advantages over a conventional air source heat pump is that the air it draws from the building's extract ventilation will be considerably warmer than the ambient air.

E.3 Lighting

The level of daylight and artificial light is good, judging by the results of the BUS questionnaire. The use of white soffits, light walls and neutral floor finishes was part of the design intent to contribute to a pleasant visual environment. The usability of the lighting control however is hindered by the lack of instructions about the dimming function, which would give occupants the ability to set the desired light level. There is a further problem, apparently inherent in the lighting control, that the dimmed level is not retained, i.e. the lights return to their full brightness when they have been turned off and on again. This can happen during the day when tenants have left the office for lunch or meetings. Some tenants have requested the ability to change the default light level, however this adjustment is typically carried out once during commissioning and requires a lighting remote programmer. If a programmer were available, light levels could be recommissioned in individual units if necessary.

Appendix F

Publications

The work described in this thesis has contributed to the following publications:

Rowley, P., Gough, R., Doylend, N., Thirkill, A., Leicester, P. From smart homes to smart communities: Advanced data acquisition and analysis for improved sustainability and decision making In *International Conference on Information Society, i-Society 2013*, Toronto, Canada, 24–26 June 2013. Pages 263–268. 2013

McKenna, E., Doylend, N., Thomson, M. End-use demand in commercial office buildings: case-study and modelling recommendations. In *5th BauSim International Building Performance Simulation Association Conference*, Aachen, Germany, 22–24 September 2014. Pages 67–74. 2014

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