AN APPRAISAL OF THE PERFORMANCE OF A 'GREEN' OFFICE BUILDING

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The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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Abstract

The challenges of a 'greener' future are now a responsibility for everyone and particularly for the built environment, where sustainable building design is no longer an innovative option but more of a legislative must. Unfortunately significant differences are often found between the design and measured performance of buildings, with many factors contributing towards these discrepancies.

This thesis investigates, using Post Occupancy Evaluation (POE) techniques, the credibility gap between design and measured performance of a partially occupied 'green' office building selected as the case study. The results found that the measured energy consumption was over three times the design estimates, and the performance compared poorly against good practice benchmarks for similar buildings. The study's POE also revealed inefficient control settings, high out-of-hours energy consumption and ineffective building management.

This study goes beyond a typical POE as it also includes investigations into how the occupancy variations, and the management strategies applied under these conditions, can impact on building energy performance through the use of simulation modelling techniques. This is an area where very little research has previously been carried out. At the current 50% occupancy levels, potential annual savings of over £30,000 in utility bills and 60% in energy consumption were estimated if more effective management and control was implemented.

Social-related aspects of building performance are also investigated. Occupant surveys were conducted and the results were compared to previous findings. The perceived comfort and satisfaction with temperature was the most disappointing finding from the survey, however overall the building was comparable to the average benchmarks, but did not perform well when compared to other 'green' office buildings.

The study revealed that there is potential for the building to be fine-tuned to perform more efficiently than it currently is, however there must be suitably skilled Facility Management to ensure this is delivered.

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List of Acronyms and Abbreviations

AHU	Air Handling Unit
BCO	British Council for Offices
BMS	Building Management System
BPE	Building Performance Evaluation
BREEAM	Building Research Establishment Environmental Assessment Method
BSRIA	Building Services Research and Information Association
BUS	Building Use Studies
CCL	Climate Change Levy
CHP	Combined Heat and Power
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon Dioxide
DEFRA	Department for Environment, Food and Rural Affairs
DTM	Dynamic Thermal Modelling
ECON 19	Energy Consumption Guide 19
EUI	Energy Unit Intensity
FM	Facilities Management
HVAC	Heating, Ventilation and Air Conditioning
IES	Integrated Environmental Solutions
NPI	Normalised Performance Indicators
O&M	Operation and Maintenance
PC	Practical Completion
POE	Post Occupancy Evaluation
PROBE	Post-occupancy Review Of Building Engineering
RIBA	Royal Institute of British Architects
UBT	Usable Buildings Trust
VAV	Variable Air Volume
VDU	Visual Display Unit

Chapter One - Introduction

1.1 Introduction

Buildings are of fundamental importance to us as humans as they provide shelter from external weather conditions, a home, a place to work or study and security. With the need for buildings comes the need to provide them with energy. Buildings consume energy in a variety of ways including heating, ventilation, cooling, lighting, small power loads and hot water demands. Unfortunately, these energy requirements associated with buildings have a negative impact on the environment.

Buildings in the UK are responsible for just under half of the country's carbon dioxide (CO_2) emissions. This is a considerable proportion and should be addressed. The industry is facing the challenge of designing buildings which minimise energy use and the associated environmental impacts. Consequently alternative approaches to traditional design methods are evolving and more innovative concepts are being tested, including a range of renewable technologies and passive design techniques.

By the time a building is constructed to Practical Completion (PC) and handed over to the client the design team has often moved on to a new project and little follow-up has taken place. However, it shouldn't be taken for granted that a building will perform to the efficient standards assumed in the design once it is at the occupation phase, as previous research has shown that in fact they often don't (Bordass, Cohen et al. 2004).

The post-occupancy performance of a building is seldom monitored to see how it compares with design expectations. When monitored, aspects of the building that perform ineffectively (and also effectively) can be identified and the information can be used to improve energy efficiency and comfort (Preiser and Schramn 2002). A feedback process is important to ensure that lessons are learnt, which can then be applied to future building designs (Andreu and Oreszczyn 2004).

1.2 Impacts of climate change and the need for a sustainable future

Sustainable improvements to the design of buildings primarily stems from the need to preserve natural resources and the issues relating to increasing CO_2 levels in the atmosphere, global warming and climate change. There is scientific evidence that the Earth is warming due to changes in greenhouse gases (Stern 2007). The natural occurrence of the greenhouse effect preserves the warmth of the planet, but unfortunately it is being accelerated due to the burning of natural resources. The accelerated levels are trapping heat energy in the atmosphere and causing the Earth's climate to change. The production of CO_2 mainly results from the burning of compounds that contain carbon such as gas, oil, coal and wood. Consequently, the CO_2 concentrations have increased from 280 parts per million (ppm) in the pre-industrial times to 380 ppm today (Stern 2007). The amount of CO_2 emissions released into the atmosphere must be reduced to avoid the predicted damaging consequences of climate change.

In the Bruntland Report 'sustainable development' was defined as "development which meets the needs of the present without compromising the ability of the future generations to meet their own needs" (Boonstra 2001). Unfortunately, if current levels of CO_2 are not reduced then the needs of the future generations will be compromised. In the UK targets of an 80% reduction in CO_2 levels by 2050 compared to the levels of the 1990's have been set (Climate Change Act 2008). Commitments to reduce CO_2 levels are not just on a national level, but a global one too.

Despite being a major contributor of CO_2 emissions, buildings are essential in society. Yet, built in a sustainable manner they can reduce the environmental damage caused. These sustainable buildings have recently become known as 'green' buildings. There are many definitions as to what a 'green' building is; including one that "provides the specified building performance requirements while minimising the disturbance to and improving the functioning of local, regional, and global ecosystems both during and after its construction and specified service life" (Burnett 2007). More simply, a 'green' building is one which is environmentally considerate in both construction and operation. A 'green' building should be energy efficient but still able to maintain a good internal environment and comfort levels. Some of the common characteristics include:

- One that minimises:
    - Fossil fuel consumption, energy consumption, water consumption, environmental impact, use of natural materials, transport related emissions, the use of materials with high embodied energy.

- One that maximises:
    - Efficient systems, use of natural daylight, passive approaches/systems, locally sourced materials that have been recycled or reused, the use of renewable energy sources.

Regardless of how sustainable a building has been designed, it is the in-use performance that will affect the environment. However, the performance of the building remains uncertain unless it is investigated. An effective way to evaluate in-use building performance is through an activity commonly known as Post Occupancy Evaluation (POE) or Building Performance

Evaluation (BPE) (as it is more recently been referred to). Outside of the literature review this type of evaluation will be referred to as POE.

It has been quoted that 'in theory, theory and practice are the same, but in practice they are not' (Leaman and Bordass 2005) and this is particularly relevant to buildings. Sustainable 'green' buildings need to exist in reality and not just in a theoretical sense. Therefore, the credibility gap between theory and practice is investigated in the research presented.

1.3 Case study building

A case study 'green' office building was selected for the research study and subjected to a POE. The building is located approximately 6 miles east of Leeds city centre in West Yorkshire, UK. The BREEAM 'Excellent' office has won numerous awards for its design. The building incorporates many 'green' features including an exposed thermal mass internally, a good level of air tightness, a low-volume vacuum drainage system using low-flush WC's which utilise rainwater harvested from the roof, a 'green' sedum roof, a Combined Heat and Power (CHP) unit with a matched absorption chiller for tri-generation, a low energy lighting installation incorporating an atrium design and a low energy heating, cooling and ventilating 'Termodeck' system. The construction phase of the project was carried out in an environmentally considerate manner with energy and water management, offsite pre-fabrication techniques and strict segregation of construction waste. The building materials used were, where possible, sourced locally and incorporated recycled materials

A full description of the case study building is given in Chapter 3.

1.4 Aims of the research

This research aims to evaluate the performance of a 'green' office building during the first three years of occupancy (August 2007 to August 2010) to highlight potential shortfalls and make comparisons with the simulated performance predicted during the design and benchmark data for similar buildings. Such an evaluation allows for feedback and lessons learnt and will quantify potential energy savings that can be obtained from future improvements to the building.

This study goes beyond a typical POE as it includes additional investigations into how the occupancy variations (seen at the post occupancy stage), and management strategies applied under these conditions, can impact on building energy performance through the use of simulation modelling techniques.

1.4.1 Objectives

To achieve the overall aims of the study, a number of objectives have been defined as listed below:

1. To monitor the physical performance of a 'green' office building to gain feedback during occupancy and make comparisons with the design predictions and published benchmark data. This will include evaluations of:
    a. The overall energy performance in the building
    b. 'Termodeck' system
    c. CHP unit
    d. Small power demands
    e. Lighting system performance
    f. Lift energy consumption
    g. Water usage for both recycled rain-harvested and mains water
    h. Internal environment
    i. The total annual CO_2 emissions resulting from the occupied green office building

2. To investigate, using a dynamic thermal model, how partial occupancy and the way the building is managed affect energy performance, specifically:

    a. To simulate the performance of the building at the current level of occupancy and compare this with measured data.
    b. To investigate the impact internal heat gains have on the energy performance of the building.
    c. To investigate the building's energy consumption when partial occupancy exists.
    d. To evaluate the potential environmental and economic savings resulting from the implementation of effective management strategies when partial occupancy exists.

3. To evaluate the social-related aspects of the building's performance, specifically:

    a. To investigate the comfort and satisfaction levels of the occupants in the 'green' office building and make comparisons with similar buildings.
    b. To evaluate how these perceived levels of satisfaction vary amongst different groups of people within the building.

1.5 Research constraints

In June 2008 Innovate Office Ltd, the tenants of the case study building, went into administration. This caused some disruption to the monitoring of the building. In October 2008 new managers (now known as Icon Business Centres) took over the administration and allowed for monitoring to continue.

In addition to the administration problems, as of August 2010 the release of retention monies (intended for remediation work) still hadn't occurred due to complications in original contracts and this resulted in other aspects of the monitoring being affected.

1.6 Structure of the thesis

This thesis is presented in nine chapters. Chapter 1 has introduced the research, case study building and stated the aims and objectives of the work.

A literature review is presented in Chapter 2. It reviews information relevant to this research including previous literature regarding energy consumption in buildings, benchmarking data, previous POE/BPE studies and key findings, BREEAM and Dynamic Thermal Modelling (DTM).

Chapter 3 provides a detailed description of the case study 'green' office building and an overview of the BREEAM credits awarded.

Chapter 4 presents an overview of the research methodology developed to achieve the aims and objectives set out in Chapter 1.

Chapter 5 evaluates the energy-related aspects of the building's performance including overall gas and electricity consumptions, analysis of the lighting demands, water consumption, CHP unit performance, small power demands and lift energy consumption.

Chapters 6 and 7 use DTM techniques to investigate and compare the performance of the partially occupied building. Chapter 6 presents the building performance at varying occupancy levels under various management strategies. The actual operation of the building at the current occupancy levels is compared to a potentially more energy efficient control setting. Chapter 7 presents the sensitivity analysis for the heat recovery device and has been included to support the results in Chapter 6.

Chapter 8 presents the social-related aspects of the building performance and analyses perceived comfort and satisfaction levels.

There are discussions in each chapter. Overall summary, conclusions and recommendations for further work are presented in Chapter 9.

Chapter Two - Literature review

2.1 Introduction

The literature review reports on findings from previous research applicable to the scope of this work. The conclusions from the reviewed literature are used to compare and support the research presented.

2.2 Energy use in building

Buildings account for 47% of total CO_2 in the UK (Pout, MacKenzie et al. 2002), thus there is great need to reduce this contribution. Similarly the rate of resource consumption must decrease. Industry must start assessing the way buildings are actually performing and designers must take responsibility in ensuring low energy and low carbon design approaches are being implemented effectively. With the turnover of building stock being only around 1% per year, it has been estimated that 80% of the buildings that will exist in 2050 have already been built (King 2007). So clearly, not only is there the issue of addressing new buildings, but enormous amounts of attention is required to the refurbishing of existing building stock to improve and reduce the operational CO_2 emissions (Kelly 2009).

The ratio of CO_2 emissions from domestic and non-domestic buildings is 60% and 40% respectively (Pout, MacKenzie et al. 2002). Government targets have been set to reduce CO_2 emissions with requirement that from 2016 onwards all domestic new homes will be zero carbon and all new non-domestic buildings zero carbon by 2019.

Part L of the England and Wales Building Regulations (HM Government 2010) is forcing designers to comply with stricter measures and tougher designs. From October 2008 regulations came into force that require all commercial buildings to have an Energy Performance Certificate (EPC) on sale, rental or upon construction (Communities and Local Government 2008a). EPCs provide an informative visual aid of the energy efficiency performance of the building based on design data, using an A to G style rating system (where A is the most efficient and G represents a poor rating of building efficiency). In October 2008, Display Energy Certificates (DECs) in public buildings in England and Wales were also introduced by the Energy Performance of Building Regulations (Communities and Local Government 2008b). This covers most public buildings with gross floor areas greater than $1000m^2$. The purpose of a DEC is to convey the actual operational rating of a building in terms of energy and CO_2 emissions using a similar A to

G style grading system to the EPC (CIBSE 2009a). To maximise visual impact EPC and DEC should be displayed together.

2.2.1 Non-domestic buildings including offices

Non-domestic buildings cover a wide range of building types including offices, schools, industrial structures, hotels and sports centres. Non-domestic buildings have been reported to account for 17% of total energy consumption in the UK (Pout, MacKenzie et al. 2002) and the same source states that commercial offices account for 11% of the total energy consumption (and also CO_2 emissions) of commercial and public sectors. It has been estimated that commercial offices have an energy consumption index of around 0.9 $GJ/m^2/yr$, with 84% of this energy being used to heat, light, cool and ventilate such buildings (Ward 2004). In terms of CO_2 emissions a balance in current commercial buildings is provided in a recent publication (King 2010). Figure 2-1 shows that the lighting, office equipment and mechanical ventilation account for the largest fraction of the carbon emissions in commercial buildings.

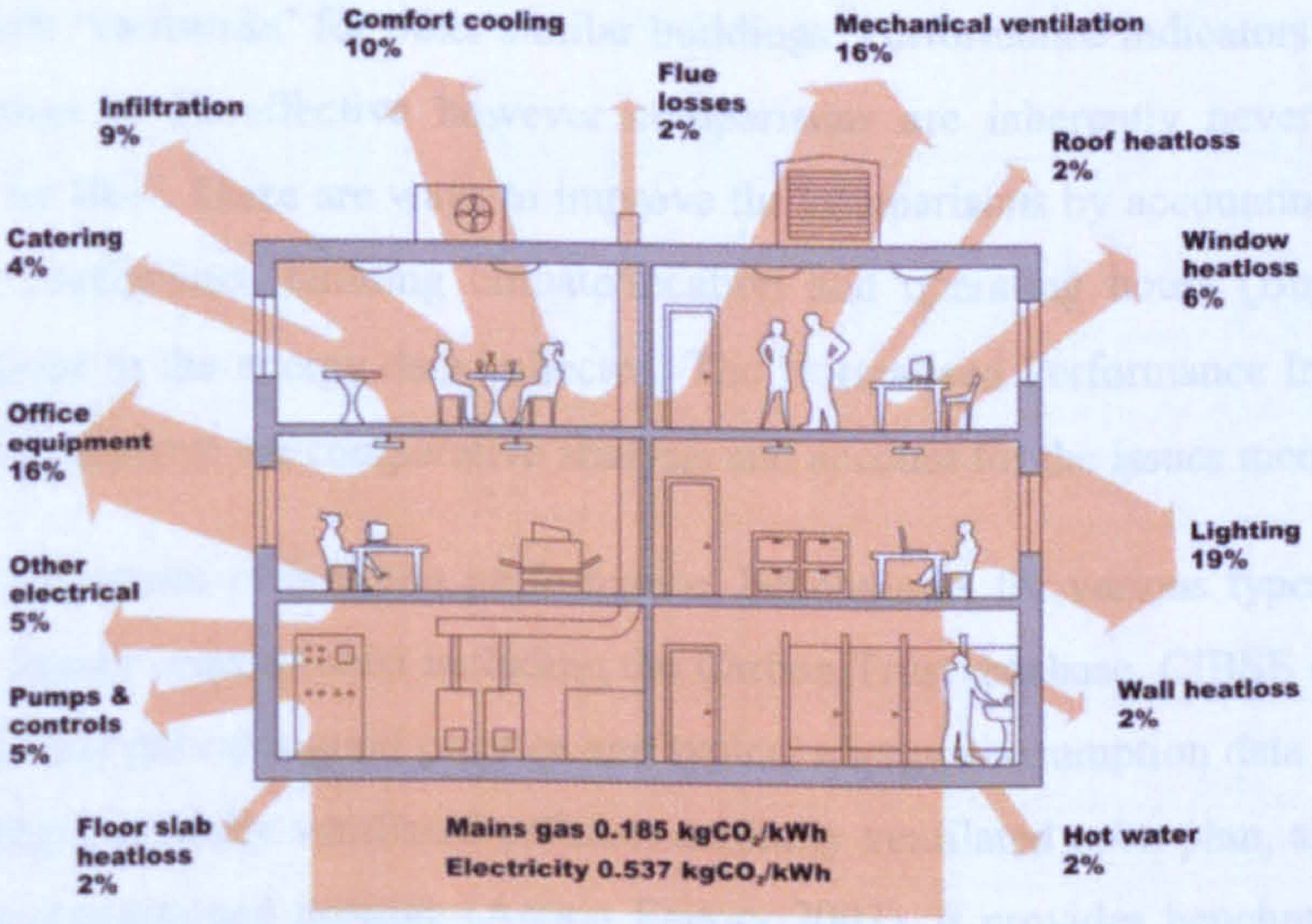


Figure 2-1: Typical balance of CO_2 in commercial buildings
(King 2010)

In terms of energy consumption, the percentages by end use in commercial offices as shown in Table 2-1 (Pout, MacKenzie et al. 2002).

Table 2-1: Energy end-use (kWh) in commercial offices (Pout, MacKenzie et al. 2002)

End-use energy in commercial offices	% of total energy consumption
Catering	3.3
Computing	6.5
Cooling and ventilation	5.4
Hot water	4.3
Heating	64.2
Lighting	13.0
Other	3.3
Total	**100.0**

Table 2-1 shows there is a significant amount of energy used in the space heating of commercial offices. However the figures in Table 2-1 are generalised and do not provide breakdown of energy consumptions by office type.

The processes involved in a building energy audit include data collection, analysis, effective presentation of data and the establishment of priorities and recommendations (Beggs 2005). It is important that the data collected is interpreted in an effective way to allow for feedback and comparisons with 'yardsticks' for other similar buildings. Performance indicators can allow for these comparisons to be effective however comparisons are inherently never going to be perfectly 'like for like'. There are ways to improve the comparisons by accounting for building size, exposure coefficients, building climate/location and operating hours (Beggs 2005) by making corrections to the energy data collected. The Normalised Performance Indicator (NPI) was developed to improve the comparative analysis and account for the issues mentioned above.

To allow for comparison of building performance, benchmarks for various types of buildings (office, hotels, leisure centres) exist including the Carbon Trust database, CIBSE etc. ECON 19 presents a guide that provides good practice and typical energy consumption data for four types of office buildings; naturally ventilated cellular, naturally ventilated open plan, air-conditioned standard and air-conditioned prestige (Action Energy 2003). It provides benchmarking details for energy consumption and costs, fuel consumption, lighting, air handling and CO_2 emissions. These good practice and typical energy consumptions are presented in Table 2-2. This data is expressed in terms of percentages in Table 2-3. Note 'GP' is 'good practice' and 'T' is 'typical'.

Table 2-2: Annual delivered energy consumption (EUI) of good practice and typical offices. (kWh/m^2 treated floor area) (Action Energy 2003)

	Naturally ventilated cellular		Naturally ventilated open plan		Air-conditioned, standard		Air-conditioned, prestige	
	GP	T	GP	T	GP	T	GP	T
Heating & hot water- gas /oil	79	151	79	151	97	178	107	201
Cooling	0	0	1	2	14	31	21	41
Fans, pumps, controls	2	6	4	8	30	60	36	67
Humidification (where fitted)	0	0	0	0	8	18	12	23
Lighting	14	23	22	38	27	54	29	60
Office Equipment	12	18	20	27	23	31	23	32
Catering, gas	0	0	0	0	0	0	7	9
Catering, electricity	2	3	3	5	5	6	13	15
Other electricity	3	4	4	5	7	8	13	15
Computer room	0	0	0	0	14	18	87	105
Total gas or oil	79	151	79	151	97	178	114	210
Total electricity	33	54	54	85	128	226	234	358

Table 2-3: Energy end-use as a % of total energy (based on the data in Table 2-2)

	Naturally ventilated cellular		Naturally ventilated open plan		Air-conditioned, standard		Air-conditioned, prestige	
	GP	T	GP	T	GP	T	GP	T
Heating & hot water- gas /oil	70.5	73.7	59.4	64.0	43.1	44.1	30.7	35.4
Cooling	0.0	0.0	0.8	0.8	6.2	7.7	6.0	7.2
Fans, pumps, controls	1.8	2.9	3.0	3.4	13.3	14.9	10.3	11.8
Humidification (where fitted)	0.0	0.0	0.0	0.0	3.6	4.5	3.4	4.0
Lighting	12.5	11.2	16.5	16.1	12.0	13.4	8.3	10.6
Office Equipment	10.7	8.8	15.0	11.4	10.2	7.7	6.6	5.6
Catering, gas	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.6
Catering, electricity	1.8	1.5	2.3	2.1	2.2	1.5	3.7	2.6
Other electricity	2.7	2.0	3.0	2.1	3.1	2.0	3.7	2.6
Computer room	0.0	0.0	0.0	0.0	6.2	4.5	25.0	18.5
Total energy	100%	100%	100%	100%	100%	100%	100%	100%

2.3 Water use in building

Water consumption in the UK has risen by 70% in the last 30 years (BCO 2006). In a recent study (Waggett and Arotsky 2006), it was shown that water used in toilet flushing accounts for the largest percentage of the total water usage in UK offices. Minimising consumption by integrating vacuum flush systems is a method that can be utilised.

The typical water consumption for an office building, with no canteen, is quoted as 25.0 litres/full time employee/day (BCO 2006). In close agreement with this value, another source (Water UK 2008) estimates the average water consumption in an office building to be 24.5 litres/full time employee/day (based on 253 working days in a year).

Yet other sources (Waggett and Arotsky 2006b) have suggested considerably different water consumption benchmarks for offices and these are shown in Table 2-4.

Table 2-4: Water consumption benchmarks for offices

		m^3/year	Litres per day
Typical use	By employee	4.0 m^3/employee/year	15.8 litres/employee/day
	By area	0.6 m^3/m^2/year	2.4 litres/m^2/day
Best practice use	By employee	2.0 m^3/employee/year	7.9 litres/employee/day
	By area	0.4 m^3/m^2/year	1.6 litres/m^2/day
Excessive use	By employee	7.0 m^3/employee/year	27.7 litres/employee/day
	By area	0.8 m^3/m^2/year	3.2 litres/m^2/day

Note the data presented in Table 2-4 is taken from (Waggett and Arotsky 2006b)

Rain water can be collected and used in the flushing system, hence reducing the mains water demand by a significant amount. In a recent study carried out in Hong Kong (Yang, Lou et al. 2006) it was found that in residential high rise buildings rainwater supply was insufficient due to the roof area available for rainwater collection, but performed much better in commercial buildings. It has been estimated that 0.2868 tCO_2e/Ml (0.2868 $x10^{-3}$ $kgCO_2e/l$) is emitted when supplying mains water (Yorkshire Water Services Ltd 2008).

2.4 Thermal behaviour of buildings

Energy conscious design is a requirement in the development of all new buildings. The thermal response of a building is mainly determined by the heat loses/gains through the structural building envelope, internal heat loads and ventilation losses. It is therefore important to control the rate at which energy is exchanged with the surroundings for reasons related to comfort (constant temperature) and energy use (McMullan 1998). Many factors can affect the rate/amount of the heat loss in a building, including the climate, insulation, area and construction of the building envelope, air change rate (infiltration) and use of the building. Specifying low U-values (a measure of the overall rate of heat transfer through a section of construction) in the design reduces the rate of heat transfer into/out of a building. Many interrelating energy flow paths, each of which can be significantly influenced by occupant behaviour and design, can affect the energy demand and performance of a building. These complex interrelating functions are difficult to accurately calculate. The two methods used to estimate the energy demands of a building are steady-state and transient/dynamic calculations, however only transient methods are considered here.

2.5 Transient methods/Dynamic Thermal Modelling (DTM)

During design engineers and architects use the available information and assumed operation of the building (at that time) to conduct the calculations and simulations so that the energy performance of a building can be predicted. Modelling methods and tools are often used to optimise building design and improve energy efficiency.

Transient (non-steady state) methods allow for accurate load profiles to be calculated. There are many interrelated energy flow paths that exist within buildings (Clarke 1989). This added complexity means that highly sophisticated computer software is required to calculate and solve simultaneous equations for different variables at the same time through which they apply the first laws of thermodynamics.

Energy saving costs delivered through the use of simulation software has been presented in literature (Larsen, Filippín et al. 2008). Various inputs parameters, which provide the required information to perform the building performance simulation, are defined in the software. These inputs are made up of constant (or static) inputs such as building location, building size and orientation, construction materials and variable inputs referred to as 'schedules' and 'profiles' which account for inputs that may vary throughout the day, such as occupancy, lighting, small power use (Davis Iii and Nutter 2010).

Building simulation techniques have been used to compare the measurements at post-occupancy stage to those simulated during design. Good agreement was found when conducting this type of comparison on an office building in Switzerland (Citherlet and Hand 2002).

On the market today are many various packages for building performance modelling and analysis software tools (Crawley, Hand et al. 2008). Some of the well-known ones include IES <VE>, TAS, Energy Plus, ESP-R, DOE-2 and Ecotect; each providing a means to predict the energy consumption of a building.

The software selected during the design stage of the building and used later in this research is IES<VE> (Integrated Environmental Solutions 2011). IES Ltd was established in Scotland in

1994, however the beginning of such computer software packages dates back to the 1970's. The software is a performance analysis suite. By using the software it allows designers to optimise the design of buildings by simulating various options and predicting the performance. More detail about the software and its functionality is given in Chapter 6.

2.6 Heat gains

Heat losses through the building envelope are caused by transmission of heat and are dependent upon the U-values of the materials, areas and temperature differences between indoor and outdoor environments. Heat gains also exist in buildings. Solar heat gains depend upon various factors including building orientation and geographical latitude, time of year, cloud conditions, sun angles, windows and fenestration (McMullan 1998). Internal heat gains are mainly generated from occupants and their activities within buildings.

2.7 Internal heat gains

CIBSE's Environmental Design Guide A (CIBSE 2006a) defines an internal gain as "the sensible and latent heat emitted within an internal space from any source that is to be removed by air conditioning or ventilation, and/or results in an increase in the temperature and humidity within a space". These internal gain (also known as casual heat gain) sources include people (metabolic heat transfer from occupants), artificial lighting, computers and other office equipment, cooking appliances/other domestic equipment and electric motors. In office buildings the main sources of internal heat gains come from the occupants, artificial lighting and from computers and other pieces of office equipment.

A BSRIA guide (Pennycook 2003) suggests heat gains for metabolic, lighting and small power loads in offices as $10W/m^2$, $12W/m^2$ and $15W/m^2$ respectively.

The thermal performance of a building is influenced by the heat released from internal heat sources (Straaten 1967). Minimising internal heat gains is something that is often desired as it can reduce the occurrence of over-heating, although conversely the utilisation of this heat can offset heating demands. In some countries in the world, where the climate results in higher external temperatures, internal heat gains and solar gains are often unwanted and result in an increase in cooling requirements. In the UK building design is usually governed by winter conditions, making heating loads high (Eastop and Watson 1997). In these climates where heating demand often far outweighs the cooling demand, the benefits of internal heat gains should be utilised effectively (in appropriate seasons).

In a physical sense, buildings are thermal systems subject to many thermal inputs and outputs. The processes within this system can be described using;

$$Qi + Qc + Qs + Qv + Qe = \Delta S$$

Where:

Qi – Internal heat gains (occupants, lighting, electrical appliances)

Qc – Conduction heat gain or loss through the building fabric

Qs – Solar heat gains

Qv – Ventilation heat gains or losses

Qe – Evaporative heat losses

ΔS - Change in heat stored in the building (Szokolay 2003)

An energy balance must exist to ensure that conditions are thermally comfortable for the occupants of a building. McMullan describes this balance as,

Fabric Heat Losses + Ventilation Heat Losses =

Solar Heat Gains + Casual Heat Gains +

Energy input required for heating and cooling

(McMullan 1998)

The balanced equation shows that to maintain a comfortable internal environment for the occupants, there will be an effect on the energy input required if casual heat gains are removed.

2.7.1 Heat gains from people

The human body is often described as a 'complex thermodynamic machine susceptible to slight changes in the environment' (Ward 2004). Heat transfers to and from the body from the environment via conduction, convection and radiation. Figure 2-2 presents the thermal exchanges that take place between the body and the environment as suggested by Ward (2004).

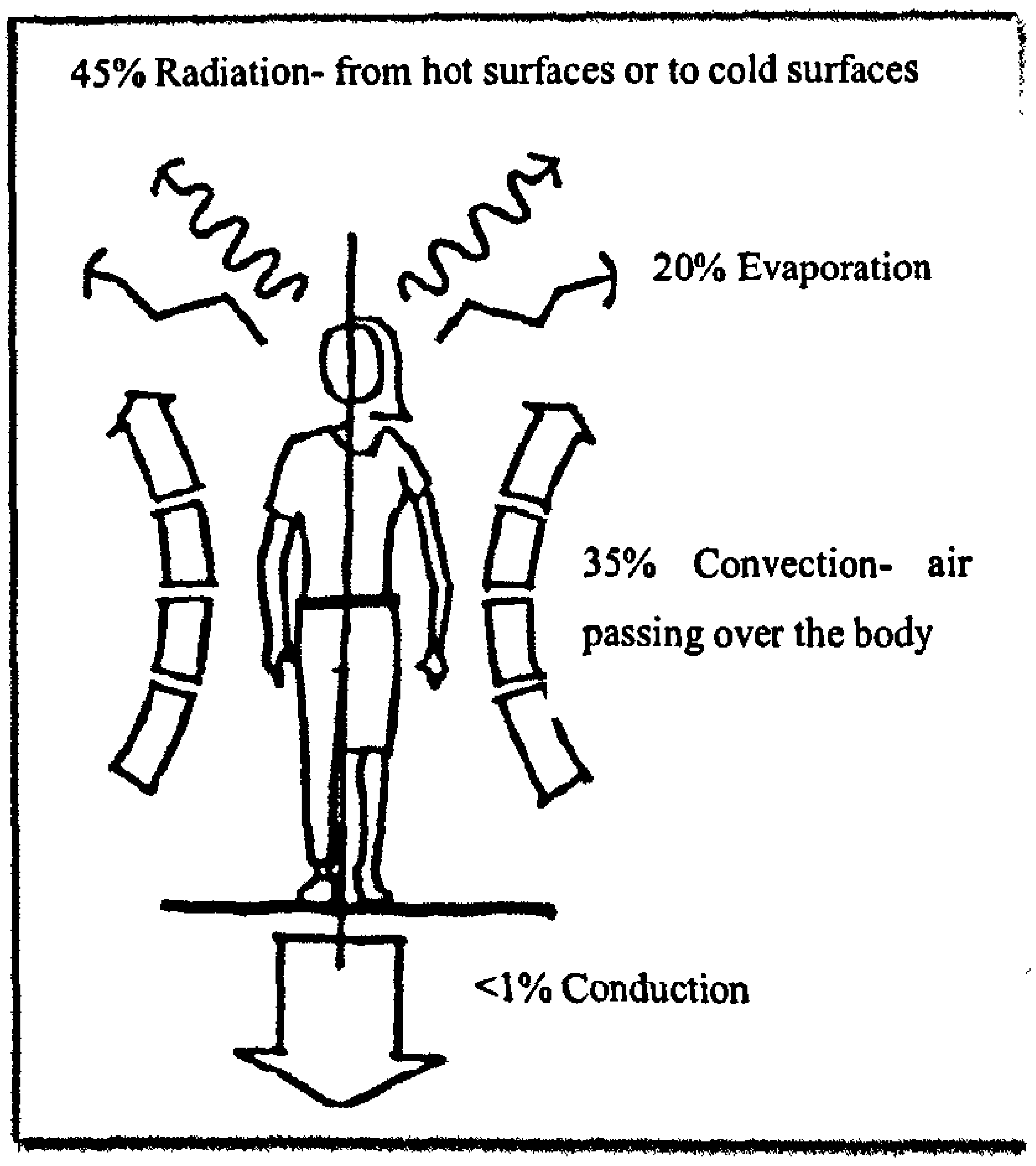


Figure 2-2: Thermal exchanges that take place between the body and the environment (Ward 2004)

The heat emissions from the human body depend largely on the level of activity. This energy is in the form of sensible and latent heat. Examples of some activities and the associated heat emissions are presented in Table 2-5.

Table 2-5: Typical rates at which heat is given off by human beings in different states of activity (CIBSE 2006a)

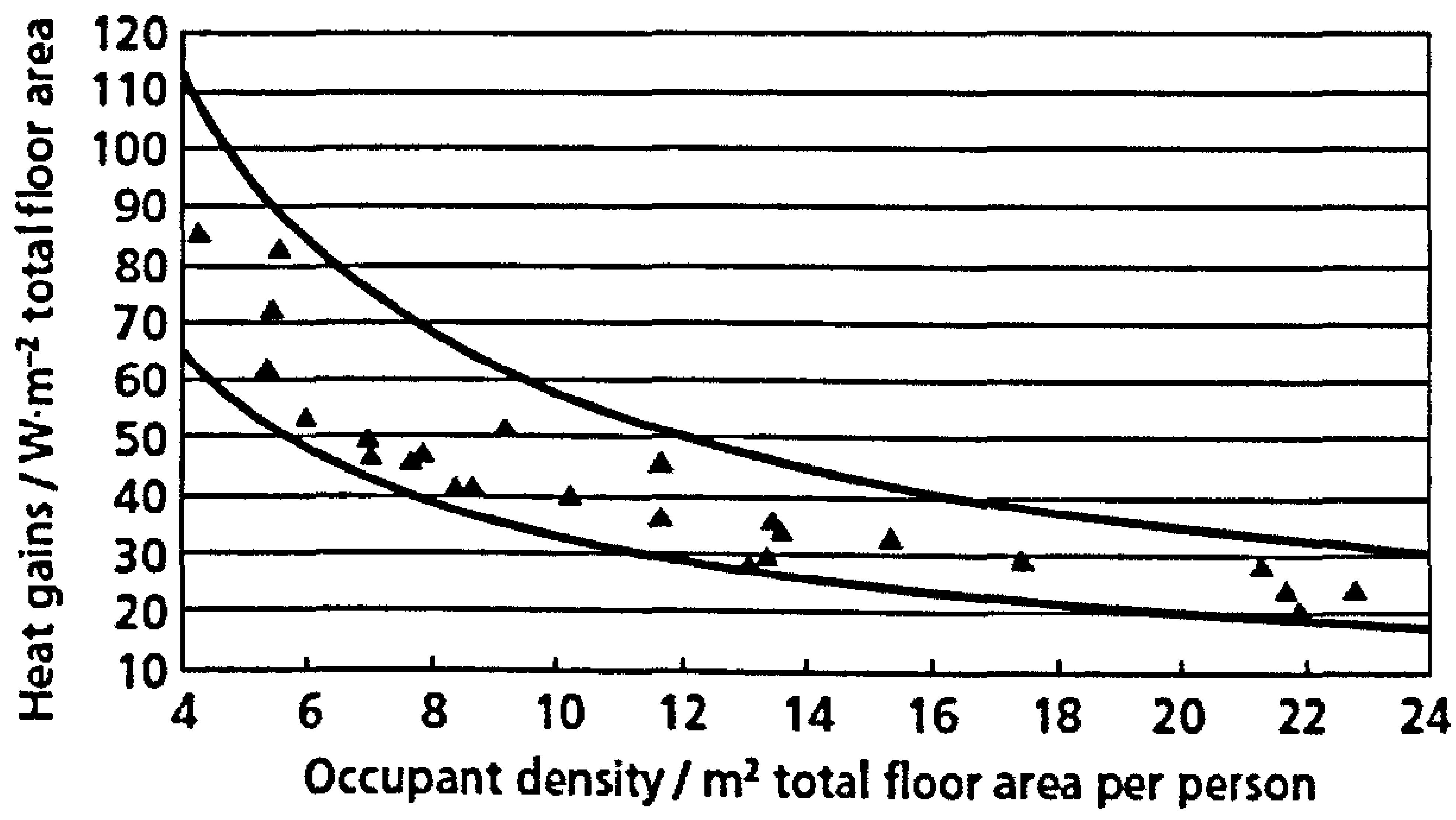
Degree of activity	Total rate of heat emission for adult male (W)	Rate of heat emission for mixture of males and females (W)		
		Total	Sensible	Latent
Seated, very light work	130	115	70	45
Moderate office work	140	130	75	55
Moderate dancing	265	250	90	160
Heavy work	440	425	170	255
Athletics	585	525	210	315

Depending on the occupancy density the heat gains assumed in the design for offices with general use vary as shown in Table 2-6 (CIBSE 2006a).

Table 2-6: Benchmark value for internal heat gains for offices (at 24°C, 50% RH)

Density of occupation m^2/person	Sensible heat gain W/m^2		
	People	Lighting	Equipment
4	20	12	25
8	10	12	20
12	6.7	12	15
16	5	12	12
20	4	12	10

The total heat gains according to occupancy density are shown graphically in Figure 2-3.



Note, graph taken directly from CIBSE Guide A

Figure 2-3: Total heat gain with occupancy density (CIBSE 2006a)

2.7.2 Lighting

When in use, internal heat gains are emitted from artificial light sources. The amount of heat gain from these sources depends on the lamp type and required illuminance. Frequently, a value of 12W/m^2 is used in design calculations (CIBSE 2006a).

2.7.3 Office equipment

Compared to the office environments of the pre-early 1990's, computers are an extremely common tool/feature and utilised by the majority of people in most offices today. The typical heat gains from PC and monitors are summarised in the Table 2-7.

Table 2-7: Typical heat gains from PCs (CIBSE 2006a)

Equipment	Typical heat gain W	
	Continuous mode	Energy saving mode
Average PC	55	20
Medium size PC monitor	70	0

2.8 Energy impacts due to partial occupancy

During un-occupied periods internal heat gains from people are non-existent, and provided occupants adhere to good housekeeping, there should be minimal internal heat gains from sources such as artificial lighting and small power equipment. However, the energy use from small power during un-occupied periods has been reported as high and wasteful (Masoso and

Grobler 2010) implying that occupants often leave small power electrical items on. Depending on whether or not any solar control strategies are implemented and the use of blinds are well managed, solar gains may be independent to occupancy.

Internal heat gains contribute to the heating requirements within a building. The way improved efficiency of equipment along with the change in climate will affect internal temperature has been investigated using ESP-r software (Jenkins, Liu et al. 2008). However, only the electrical internal gains from lights and small power were considered. The researchers stated that "while improving the equipment should result in a reduction of overall energy use of the building regardless of location (due to the decrease in small power energy consumption) the negative effects should be quantified". In another study the internal heat gains (occupants, lighting and small power) in thirty office buildings were assessed (Dunn and Knight 2005). The CIBSE TM22 method was used to facilitate the energy surveys. The CIBSE nameplate ratio method was used to calculate the internal heat gains. An average internal heat gain was calculated as 44.9 W/m^2 of treated floor area, and an average of 422 W/person. The individual average heat gains from people (occupancy), lighting and small power were calculated as 14.6 W/m^2, 12.7 W/m^2 and 17.5 W/m^2 respectively. Knight and Dunn show that the higher the density of occupants the higher the internal gains within the office space. This may imply that the greater the occupancy density the greater the energy use within a building. The extent and impact on energy performance that the varying amounts of internal heat gains (i.e. people, lights and equipment) have on building performance has not been investigated to a large extent.

2.9 Green buildings

As a result of the implementation of more stringent government legislation and tightening Building Regulations, the industry has had to alter traditional approaches in the design and construction of buildings. The Energy White Paper outlined the targets set out to generate 10% of UK electricity from renewable energy by 2010 and this doubling to 20% by 2020 (CIBSE 2006c). Energy demands associated with buildings must be reduced and alternative means of providing energy have to be implemented to enable this reduction target to be achieved.

Passive design strategies can be implemented to reduce the energy use within a green building. The use of such passive techniques negate (or minimise) the need for mechanical equipment, hence reduction in energy use and associated CO_2 emissions. Other approaches are to use renewable technologies, sometimes referred to as 'green bling' bolt-ons including technologies such as solar photovoltaic, solar thermal water heating, wind turbines, ground source heat pumps, biomass boilers that burn woodchips and other forms of biomass as an alternative to traditional gas-fired boilers, CHP, solar air heating, solar cooling (Pennycook 2008). Some common sustainable building technologies implemented in many 'green' building designs include exposed thermal mass, recycled materials in construction, vacuum flush toilets, phase change materials, low energy lighting systems and use of natural ventilation strategies.

Recent years have seen the development and construction of many sustainable and flagship low-energy buildings. Various energy efficient techniques have been tried with sustainability as the key objective in mind. 1961 has been marked as the time when the first low energy building (a secondary school in Wallasey, Cheshire) was constructed in the UK (Turrent 2007). Some of the well-known flagship low energy buildings include the Elizabeth Fry Building at the University of East Anglia (built in 2005) and the BRE's Building 16 (built in 1996) (Halliday 2008).

In the UK there are a number of other green offices that have been built including South Cambs District Offices, built in Cambridge in 2004, which contained low energy concepts in the heating and cooling, grey water for WC flushing and solar water heating. The estimated CO_2 emissions at the design stage were 45 $kgCO_2/m^2/year$. The building achieved a Building Research Establishment Environmental Assessment Method (BREEAM) rating of 'Excellent'. Once operational the building was subjected to a post-occupancy monitoring and evaluation exercise and this resulted in the alterations being made to the BMS settings to improve efficiency (Turrent 2007).

The Red Kite House, an office development for the Environmental Agency, was completed in Oxford in 2005 and the aim was to be a flagship sustainable building. It incorporated many sustainable design aspects including natural ventilations, photovoltaic installations, solar panels, rainwater collection, high thermal mass, and exploitation of sunlight to reduce the artificial lighting but reducing overheating from solar gains. This building was subjected to monitoring to check the energy consumption in the building (Turrent 2007).

Buildings typically perform in such a way that is more energy intensive than was originally expected. Often the design claims will only include the energy figures for the building-services related aspects and omit the energy consumptions for the small power, which also contribute towards the total energy use within a building. In fact electrical consumptions for office equipment, catering and computer rooms within typical air conditioned office buildings can account for almost 25% of the total electrical consumption within these types of buildings (Action Energy 2003).

2.10 People and buildings

Buildings have a long design life, in many cases 60 years or more. In terms of whole life cost of operating and owning a commercial office building, the ratio of 1:5:200 is often used to shown the construction costs: maintenance and building operating costs: business operating costs

(Kirsten 2005). It is also suggested that a fourth term is added to this, reporting a ratio of 0.1:1:5:200 representing the design costs: construction costs: maintenance and building operating costs: business operating costs (Saxon 2002). This shows that in comparison to the overall business costs, the energy costs associated with the running of a building is a small fraction when compared against staff salaries, so the expenditure to a company is often small in relation to the benefits that can be delivered through greater efficiency. However, this 1:5:200 ratio has been criticised as "urban myth" by other researchers who suggest, from data for three office buildings, a ratio of 1:0.4:12 is more appropriate (Hughes, Ancell et al. 2004). Either way, in terms of whole life costs it highlights how the money spent on improving building performance is small in comparison to the benefits it could bring through better productivity of staff.

Energy performance and user satisfaction should be the main drivers in the design of buildings. Functionally, office buildings exist to provide comfortable and productive working environments that provide a space that enables businesses to operate effectively and generate profit. Occupant comfort is essential to enable productive workers. A number of studies have examined how occupant comfort can affect productivity (Leaman 1993) (Leaman 1995). The positive correlation between comfort levels and increased productivity levels has been well documented. The relationship between energy efficiency and productivity within office buildings have also been explored (Fewson 2007).

If the legislative targets that have been set are to be met, behavioural change from people is required. Yet this is a challenge in itself. People become used to their usual ways of life and adapting to new ways takes convincing, as well as time. The level of control given to occupants can affect the energy used within a building.

2.10.1 Thermal comfort

Building service engineers design heating and cooling systems to provide a thermally comfortable environment for the end users. In BS EN ISO 7730:2005 Thermal Comfort is defined as the "condition of mind which expresses satisfaction with the thermal environment" (BSI 2005). Research by Fanger (1970) showed how the comfort equation can be used to calculate how the combinations of different variables can create thermal comfort. These variables include activity levels, clothing and environmental variables (air temperature, mean radiant temperature, humidity and relative air velocity). From the tests that were conducted, Fanger found that there was no significant difference in age, gender or temperature climate zones when using the comfort equation (Fanger 1970). Whereas other sources (McMullan 1998) report the main factors affecting thermal comfort are air temperature, surface temperatures, air movement and humidity, and personal variables including activity, clothing, age and gender.

Fanger developed a method for assessing thermal environments, resulting in a thermal index known as the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). However, Fanger's PMV and PPD method has limitations (Djongyang, Tchinda et al. 2010). The subjective nature of thermal comfort causes difficulties when trying to create an internal environment perceived as comfortable by all.

The PMV and PPD methods have been used in many studies. However the method is confined to comfort in the thermal sense and pays no attention to the comfort and satisfaction levels associated with other aspects of a working environment such as noise, lighting and other facilities within a building. For this reason other avenues such as the use of questionnaires and other surveying means should also be considered.

Comfort factor rules of thumb guidelines are presented in a recent BSRIA publication (Pennycook 2003), with internal design temperatures in offices given as 24°C in the summer and 22°C in the winter.

There is published UK overheating criterion which state that the dry resultant temperature in offices should not exceed:

- 28°C for more than 1% of the occupied hours in a year (HM Government 2010) (CIBSE 2005b).
- 25°C for more than 5% of the occupied hours in a year (CIBSE 2002).

The law has no minimum temperature stated for offices but health and safety stipulates that these should not be less than 16°C (HSE 1992).

2.11 Lighting requirements within offices

From the social, comfort and productivity perspective, sufficient lighting within the working space is vital. Natural daylight is the best source of light available as it is cost effective due to the decreased demand for artificial lighting. In addition, it also brings physiological and social benefits (Nicol, Wilson et al. 2006). People prefer a view and to feel connected to the outside world, and as a result of these, productivity can be enhanced.

Innovative, low energy artificial lighting systems are also being developed in an attempt to reduce the associated energy consumption, such as the use of LEDs. Artificial lighting is a high end user of electricity and in a standard air-conditioned building it typically accounts for 24% of the total electrical consumption and 13% of the total energy consumption. In comparison, the artificial lighting in a typical naturally ventilated office building accounts for around 45% of the electrical consumption and 16% of the total energy consumption (Action Energy 2003).

According to a CIBSE report, lighting in non-domestic buildings accounts for 23% of the total UK CO_2 emission for energy use (CIBSE 2004).

Recommended lighting levels for various building types are given in the CIBSE Code for Lighting (CIBSE 2002a) and for office buildings, it is suggested that 300 to 500 lux is achieved on the working plane for computer-based work and 500 lux for paper work only (CIBSE 2005c).

Previous studies found that occupants prefer illuminance levels in the region of 100 lux to 600 lux (Escvyer and Fontoynont 2001), and when given the choice, an illuminance of between 100 to 300 lux is preferred for computer based tasks. Other researchers have investigated occupant's ideal level of lighting when given control over the switching and dimming controls, and the preferred illuminance was 400 lux (Boyce et al 2006).

BS 8206-2:2008 reports that it is good practice for buildings to have a "predominantly day-lit appearance". It is stated that "in order to achieve this, the average daylight factor should be at least 2%. If the average daylight factor in a space is at least 5% then electric lighting is not normally needed during the daytime, provided the uniformity is satisfactory. If the average daylight factor in a space is between 2% and 5% then supplementary electric lighting is usually required" (BSI 2008). Therefore a 2% minimum average daylight factor and an average 5% daylight factor are recommended (CIBSE 2009). Work by Roche et al (Roche et al 2000) supports these values and reports that maximum occupant satisfaction is achieved when the average daylight factor lies between 2 to 5%.

The daylight factor is defined as:

$$\frac{\text{Instantaneous illumination indoors}}{\text{Simultaneous occurring illumination outdoors}} \times 100\%$$

The daylight reaching a point indoors is made up of the sky component, the externally reflected component and the internally reflected component (Littlefair 1988)

A procedure to measure daylight factors has been suggested (Littlefair 1993). A major potential source of error is often experienced when trying to measure the simultaneous indoor and outdoor illuminances (Fontoynont 1999). Ensuring measurements are taken under standard CIE overcast sky conditions can also be challenging.

There are many control options to consider when designing an office lighting system and these include manual control, timed switch off, photoelectric switching on/off or photoelectric dimming. Some of these could additionally be linked to occupancy sensing detectors. Photoelectric control and presence detection is often not well received by occupants (Littlefair et al 2001) as they have no control and there are frequent annoyances associated with them.

Occupant productivity in offices increases with the higher level of control they have (Bordass et al 1993). Giving occupants full control lighting is often preferred (by the occupants) but from an energy point of view this could well be inefficient as lights may be left on during unoccupied periods.

The lighting preferences of office occupants were presented in a recent detailed literature review (Galasiu and Veitch 2006) which highlighted that information on occupant response to daylight linked lighting controls is limited. Some of the more relevant findings in the study include:

- Lighting systems that are fully automated are not well received by occupants; when there is an override control, it has a higher level of acceptance.
- Complicated systems are not favoured by occupants or facility managers.
- Preferred illuminance levels vary from person to person.

Many daylighting studies have been reported however these contain little data on the actual in-use performance of the lighting system (Galasiu and Atif 2002). One study found differences in measured daylight and simulated daylight availability (Galasiu and Atif 2002).

The use of daylight can be exploited to lower the demand on the artificial lighting and therefore reduce the energy consumption. Well-designed daylighting schemes that can result in energy savings have been reported (Li and Lam 2001) with claims that daylighting controls can bring a 50% energy saving in cellular office buildings. For open plan offices it was reported that a dimming control system could achieve a 33% reduction in electricity use (Li, Lam et al. 2006). Studies suggest that by integrating a dimming control system, annual savings of 60% could be achieved (Ihm, Nemri et al. 2009).

A large European monitoring program took place between 1994 and 1997 to explore the daylight behaviour in buildings (Fontoynont 1999). The daylight performances of sixty different buildings throughout Europe were assessed, including seventeen office buildings, one of which was in the UK. The details relating to the procedure used to carry out this 3 year monitoring programme are documented (Fontoynont 1999). Very few other studies have evaluated the lighting provision in buildings in such detail. The PROBE studies (explained in more detail later) evaluated the in-use performance of a number of buildings in the mid- 1990's and beyond (Bordass, Cohen et al. 2001). In these studies lighting performance was investigated using illuminance spot measurements, an occupant survey and discussions with the building users (Cohen, Standeven et al. 2001).

With regards to lighting, there appears to be a great deal of research has taken place to predict and optimise lighting at design stage but very little work has been carried out to evaluate the achieved performance once in use.

2.12 Ventilation

Ventilation is an important requirement in building for reasons including pollutant control (airborne contaminates), removal of undesirable odours and replacement of CO_2 with adequate amounts of oxygen. The main purpose of ventilation is to ensure the indoor air quality is acceptable and a healthy environment is achieved for the occupants (Palmer and Rawlings 2002). Ventilation is the process of bringing fresh air into a building then diluting and removing the stale unwanted air which contains harmful pollutants (CIBSE 2006a).

2.12.1 Modes of ventilation

There are a number of ways of ventilating buildings and these are mainly classed as either natural ventilation, mechanical ventilation or mixed-mode ventilation. Ventilation is used in passive strategies to cool buildings (natural ventilation). In mechanical strategies it is used as a means of distributing air that is thermally conditioned (whether it be heated or cooled) to the desired space. Mixed-mode is a combination of natural and mechanical ventilation.

Natural ventilation relies on wind forces and differences in air (temperature, pressure, density for example) to cause air movement in a building (Pennycook 2009). The main air flow paths used in building with this strategy include cross ventilation, single-sided ventilation and passive stack ventilation.

Natural ventilation is not always appropriate, particularly where there are high heat gains. In these cases mechanical ventilation is utilised. Mechanical ventilation systems require fans and ducts to force the air into and/or out of the building. There are three main types of mechanical ventilation; extraction ventilation, supply ventilation and a balanced mechanical ventilation system involving supply and extract systems.

It may not be possible to have a wholly naturally ventilated building, particularly when it comes to deep plan buildings or offices. In these situations a mixed-mode system can be used to provide a more energy efficient solution compared to a fully mechanical system.

2.12.2 Recommended ventilation rates in offices

The amount of ventilation required depends on the occupancy density, activities associated with the room/building and the pollutant emissions. CIBSE Guide A: Environmental Design recommends an outdoor air supply rate of 10 l/s per person in offices (CIBSE 2006a). A similar rate is recommended for other building types such as schools, libraries, hospitals, museums and restaurants. These are in line with the Building Regulation Part F requirement which specifies a minimum ventilation rate of 10 l/s/person for non-domestic applications (HM Government

(2010a). ASHRAE 62-1999 also recommends 10 l/s/person in offices (Palmer and Rawlings 2002).

2.12.3 Night cooling strategies

In thermally heavyweight structures, night cooling strategies can be an effective means of reducing cooling demand in a building due to the heat transfer of the exposed mass. With a night cooling strategy the heat gains that have built up during the preceding day can be discharged purging the building with cool night air using the installed ventilation system (Pennycook 2009). It is important that the night time air is below a threshold temperature of around 20°C to ensure the strategy works effectively.

2.12.4 Termodeck

Swedish designed 'Termodeck' is a hollow core concrete floor slab system which maximises heat transfer between the exposed mass (maximised by the hollow cores) and the ventilated air. Using low air velocities, the heat transfer between the air and the hollow core slab can be prolonged. The exposed thermal mass stores and releases heat (in response to the temperature of the surrounding air). It essentially works as a fabric energy storage unit. Figure 2-4 shows how air is passed through the Termodeck system.

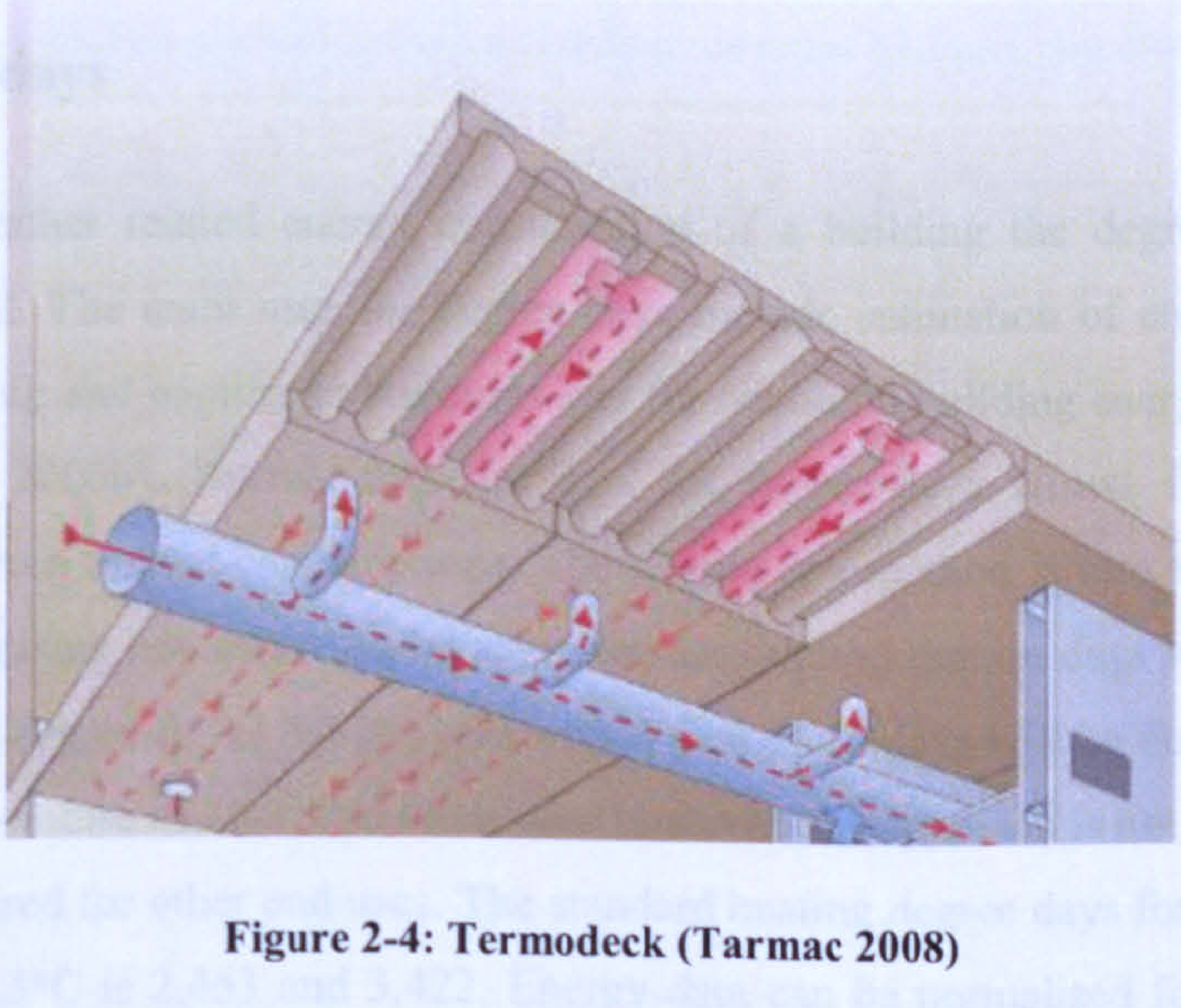


Figure 2-4: Termodeck (Tarmac 2008)

The Termodeck system, used in conjunction with a night cooling regime, helps control fluctuations in temperature, reduce peak temperatures and create a more thermally stable environment (Pennycook 2009). During cooling periods the ventilation air is pushed through the hollow cores of the slabs, which have been cooled overnight, where effective heat transfer occurs before the air then enters the space (Beggs2005). During winter the heat stored in the slabs overnight are used to heat the rooms in preparation for the next morning. The Swedish

Termodeck system has been successfully integrated in other building in England, providing both an energy efficient and thermally stable solution (Beggs 2005).

2.12.5 Control options in ventilation systems

To improve efficiency it is important that ventilation is controlled in buildings. Control options include:

- Simple on/off control: this may or may not be time controlled
- Demand controlled: this may be used in areas that are used occasionally and can be switched on via sensors such as infra-red occupancy detection.
- Variable demand control: this may type of control will vary the ventilation rate according to occupancy. This can be controlled using sensors to measure the CO_2 levels in the room.
- Constant supply air temperature, constant air flow rate
- Variable air flow rate: the air flow rate can be adjusted to take account of variations in heat loads
- Variable supply air temperature: this is usually limited to variations between 19°C and 21°C (Pennycook 2009).

2.13 Degree-days

To assess the weather related energy consumption of a building the degree day method is commonly utilised. The main uses for degree-days include estimation of energy consumption due to space heating and cooling in buildings and for continual building energy monitoring and analysis (CIBSE 2006b). Normalising the data for degree-days allows for more accurate comparisons between annual consumptions. The degree-day method is also sometimes utilised as a means of assessing hot water use by using the assumption that on days when no heating is required (i.e. zero degree-days) the gas consumption on those days will be due to hot water use only. A base temperature of 15.5°C is often used however this approach is not always applicable if gas fuel is required for other end uses. The standard heating degree days for base temperature of 15.5°C and 18.5°C is 2,463 and 3,422. Energy data can be normalised for standard degree days by dividing the measured energy consumption by the number of actual degree days, then multiplying this by the standard degree day figure (Vesma 2011).

2.14 BREEAM assessment and others

Worldwide there are a number of environmental assessments methods used. In the UK BREEAM (BRE Environmental Assessment Method) is the most recognised method, LEED is used in the USA, Green Star is the method developed in Australia and in Japan CASBEE is used. BREEAM was first introduced in 1990 and provides an environmental standard and labelling tool for various types of building (BRE 2007). The BREEAM assessment, carried out by an accredited assessor, provides an environmental and energy rating for a building at the design stage. Various versions of BREEAM assessments have been developed including BREEAM Offices, BREEAM Schools, and BREEAM Prisons. In the BREEAM office assessment credits are awarded in each of the following categories:

- Management
- Health and well being
- Energy
- Transport
- Water
- Materials and waste
- Land use and ecology
- Pollution

The categories are weighted according to their environmental importance and the overall percentage rating of the building is awarded as either: Pass, Good, Very Good or Excellent.

2.15 POE and BPE- investigating design versus actual performance

The purpose of any building is to provide a safe, comfortable shelter for occupants or other pieces of equipment, whereas a building's performance is a measure of its ability to do this (Preiser 2001). Only in more recent years has increasing attention towards the operational stage of building projects occurred. Many recent studies have shown that the actual, operational performance of a building is often much more than the calculated aspirations at the design stage.

It is important to identify why these discrepancies are occurring time and time again. In order to investigate and measure the operational performance of a building a process of evaluating the building once it is in-use is required. It is vital to evaluate how well a building is actually performing, rather than relying on theoretical performance figures made during the design. Three perspectives for evaluating how well a building actually works in-use have been suggested, these include:

- "Occupants and how well their needs are met
- Environmental performance, normally energy and water efficiency
- Whether the building makes economic sense, such as value for money or return on investment" (Leaman, Stevenson et al. 2010).

A building project needs to include a feedback stage to allow for a 'closed loop'. This 'closing of the loop' can be achieved through Post Occupancy Evaluation (POE) (or sometimes referred to as Building Performance Evaluation (BPE)).

It has been suggested that POE tries to answer four broad questions; 'how is this building performing, is it operating as intended, how can it be improved and how can future buildings be improved?' (Bordass and Leaman 2005). POE should become an essential stage of the design process. Unfortunately, many architects and designers have a 'walk away' approach once the building is constructed and becomes operational by the occupants. Disappointingly, designers are currently not routinely including feedback in their work. They are unaware of the failing aspects of the building design and therefore are not learning from these mistakes (Leaman, Stevenson et al. 2010).

At present there is no standard method for conducting performance evaluations at the post occupancy stage of a building's life hence there is no industry-accepted definition for POE (Federal Facilities Council 2001). In the UK one definition for POE is 'the systematic process for measuring the building's performance' (BCO 2007). POE has also been defined as "the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time" (Preiser 2001). A similar definition of POE is given as "a process systematically evaluating the performance of buildings after they have been built and occupied for some time" (Federal Facilities Council 2001). Presier views BPE as a process made up of six phases, where POE is one of these phases.

Interest in the field of POE is apparent not only in the UK but in USA, Canada, Australia (Paul and Taylor 2008) and New Zealand (Daish, Gray et al. 1982). But despite its recent increasing attention, POE is still seldom conducted. A number of issues surround POE, including:

- Cost- There is a cost associated with POE and who will, or should, pay for this?
- Risk- The results of the POE may not be as positive as originally hoped and some may be concerned over the impact this may have on reputations.
- Ownership – If problems are identified, who will take responsibility of them?

Leading researchers in the field of POE strongly believe it's lack of popularity is due to academics failing to understand the potential that individual case study building evaluations can bring (Leaman, Stevenson et al. 2010). The same research team report on the five types of feedback that can benefit buildings as shown in Figure 2-5. The figure demonstrates not only the types of feedback but the continuous loops involved.

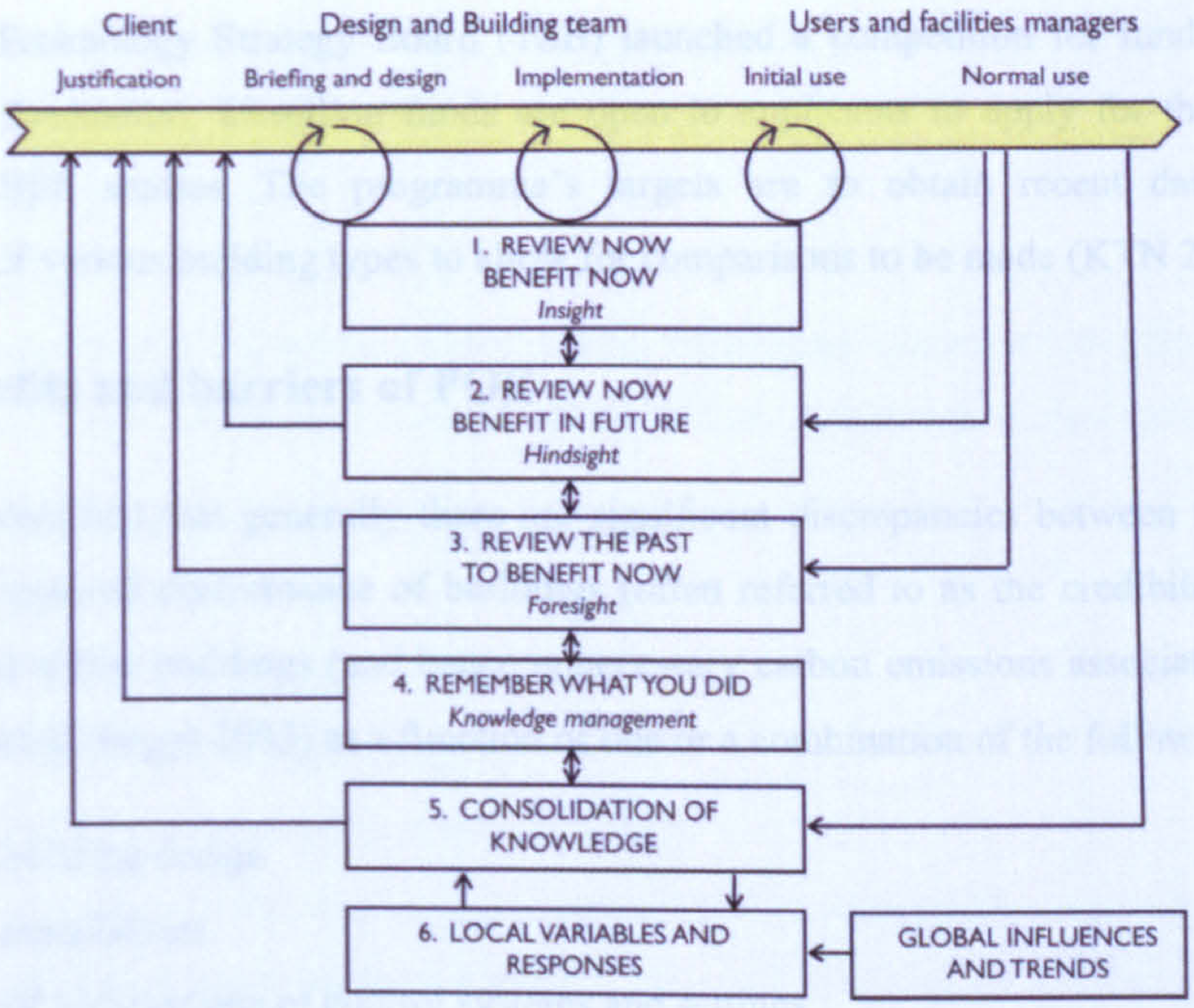


Figure 2-5: Types of feedback given by Leaman, Stevenson et al. 2010

2.15.1 History of Post Occupancy Evaluation (POE)

Within the UK, early development of POE was first seen in the 1960's when the Stage M Feedback of the Royal Institute of British Architects (RIBA) Plan of Works was published (BCO 2007). Stage M was introduced to encourage architects to examine the success of their designs. In the late 1960's the BPRU at the University of Strathcylde was sponsored by a number of architectural and engineering practices, RIBA, Architecturals Journal and Ministry of Public Buildings to undertake feedback work and publish the results in both the Architecturals Journal and the famous Building Performance book (Bordass and Leaman 2005). The results were aimed at encouraging architects to engage in feedback. However, a few years later (in 1972) Stage M Feedback was removed from RIBA's Plan of Works as it was not seen as a matter of course and many of the clients were not willing to pay for it. Efforts into POE were generally not undertaken in the 1980s however the "Sick Buildings Syndrome" issues increased concerns relating to building performance.

In 1995 the PROBE studies were given funding by UK government to undertake POE on twenty buildings. The PROBE studies are discussed in more detail later in this chapter. In 2003 Stage M was re-introduced into the RIBA plan and interest amongst architects slowly started to grow. When the RIBA Plan was reviewed in 2007 Stage M was again removed. However Stage L was expanded to include L3- Review of Project Performance (RIBA 2009). In this last decade there have been a number of research projects involving POE studies at a number of universities in England (Turner 2007).

In 2010 the Technology Strategy Board (TSB) launched a competition for funding Building Performance Evaluation; £8million funds are open to applicants to apply for the funding to commission BPE studies. The programme's targets are to obtain recent data about the performance of various building types to allow for comparisons to be made (KTN 2011).

2.15.2 Benefits and barriers of POE

It has been identified that generally there are significant discrepancies between the predicted energy and measured performance of buildings (often referred to as the credibility gap). The energy wasted within buildings (and hence unnecessary carbon emissions associated with this) has been reported (Beggs 2005) as a function of one or a combination of the following:

a) Poor building design
b) Poor installations
c) Lack of optimisation of control systems and settings
d) Inefficient plant operation
e) Poor operating and working practices

POE can ensure lessons are learnt from completed building projects, allowing designers to evaluate what design choices were/weren't effective or well received by the occupants. Secondly, through POE buildings can be fine-tuned to perform more efficiently and provide more comfortable internal environments for the occupants.

Benefits in terms of energy efficiency, comfort and well-being of occupants within buildings, brought about by POE, monitoring and fine tuning have been reported by many researchers. Summarising various sources of literature (Federal Facilities Council 2001) (Hadjri and Crozier 2009) (BCO 2007), the benefits brought about from conducting a POE include:

- Improved end user satisfaction/requirements
- Identify any inefficient areas of building performance to optimise energy performance
- The supporting of policy development and knowledge for guides
- Feedback and feed forward of lessons learnt to the designers and future designers
- Testing of new concepts allowing designers to determine what is successful and what is not
- Information for future designing
- Improvement to the building throughout the life cycle
- On-going building adaptation to improve performance
- Identifying if the building is meeting the original intentions
- Identifying who is accountable for any issues or failures in the performance
- Improved communication between all parties involved (from stakeholders to end users)
- Improvement of management procedures

- Greater awareness and accountability, resulting in greater productivity
- Examine refurbishment requirements and timescales
- Measuring project success

Despite the benefits that it can bring unfortunately POE is not carried out as often as it should be. There appear to be a number of reasons for the barriers to such approaches including:

a) Cost and the issue of who will pay for the POE
b) Ownership of POE
c) Fear of what the POE may reveal
d) Protection of professional integrity
e) Responsibility of failures within the building
f) Lack of understanding the "new professionalism" (Leaman, Stevenson et al. 2010)
g) Lack of enthusiasm from the occupants
h) Many clients do not recognise POE as part of the "normal architectural services"
i) Experience: as POE is not commonly conducted there is a lack of people who are experienced enough to carry out this type of work

It is vital that the occupants are engaged and understand the benefits that a POE can deliver. This is specific to those at a managerial level who may be reluctant to pay for a POE and all occupants who may participate in a survey or questionnaire.

The feedback and feed forward processes associated with POE is significant as this allows for the loop to be closed. The collection of actual performance-related data, and even more important the dissemination of this information is crucial to the industry to allow lessons to be learnt.

2.15.3 POE methods

There are a number of various POE methods/techniques available and depending on the aims and objectives, the most appropriate method may vary.

Bordass and Leaman developed a portfolio of techniques with various tested methods of POE detailing the suitability of each technique to the building and application in question. There are a number of available POE methods described in UBT's portfolio (Usable Buildings Trust 2009a). BRE have produced a checklist to help those carrying out POE. This is a simple yet useful tool to aid POE type work (BRE 2003).

Focusing on the non-domestic building systems and more specifically commercial offices, the British Council for Offices (BCO 2007) recognised the following techniques that are used to carry out POE:

- Questionnaires/occupant surveys
- Interviews
- Focus groups
- Walkthroughs and general observations
- Physical monitoring- including internal/external environmental monitoring of the building, both long-term and short-term monitoring
- Environmental assessment – BREEAM (Building Research Establishments Environmental Assessment Method) or US equivalent known as LEED (Leadership in Energy & Environmental Design)
- Space analysis and utilisation
- Cost analysis

The physical monitoring technique/phase can vary in detail of analysis ranging from energy audit using annual energy use collected from utility data, to detailed energy profiling using BMS data, meter-read data and the installation of remote monitoring systems, spot checks, collection of other performance-related aspects such as temperature, humidity, CO_2 levels, acoustics, investigation of any issues.

When considering using a questionnaire/survey as a tool to obtain feedback a decision needs to be made whether a new questionnaire will be created or an existing one will be utilised. There are advantages and disadvantages of both and these are considered in the Table 2-8.

Table 2-8: Advantages and disadvantages of using a new and or existing survey

Survey type	Advantages	Disadvantages
New Survey	Allows the assessor to customise questions to the building in question	No existing database to allow for comparisons with benchmarks Risk of including bias questions if not carefully written
Existing survey	Comparisons can be made Tested and proven method	May not be possible to customise questions to the building in question May require licence Fees

In terms of gathering occupant satisfaction data some of the established and well recognised methodologies (BCO 2007) are shown in Table 2-9. Comparisons between some of the established occupant surveys have been made in a recent paper (Turpin-Brooks and Viccars 2006).

Table 2-9: Established occupant surveys

Methodology	Website
Building use studies (BUS) occupant survey and reporting method	www.usablebuildings.co.uk
OPN index, OPN survey	www.officeproductivity.co.uk
Overall liking score (OLS)	www.ols-survey.com
Design quality index (DQI)	www.dqi.org.uk
DEGW workplace evaluation	www.degw.com/services/research.htm
IPD workplace productivity appraisal	www.opd.co.uk/service-measuring.asp
RICS tenant satisfaction index	www.ipindex.co.uk www.rics.org
Ryder occupant evaluation methodology	www.ryders.com/main2.html
SHCA workplace evaluation survey	www.shca.com/profile/perf_measure.asp
ZZA responsive user environments: integrated building- user focus	www.zza.co.uk

The Soft Landings Framework has been developed by Usable Buildings Trust (UBT) and BSRIA in 2009. The idea behind the framework is that designers and contractors stay involved with building beyond practical completion to help deliver a 'soft landing' for a building becoming operational. The framework has five distinct stages including: inception and briefing, design development and review, pre-handover, initial aftercare and extended after care for 1 to 3 years and POE. Soft Landings is a process "for designer and constructors to improve the operational performance of buildings and provide valuable feedback to project teams". The approach is to ensure a virtuous closed-loop, between the design, construction, feedback and then feeding forward into the design again (Usable Buildings Trust 2009b).

2.15.4 Previous in-use building performance studies and findings

There is a lack of feedback from the buildings that have been constructed and are now operational. Design predictions are rarely checked at the post occupancy phase of a buildings life (Andreu and Oreszczyn 2004). It has been reported on many occasions (Bordass, Cohen et al. 2004) that there is a strong need to learn more from buildings and that they rarely perform as well as originally expected. The actual performance of buildings can often be three times more than that predicted (Roaf 2004). Figure 2-6 represents the common occurrence of differences in the design and actual performance of office buildings. It shows how the actual CO_2 emissions for an office building were over twice the predicted emissions made at design stage. Interestingly a building that was designed to perform much better than the ECON 19 'Good

Practice' benchmark actually only performed between the 'Good Practice' and 'Typical' benchmark once in operation. This reflects the importance of conducting investigations into the post occupancy performance.

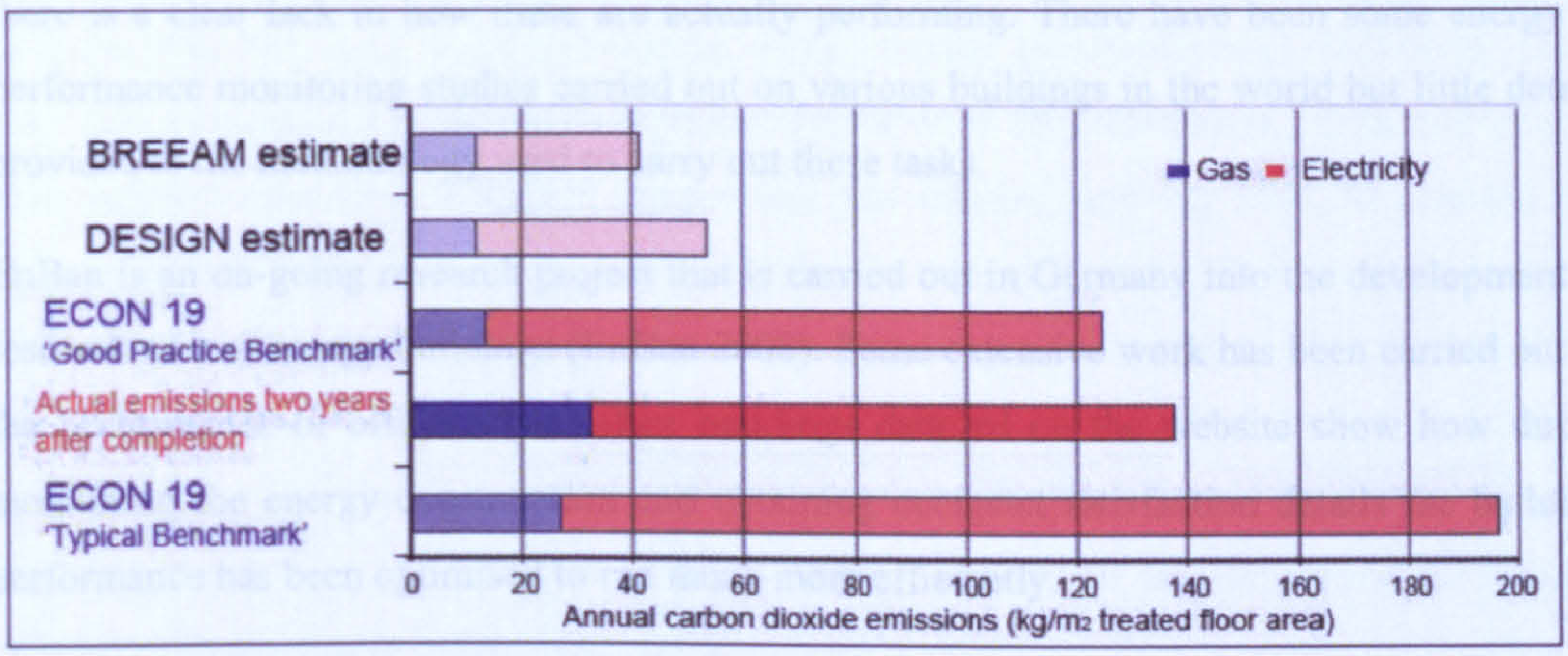


Figure 2-6: Differences between actual CO_2 emissions and predictions at the design stage. (Bordass, Cohen et al. 2004)

It has been suggested that the reasons buildings rarely perform as expected is due to lack of commissioning and maintenance, lack of feedback on operational and energy performance and errors in installation or selection of equipment (Piette, Kinney et al. 2001).

Researchers have the opinion that occupants can have a strong influence on the differences between the energy consumption from design to actual performance (Filippin and Beascochea 2007).

The under-performance of buildings is often due to over use of electrical energy consumption, mainly electrical equipment and artificial lighting by occupants. It is urged that post-occupancy surveys must become another stage of every project (Turrent 2007). There appears to be a lot of discussion and strong opinion from many researchers that approaches to obtain feedback about how buildings perform are essential at every stage of a project. Differences in actual and design performance are often only recognised through a monitoring process. This underpins the increasing need for feedback in buildings.

In a recent study carried out into the performance of twenty three buildings in Germany (Wagner, Klebe et al. 2007) it was found that, in all twenty three cases, monitoring the energy performance of the buildings facilitated in optimising the energy performance through the analysis of the results. It resulted in the buildings becoming much more energy efficient. It demonstrated that actual performance can often differ from predicted performance. This difference can have significant increases in energy cost and environmental impact. It has been stated that in order to continually deliver improvements to its performance, BPE should be applied at every stage in a buildings life (Wolfgang and Vischer 2005). There is a strong need for continual monitoring.

There have been studies carried out relating to what technologies go into green buildings, but there is a clear lack in how these are actually performing. There have been some energy and performance monitoring studies carried out on various buildings in the world but little detail is provided to the methodology used to carry out these tasks.

EnBau is an on-going research project that is carried out in Germany into the development and research of low energy buildings (EnBau 2008). Some extensive work has been carried out into the performance of offices. The office buildings detailed on the website show how through monitoring the energy consumption and obtaining occupant satisfaction details the building's performance has been optimised to run much more efficiently.

In a two year study into monitoring a low energy office building in Germany researchers (Pfafferott, Herkel et al. 2004) used a building simulation program to delve deeper into the performance and efficiency. Physical data such as temperature was collected, along with tracer gas techniques to measure air leakage. The measured temperatures were then compared against the simulated to see how they compared.

Energy and thermal performance assessments on a number of low energy buildings were conducted in Argentina (Filippin and Beascochea 2007). These included a number of schools, colleges and residential buildings. From their work, a number of factors were found to have a strong influence on the energy performance and thermal comfort. These include the varying climate, design and construction technologies used and the behaviour of the occupants. The researchers recognised that high standard of design and construction can be redundant if the occupants don't use and understand the building effectively.

In the UK, the ZICER (Zuckerman Institute for Connective Environmental Research) building was monitored and evaluated (Turner 2006). The TermoDeck building is situated at the University of East Anglia, which is also home to the famous Elizabeth Fry Building. The researcher highlighted that a low energy building shouldn't be taken as given and monitoring should be set up to assess the actual energy performance (Turner 2006, Turner 2007) . In this case study, two phases of monitoring took place to fine tune the building so that its performance was enhanced.

Many of the papers provide figures to the energy consumption per meter squared per year but don't go into the detail of how the monitoring was actually carried out. In a published paper (Walker 2006) the methodology used to assess the performance of a naturally ventilated office building in London was described. A combination of long and short term monitoring and observations of occupant behaviour were used. The long term monitoring was carried out over a twelve month period, with fifteen minute interval measurements taken. The monitoring for long term evaluation includes energy consumption (overall and sub-metered), internal temperature conditions and other internal conditions and external condition patterns. Short term monitoring are 'snap shot' measurements. These can be used to explain long term measurements in the end analysis. For the long term monitoring, data relating to temperature conditions, relative humidity, external condition and sub-metered data were all collected at 15 minute intervals. Data loggers were used to collect temperature and relative humidity data. At selected times short term monitoring was carried out to obtain more specific detail. The energy consumption for all the various electrical demands was collected using electric-energy data loggers. After a twelve month monitoring period the data was analysed. The annual energy end use was determined for the building and energy patterns were identified, based on occupied and un-occupied times. The building was to be continually monitored and fine-tuned to deliver an efficient office that satisfies its occupants.

In 2007, (Krausse, Cook et al. 2007) data from the BMS (Building Management System) installation was used to assess the in-use energy and environmental performance of a naturally ventilated library in Coventry, UK. The assessment was carried out to compare the actual performance to its original design. The total annual consumption was 0.049 kWh/(m^2h), which is above good practice guidelines for offices.

In the UK the most well-known POE studies carried out were probably the ones in the PROBE studies (Cohen, Standeven et al. 2001). Early in the 1990's data collection and analyses regarding the operation of buildings began. Credibility gaps in the predicted and actual performance of buildings were realised. So with the 50% government funding the PROBE project was set up and began to establish in 1995. The need for improved building performance was the driver for the PROBE study. The extensive work of Bill Bordass, Adrian Leaman and others is well worth the recognition. The PROBE study provided feedback; something that is often not readily available. The Probe study was set up to improve the openness and availability of such information. The series of POEs that were carried out on completed buildings from 1995 to 2002 formed PROBE (Post-occupancy Review of Buildings and their Engineering). The twenty PROBE surveys (offices, schools and other) evaluated social and physical performance. A PROBE study consisted of two elements; occupant surveys (the Building Use Studies (BUS) occupant questionnaires[1]) and energy surveys (the Energy Assessment and Reporting Methodology (EARM) and the air pressure test to CIBSE TM23 standard) (CIBSE 2006d), (Roaf 2004). The energy surveys looked at gas and electricity consumption, air leakage and carbon emissions. The projects had a good strategy for dissemination. The findings from the

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[1] BUS survey can be obtained under a licence from http://www.usablebuildings.co.uk/

research were published in Building Services Journal (Probe 1998). A summary of the annual CO_2 emissions from these buildings are shown in Figure 2-7.

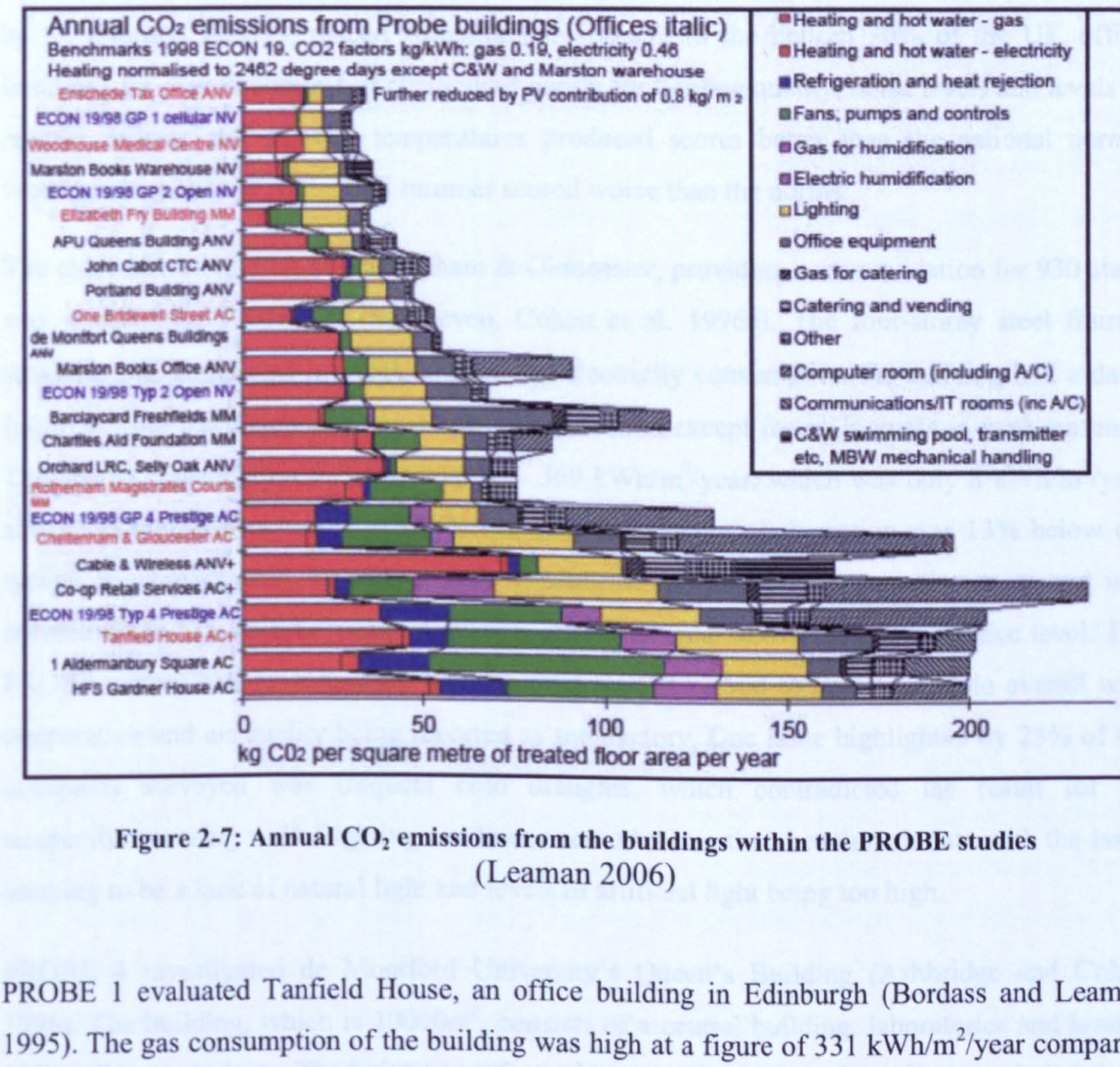

Figure 2-7: Annual CO_2 emissions from the buildings within the PROBE studies
(Leaman 2006)

PROBE 1 evaluated Tanfield House, an office building in Edinburgh (Bordass and Leaman 1995). The gas consumption of the building was high at a figure of 331 kWh/m^2/year compared to the 'typical' value of 273 kWh/m^2/year for a prestige air conditioned office. Heating and hot water was close to double the EEO's good practice level. Although electricity consumption was low for lighting at 13 kWh/m^2/year in the offices and 16 kWh/m^2/year elsewhere it compared well to the typical value of 20-25 kWh/m^2/year. Tanfield House was the first building to use the BUS questionnaire which was developed for PROBE. 119 people were surveyed and the building scored in the top 10% of the BUS data for overall comfort, lighting, temperature and air quality in both summer and winter. Although perception of noise scored low, it was still placed in the top 30% of the BUS data. One of the main problems reported was a lack of control over heating however this was overcome by effective management response to requests by the occupants for adjustments.

Aldermanbury Square was the subject of PROBE 2 (Standeven, Cohen et al. 1995). It is a nine storey office building. The building performed well when comparing gas consumption and CO_2 emissions to ECON 19 benchmarks for an air conditioned open plan office building with results of 32 kWh/m^2/year and 282 kg/m^2/year respectively. The electricity consumption was 371 kWh/m2/year, which is worse than typical values. The chillers used by the ice storage system were found to be one of the problems causing the high electricity consumption. It was found that 70% of the chiller operating hours were at night. The BUS occupant survey results provided by 61 returned surveys, placed Aldermanbury Square in the bottom 30% of the UK office buildings for overall comfort. It also scored poorly for lighting quality, noise levels and levels of control. Winter and summer temperatures produced scores better than the national norms, whereas air quality in winter and summer scored worse than the norms.

The chief office building of Cheltenham & Gloucester, providing accommodation for 930 staff, was selected for PROBE 3 (Standeven, Cohen et al. 1996a). The four-storey steel framed structure was completed in 1989. In terms of electricity consumption the building had a daily figure of 16MWh which was consistent all year round except for an increase in peak summer. The annual consumption for electricity was 369 kWh/m^2/year, which was only 8 kWh/m^2/year above the typical benchmark in ECON 19. Lighting energy consumption was 13% below the typical benchmark data, a result of long running hours. The gas consumption measured was normalised to 135 kWh/m^2/year, which was 3 kWh/m^2/year above the good practice level. The PROBE survey had 72 responses. The building was perceived to be comfortable overall with temperature and air quality being reported as satisfactory. One issue highlighted by 25% of the occupants surveyed was frequent cold draughts, which contradicted the result for air temperature scoring well. Lighting conditions scored worse than benchmark data with the issue seeming to be a lack of natural light and levels of artificial light being too high.

PROBE 4 investigated de Montford University's Queen's Building (Ashbridge and Cohen 1996). The building, which is 10000m^2, consists of a central building, laboratories and houses 1500 full time students. The building performed very well on all levels with gas and electricity consumption reported at 143 kWh/m^2 and 52 kWh/m^2 respectively compared to the respective 'low' targets of 185 kWh/m^2 and 75 kWh/m^2. The building also performed well with CO_2 emissions at 65 kg/m^2 with an EEO 'low' target of 90 kg/m^2. Although the building performed well it was claimed that the gas consumption could be lower had the building met the design levels for usage due to an increase in internal heat gains. Most of the electrical consumption was attributed to lighting with an annual consumption of 37 kWh/m^2 which was slightly higher than 'good' practice levels. The team noted that some of this could be caused by lighting used for cleaning during closed hours. 71 occupants returned the standard PROBE questionnaire. The Queen's Building scored similar to benchmarks for perception of thermal comfort and air quality with overall air quality in winter considered significantly better than the benchmarks. High summer temperatures and stuffiness in both winter and summer were considered unsatisfactory. Although too much natural light was reported, this did not result in glare scoring any less than the national benchmark. The most alarming result from the survey was the occupants reporting the working environment had an average negative 10% effect on productivity and placed the Queen's Building in the bottom 10% of the BUS database.

Located in the outskirts of Coventry is the Cable & Wireless College which was the focus for PROBE 5 (Standeven and Cohen 1996b). The building consists of a single storey teaching block, three storey administration block and a sports and leisure centre with a treated floor area of 11400 m^2. With the college not falling into an existing category for benchmarks, the PROBE team combined the benchmarks for a standard hotel, university academic buildings, leisure centres and swimming pools. Based on these benchmarks annual gas and electricity consumption was reported as higher than typical/poor with 400 kWh/m^2 and 187 kWh/m^2 respectively. CO_2 emissions were about a third above benchmark at 211 kg/m^2/year and lighting consumption was measured at 50 kWh/m^2/year. The standard PROBE questionnaire was returned by 44 employees. Overall comfort, winter temperature and winter air quality were all perceived at levels similar to the benchmarks. Factors considered worse than benchmarks were summer temperature and air quality, lighting and noise levels. The poor perception for lighting was reinforced by employees reporting too much artificial light and too much sun and sky glare. Overall the staff perceived that the working environment causes a productivity loss of -8%.

The Woodhouse Medical centre was selected for PROBE 6 (Standeven, Cohen et al. 1996c). The building consists of a single-storey terrace of three units with a total floor area of 640 m^2. Although gas consumption was reported sufficiently low when compared to benchmarks for the centre, there were no actual figures given in the report. However a reading for fuel bills from 1991 for one of the three sections of the centre showed a gas consumption of 55 kWh/m^2. Annual electricity consumption for the entire centre was 50 kWh/m^2/year for the period of February 1995 to January 1996 with 17 kWh/m^2/year was attributed to hot water. The two reasons given for this was the large number of point-of-use water heaters (a total of 27), and the large number of hand washes per person per day given the nature of the working environment which resulted in a figure of 8kWh/m^2/year for the point-of-use heaters alone. Lighting energy consumption at 14 kWh/m^2/year was lower than for a good practice office. At 10 kWh/m^2, energy consumption accounted for by office equipment is similar to a typical office. Overall comfort, winter air temperature, winter air quality and noise levels were all perceived as significantly better than BUS benchmark data. The building had the best recorded score by the BUS (at that time when 55 buildings had been surveyed) for overall comfort and second best for winter temperature. Overall summer air quality and lighting was perceived as similar to the benchmark data. Yet summer air temperature was perceived as much worse and scored in the lowest 10% of the BUS data. Levels of control scored well and better than the benchmarks. The team noted that this could have been due to work areas only being shared by a few employees. An average of 3.8% perceived productivity gains placed Woodhouse Medical centre in the top 10% of the BUS dataset.

LEEDS UNIVERSITY LIBRARY

PROBE 7 reported on Gardner House, the Homeowners Friendly Society headquarters which has a treated floor area of 3800m^2 and used chilled beams and displacement ventilation (Bordass, Leaman et al. 1996). Annual electricity consumption for the treated floor area was slightly below typical benchmarks for an air conditioned office. When taking the computer room and restaurant into consideration the building then scored disappointingly above the norm. Refrigeration consumption was 40 kWh/m^2/year, which was similar to typical values. However this was considered high considering the low occupancy densities and internal heat gains. Extended hours of chiller operation in winter and simultaneous heating in summer could be the cause of this. It was reported that when chilling was required the building's two chillers would operate; even in high summer it was found that often only one was required. Annual fan energy consumption and pump energy consumption was 45 kWh/m^2 and 42 kWh/m^2 respectively. With this being between typical and good levels for fan consumption, the pump consumption was extremely high in relation to typical levels. Lighting energy consumption was 63 kWh/m^2/year. The monitoring team observed that too many lights defaulted to 'on'. Gas consumption was similar to typical values, normalised to 271 kWh/m^2/year. 86 people returned the standard PROBE questionnaire. 35% of occupants reported a dislike in the floor air supply, mainly due to draughts, coldness and variability. Overall comfort, winter temperature, lighting and summer and winter air quality were all similar to benchmark norms with summer temperature perceived as more comfortable. Noise levels scored well and better than average. The PROBE team noted that his could be due to low occupancy levels. Perceived levels of control were lower than national benchmarks, with some occupant comments about the inability to open windows or blinds. The survey did report some conflicting responses. Overall the building scored well with a perceived productivity level gain of 2% which, at that time, placed Gardner House in the upper quartile of the BUS dataset.

PROBE 8 evaluated the Learning Resource Centre, also known as the Queens Building, at Anglia Polytechnic University considered to be a low energy, naturally ventilated building with a treated floor area of 5656 m^2 (Cohen, Leaman et al. 1996). The building has a main axis with two separate atria providing a source of natural light. The building wasn't fully occupied, the third floor was used as an open plan office with only 166 out of the 750 workstations intended installed. Consumption of the building was measured using 150 sensors transferring hourly records to a computerised spreadsheet programme and reported for the period July 1995 to June 1996. Electricity consumption was calculated at 50 kWh/m^2/year, which was considered respectable. However, it was recognised that low occupancy will have contributed to this value. Lighting consumption was 16 kWh/m^2 which is half the good practice figure. It was found that the building's systems were mainly left to operate as commissioned. Gas consumption was normalised to 108kWh/m^2/year (97 kWh/m^2/year excluding catering). This was slightly above the normalised annual figure of 95 kWh/m^2, however given the low internal heat gains from occupants and equipment (due to low occupancy) this was considered respectable. The occupant survey used the standard PROBE questionnaire and was completed by 79 staff. Overall comfort was perceived as significantly lower than national benchmarks. Temperature in winter and summer and air quality in summer all scored similar to national benchmarks. Average levels of daylight and high levels of sun and sky glare contributed to a lighting score lower than benchmarks. A total of 97% staff reported some sort of discomfort in reference to the environmental questions. Consequently productivity levels scored -5.6%. The building was placed in the 30th percentile of the BUS data.

The PROBE 9 publication reviewed the eight of the buildings that were studied under the PROBE research project and drew conclusions on building performance (Bordass, Cohen et al. 1997).

The four non-office buildings shared a lot of the same methods. They all had gas fired boilers as well as a range of ventilation control strategies, from a simple manual system to a mix of manual and automatic systems. The findings showed HVAC consumption was found to be high in all buildings due to long hours of occupancy (Bordass, Cohen et al. 1997).

Lighting energy in all the buildings was found to be below typical even though automatic lighting systems didn't deliver the expected savings and all the buildings had the tendency to default to on. One issue with the automatic lighting systems was the lights activating when people were passing through an area activating the light which then remained on for 15 minutes. Two key lessons learned were that extended hours of operation and diversity of use make it very important that engineering systems are designed to respond in a gradual manner to varying and sometimes small loads (Bordass, Cohen et al. 1997). Also that training on the management of the automatic controls is important as all the studies showed misuse; resulting in increased energy consumption.

PROBE 11 evaluated The John Cabot City Technology College in Kingswood, Bristol (Standeven, Cohen et al. 1997a). Electricity consumption, based on energy bills from June 1996 to May 1997, was 57 kWh/m^2 which was considerably more than the medium to high benchmark of 31 kW/h/m^2. 20% of the consumption was found to be during the night and was attributed to standing losses from local electrical HWS, the computer base unit being on 24 hours per day, the network servers, air conditioning and external security lighting. By taking the night time consumption for all of the above out of the equation for the annual electricity consumption, a reading of 30 kWh/m^2 would be given which is slightly below benchmark. Annual gas consumption was normalised to 130kWh/m^2 which was better than the low to medium EEO benchmark of 151 kWh/m^2. CO_2 emissions were also found to be above the benchmark of 43 kg/m^2 at a value of 54 kg/m^2. The occupant survey used the standard PROBE questionnaire and was completed by 40 staff. Overall comfort, noise, lighting, winter temperature and winter air quality all were perceived to be better than the benchmark BUS data with overall comfort being placed in the top 25% percentile of the benchmark dataset at that time. Perceived control over heating, cooling and lighting was reported as low. The building did score well for perceived productivity with a gain of 6% placing the building in the top 10% of the BUS dataset at that time.

Rotherham Magistrates Court was the focus of PROBE 12 (Standeven, Cohen et al. 1997b). The building had a treated floor area of 4350 m^2. Annual electricity consumption was 102 kWh/m^2 and was above the 'high' yardstick using the benchmark data. Total consumption was up 5.7% on the previous 12 months. The monitoring team noted that this could be due to increased use and the addition of air conditioning systems in offices. The whole ventilation system that serves the courtrooms was found to be operational 11 hours per day when the courtrooms are only required for up to 6 hours per day. Lighting consumption was low at 16 kWh/m^2, mainly due to a high proportion of circulation area and low lighting requirement. Equipment being left on overnight was also discovered. One of the main reasons given for Rotherham Magistrates Court not achieving as low energy levels as at design stage was due to the fans supplying air at a continuous rate rather than the minimum rate or controlled on demand. For the occupant survey 40 office staff and 40 magistrates were given questionnaires. However, only the office staff results could be compared as there were no benchmarks for magistrates. The building scored very well and based on overall comfort was placed in the top 10% of the relevant BUS dataset. It was also placed fourth best in the dataset based on the average scores for summer and winter air quality, lighting, noise and overall comfort. A perceived productivity gain of 1.8% also placed the building in the top 25% of the BUS dataset.

PROBE 13 investigated the headquarters building for the Charities Aid Foundation (Standeven, Cohen et al. 1998a) which is a mixed-mode, open office building with 3700 m^2 of treated floor area housing 200 staff. Electricity consumption was 117 kWh/m^2 which scored well when compared to benchmark 'good practice' data. Performance was also close to the design estimate of 120 kWh/m^2. The building also scored well for water consumption with a consumption of 7000 litres/person/year compared to BRE's good level of 10000 litres/person/year. Good practice lighting was found (consumption of 26 kWh/m^2). This was a result of lights not being left on when not in use. Office equipment energy consumption was at the typical level regardless of a high use of PC's. Energy efficient PC's and screens could have been the reason for this however low occupancy will have attributed towards this. Annual gas consumption was normalised to 165 kWh/m^2. Compared to the ECON 19 data for both naturally ventilated and air conditioned offices this was well above the 'good' level and the building's design estimate of 100 kWh/m^2. A total of 95% of staff responded to the BUS survey. Overall air quality and winter temperature was perceived to be close to the benchmarks. Summer temperature was rated as much hotter, less comfortable and more variable than the benchmarks. Perceived levels of natural light being low and artificial light being high suggested that the building suffered from a low source of natural light. Noise scored close to the benchmark for the ground and second floor, however the first floor scored significantly worse. The PROBE team noted that this may have been a result of the first floor being more open plan than the other floors.

PROBE 14 evaluated the Elizabeth Fry building at the University of East Anglia (Standeven, Cohen et al. 1998b). The energy and environmental performance was monitored from January 1996 to August 1997. The building consisted of 50 cellular offices spanning the top 2 floors with lecture rooms and seminar rooms on the lower floors. It was the second building in the UK to use the Termodeck technique. The building was subjected to an energy audit and an occupant survey. The total gas and electrical consumption in 1997 was 37 kWh/m^2/year and 61 kWh/m^2/year respectively. The PROBE team found that as occupancy increased there was an increase in electrical consumption whereas the gas consumption decreased. As a result of initial teething problems a new BMS was fitted to fine-tune the control strategy and settings. The overall occupant satisfaction scores were exceptional. It had the highest BUS for overall comfort, winter and summer air quality and lighting, for all other criteria it scored within the top 20% of the BUS dataset

As mentioned earlier, TSB recently set up a programme to fund BPE/POE studies of both domestic and non-domestic buildings, mainly for new builds but also for major refurbishments (KTN 2011). This programme will remain open until 2012. It is hoped that, like the PROBE studies, the results of this will be widely disseminated.

Industry has begun to slowly recognise the important and available market for the Building Performance Evaluation. Organisations and large consultancies including BSRIA, Arup, Mott MacDonald, Buro Happold are all marketing POE/BPE as a service they can now provide.

2.15.5 CIBSE TM22

CIBSE TM22 provides a methodology and reporting tool for assessing the energy performance of an occupied building based on metered energy (CIBSE 2006d). It was first published in 1999 with a reprint (with minor changes) in 2006 and a more recent version is due for release in 2011. The TM22 software comes in Microsoft Excel format.

The method provides an effective way to obtain feedback and make comparisons with similar building types (namely the four types benchmarked in ECG019- cellular naturally ventilated, open plan naturally ventilated, standard air conditioned and prestige air conditioned).

TM22 has are three assessment procedures (Options A, B and C) ranging in complexity. Option A is a simple building assessment of the actual (operational) energy usage and carbon emissions based on the metered energy and represented per unit floor area. Option B is a general building assessment and involves the same aspects as those of Option A, but accounts for different zones and allows for non-standard occupancy, weather and system adjustments to be made. Option C is principally the same as Option B but it goes into more detail and allows for assessments of a building at the system level. All three options focus on annual energy use and carbon emissions. There are default emission conversions set in the software, which can be adjusted as required.

There are quality assurance features included in the TM22 assessment methodology to ensure procedure and data standards are maintained (CIBSE 2006d).

The TM22 assessment tool is useful for building performance evaluation and can also be a useful tool for facilities managers, building managers and operators, energy assessors, building specialist and designers.

2.15.6 Thermography

Thermal imaging cameras can detect and map the intensity of infrared radiation, which varies with surface temperature of the object being surveyed (Walker 2004). In terms non-destructive, post-construction testing of a buildings fabric, thermal imaging is an excellent way of evaluating the continuity of the insulation and identifying defects. These defects can be detected by finding differences in the surface temperatures caused by differences in heat flow through the boundary layer (Pearson 2011). Thermal bridging occurs at components where there is a higher rate of heat transfer compared to the surrounding areas of the building envelope. Thermal bridging commonly occurs around doors and windows, yet efforts should be made to reduce the extent to which it occurs.

There are different approaches to conducting a thermographic survey of a building. These can be qualitative or quantitative. Most surveys are of the qualitative type, as they highlight defects but do not include measurements. Quantitative studies may evaluate the amount of heat loss and can be used to enhance the results from a qualitative study. Other types of surveys include external, internal, roof, air leakage surveys or estimating areas. External surveys are useful as they can provide an overview of the building. However certain weather conditions are required when conducting external thermographic surveys including:

- At least a 10°C temperature difference between internal and external temperatures
- Cloudy sky conditions
- No precipitation or mist
- Wind speed must be no greater than 5 m/s

It is impossible to control the weather conditions which may restrict when external surveys can be conducted. Internal surveys are not restricted by the weather conditions and therefore may sometimes be more effective however hot objects such as radiators or other pieces of electrical equipment can cause anomalies (Pearson 2011).

There are supplementary testing that can be conducted in conjunction with thermal imaging such as heat flux tests to measure the U-value of the element being tested. Also results from an airtightness test will quantify air leakage, with which thermal imaging can be used to identify the location (Pearson 2011).

2.16 Conclusions and salient points from literature review

Buildings are responsible for a significant proportion of energy consumption and CO_2 emissions and this must be reduced. Only by conducting POE at the operational stage of a building's life can inefficient areas of a building be identified. There are often significant differences between the predicted and measured performances of buildings. A number of examples of previous studies and the results of the findings have been presented in the literature review above. However it appears that industry are still not routinely learning from previous projects and feeding successful aspects into future projects to optimise performance.

An interesting, and in many ways opportunistic gap in research exists for the performance of partially occupied commercial buildings. In a number of the PROBE studies low-occupancy was mentioned as a reason for low electrical consumption but no detailed investigations were followed through. Under-occupied buildings are common, and particularly with the nature of the case study building selected, rented space may not be at 100%. Occupancy density may have an impact on the way buildings perform. From the occupancy satisfaction perspective higher densities along with reduced storage and desk space can have negative impacts on comfort and productivity levels. However, with regards to energy, there is little research available to suggest how the occupancy levels will affect the energy and comfort performances of a building.

Occupant behaviour can significantly affect the performance of a building and this is influenced also by the given level of control. The buildings that are created must be manageable and not too complicated. High-quality Facilities Management (FM) is essential to ensure that there is a good understanding of a building design and control philosophy and systems that are in place. FMs may not have the knowledge to make the required changes or challenge settings. Hence, POE may be very relevant to support Facility Management particularly when building use and occupancy change from design intent.

Chapter Three - Case study building

3.1 Introduction

The case study building was briefly introduced in the initial chapter. Chapter Three presents detailed information about the building. A summary of the BREEAM assessment completed at the end of the design stage is also presented. The chapter concludes with the designer's predicted energy performance of the building.

3.2 Building description

The building that was available for the case study and subjected Post Occupancy Evaluation (POE) is an award winning BREEAM 'Excellent' office building (shown in Figure 3-1) located approximately six miles east of Leeds city centre in the UK. The building location can be seen in relation to the proximity of Junction 46 on the M1 in Figure 3-2.

Figure 3-1: Case study office building

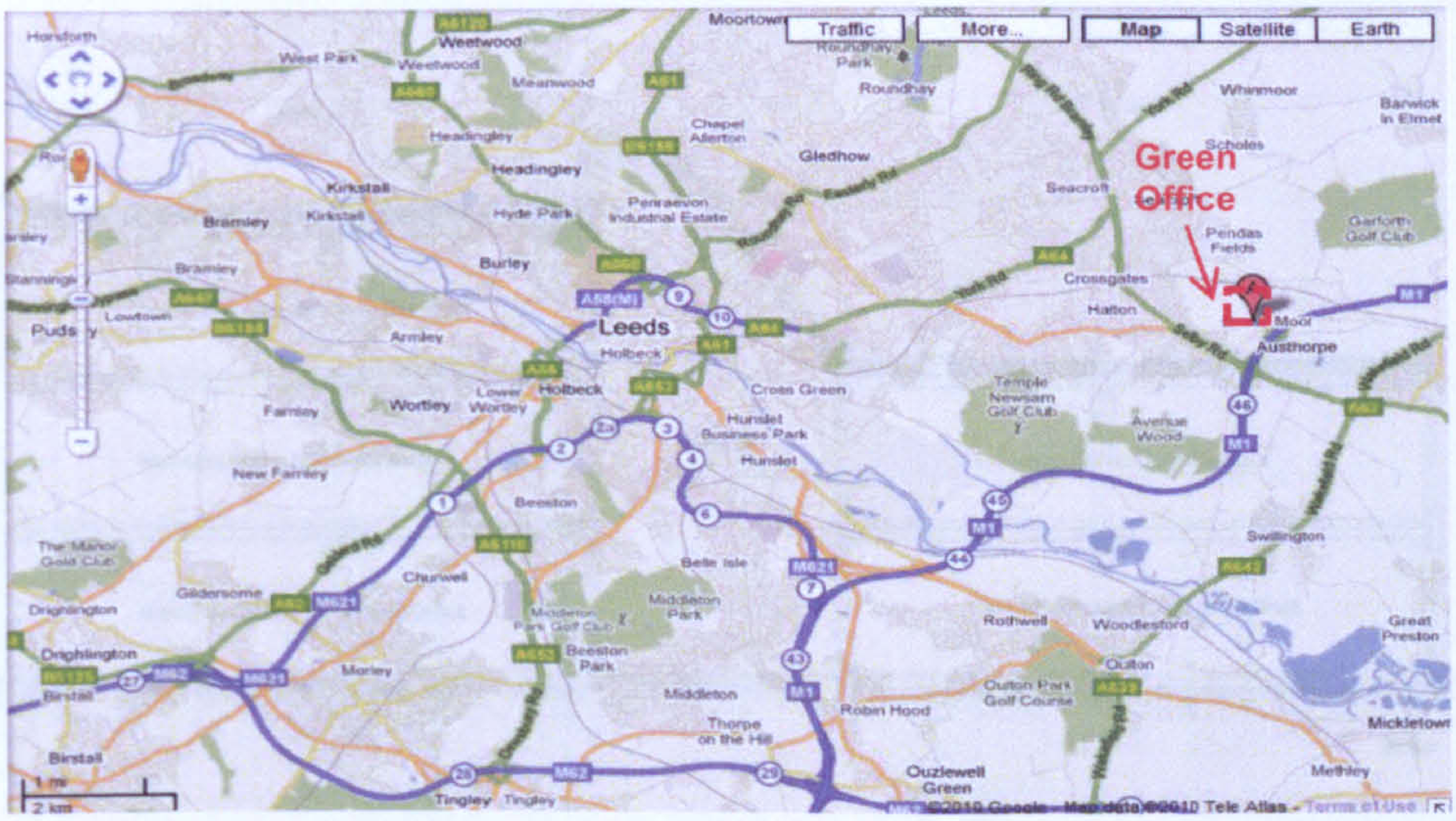

Figure 3-2: Location of the case study building[2]

The completed office building consists of a precast concrete structural frame and comprises of two independent modular structures creating two 54 m x 13.5 m wings (a two storey east wing and a three storey west wing) separated by a central glazed atrium. The atrium, known as "the street", creates a usable space for the occupants and minimises the area taken by the office building. Floor to ceiling height of 3m was used to maximise daylight penetration and to allow for air stratification (King 2007). The roofs are insulated and have a single ply water proof membrane. The east wing roof also includes a green roof which will be discussed later.

The building was designed to provide flexible office space that could be used as either open plan or as cellular offices (based on a $18m^2$ minimum area), depending upon tenant needs. The building plans are shown in Figures 3-3 to 3-6

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[2] http://maps.google.co.uk/maps?hl=en&q=ls158gb&um=1&ie=UTF-8&hq=&hnear=Leeds,+West+Yorkshire+LS15+8GB&gl=uk&ei=ajBhTJPODZeHOK3r4OoJ&sa=X&oi=geocode_result&ct=image&resnum=1&ved=0CBcQ8gEwAA

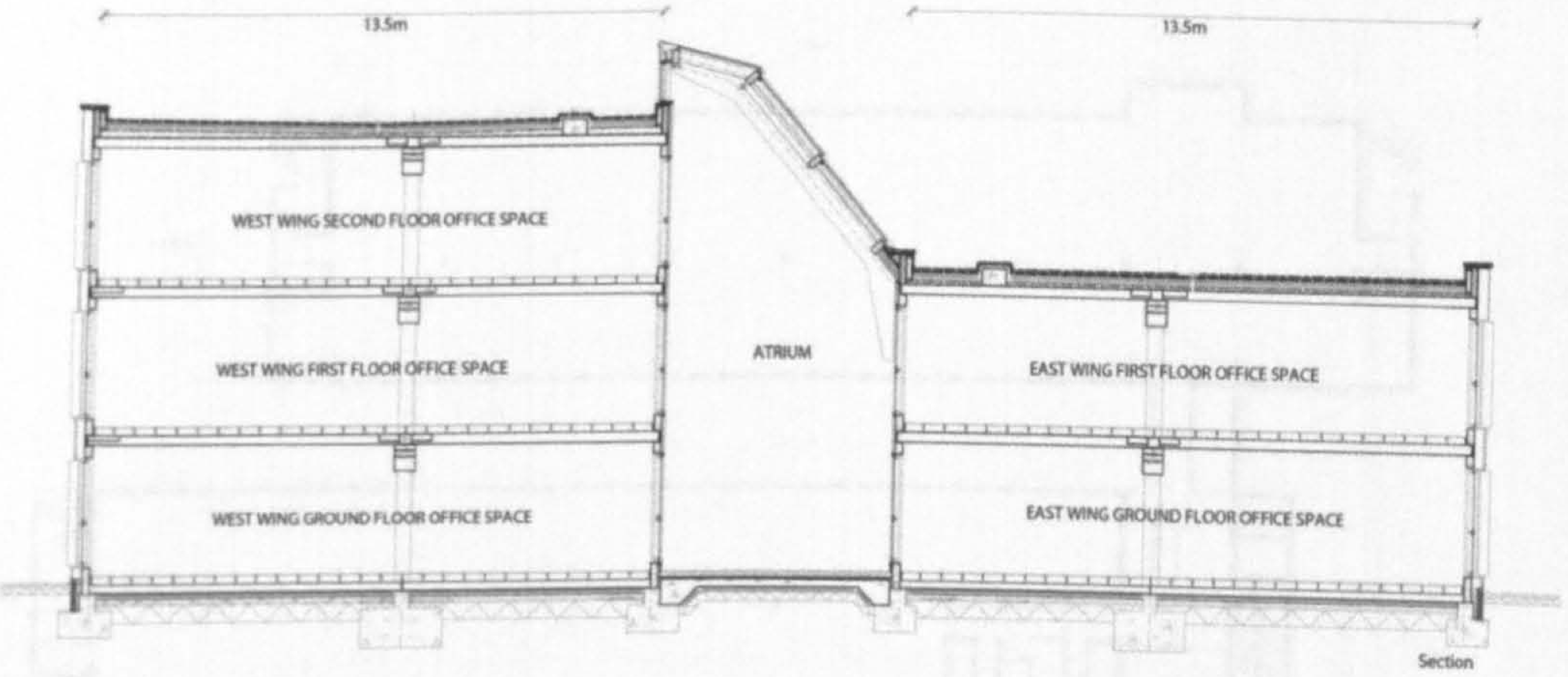

Figure 3-3: Section of the case study office building

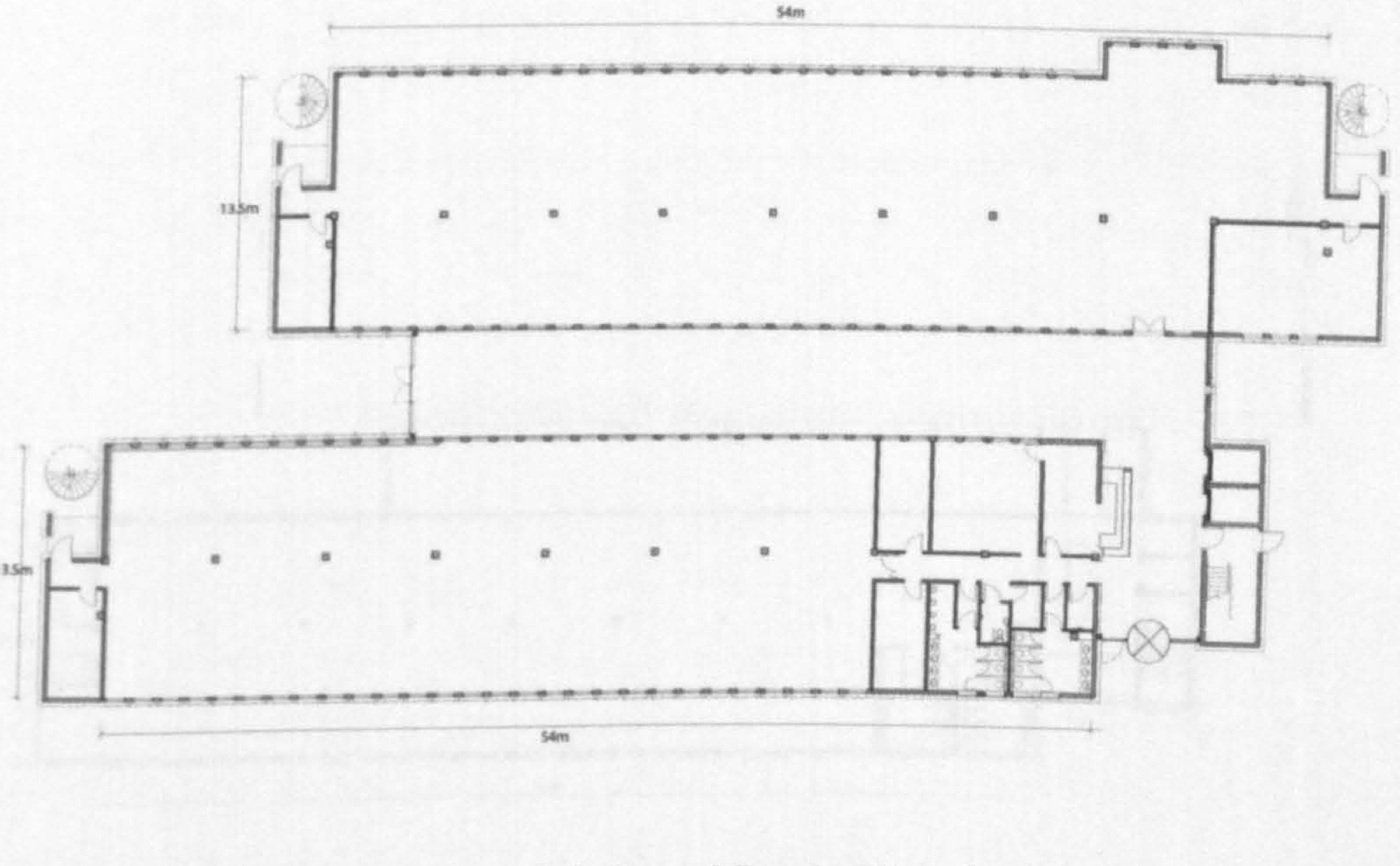

Figure 3-4: Ground floor building plan

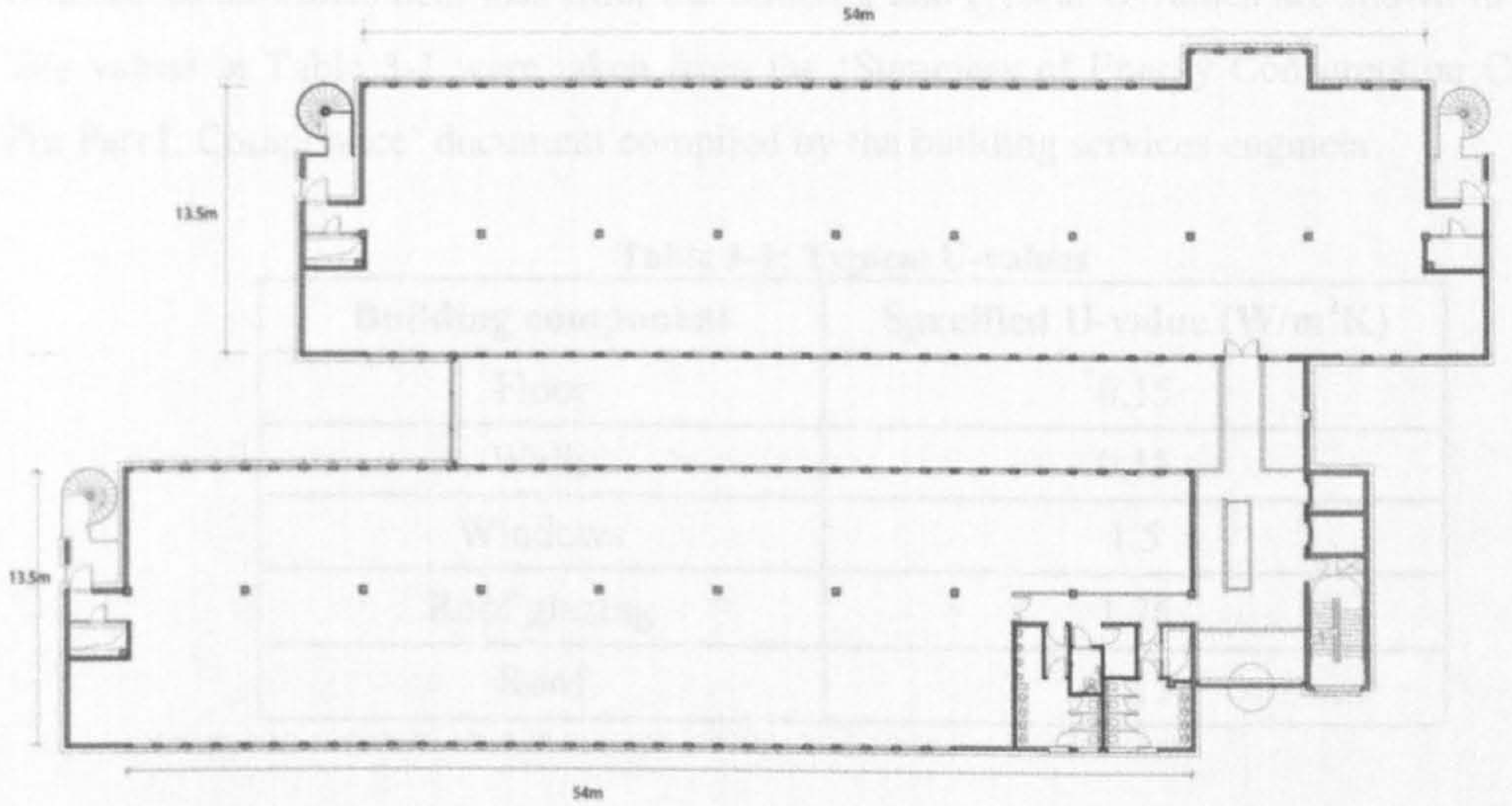

Figure 3-5: First floor building plan

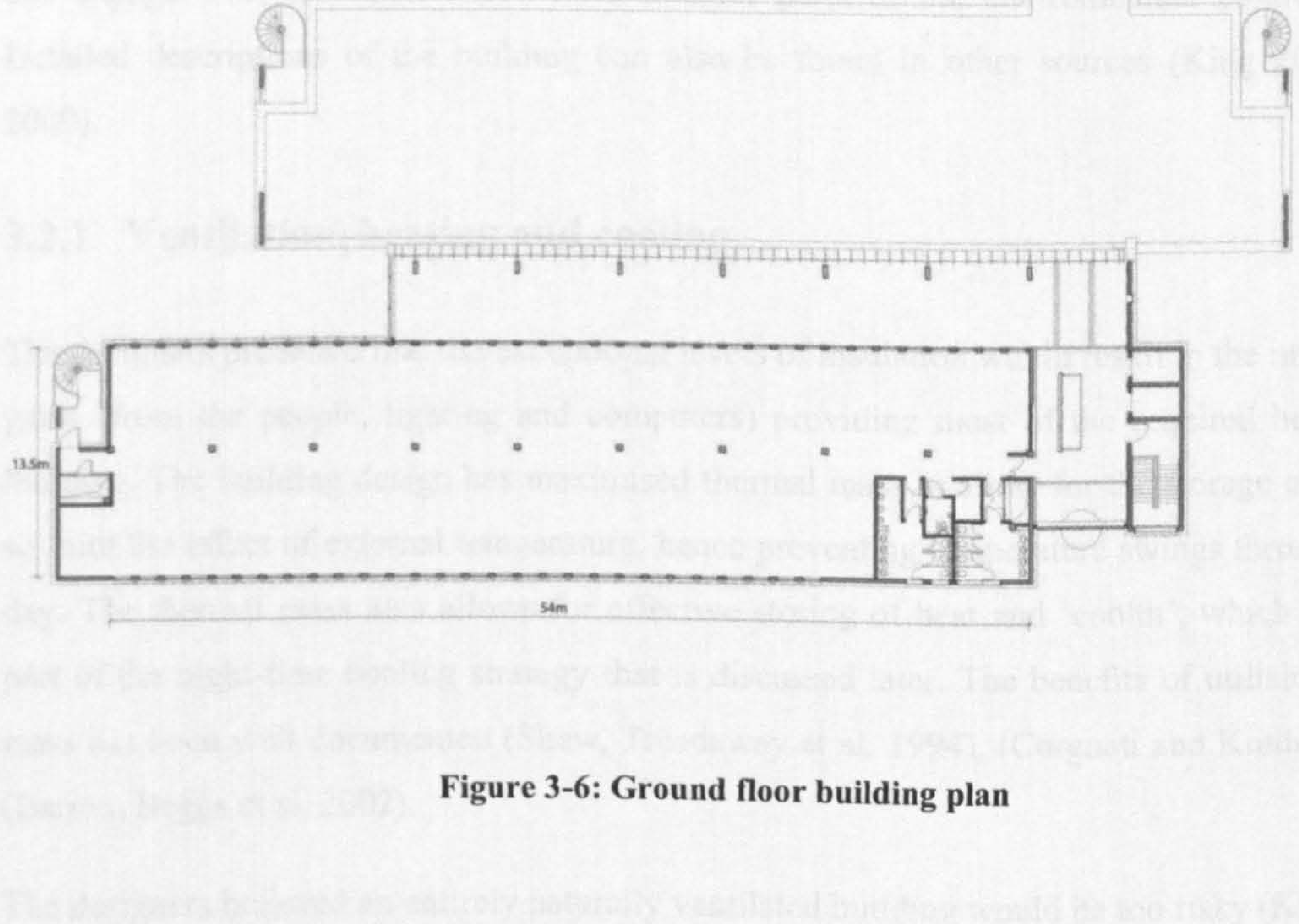

Figure 3-6: Ground floor building plan

The building was designed for a full occupancy of 420 people, based on an occupancy density of 7.5 m^2/person in the office spaces.

The approach taken by the design team meant the elements of the design were examined from first principles. Passive environmental design techniques were exhausted initially as opposed to immediately specifying a design with renewable technologies.

Insulation blocks, of 250 mm thick expanded polystyrene, were glued to the exterior of the concrete to minimise heat loss from the building and typical U-values are shown in Table 3-1. The values in Table 3-1 were taken from the 'Summary of Energy Consumption Calculations For Part L Compliance' document compiled by the building services engineer.

Table 3-1: Typical U-values

Building component	Specified U-value (W/m^{2}K)
Floor	0.15
Walls	0.15
Windows	1.5
Roof glazing	1.76
Roof	0.15

The highly insulated concrete structure provides a high level of thermal mass. The floor slabs are 260mm deep precast concrete hollow core units and are used to accommodate the proprietary heating & ventilation system known as 'Termodeck'. The hollow cores of this system further increase the thermal mass. Therefore the mass of the structure and Termodeck can engage with the interior and form integral parts of the environmental control system. Detailed descriptions of the building can also be found in other sources (King 2007, Jones 2009).

3.2.1 Ventilation, heating and cooling

The designers predicted that the exceptional levels of insulation would result in the internal heat gains (from the people, lighting and computers) providing most of the required heat for the building. The building design has maximised thermal mass to allow for the storage of heat and so limit the effect of external temperature, hence preventing temperature swings throughout the day. The thermal mass also allows for effective storing of heat and 'coolth', which is used as part of the night-time cooling strategy that is discussed later. The benefits of utilising thermal mass has been well documented (Shaw, Treadaway et al. 1994), (Corgnati and Kindinis 2007), (Barton, Beggs et al. 2002).

The designers believed an entirely naturally ventilated building would be too risky (King 2007), so a mechanical ventilation system which could actively work with the thermal mass of the building was selected.

There are four air handling units (AHU) serving the east and west zones of the east and west wings. The AHU units are housed in cylindrical units on the roofs, with two placed on each wing. Each AHU comprises of: fresh air inlet section and exhaust air section with motorised dampers, heat recovery thermal wheel or recuperator, pre-filter panel, main filter bag, high efficiency supply and extract fans/drives/motors, variable speed fan motors, heater battery and cooling coils both with motorised control valve and acoustic attenuators[3].

The air handling units incorporate heat recovery wheels (thermal wheels) to minimise the energy required to heat the incoming fresh air by utilising heat gains from the occupants of the building.

The majority of the building is mechanically ventilated with balanced supply and extract via the Termodeck (Tarmac 2010). A fresh air supply of 10 l/s/person is specified as a minimum. The supply air passes through the AHU and is circulated through the Termodeck labyrinth in the floor/roof slabs (thereby acting as a supply air duct) before entering the office areas via ceiling diffusers. The differences in air temperate and slab temperature will cause heat to be absorbed or given up when contact is made, thus moderating the supply air temperature (King 2007). The air is then extracted via the extract vents within the offices as shown in Figure 3-7.

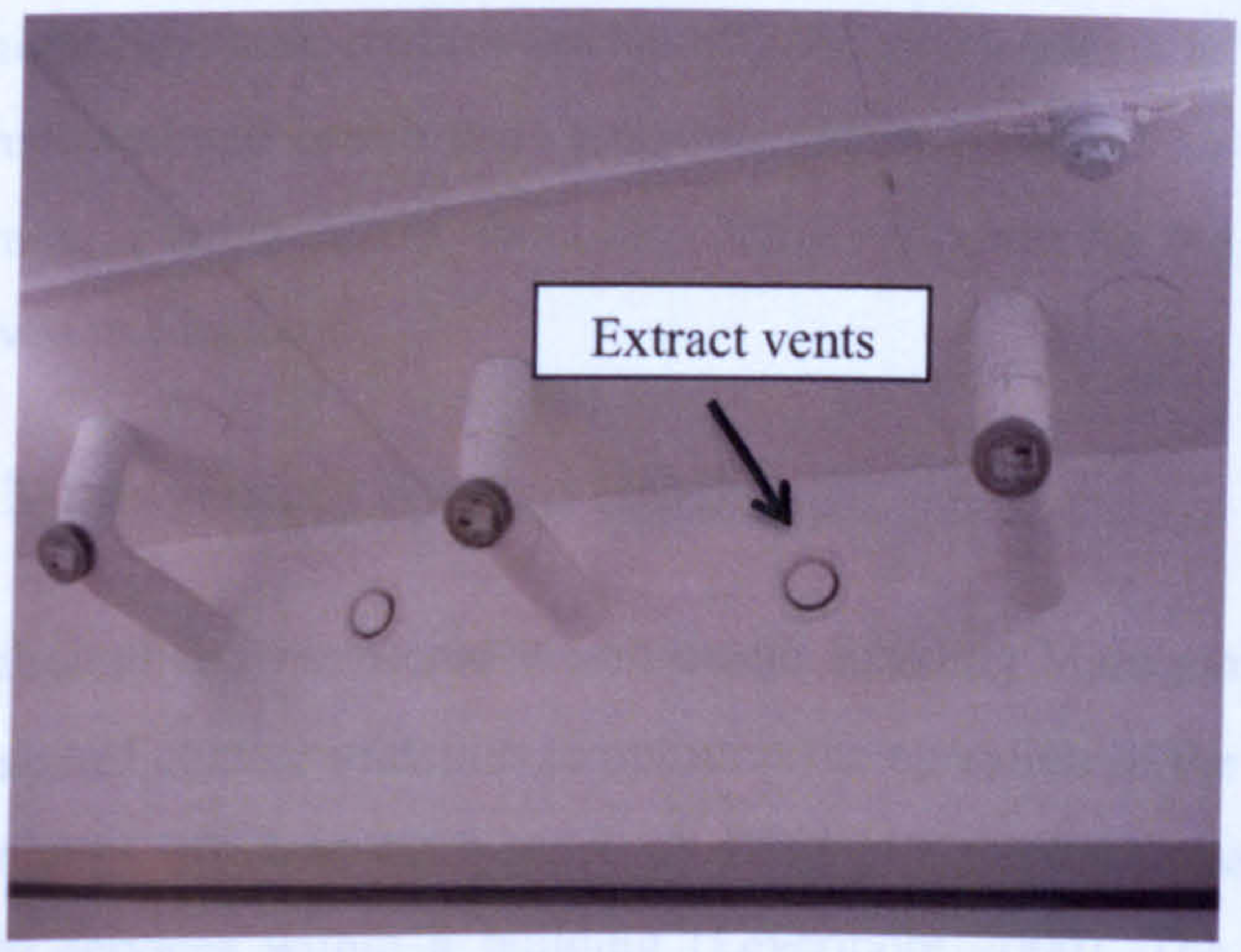

Figure 3-7: Termodeck

The atrium and entrance foyer are naturally ventilated by stack effect and are heated via an underfloor heating system. Automatic actuators in the atrium operate low and high vents that are configured to the BMS. The high and low vents will automatically open when the atrium space temperatures exceed 23°C and 25°C respectively.

The heating and cooling is designed to be provided by a gas fired tri-generation plant consisting of two high efficiency boilers (85%), a 35kWe CHP, absorption chiller and electric chiller. The CHP unit was installed in the building to enhance its energy efficiency. Utilising a CHP unit allows for the simultaneous generation of heat and electrical power from the same source (Pennycook 2008), often referred to as co-generation. CHP units are often used when there is a

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[3] Taken from the Operating & Maintenance manual for Mechanical Services Installation prepared by the design team

steady demand for both heating and electricity all year round. In some situations, the waste heat can also be utilised to drive a cooling process via an absorption chiller, known as tri-generation.

The CHP unit installed was designed to provide hot water for hand basins, underfloor, space heating and the baseload electrical demand in the building. CHP units are less commonly used in office buildings, however the waste heat from the CHP unit was intended to utilise the matched absorption chiller which, in this case, made the installation of a CHP unit more commercially viable.

The cooling design strategy involves passive night time cooling and some active cooling from the absorption and conventional electric chiller. The additional cooling requirements from the absorption chiller were intended to be supplied via the hot water from the CHP unit as a means of energising the absorption chiller.

The night time cooling strategy is specified to reduce the demand for active cooling from the chillers. Provided night-time temperatures are below 20°C, the building is "purged" at night so the excess heat is removed and comfortable temperatures are provided for when the occupants arrive the next morning. Further details about the control set points for the heating and cooling requirements are given in Chapter 6.

3.2.2 Building Management System (BMS)

The building is controlled and monitored via an onsite Building Management System (BMS) with specifically designed control strategies to optimise the operation of the building to provide a comfortable and energy efficient work space. A BMS is a microprocessor system that can control one or more services within a building (Levermore 2000). The system allows the building system to operate within the control parameters programmed within the operator terminal. Remote access to the BMS was originally granted, however due to problems with viruses getting into the system the computer was later disconnected from the internet and access was only available during visits to site.

BMSs have developed greatly in recent years and have become an energy efficient way to control the environment within a building. The system also allows easy identification of any plant faults or areas performing inefficiently. However it has been reported (Levermore 2000) that BMSs are often not used to their full potential and their capabilities are not exploited.

Understanding and training to use a BMS system is important in order to maximise the benefits it can deliver. It has been suggested that buildings that incorporate BMS have lower energy consumptions than those with separate control (Nicholls 2002) with reports of a 10-20% energy saving being made (CIBSE 2004). Nicholls (2002) recognised that the only way to successfully save energy with a BMS installation is for it to be designed and set up correctly in the first place.

3.2.3 Natural and artificial light

The building is glazed on the east and west facades, and orientated in such a way that the offices are subjected to direct sunshine in the morning and late afternoon. The central atrium, shown in Figure 3-8, allows for additional daylight to penetrate into the office wings.

Figure 3-8: Atrium, known as "The Street"

The lighting system within the office spaces utilises presence motion sensors and daylight linked photocells that allow for the lamps within the light fittings to dim down in response to the detected lighting levels available. When appropriate, this reduces the output therefore reducing electrical demand for artificial lighting. Using the installed lighting system with the penetrated daylight a 450 lux internal illuminance was to be maintained rather than constant 500 lux in conventional lighting systems. The windows incorporate solar controlled glass and those on the main elevations have fixed shading fins fitted around them. Perforated blinds were also fitted to allow occupant control over glazing from the sun.

3.2.4 Green roof and permeable drainage system

An extensive, sedum green roof is installed on the east wing roof (shown in Figure 3-9). These types of green roof require low levels of maintenance. Incorporating a green roof has restored the grass area originally removed when the building was constructed, therefore improved the bio-diversity and re-created the wildlife habitat.

Figure 3-9: Sedum green roof on the roof of the east wing block

Permeable block paving was used in the construction of the car park. This system allows the rainwater to pass through voids in the paving and infiltrate through the soil. Storm water seeps through the voids in the paving and will either pass through the sub-base or, once the soil is saturated enough, will be collected in a tanked system. The storm water flows from the tank to the lined pond on the south side of the building, with an overflow to the wetland area/ balanced pond which is located on the east side of the building. From here the water can naturally drain into the sub base or naturally evaporate.

3.2.5 Water

In attempts to minimise water use in the building a vacuum drainage system for the WCs, waterless urinals and low volume fittings in the hand wash basins were all installed. The water consumption was estimated to be 1.27m^3/person/year. The low volume WCs used rain water harvested from the west wing roof and used only 1.2 litres per flush compared to approximately 6 to 9 litres per flush in a conventional system. The harvested rain water is stored in an underground tank and treated prior to use. The overflow from the underground storage tank discharges into to the pond.

The water consumption for mains water, grey water (harvested rain water) and mains 'top up' water are all logged on the BMS (see Figure 3-10).

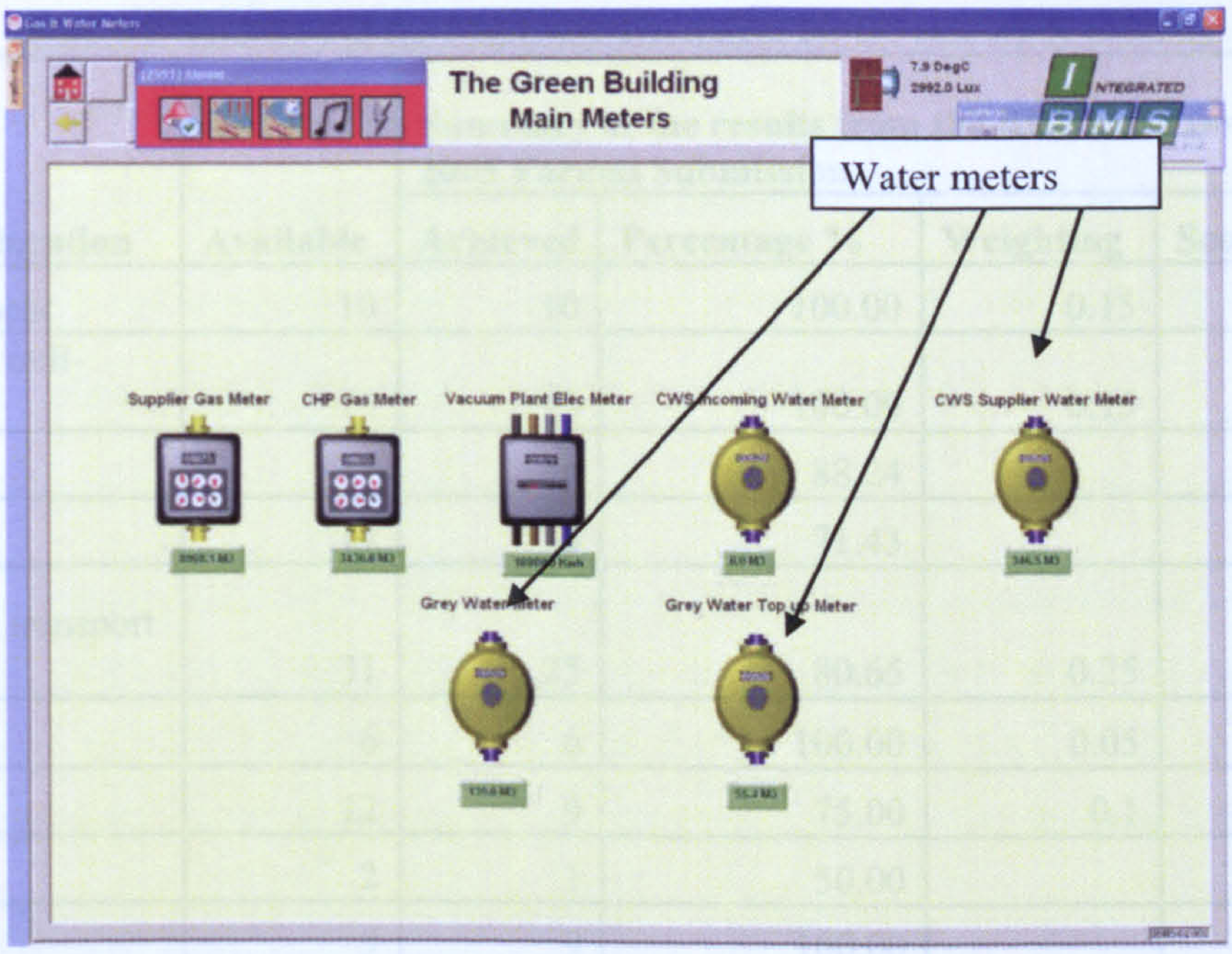

Figure 3-10: Water consumption logged on the BMS

3.3 BREEAM and an overview of the assessment

A BREEAM for Offices 2005 assessment[4] for Design & Procurement was carried out on the building at the design stage. The overall rating awarded was an 87.55% 'Excellent'. The BREEAM assessment is structured by category with details of the how and where credit can be awarded, the compliance of the building being assessed which is supported by reference to documentation provided by those having the assessment carried out.

The assessment is broken down into the following sections; Management, Health & well-being, Energy, Transport, Water, Materials, Land use, Ecology and Pollution. The credits are awarded for each section and then environmental weightings are applied to allow the overall percentage rating to be calculated. The weighting for each section provides an indication of the importance that category has on the environmental rating of an office building. The heaviest weighted category, and therefore the one most significantly impacting the rating, is Energy & Transport.

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[4] All with reference to the BREEAM for Offices 2005 Formal submission. October 2006

Table 3-2: Summary of the BREEAM assessment for the case study building

Credit allocation	Available	Summary of the results from the BREEAM for Offices 2005 Formal Submission			
		Achieved	Percentage %	Weighting	Score
Management	10	10	100.00	0.15	15.00
Health & well-being	15	15	100.00	0.15	15.00
Energy	17	15	88.24		
Transport	14	10	71.43		
Energy & transport sub-total	31	25	80.65	0.25	20.16
Water	6	6	100.00	0.05	5.00
Materials	12	9	75.00	0.1	7.50
Land use	2	1	50.00		
Ecology	9	9	100.00		
Land use & Ecology sub total	11	10	90.91	0.15	13.64
Pollution	12	9	75.00	0.15	11.25
TOTAL	139	119		1	87.55%
RATING					Excellent

3.4 Commissioning, hand-over and early occupancy

The building was handed over to Innovate Office Ltd in February 2007. Prior to handover an air pressure test was conducted.

3.4.1 Air pressure test

One of the most effective ways to reduce the energy losses from a building is to minimise air infiltration by ensuring a well-sealed building envelope. In 2006 air tightness testing (also known as air pressure test) became a compulsory requirement on all new buildings constructed in the UK under Part L of its England & Wales Building Regulations and the maximum allowable air permeability index must be less than, or equal to 10.0m^3/h/m^2. Air pressure tests became part of the methodology used in the PROBE 2 studies (Cohen, Standeven et al 2001.)

Air pressure testing is a specialised activity. A basic summary of how it is carried out is:

- Weather checks (conditions must be within a standard range)
- Select an opening in the building envelope and install a number of fans, with all other openings sealed/blocked off.

- A 50 Pascal pressure difference between the inside and outside of the building is created using the fans.
- Air must be able to pass freely through the building.
- Air flow measurements are taken and used to calculate the air leakage for the building.
- An airflow rate in $m^3/h/m^2$ at 50 Pascal is then calculated.
- Minimum allowable result must be less than, or equal to, $10m^3/h/m^2$ (Tomic 2005).

During the commissioning stage of the building an air tightness test was carried out according to CIBSE TM23:2000 and BS EN 13829:2001 when the air permeability index was measured to be $3.3m^3/h/m^2$ at 50Pa. The air permeability of the building was only 33% of its permitted maximum value and compared well against its predicted air permeability index of $5.0m^3/h/m^2$.

3.4.2 Build quality

As part of the research study, thermography was used to gain a visual indication of the quality of the build. A Fluke TiR1 Thermal Imager, with an accuracy of ± 2°C or 2% (at 25°C nominal, whichever is greater) and a resolution of 2.5 mRad was used. When carrying out thermal imaging on a building externally certain conditions are necessary to gain a good quality indication of the building. External weather conditions which permit thermal imaging are specified in British Standards.

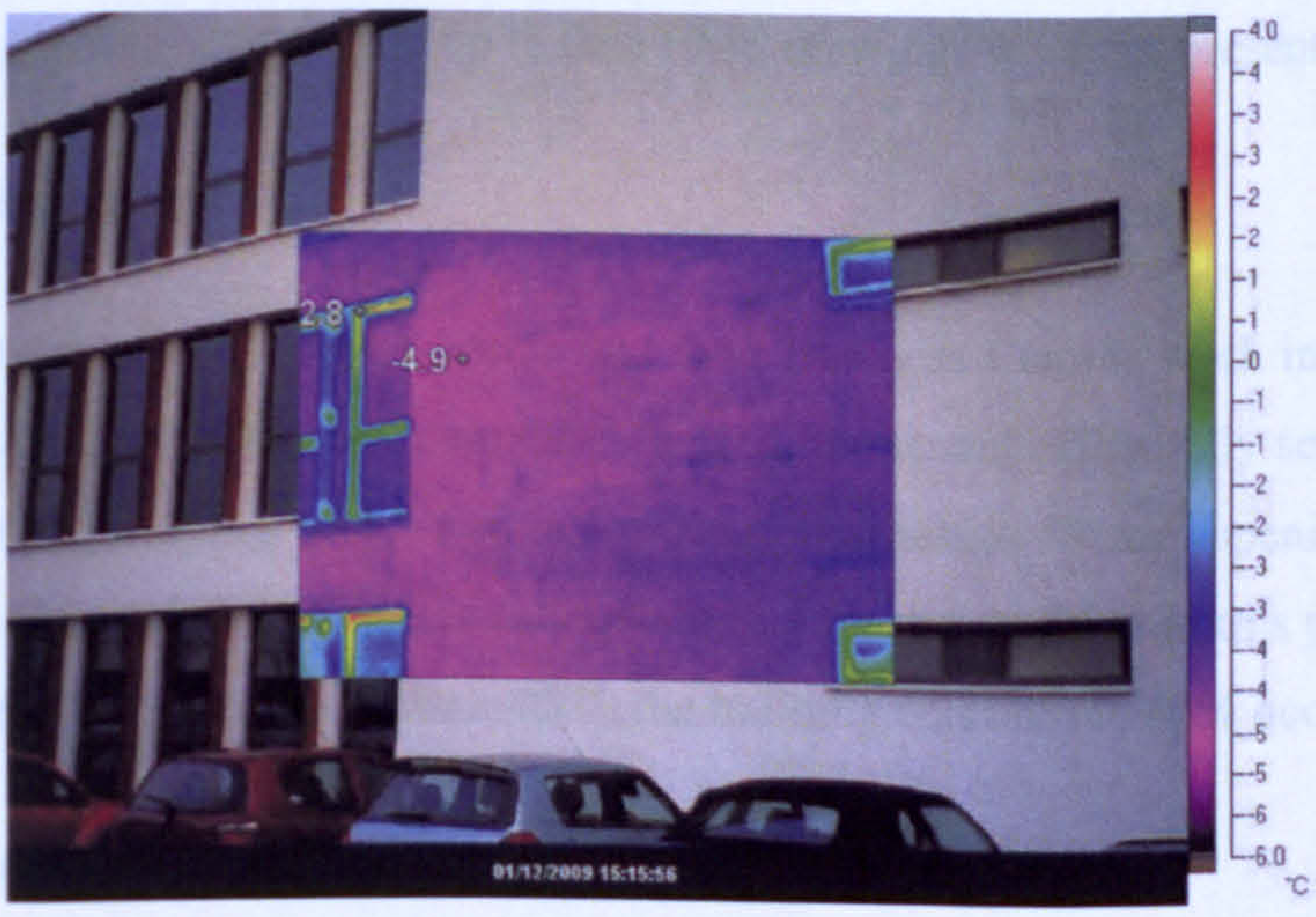


Figure 3-11: Thermal image of the building exterior

The structure is highly glazed which restricts where thermal imaging can take place. The external wall (shown in Figure 3-11) was tested on an overcast afternoon in December 2009. Thermal scans indicated that the quality of the buildings construction appeared to be consistent. Thermal imaging was carried out on the internal areas and showed a number of issues. Within the atrium there was a large gap around the door towards the north end of the building, providing a considerable path for heat loss. Internal thermography further showed that the exit doors also provided a poor level of resistance to heat loss. Leaks were also identified by the use of thermography as shown in Figure 3-12.

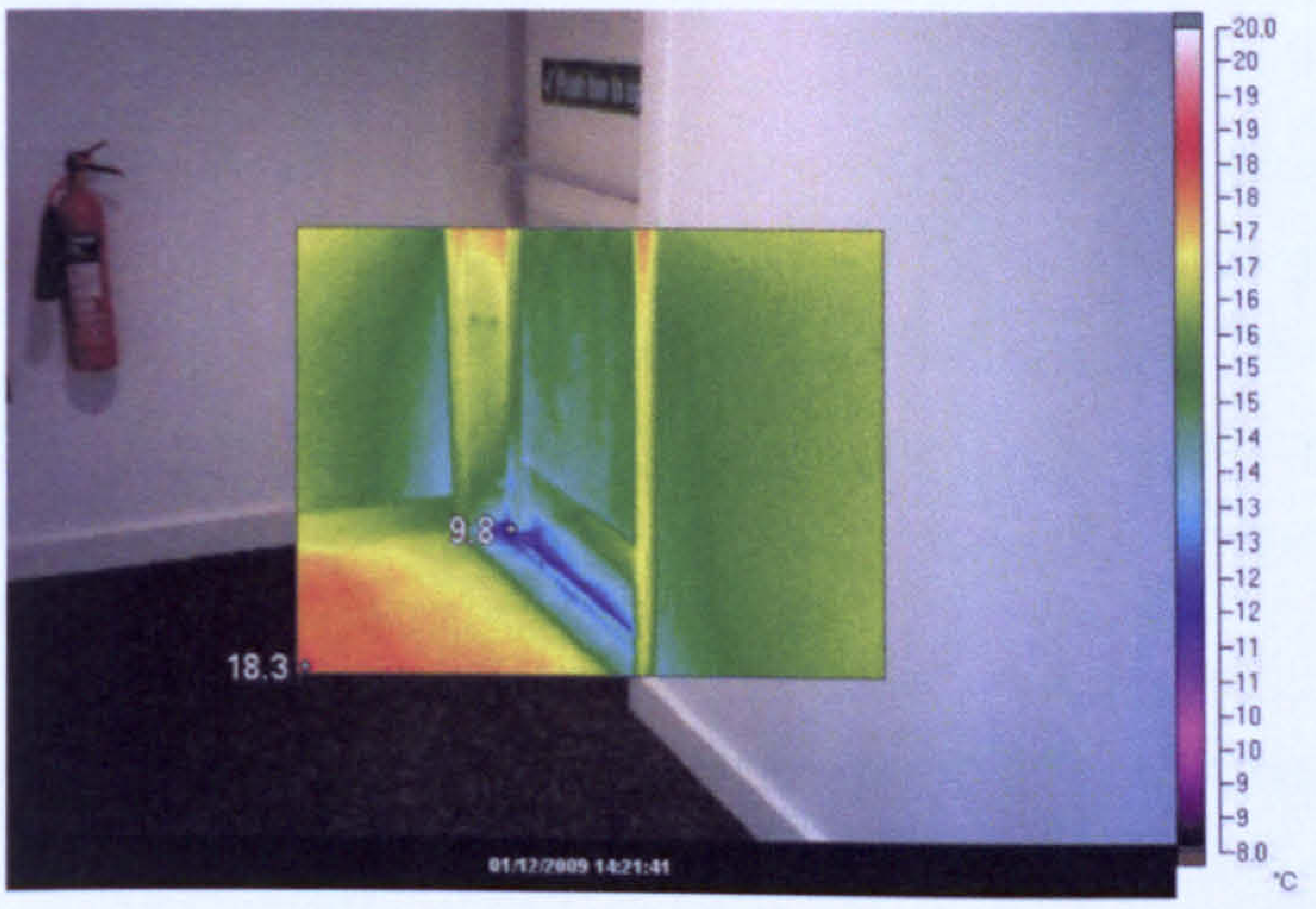


Figure 3-12: Thermal image- internal

3.4.3 Commissioning certificates, O&M files

On inspection of the commissioning certificates in the main office of the building, all certificates had been signed off. The O&M files were located in the main office and well documented, although some of the up to date BMS drawings were not present.

3.5 Occupancy

Due to the nature of the business sector that Icon Business Centres work in, the building isn't occupied by one large individual company. Instead, the tenant offers fully serviced office space to companies of varying size, usually smaller businesses. Since opening the uptake of occupancy has been slow and it was anticipated that for the duration of this project the building may not reach full occupancy. In June 2010 the building was around 60% occupied.

3.6 Operation of the building

The building officially opened in February 2007. At handover, some training was provided to the management team at the building. However from discussions with the office managers (as shown in chapter 8) it became evident that adequate training was not provided, with many of the systems installed not fully appreciated or understood by the managers at site. There had been a turnover of staff since opening and the training was not provided in each instance. Instead new members of the management team had to teach themselves how to control and change settings within the BMS. When asked about the information provided in the O&M (Operation & Maintenance) manuals they described them as "confusing and over complicated".

This could be considered as a typical outcome for buildings with complicated and multifunctional control systems and this study will later highlight the associated needs to help mitigate this.

Chapter Four - Methodology

4.1 Introduction

A research methodology was developed to meet the aims and objectives set out in Chapter One. Although this was developed specifically for the case study building, many of the approaches could be used in similar buildings subjected to monitoring activities. However it should be appreciated that difficulties exist when considering one standardised methodology for all buildings as there will inevitably be variations in size, technologies incorporated, building use, time scale for monitoring and costs associated.

The research is split into two distinct sections; simulated building performance and measured building performance determined from on-going monitoring of the operational building. These sections are broken down further to allow for the research objectives to be investigated.

As an initial overview, a process chart outlining the research strategy and the monitoring aspects are shown in Figure 4-1. Detail of how the monitoring was conducted, why a particular method was selected and previous work were similar approaches were utilised are given in the next section.

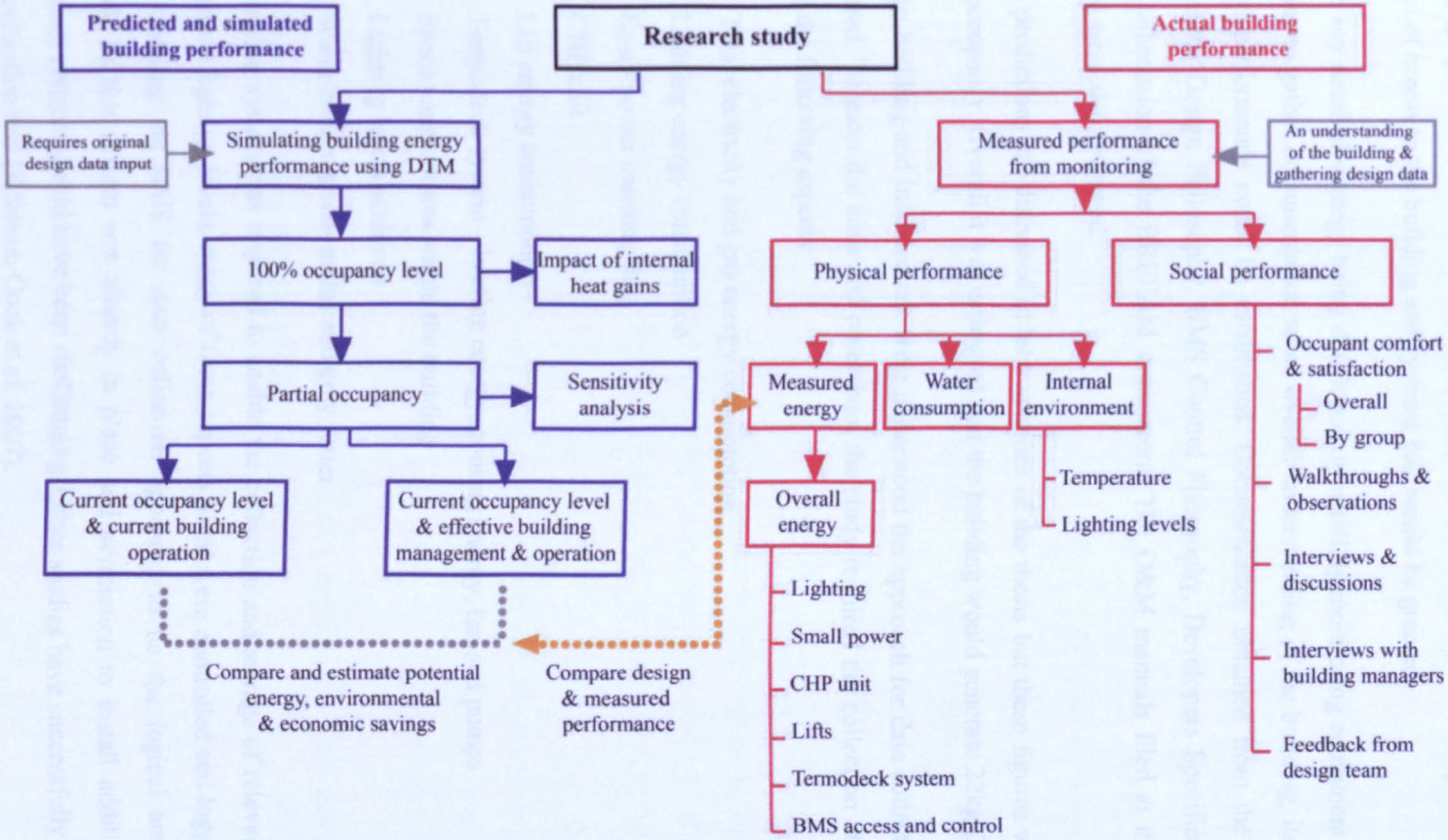


Figure 4-1: Organisational chart showing research strategy

4.2 Physical performance

The initial stage to this study was establishing good communication with the building managers and engaging in discussions about the planned research work. This was important to establish the level of access to the building and systems that would be granted.

Prior to any detailed strategy being developed or installing monitoring equipment an important stage was to gather documentation so an overall understanding of the building, its systems and intended performance could be established. Documentation obtained from the design team included the Design Philosophy, BMS Control Philosophy, Developers Specification and the formal submission of the BREEAM assessment. The O&M manuals filed at the case study building were also reviewed.

Design predictions are discussed in later sections of the thesis but these figures were based on 100% occupancy. Overall it was estimated that the building would generate 22kg/CO_2/ m^2/year.

Once the building and intended use were understood the approach for data collection had to be considered. To meet the aims and objectives, the study required the collection of performance data for the following aspects:

- Total electricity and gas energy consumption
- Lighting energy consumption
- Small power consumption
- CHP unit
- Lift energy consumption
- Termodeck system – heating energy, cooling energy, fan and pumps
- Space temperatures within the building
- Lighting levels achieved
- Water consumption- mains and grey water

A monitoring system was required to enable the collection and storage of relevant data. Other than internal lighting levels, many of these aspects listed were controlled and logged within the BMS. Utilising the BMS for data collection appeared to be the logical and appropriate approach, as this system was already in place and permission to install additional wireless monitoring systems would have been challenging. Other studies have successfully used BMS as a data collection tool (Krausse, Cook et al. 2007).

4.2.1 BMS and data acquisition

Adequate level of BMS access was required to obtain the data. Access for data collection purposes was granted but restrictions prevented any alterations to the settings or controls being made. To allow for detailed daily profiles to be investigated, logging intervals of 15 minutes were selected for all data reported. On initial inspection of the BMS many of the sensors were recording at 15 minute intervals but some of the energy meters were recording at 24 hour intervals.

It was also identified that although much of the data required was being logged by the BMS, this data was only saved for three days then overwritten by more recent data. As data could only be downloaded at site, logged data for the individual sensors and meter readings were difficult to download (there were over 100 sensors in the building recording temperature, volumes and meter readings).

Storing only a limited amount of data was impractical for trend analysis. Modification to the BMS was required if data collection was to continue in this way, otherwise alternative approaches such as wireless monitoring systems with integrated 'smart' metering would have had to been considered.

After consultation with the BMS Engineer all sensors and meters were set to log at 15 minute intervals and an additional 'store to file' facility was created within the system. By including this facility the logged data could be archived into a file on the BMS computer without the overwriting of data.

Visits were then made on a monthly basis to download the data file from the BMS onto an external hard-drive. Data processing and analysis could then take place at university.

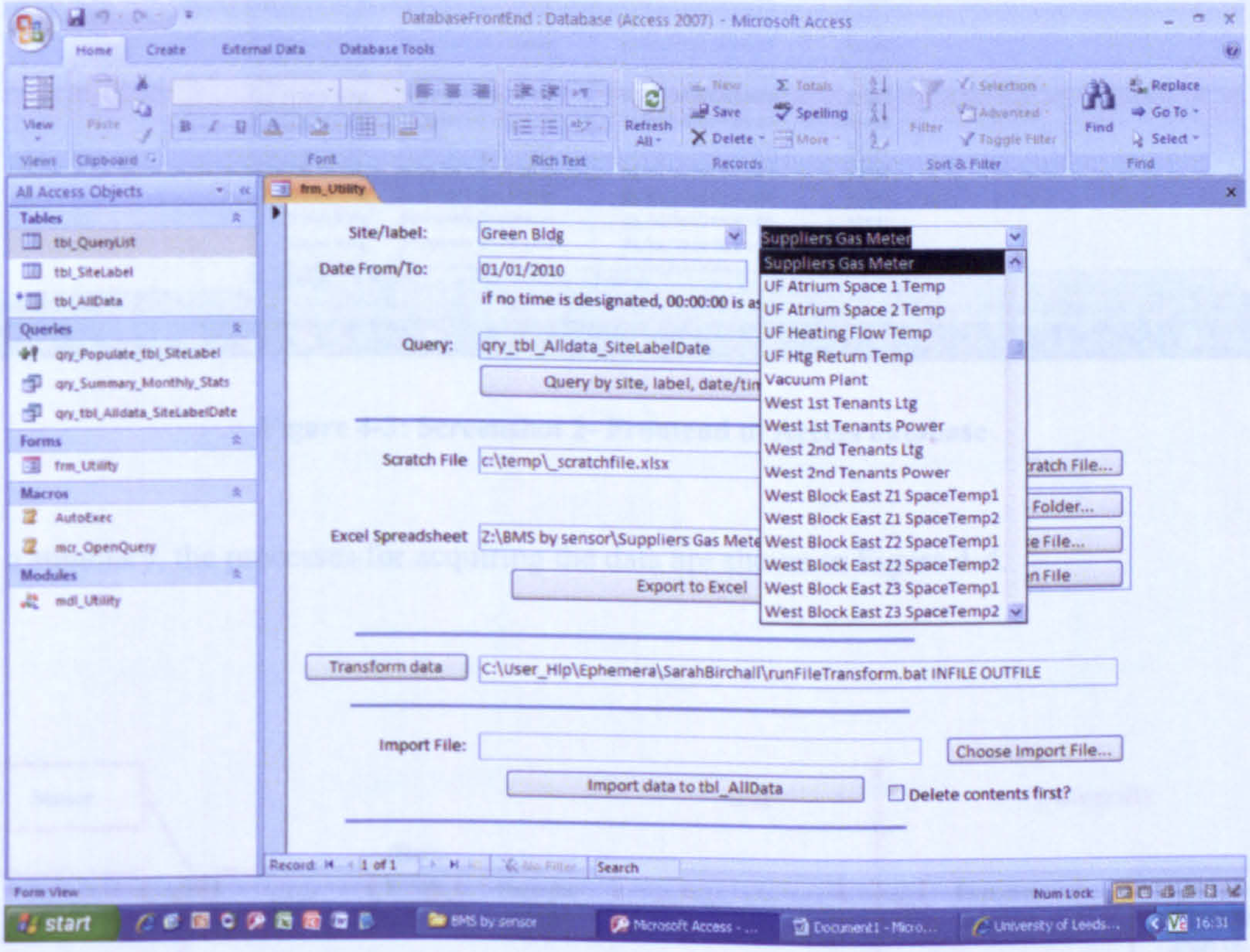
Data capture and management

The BMS proved to be a valuable data acquisition tool, capturing the data relating to energy, water and environments, both internally and externally.

This data was downloaded into a folder within the BMS computer and was available in the .xls (Excel) file format. Each 'store to file' download process generated the data as an accumulated list- adding onto the previous set of data. As work progressed, the download file size became too large to open within packages such as Excel or Notepad.

To manage the vast amounts of data, it became apparent that a database would be more appropriate. However, the data downloaded couldn't readily be exported into the selected database package (Microsoft Access). Some programming code (Java) solved this problem and the data could then be exported into a Microsoft Access database. Screenshots of the Access database are shown in the Figures 4-2 and 4-3.

The system was set up to allow for additional data to be imported on a monthly basis from the building and possibly from future buildings that utilise similar BMS systems. The site/label drop down menus on the frontend of the system allows the user to select the building site name and sensor label being investigated. Once the desired parameters (date and time range) are specified the user can run the query. There is an additional feature that allows the results from the queries to be automatically exported onto a new sheet in an existing excel file. This proved particularly useful for the month by month data collection.



Site/label: Green Bldg | Suppliers Gas Meter

Date From/To: 01/01/2010

if no time is designated, 00:00:00 is as

Query: qry_tbl_Alldata_SiteLabelDate

Scratch File c:\temp_scratchfile.xlsx

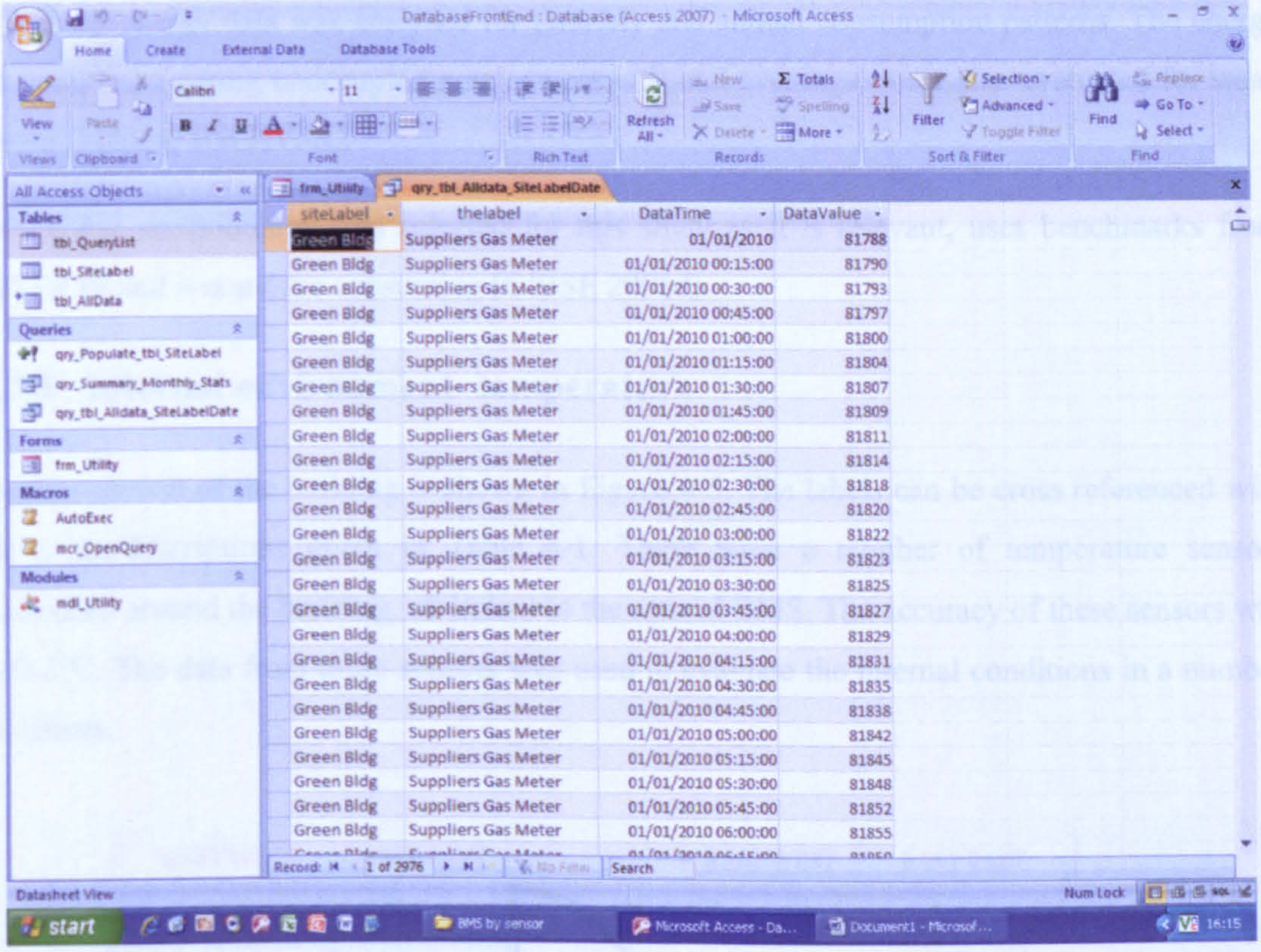
Excel Spreadsheet Z:\BMS by sensor\Suppliers Gas Mete

C:\User_Hlp\Ephemera\SarahBirchall\runFileTransform.bat INFILE OUTFILE

Import File:

☐ Delete contents first?

Figure 4-2: Screenshot 1- Frontend Access database



siteLabel	thelabel	DataTime	DataValue
Green Bldg	Suppliers Gas Meter	01/01/2010	81788
Green Bldg	Suppliers Gas Meter	01/01/2010 00:15:00	81790
Green Bldg	Suppliers Gas Meter	01/01/2010 00:30:00	81793
Green Bldg	Suppliers Gas Meter	01/01/2010 00:45:00	81797
Green Bldg	Suppliers Gas Meter	01/01/2010 01:00:00	81800
Green Bldg	Suppliers Gas Meter	01/01/2010 01:15:00	81804
Green Bldg	Suppliers Gas Meter	01/01/2010 01:30:00	81807
Green Bldg	Suppliers Gas Meter	01/01/2010 01:45:00	81809
Green Bldg	Suppliers Gas Meter	01/01/2010 02:00:00	81811
Green Bldg	Suppliers Gas Meter	01/01/2010 02:15:00	81814
Green Bldg	Suppliers Gas Meter	01/01/2010 02:30:00	81818
Green Bldg	Suppliers Gas Meter	01/01/2010 02:45:00	81820
Green Bldg	Suppliers Gas Meter	01/01/2010 03:00:00	81822
Green Bldg	Suppliers Gas Meter	01/01/2010 03:15:00	81823
Green Bldg	Suppliers Gas Meter	01/01/2010 03:30:00	81825
Green Bldg	Suppliers Gas Meter	01/01/2010 03:45:00	81827
Green Bldg	Suppliers Gas Meter	01/01/2010 04:00:00	81829
Green Bldg	Suppliers Gas Meter	01/01/2010 04:15:00	81831
Green Bldg	Suppliers Gas Meter	01/01/2010 04:30:00	81835
Green Bldg	Suppliers Gas Meter	01/01/2010 04:45:00	81838
Green Bldg	Suppliers Gas Meter	01/01/2010 05:00:00	81842
Green Bldg	Suppliers Gas Meter	01/01/2010 05:15:00	81845
Green Bldg	Suppliers Gas Meter	01/01/2010 05:30:00	81848
Green Bldg	Suppliers Gas Meter	01/01/2010 05:45:00	81852
Green Bldg	Suppliers Gas Meter	01/01/2010 06:00:00	81855

Figure 4-3: Screenshot 2- Frontend of Access database

As a summary, the processes for acquiring the data are shown in Figure 4-4.

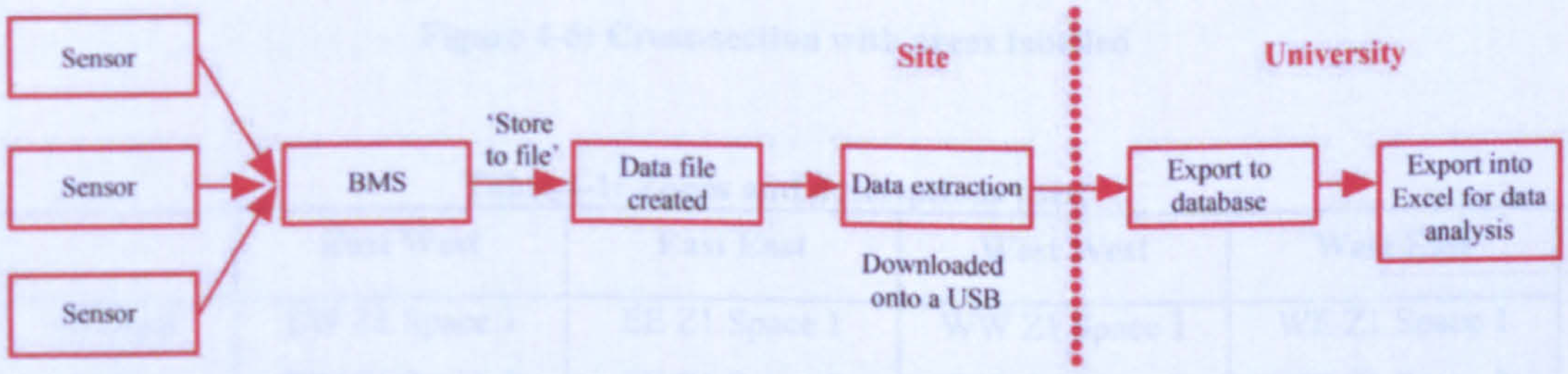


Figure 4-4: BMS data extraction through to analysis stage

4.2.2 Energy

The energy and water consumptions were determined from BMS data analysis. Monthly meter readings were manually recorded during site visits. This checked if the overall incoming electricity and gas readings from the BMS were accurately logging.

The BMS energy data was analysed for monthly and annual consumption patterns. The energy consumptions during unoccupied hours (weekends and evenings) were also evaluated for small power, lighting and HVAC.

The TM22 methodology was selected for this study as it is relevant, uses benchmarks from ECON 19 and it non-time consuming (CIBSE 2006d).

4.2.3 Internal environment- temperature

A cross section of the building is shown in Figure 4-5. The labels can be cross referenced with the zones/descriptions given in Table 4-1. There were a number of temperature sensors positioned around the building, all linked to the central BMS. The accuracy of these sensors was +/-0.2°C. The data from these sensors was used to evaluate the internal conditions in a number of offices.

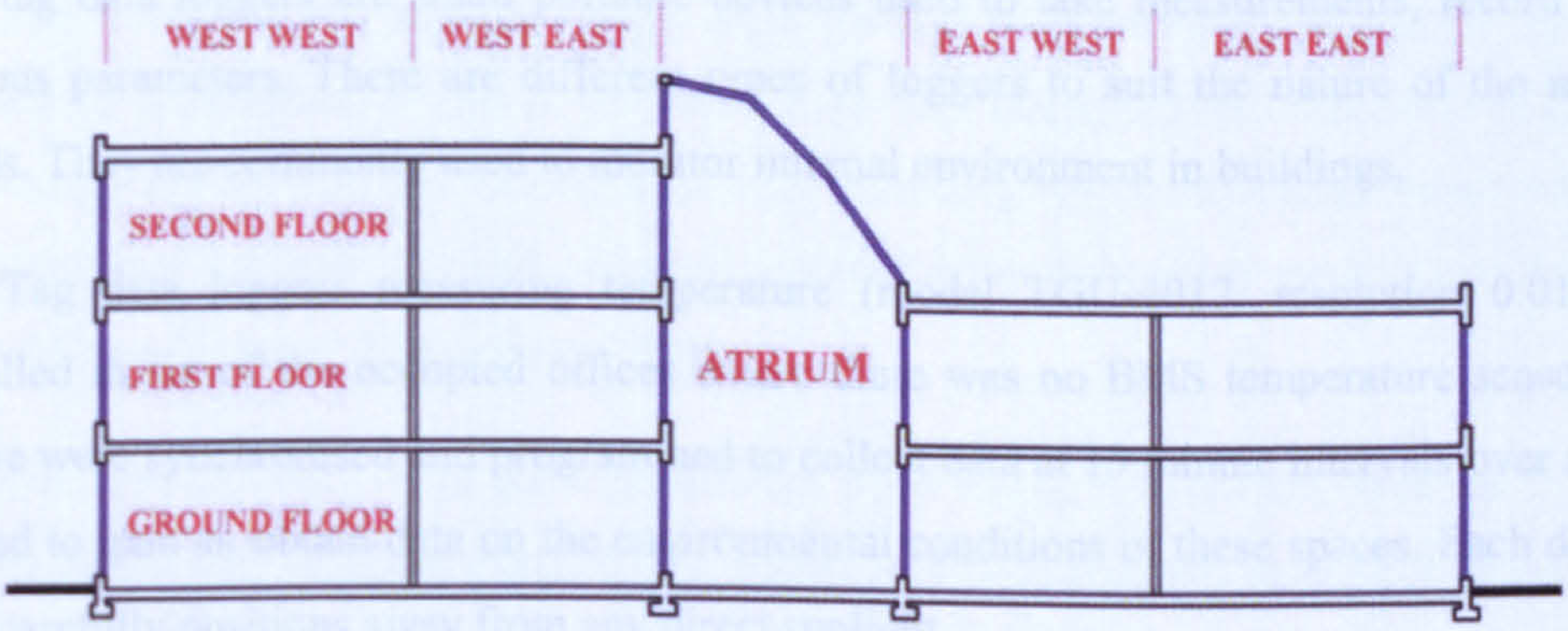


Figure 4-5: Cross-section with areas labelled

Table 4-1: Zones and descriptions used

	East West	**East East**	**West West**	**West East**
Ground Floor	EW Z1 Space 1 EW Z1 Space 2	EE Z1 Space 1 EE Z1 Space 2	WW Z1 Space 1 WW Z1 Space 2	WE Z1 Space 1 WE Z1 Space 2
First Floor	EW Z2 Space 1 EW Z2 Space 2	EE Z2 Space 1 EE Z2 Space 2	WW Z2 Space 1 WW Z2 Space 2	WE Z2 Space 1 WE Z2 Space 2
Second Floor			WW Z3 Space 1 WW Z3 Space 2	WE Z3 Space 1 WE Z3 Space 2

Each zone has two BMS sensors located within it (i.e. Space 1 sensor and Space 2 sensor). These sensors are only positioned in two offices per zone in the building. Figure 4-6 shows the typical positions of the BMS temperature sensors.

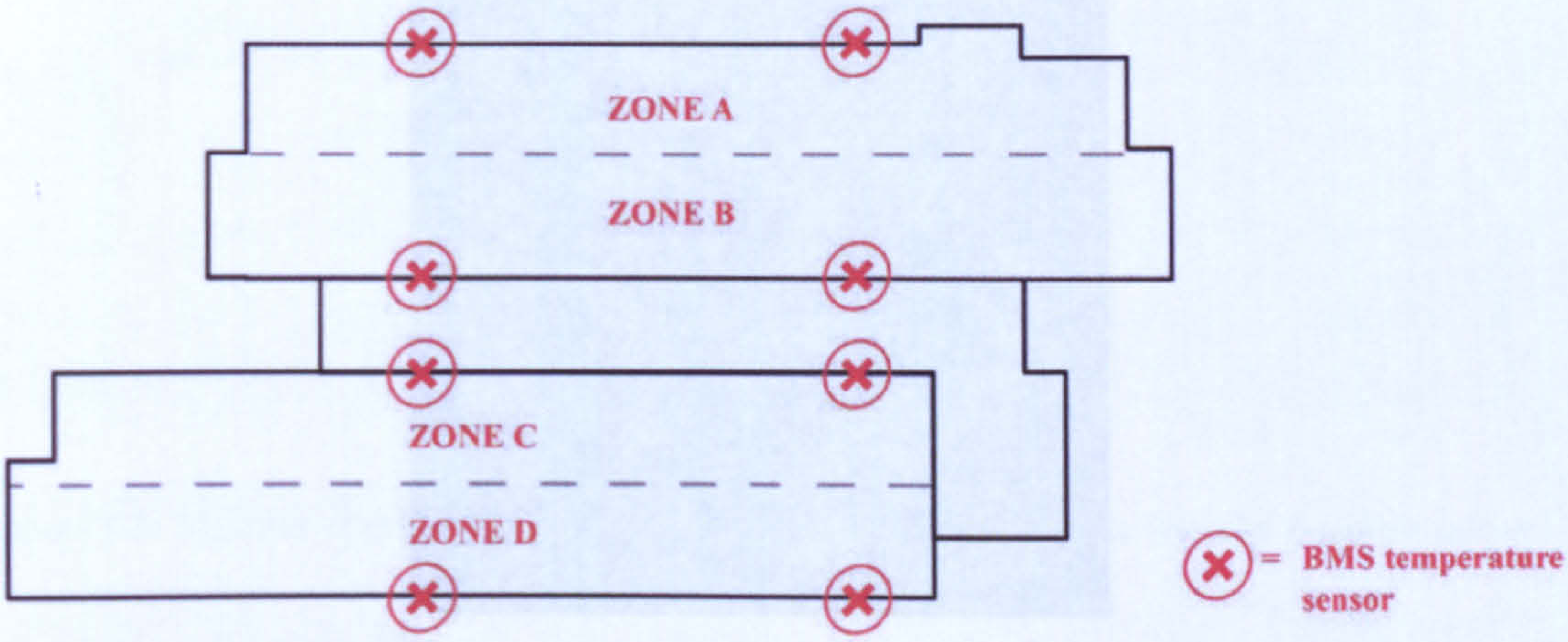


Figure 4-6: The typical locations of BMS temperature sensors

Tinytag data loggers are small portable devices used to take measurements, record and store various parameters. There are different types of loggers to suit the nature of the monitoring needs. They are commonly used to monitor internal environment in buildings.

TinyTag data loggers measuring temperature (model TGU-4017, resolution 0.01°C) were installed in six of the occupied offices where there was no BMS temperature sensor located. These were synchronised and programmed to collect data at 15 minute intervals over a one year period to gain an obtain data on the environmental conditions of these spaces. Each data logger was carefully positions away from any direct sunlight.

Tinytag data loggers and accuracy

With an accuracy of measuring temperature to 0.01°C or better[5] the Tinytag data loggers were also used to test the accuracy of the BMS sensors. Figure 4-7 shows the Tinytag attached to the BMS sensors. The temperatures were measured over a one week period on four different BMS temperature sensors around the building. The temperatures recorded were within 4.3% of each other. Therefore as this was within 5%, the BMS sensors were assumed to be accurate.

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[5] Specification data found at http://www.geminidataloggers.com/

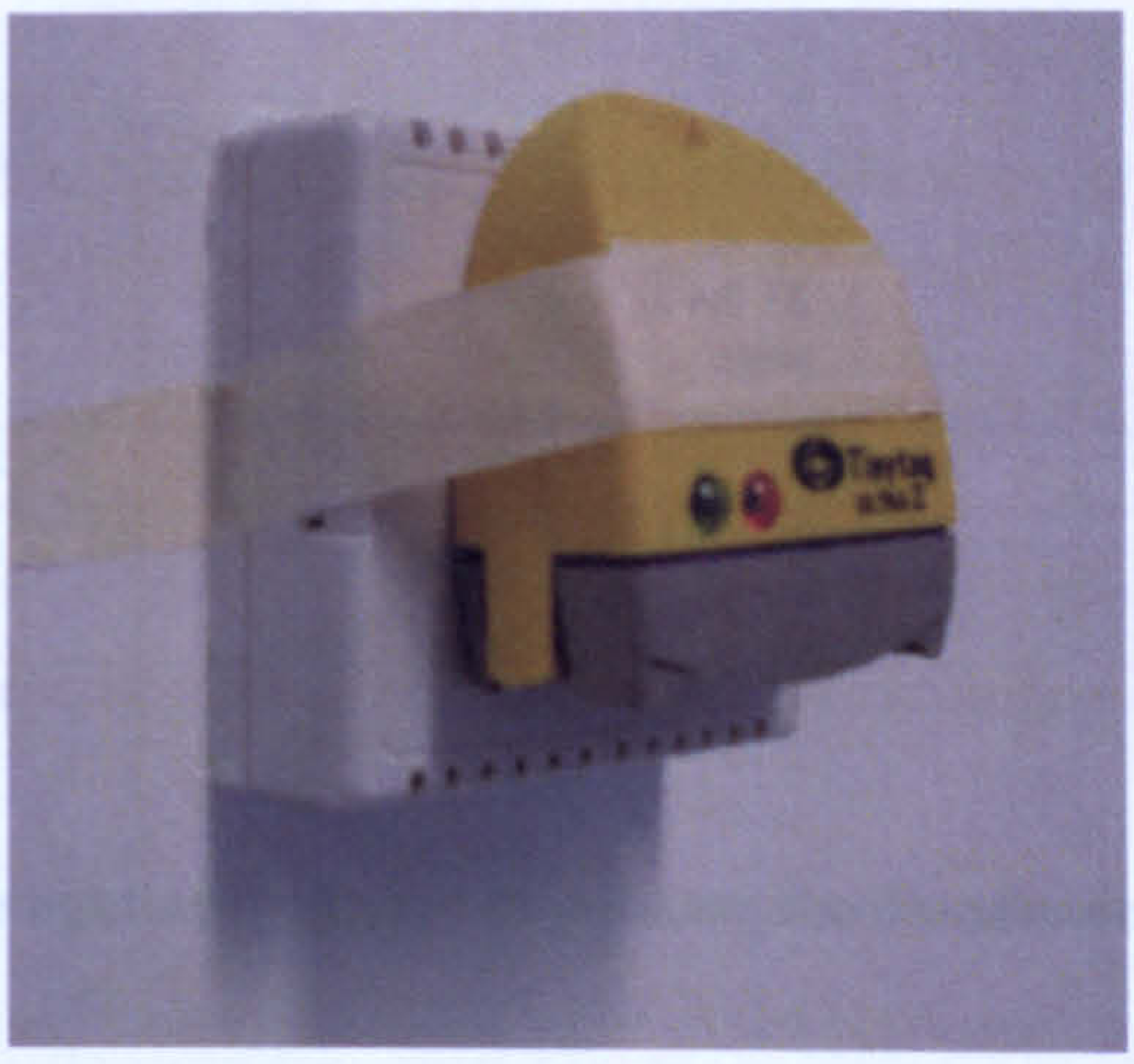


Figure 4-7: Calibrating BMS sensor and Tinytag data loggers

4.2.4 Lighting levels

Lighting levels and the daylight factors in the offices were measured as part of the proposed monitoring programme. A similar procedure to the one suggested by Littlefair (1993) was used to measure daylight factors. Consideration for obtaining the simultaneous indoor and outdoor measurements was given as this has been reported as an error often experienced during these types of measurements (Fontoynont 1999).

As often reported there were some difficulties when trying to accurately measure the daylight factors as the CIE standard overcast sky condition was impossible to control. Obtaining days that had suitable sky conditions were often difficult due to the unpredictable and ever changing sky conditions. The daylight factors presented in the study were measured under as reasonable a CIE standard overcast sky conditions as was practically possible.

The open plan layout of the office spaces on the upper floors of both wings allowed for open plan daylight studies to take place to investigate this aspect of building performance.

The modular arrangement of the windows on the east and west elevations allowed for a grid of 1.5m by 2m to be used for the lighting investigations, with a 0.5m perimeter boundary.

Figure 4-8 shows the layout of the lighting grid used for measuring the illuminance and daylight factors in the two areas of the building detailed.

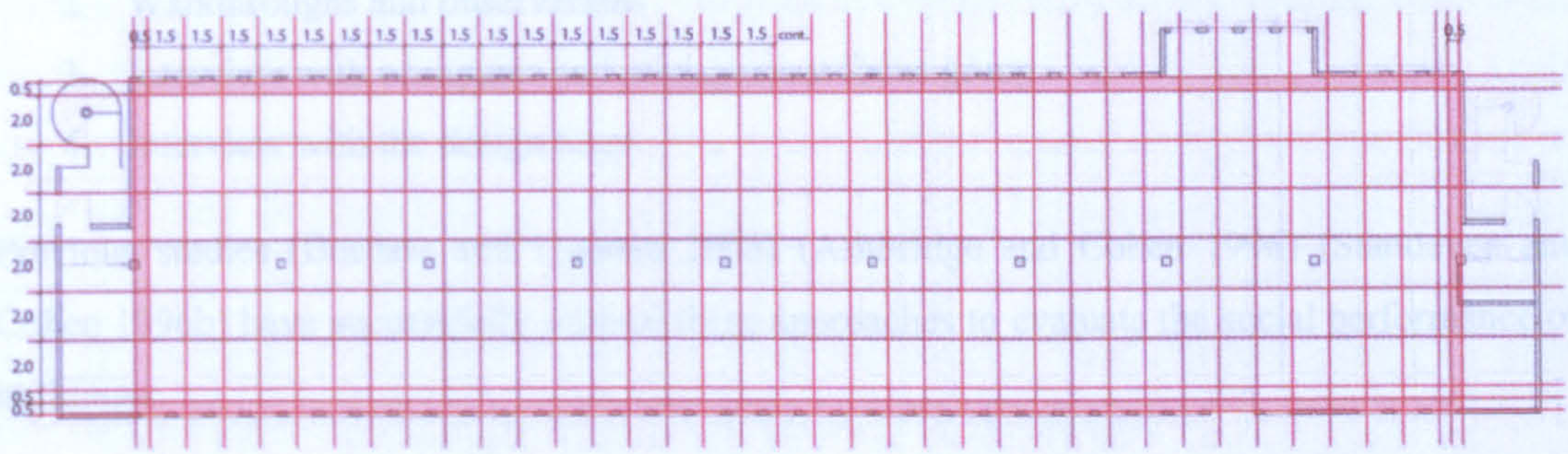


Figure 4-8: Example of the lighting grid used to measure the illuminance levels in the office spaces

The lighting measurements were conducted using two Testo 545 digital lux meters (accuracy: ±1lux for internal measurements and ±10 lux for external measurements, resolution: for 1 lux setting: 0 to 32,000, for 10 lux setting: 0 to 100,000 lux). One of the calibrated Testo light-meters was mounted on a tri-pod adjusted to a desk height of 0.85m and the illuminances at the grid points in the room were measured. All blinds were fully raised prior to the tests. To achieve a daylight factor measurement it was necessary to obtain the simultaneous outdoor illuminance and this was carried out using a second similar calibrated Testo light-meter which was set to automatically record the outdoor illuminance at 15 second intervals.

The set-time within the outdoor light meter was synchronised to the indoor light meter. The artificial lighting was disabled during the measurements however the emergency lighting in the corridor areas remained on due to health and safety reasons. The ratio of the indoor to outdoor illuminance was calculated to give the resulting daylight factors.

Similar to Cohen, Standeven et al. (2001) spot measurements for lighting levels were carried out using the same apparatus previously described to provide snapshots of the lighting levels achieved in the building. In these tests, the same desk height (0.85m) was used and time was allowed for the equipment to stabilise prior to measurements being made. The lighting system was operating as commissioned during these tests.

4.3 Social performance

The perceived levels of comfort have an impact on the productivity levels in an office (Leaman 1995). Regardless of whether a building is energy efficient or not, to be sustainable the occupants must be comfortable and be able to work productively.

In the literature review presented in Chapter 2, a number of POE approaches and methodology tools are presented. To evaluate the social performance of the building the following methods were selected.

1. Occupant survey

2. Walkthroughs and observations
3. Interview with occupants and management focus group
4. Interview with the design team

Previous studies (Bordass and Leaman 2005) (Ashbridge and Cohen 1996) (Standeven and Cohen 1996b) have successfully utilised these approaches to evaluate the social performance of buildings.

4.3.1 Occupant survey

A survey is a common approach utilised to obtain quick amounts of feedback. A decision had to be made early on in this part of the project whether to create a new survey as a means for obtaining feedback from the occupants within the buildings or to utilise an existing one. There are benefits of both approaches and these were outlined in the literature review.

To allow for the results of the survey to be compared to other buildings, the Building Use Studies (BUS) methodology was used (Building Use Studies 2009) with some additional tailored questions to gain occupant feedback about the specific building. The BUS methodology is commonly used by the industry due to the database and hence the benchmarks. Other attractive aspects are that it is quick, easy to use and tried and tested. In 2007 over 300 buildings had been assessed using the BUS methodology. The results can be added to the existing data set where comparisons can be made. The survey also included a section for travel to work. Although some analysis of this data was conducted the results were highly subjective. As a result the 'travel to work' aspect of survey was considered to be outside the scope of the study and therefore is not discussed in this report.

Survey procedure

Using the Building Use Studies (BUS) methodology the building was surveyed on 16th June 2009. The 3-page questionnaire included questions relating to temperature and air quality comfort levels, noise and lighting satisfaction levels. Prior to the survey a member of the Centre's Management team sent out an email to all the occupants to inform them about the survey and encouraged them to fill it in. On the day of the survey all the occupants present were handed a self-completion questionnaire in the morning and the responses were collected in the afternoon. A second collection was carried out the next day for those who hadn't had chance to complete the survey on the first day.

Icon Business Centres have another office building in Nottingham; this has no green credentials but is of similar size. As a means of obtaining comparable data for two buildings owned by the same company who provide the same professional services, another survey was planned for the Nottingham office. This was again planned in the same 'hand-out collect-in on the same day' manner, however after discussions with (and some resistance from) the management team at the Nottingham Office it was decided that the internet version would be more suitable. Again occupants were all sent an email prior to the survey, and the internet survey link was sent out on June 23rd 2009 for immediate completion. Only 3 out of the 150 occupants responded. Another email was sent out to prompt and encourage the occupants to fill in the survey but the response rate did not improve. This reflects the effectiveness of both the 'hand-out collect-in on the same day' and the internet based approaches to conducting effective surveys.

Unfortunately as a result of the low response rate for the second survey a comparison between the Leeds office and the Nottingham Office could not be made, thus eliminating any potential results relating to the occupant satisfaction levels for offices that are classed as 'green' and conventional offices.

4.3.2 Walkthroughs and observations

Regular walkthroughs and observations were made during site visits. Photographic evidence and notes were recorded on numerous occasions reporting any behaviour that may impact on the building performance or building environment.

4.3.3 Interview with occupants and management focus group

A combination of structured and open discussion interviews took place with some of the occupants and the management team. This enabled problems to be identified and revealed further findings beyond those asked in the survey. These were organised meeting scheduled to last approximately 30 minutes per interview. A summary of the comments made by occupants during the interviews are shown in Appendix D.

4.3.4 Interview with the design team

A questionnaire was created and circulated to all members of the design team to gain feedback about the design process. This was intended to identify if there were any design or client led limitations on the building design that may have impacted on its environmental performance. A summary of the feedback and comments made by the design team are shown in Appendix E.

4.4 Methodology- simulating performance

The simulation results during design were based on 100% occupancy; hence it would be unfair to compare the measured performance to these design figures. Consequently, the DTM tool IES<VE> was required to simulate performance at the current occupancy level and compare the results generated to those measured. The work required to update the original model to enable these comparisons are discussed in Chapter 6.

The detailed methodology for the simulation aspects of the study fits better in the specific chapters however it is briefly described here to give an overview of the work conducted.

Seldom has research reported on the impacts that lower occupancy levels have on building performance. To evaluate the contribution the internal heat gains from people make towards offsetting the heating demand and the overall affect this has on building energy, a test was developed using an 'as built' model. This model was re-simulated with the internal heat gains removed individually in the first instance and then removed collectively. All thermal loads and settings remained the unchanged throughout.

All simulations tests utilised the same benchmark model and weather file. The annual energy consumptions results for heating, cooling, fans pumps and controls, system energy, lighting and equipment were extracted from the model for analysis.

When investigating partial occupancy, the annual energy consumptions were simulated at increments of 10% for occupancy levels. A sequence was defined for the uptake of occupancy and this is described in Chapter 6. Other sequences were looked at to assist analysis and validation but not directly reported on in this thesis. A thermal template representing an unoccupied office was appropriately assigned and the simulations were conducted sequentially. Only occupancy conditions (i.e. internal heat gains from people, lighting and equipment) for office rooms were modified. Hence, the HVAC systems in the unoccupied areas were left unchanged. Again using the benchmark model, sensitivity analysis was conducted to validate the results generated for these investigations. A detailed methodology for this is given in the Chapter 7.

Similar to the previous paragraph the model was updated for 24/7 operation. Similar methods were applied to generate and analyse the annual energy results.

To test the building energy performance with more effective management the model's control settings were adjusted for each occupancy level to account for the unoccupied spaces. In these spaces the controls were set to operate on set-back control (essentially for building fabric protection).

The measured data was compared to simulated figures and published benchmark data to provide conclusions about the performance of the building.

The simulated results for various settings and management strategies were then compared to evaluate the potential improvements that could be made. The energy results were translated into CO_2 emissions and monetary figures to present the savings in both environmental and economic terms.

Chapter Five - Physical performance

5.1 Introduction

Chapter Five evaluates the building's physical performance at post-occupancy stage and is presented in three principle sections:

- Measured energy
- Water
- Internal environment

The measured energy and water consumptions are compared to the design performance, external data sources and relevant benchmarks. The internal environment including temperature and light levels are investigated to assess the levels of comfort provided. The chapter ends with a comparison of BREEAM rating awarded at design stage to measured data. The overall annual CO_2 emissions generated from the operational building are estimated.

5.2 Measured energy

Total energy uses of the building were determined from the gas and electricity meters located within the plant room. Readings were taken on a regular basis throughout the monitoring period and the results are shown in Figure 5-1.

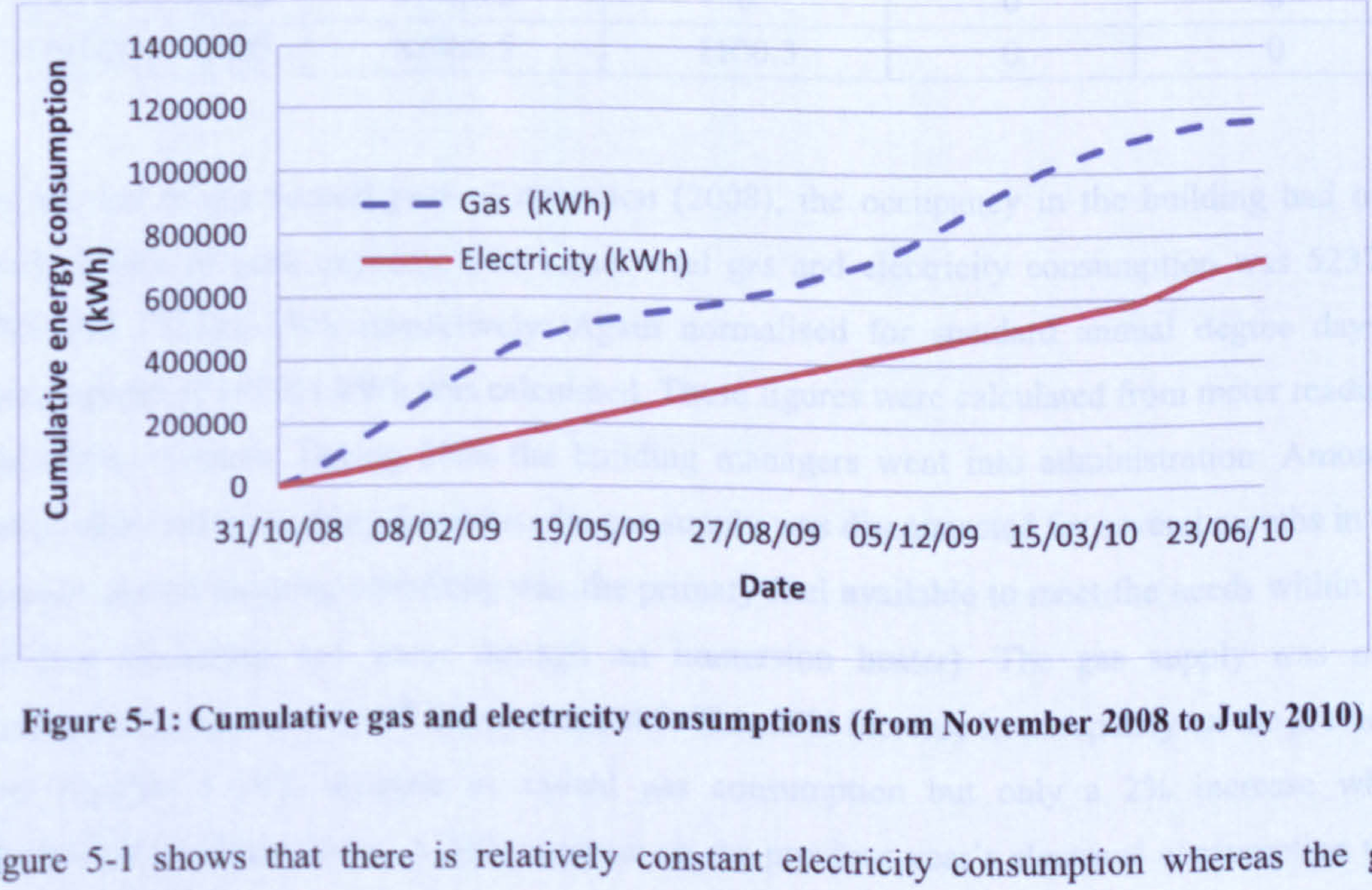


Figure 5-1: Cumulative gas and electricity consumptions (from November 2008 to July 2010)

Figure 5-1 shows that there is relatively constant electricity consumption whereas the gas consumption is more seasonal. The electricity is supplied from the grid.

Annual energy and occupancy

The building was handed over to the client in February 2007 when it became operational. Occupancy uptake was slow and by the end of this first year of opening it had only reached around 10% of full occupancy. Limited meter read data was available for this year and therefore details from utility invoices were used. Unfortunately much of this data was estimated, particularly for gas consumption. The total gas and electricity consumption from February 2007 to January 2008 was 439594 kWh (based on 38688m^3 gas consumption) and 219025 kWh respectively. When normalised for standard degree days the gas consumption was 540550 kWh.

Early interrogation of the BMS revealed issues with data logging, with many meters not connected back to the BMS despite commissioning certificates indicating otherwise. Other meters were recording in an unreliable manner. Examples of both issues are shown in Table 5-1.

Table 5-1: Sample of daily meter readings taken from the BMS

Date and time	Main incoming electricity meter		Suppliers Gas Meter	
	Meter reading (kWh)	Daily electricity usage (kWh)	Meter reading (m^3)	Daily gas usage (m^3)
21/07/2007 00:00	78485.3	0	0	0
22/07/2007 00:00	79585.6	1100.3	0	0
23/07/2007 00:00	79585.6	0	0	0
24/07/2007 00:00	79585.6	0	0	0
25/07/2007 00:00	80685.9	1100.3	0	0
26/07/2007 00:00	80685.9	0	0	0
27/07/2007 00:00	80685.9	0	0	0
28/07/2007 00:00	81786.2	1100.3	0	0
29/07/2007 00:00	81786.2	0	0	0
30/07/2007 00:00	81786.2	0	0	0
31/07/2007 00:00	82886.5	1100.3	0	0

By the end of the second year of operation (2008), the occupancy in the building had only reached 30% of peak capacity. The actual total gas and electricity consumption was 523776 kWh and 271121 kWh respectively. Again normalised for standard annual degree days a consumption of 553911 kWh was calculated. These figures were calculated from meter readings and utility invoices. During 2008 the building managers went into administration. Amongst many other issues resulting from this, the gas supply was disconnected for several months in the summer period meaning electricity was the primary fuel available to meet the needs within the building (including hot water through an immersion heater). The gas supply was only reconnected again on the 22nd September 2008. This 20% increase in occupancy on the previous year brought a 19% increase in annual gas consumption but only a 2% increase when normalised for degree days. A 24% increase on the previous year's electrical consumption was also determined.

By the end of the third year (2009) occupancy had peaked at around 50%. The measured total gas and electricity consumption was 723989 kWh and 407800 kWh respectively. Corrected for the standard 2463 degree days (Vesma 2011), this approximated to an annual gas consumption of a 749862 kWh. This was again a 20% increase in occupancy compared to the previous year yet brought a 38% increase in annual gas consumption (or 35% when normalised for standard degree days) and approximately a 50% increase in electricity consumption. This significant increase, in both fuel consumptions, compared to the previous year (occupancy increase of 20%) was potentially due to changes to the BMS settings made by management staff at the building.

Now into the fourth year (2010) of operation the building occupancy has reached approximately 60%.

The measured electricity, gas and normalised gas (Vesma 2011) consumptions for 2007, 2008 and 2009 are shown with the design consumptions in Figure 5-2. The annual heating degree days for the West Pennine area for 2007, 2008 and 2009 were 2033, 2329 and 2378 respectively. Note the design energy consumptions did not include the consumptions for small power.

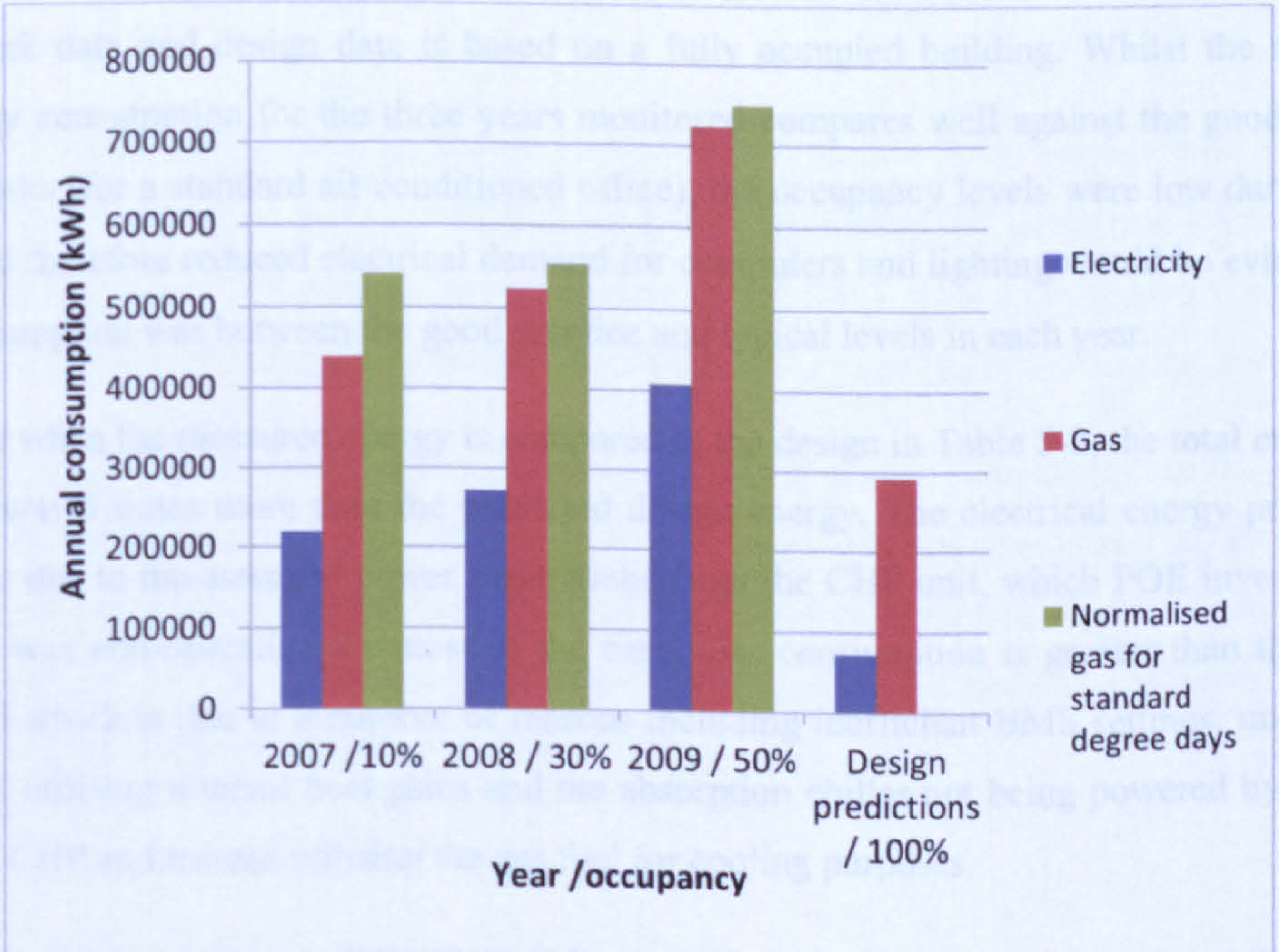


Figure 5-2: Electricity and gas consumption for 2007, 2008 and 2009

Although the results show an increase both in electricity and gas consumptions with increased occupancy, this trend shouldn't be taken as absolute as other factors affecting this should be taken into consideration and will be discussed in the BMS section below. The total measured annual electricity and gas consumptions can be compared with good practice and typical consumption benchmarks (Best Practice Programme 2003) in Table 5-2.

Table 5-2: Comparing overall annual consumption with benchmark data

	2007 / 10% occupancy	2008 / 30% occupancy	2009 / 50% occupancy	Benchmark good practice 100% occupancy	Benchmark typical 100% occupancy	Design predictions / 100%
Annual electricity (kWh/m^2)	51	63	94	128	226	20
Annual gas (kWh/m^2)	102	121	167			65
Normalised annual gas for standard degree days (kWh/m^2)	125	128	173	97	178	
Total annual energy (kWh/m^2)	176	191	267	225	404	85

The measured results were all taken at low occupancy levels (10%, 30% and 50%), whereas the benchmark data and design data is based on a fully occupied building. Whilst the measured electricity consumption for the three years monitored compares well against the good practice benchmarks (for a standard air conditioned office), the occupancy levels were low during these years and therefore reduced electrical demand for computers and lighting would be evident. The gas consumption was between the good practice and typical levels in each year.

However when the measured energy is compared to the design in Table 5-2, the total energy use in 2009 was 3 times more than the predicted design energy. The electrical energy predictions were low due to the assumed power generations from the CHP unit, which POE investigations revealed was non-operative for most of the time. Gas consumption is greater than the design predicted which is due to a number of reasons including inefficient BMS settings, unoccupied areas not utilising internal heat gains and the absorption chiller not being powered by the heat from the CHP and instead utilising the gas fuel for cooling purposes.

Design predictions anticipated that the building would perform well above good practice but the measured consumptions show that even at 50% occupancy it fell below good practice.

The total energy has been compared to previous years and benchmark figures but further analysis is required to investigate the individual energy uses in more detail to identify any inefficient performance. The BMS system is used as a tool in investigating why the energy predictions were not met. The following sections will analyse the performance of the HVAC (Termodeck system), small power, lighting, lift energy and vacuum plant using BMS data.

5.2.1 Building Management System (BMS) and control

The building is fully automated and controlled by a BMS. Built-in logic algorithms assess the building environment and adjustments are made in response to the sensor feedback to create a comfortable and safe working place for the occupants. Monthly electricity data extracted from the BMS between July 2008 and April 2010 are shown in Figure 5-3.

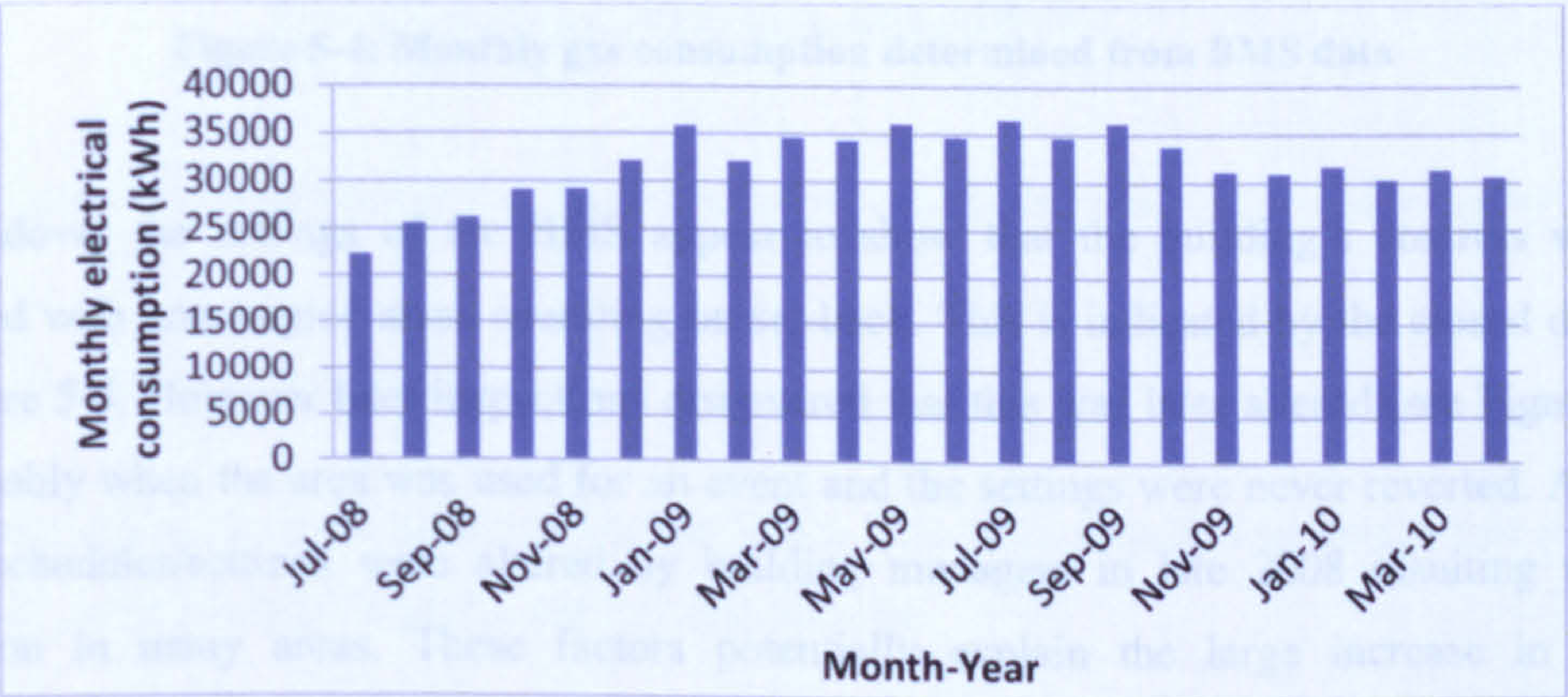


Figure 5-3: Monthly electrical consumption

Figure 5-3 shows an increase in electrical consumption in late 2008. At this time alterations were made to the settings on the BMS following Innovate Office Ltd going into administration. The overall electrical consumption was constant during 2009, with a decrease towards end of that year. Further detailed analysis of individual end uses is required to investigate this further.

The BMS was not fully commissioned and this resulted in a zero pulse output for the gas meter for most of the monitoring period. In late 2009 it was eventually connected up to the BMS and monthly gas consumptions determined from the BMS data are shown in Figure 5-4. Prior to this the gas data had to be collected from monthly meter readings and the calculated monthly consumptions are shown later in Table 5-3.

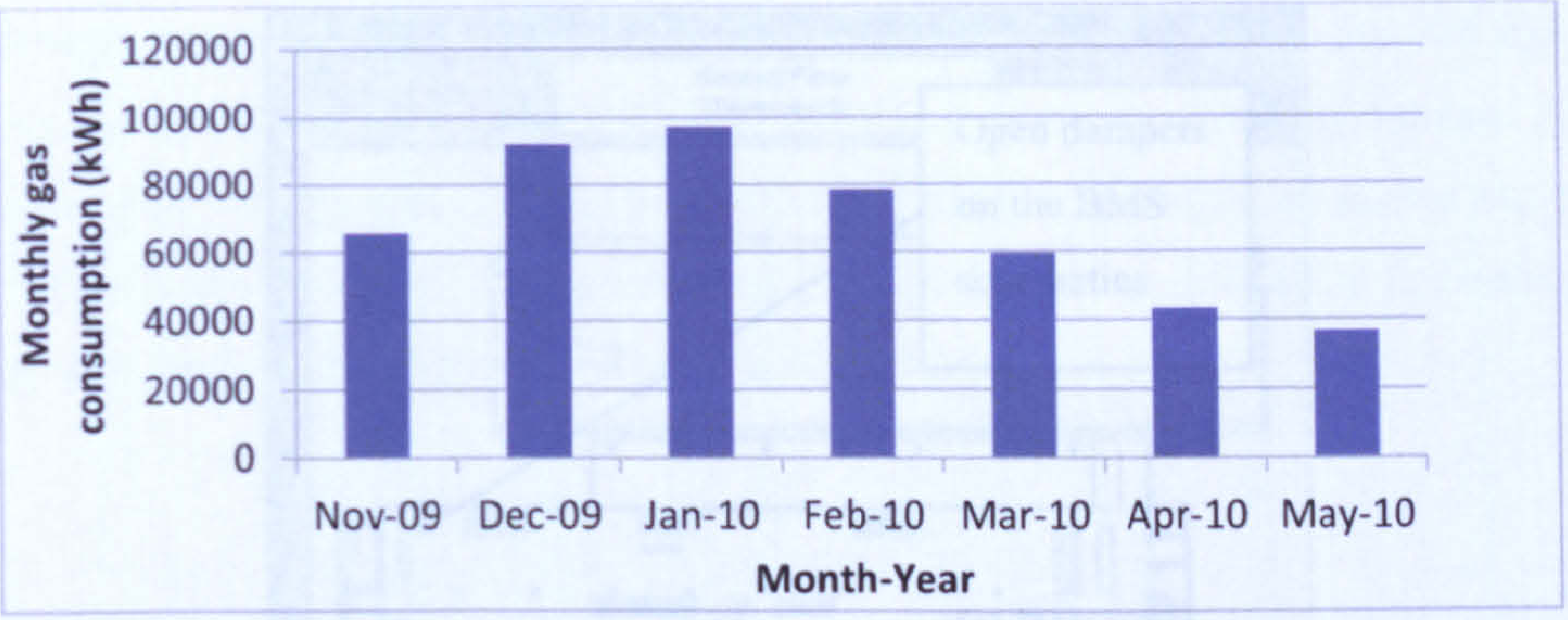


Figure 5-4: Monthly gas consumption determined from BMS data

At handover the settings of the BMS appear to show that the building's controls were as intended with unoccupied areas operating on set-back. This is indicated by the closed dampers in Figure 5-5. However later inspections discovered that this was later altered (see Figure 5-6), presumably when the area was used for an event and the settings were never reverted. Also the BMS schedules/settings were altered by building managers in late 2008 resulting in 24/7 operation in many areas. These factors potentially explain the large increase in energy consumption despite a similar increase in occupancy for years 2008 and 2009 compared to 2007 and 2008.

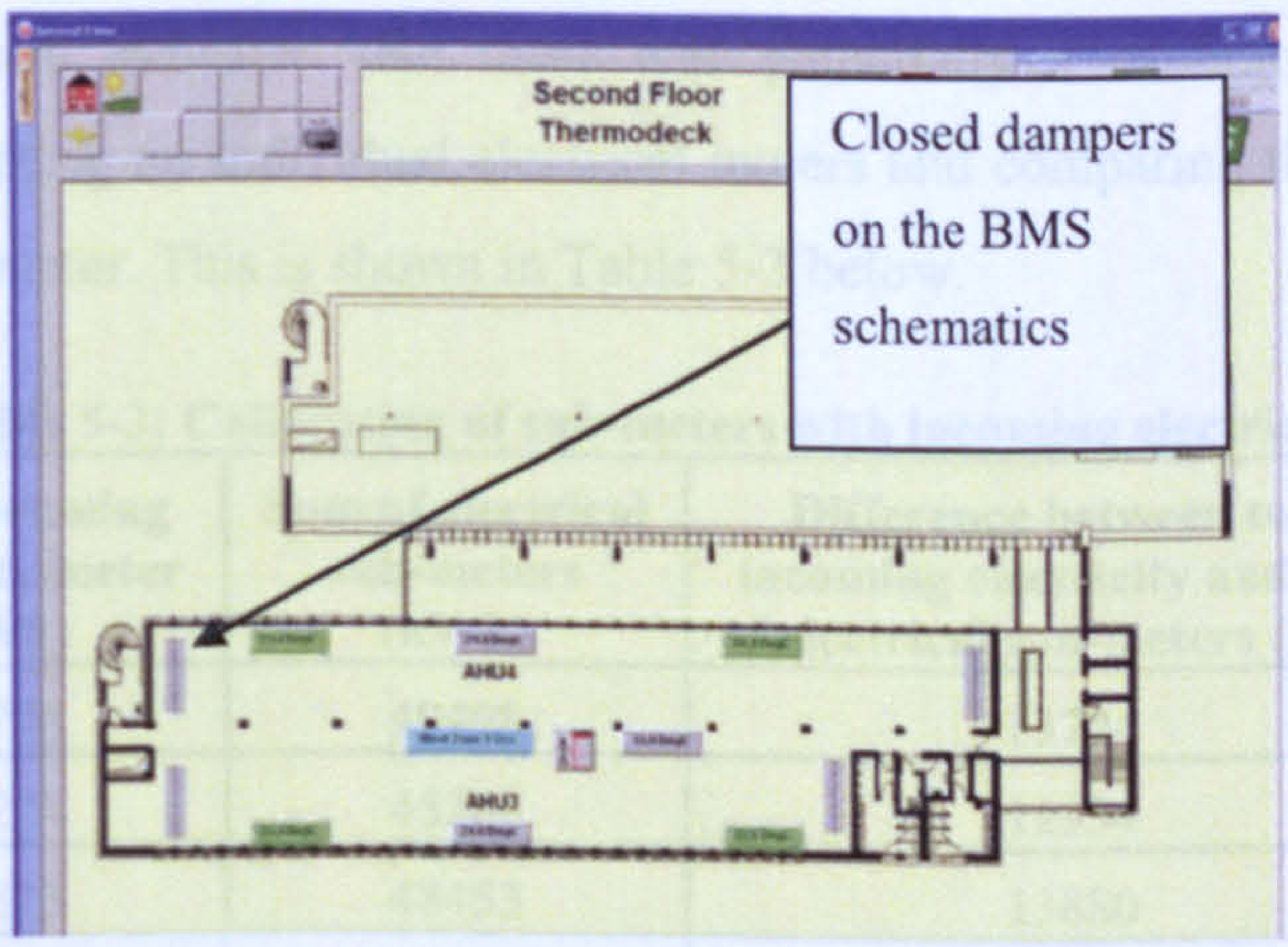
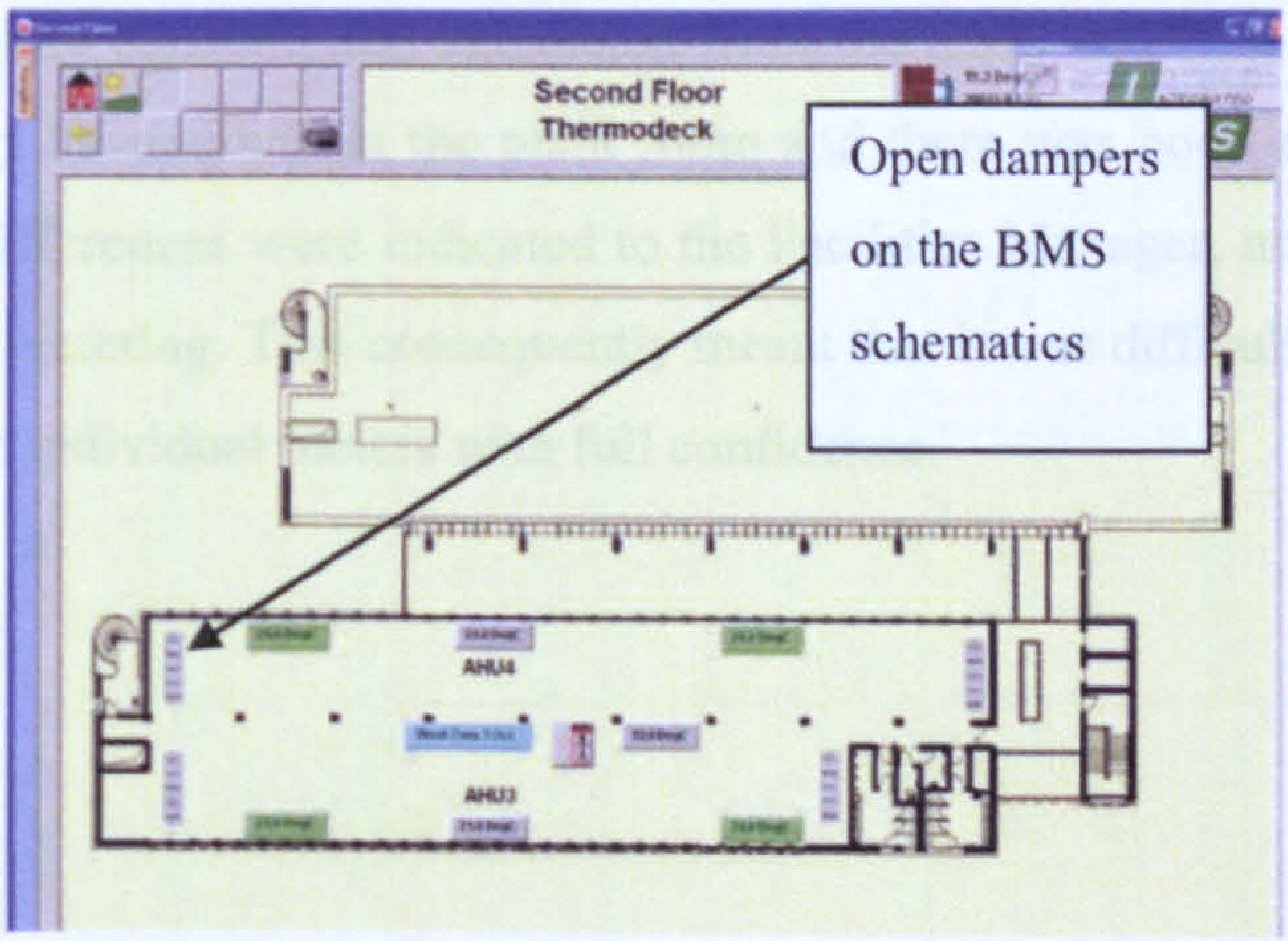


Figure 5-5: Screenshot of the BMS schematics (system set to 'unoccupied')



Open dampers on the BMS schematics

Figure 5-6: Screenshot of the BMS schematics (unoccupied zone, yet system is 'active')

5.2.2 Summary of sub-metering

Sub-metered data became available via the BMS. The work required to obtain this data was described in the Methodology chapter presented earlier.

The monthly energy consumptions for these sub-meters are shown in Table 5-4 on the next page.

Initial checks instantly indicated that there was potentially a calibration issue. This was identified when summing up individual electrical meters and comparing this figure to the total incoming electricity meter. This is shown in Table 5-3 below.

Table 5-3: Calibration of sub-meters with incoming electricity

Month-Year	Total incoming electricity meter (kWh)	Sum of electrical sub-meters (kWh)	Difference between total incoming electricity and sum of electrical sub-meters (kWh)	Percentage increase (%)
Jan-09	35774	49498	13724	38.4
Feb-09	32274	45208	12934	40.1
Mar-09	34573	48453	13880	40.1
Apr-09	34330	47281	12951	37.7
May-09	35993	49590	13597	37.8
Jun-09	34646	47044	12398	35.8
Jul-09	36530	48486	11956	32.7
Aug-09	34673	46895	12222	35.2
Sep-09	36142	48631	12489	34.6
Oct-09	33797	48173	14376	42.5
Nov-09	31158	45347	14189	45.5
Dec-09	30967	44580	13613	44.0
Totals	**410857**	**569186**	**158329**	**38.5**

The incoming electricity consumption calculated from the BMS data was checked against the reading on the meters located within the plant room and there was good agreement. Although the concerns in the differences were indicated to the Facilities Manager, no action was taken to inspect or rectify the metering. This consequently meant that it was difficult to accurately assess the energy use for the individual meters with full confidence.

Table 5-4: Monthly consumption for the BMS meters and sub-meters for 2009 when occupancy was at 50%

Month-Year	Total incoming electricity meter (kWh)	Gas for space heating, hot water and absorption chilling (kWh)	Total energy (kWh)	CHP Gas Meter (kWh)	CHP (kWh) Meter	Fans, pumps, electric chiller-"CP1" (kWh)	Lifts (kWh)	Vacuum Plant Meter (kWh)	Tenant small power (kWh)	Tenant lighting (kWh)	East Landlord (kWh)	West Landlord lighting (kWh)	West Landlord Power (kWh)	Comms Room Elec Meter (kWh)	CWS Water Meter (m3)
Jan-09	35774	103024	138798	0	0	18101	249	756	7667	5184	1878	10932	2782	1949	12.6
Feb-09	32274	83311	115585	0	0	16122	223	1221	7263	4575	1625	9837	2659	1683	12.8
Mar-09	34573	83409	117982	0	0	17756	244	735	7339	4813	1361	11392	2930	1883	94
Apr-09	34330	47217	81547	0	0	18913	244	678	7279	4154	908	10142	3154	1809	132.2
May-09	35993	33588	69581	0	0	19640	245	691	8280	4071	856	10442	3411	1954	347.4
Jun-09	34646	22404	57050	0	0	18977	281	690	8698	4573	840	9713	1433	1839	143.8
Jul-09	36530	27488	64018	0	0	20314	339	734	8346	4717	845	9935	1246	2010	136.5
Aug-09	34673	35845	70518	0	0	19262	228	907	7897	4462	1143	10378	985	1633	11.1
Sep-09	36142	47983	84125	0	0	19774	237	1051	8265	5007	1413	10059	1193	1632	13.2
Oct-09	33797	46337	80134	0	0	15899	239	1200	8537	5773	1645	11808	1384	1688	13.5
Nov-09	31158	65665	96823	0	0	13154	235	1474	7288	6223	1923	11747	1660	1643	13.2
Dec-09	30967	91981	122948	0	0	13602	239	1548	7053	5456	2018	11261	1650	1753	10.7
Annual total	410857	688252	1099109	0	0	211514	3003	11685	93912	59008	16455	127646	24487	21476	941
% of total electricity						51%	0.7%	3%	23%	13%	4%	31%	6%	5%	
% of total energy	37%	63%	100%			19%	0.3%	1%	9%	5%	1%	12%	2%	2%	

The end uses in Table 5-4 are individually discussed in detail later in this chapter.

Table 5-4 showed the electrical end-use (recorded on the BMS) as a percentage of total electricity. When comparing these percentages to published benchmarks and rules of thumb, a calibration/pulsing issue with the 'west landlord lighting' sub-meter was identified. This meter also included energy for external lighting in the car park which could account towards the excessive use recorded, however the consumption was treated as suspicious. The percentages for the other uses can be compared to those in a good practice office building given in Figure 5-7.

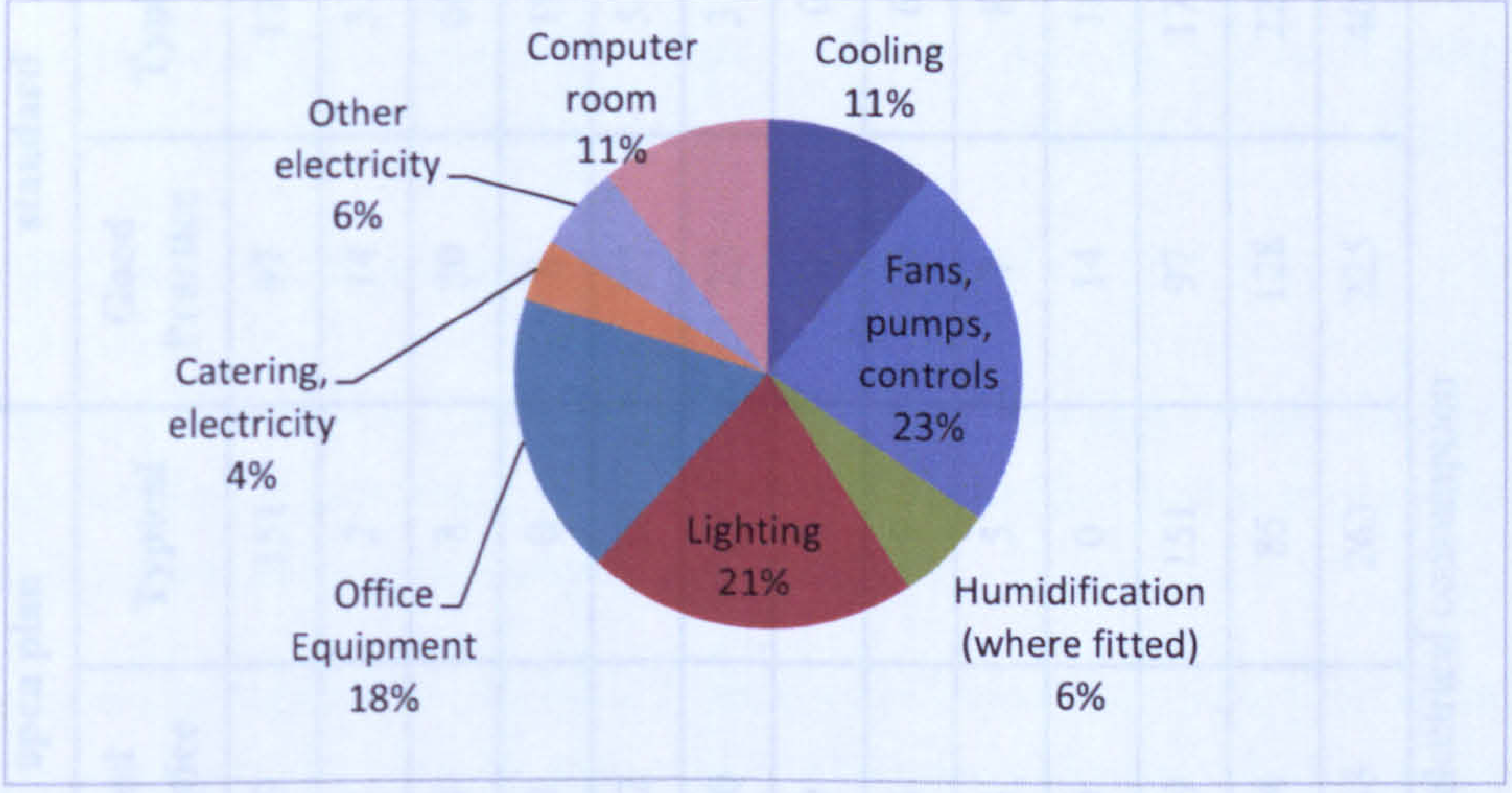


Figure 5-7: Electrical energy by end use for a good practice ECON 19 benchmark

The excessive use (51%) of the fans, pumps and electric chiller in the building is a result of 24/7 building operation. The small power accounts for around 29% of the total electrical consumption, compared to the 18% given in a good practice building. This was poor particularly given that the building is currently only partially occupied. The tenant lighting was only 13% compared with the 21% for a good practice building, again presumably due to the low occupancy levels.

Table 5-5 compares measured data in the case study office building in the right-hand column to the published benchmark data for typical and good practice office building types taken from ECON 19 (Best Practice Programme 2003). The measured performance should be compared the standard air-conditioned building but other types of offices are also presented. For most end-uses the case study building was better than typical, but worse than good practice levels.

Table 5-5: Comparison to ECON 19 benchmarks kWh/m²/year

	Naturally ventilated cellular		Naturally ventilated open plan		Air-conditioned, standard		Air-conditioned, prestige		Case study office building
	Good Practice	Typical	Good Practice	Typical	Good Practice	Typical	Good Practice	Typical	
Heating & hot water- gas /oil	79	151	79	151	97	178	107	201	159*
Cooling	0	0	1	2	14	31	21	41	49
Fans, pumps, controls	2	6	4	8	30	60	36	67	
Humidification (where fitted)	0	0	0	0	8	18	12	23	0
Lighting	14	23	22	38	27	54	29	60	43
Office Equipment	12	18	20	27	23	31	23	32	27
Catering, gas	0	0	0	0	0	0	7	9	-
Catering, electricity	2	3	3	5	5	6	13	15	-
Other electricity	3	4	4	5	7	8	13	15	7
Computer room	0	0	0	0	14	18	87	105	5
Total gas or oil	79	151	79	151	97	178	114	210	159
Total electricity	33	54	54	85	128	226	234	358	95
Total energy	112	205	133	263	225	404	348	568	254

Note other electricity includes lift energy, vacuum flush and east landlord's electrical consumption

*This also included the gas consumption for absorption chilling as could not be accurately divided out from this consumption.

** The West Landlords lighting consumption data should be treated as suspicious

5.2.3 Combined Heat and Power (CHP)

The 35kWe CHP unit, with a 2:1, thermal: electric output has disappointingly, for most of the monitoring period, not been operational due to missing vibration-dampening on the CHP base. Only 329 hours of operation has been recorded since the building opened four years ago compared with the predicted 4000 hours per year (which would make it commercially viable) estimated at design. The CHP unit was selected for tri-generation in the building with a matched absorption chiller. It was intended that the CHP would generate the power for lighting and computer loads. As this was not the case electricity from the grid was utilised. It was hoped that the fault with the operation of CHP unit would be restored during the monitoring period, however due to financial restraints and difficulties following Innovate Office Ltd going into administration the unit has remained inoperative. On the whole, the two small boilers located within the plant room have provided all the heat for space heating and hot water requirements.

5.2.4 HVAC and Termodeck

The proprietary 'Termodeck' system was integrated into the building design. The thermal mass within the building is maximised through the use of the hollow core concrete labyrinth and exposed concrete surfaces in the building (King 2007).

The electrical consumption for all the AHU supply and extract fans, pumps and electric chiller were all connected to one meter known as the 'CP1' (control panel 1). This accounted for 51% of total electricity use in the building. Monthly consumption is shown in Figure 5-8. It was disappointing that the components of the system are collectively metered in this way as it makes it difficult to accurately determine the energy consumption for the chiller and fans separately as the exact hours of use are not known. Without additional BMS data and additional sub-metering it is impossible to break down the 'CP1' electrical consumption to fans, pumps and chiller components.

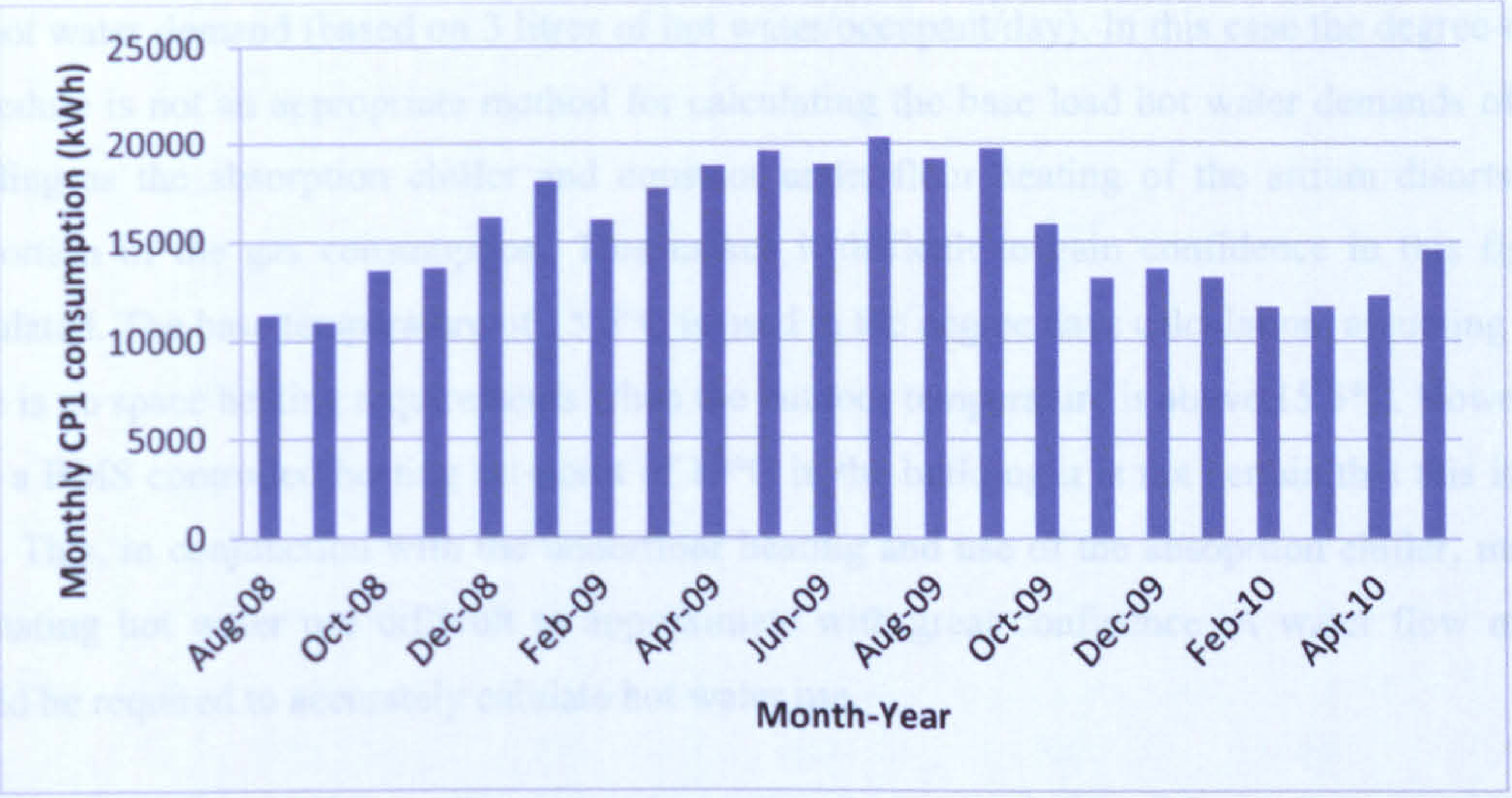


Figure 5-8: Monthly 'CP1' electricity meter consumption

Figure 5-8 shows the increase in consumption in late 2008 due to the changes in the BMS settings. It also shows a seasonal pattern in consumption due to an increased electrical chiller demand during the summer months. An annual energy consumption of 116173 kWh was predicted for fans and pumps and electric cooling was predicted. The measured annual consumption for the fans, pumps and electric chiller was 211514 kWh; 82% more than predicted.

It was also disappointing that the absorption chiller didn't have an output meter to facilitate when separating out gas use. The gas accounted for almost two thirds of total energy in the building (shown in Figure 5-9). The gas fuel is used for space heating, hot water, underfloor heating and absorption chilling purposes however it is difficult to calculate these individual energy consumptions.

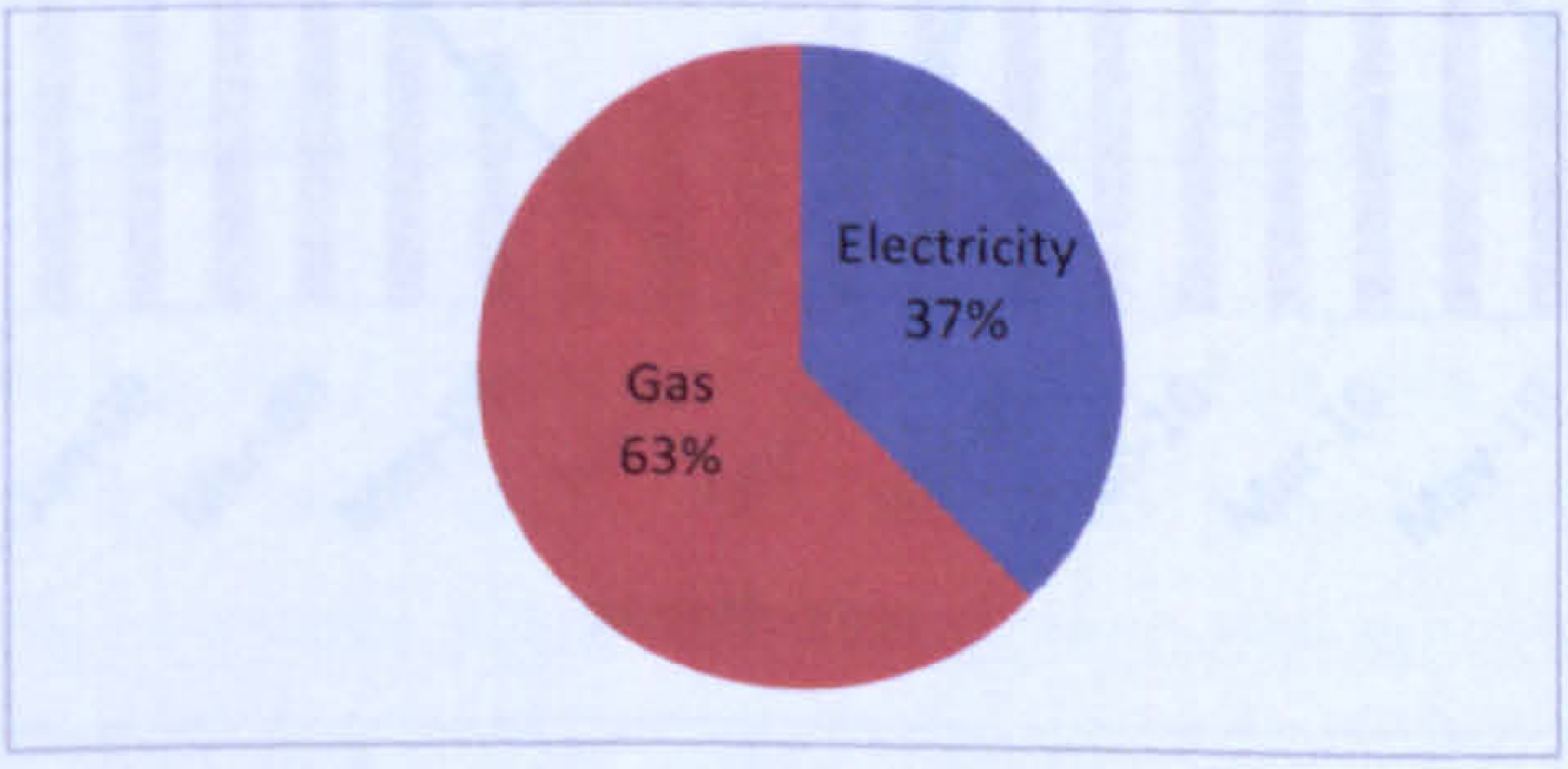


Figure 5-9: Measured energy use percentage by fuel type

Figure 5-10 shows the monthly heating degree days and the monthly gas consumption. The degree-days procedure is sometimes used to calculate the monthly baseload gas use for hot water. In this case it can be approximated as 21655 kWh (estimated by y-intersect) as shown in Figure 5-11. Design estimates suggested an energy consumption of around 20000 kWh a year for hot water demand (based on 3 litres of hot water/occupant/day). In this case the degree-days procedure is not an appropriate method for calculating the base load hot water demands of the building as the absorption chiller and constant under-floor heating of the atrium disorts the proportion of the gas consumption. This makes it difficult to gain confidence in this figure calculated. The base temperature of 15.5°C is used in the degree days calculation, assuming that there is no space heating requirements when the outdoor temperature is above 15.5°C. However, with a BMS controlled heating set-point of 19°C in the building it is not certain that this is the case. This, in conjunction with the underfloor heating and use of the absoprtion chiller, makes estimating hot water use difficult to approximate with great confidence. A water flow meter would be required to accurately calulate hot water use.

Within the building, the cooling related conditioning was designed in such a way that a conventional (electric) chiller was to be utilised when cooling demand in the building is between 1% to 25%, at demands between 26% to 50% the absorption chiller is used and when a cooling demand greater than 50% is needed both the electric and absorption chillers will be utilised (with full utilisation of the absorption chiller and the conventional chiller meeting the extra demand). However on many occasions faults with the absorption chiller were reported on the BMS.

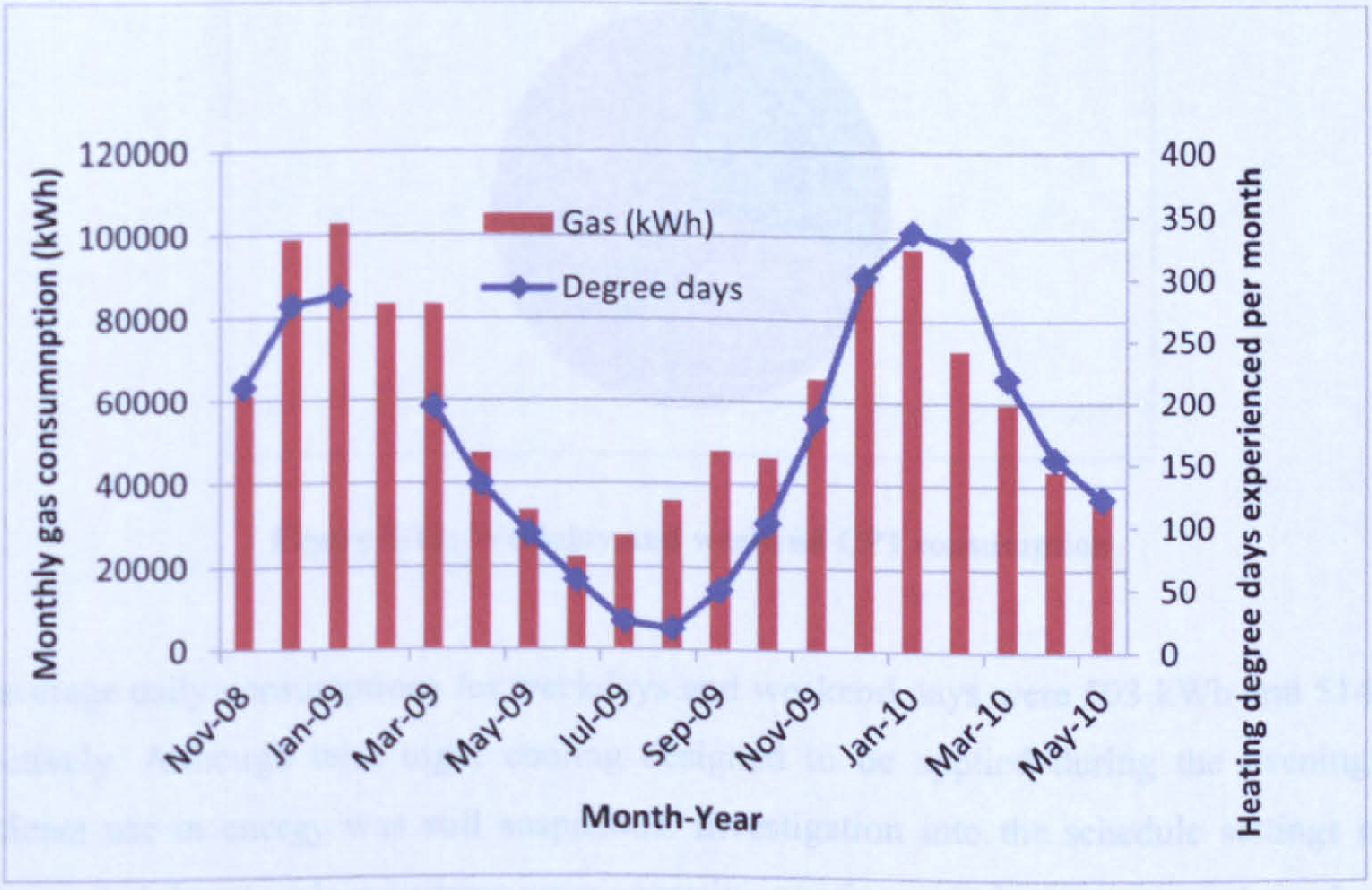


Figure 5-10: Monthly heating degree days and gas consumption

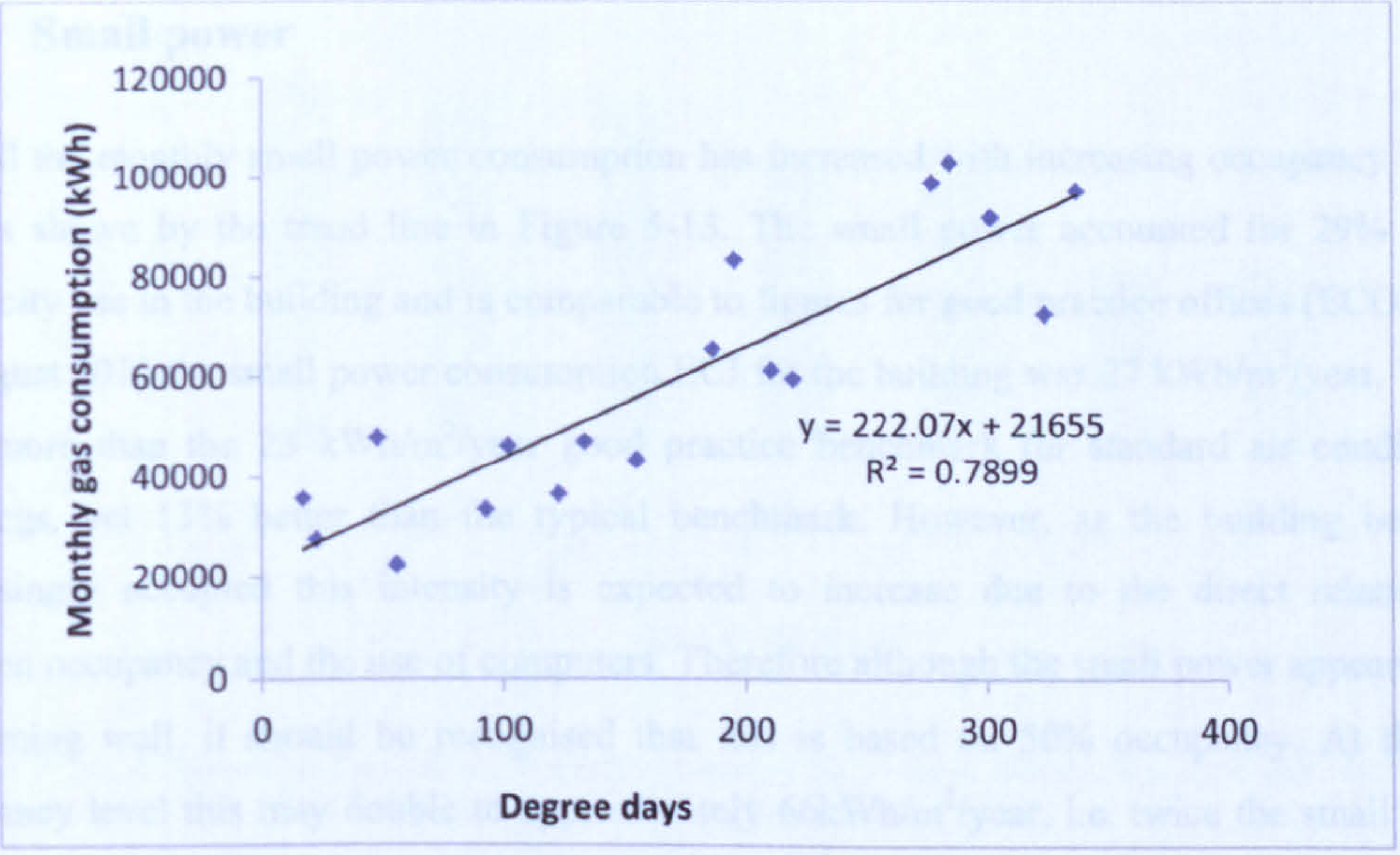


Figure 5-11: Scatterplot showing degree days and gas consumption

With the lack of sub-metering from the CP1 it is impossible to accurately provide detailed individual energy consumptions for the fans, pumps and electric chiller. However, from the data collected over a one year period it was found that 29% of the CP1 meter energy was used during weekends when the building is empty. This is shown in Figure 5-12.

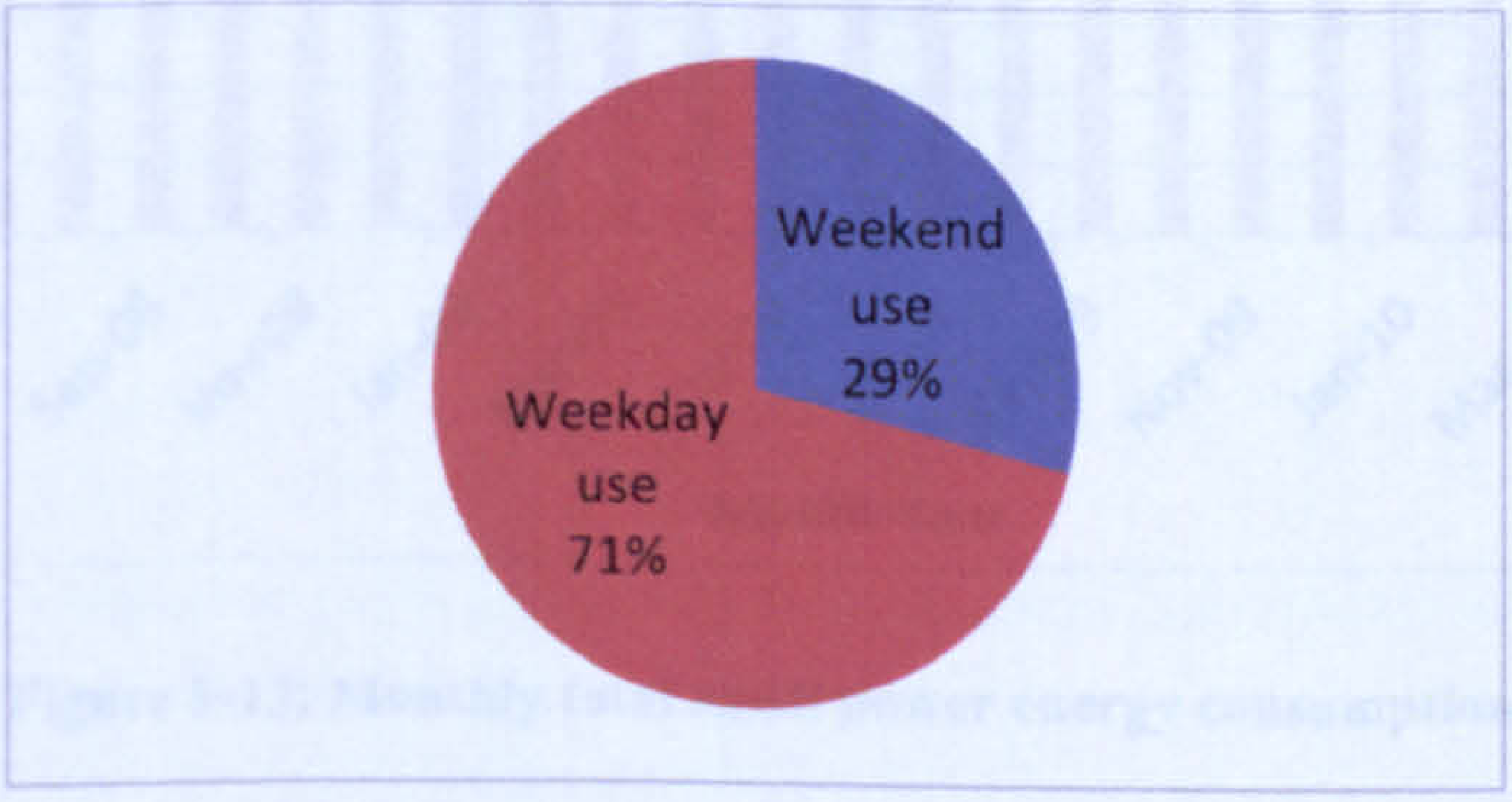


Figure 5-12: Weekday and weekend CP1 consumption

The average daily consumptions for weekdays and weekend days were 503 kWh and 514 kWh respectively. Although with night cooling designed to be applied during the evenings this significant use in energy was still suspicious. Investigation into the schedule settings on the BMS revealed that the plant systems were operating continuously in many areas throughout the building, with unoccupied and under-occupied areas not being accounted for in the current control settings. As a result the building was being treated on a 24/7 basis, with all AHU's operating on a fully occupied scenario although this was not the case.

5.2.5 Small power

Overall the monthly small power consumption has increased with increasing occupancy levels. This is shown by the trend line in Figure 5-13. The small power accounted for 29% of the electricity use in the building and is comparable to figures for good practice offices (ECON 19). In August 2010 the small power consumption EUI for the building was 27 kWh/m^2/year. This is 17% more than the 23 kWh/m^2/year good practice benchmark for standard air conditioned buildings, yet 13% better than the typical benchmark. However, as the building becomes increasingly occupied this intensity is expected to increase due to the direct relationship between occupancy and the use of computers. Therefore although the small power appears to be performing well, it should be recognised that this is based on 50% occupancy. At the full occupancy level this may double to approximately 66kWh/m^2/year, i.e. twice the small power use in a typical office (Action Energy 2003).

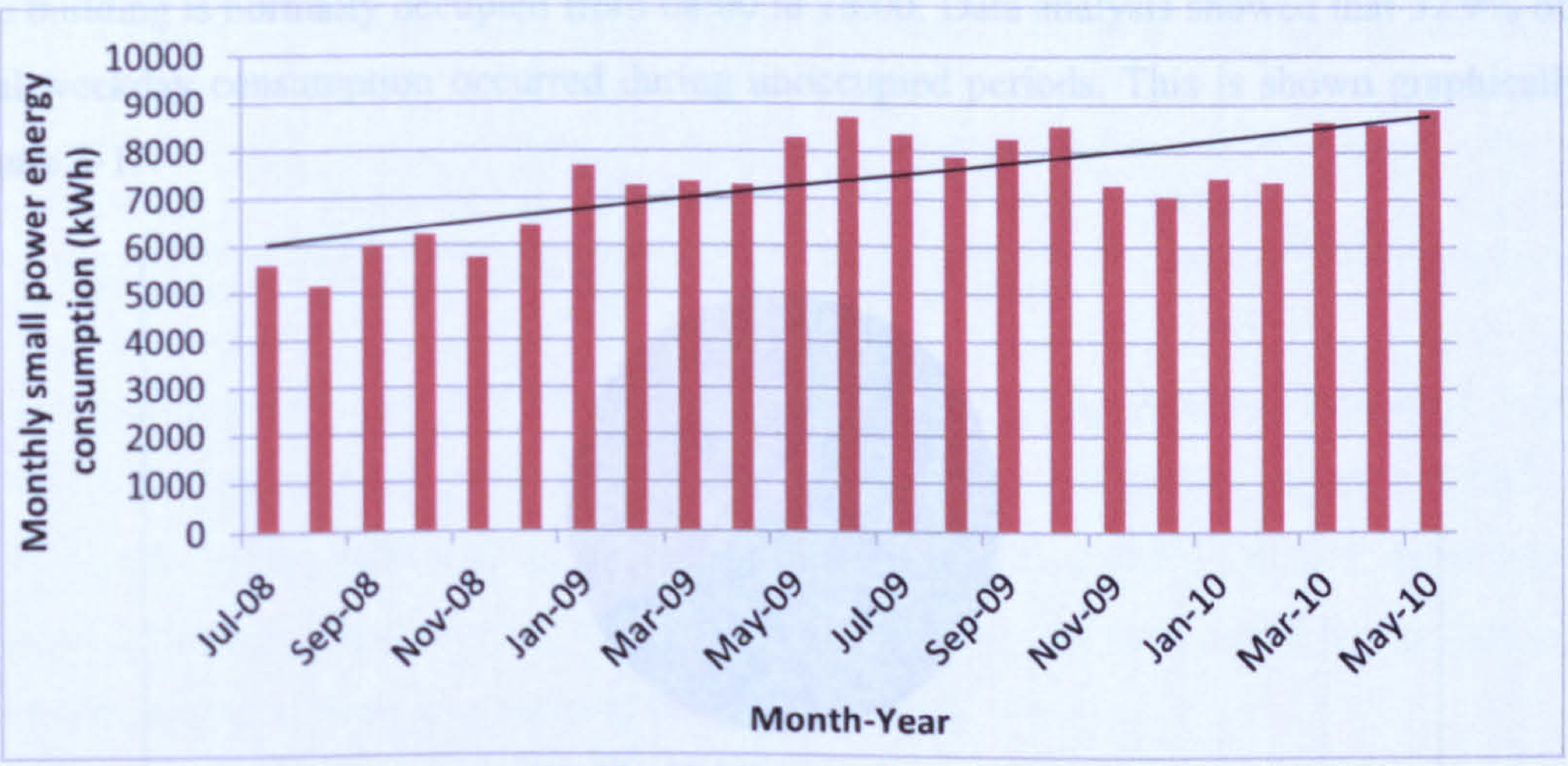


Figure 5-13: Monthly total small power energy consumption

5.2.6 East wing ground floor small power

The east wing ground floor small power use was further investigated using the data collected over a one year period. The analysis revealed a 14007 kWh annual consumption, with 19.1 % of this energy being used at weekends. The average daily consumptions for weekdays and weekend days were 43.6 kWh and 25.2 kWh respectively. A typical pattern of small power consumption over a one week period is shown in Figure 5-14.

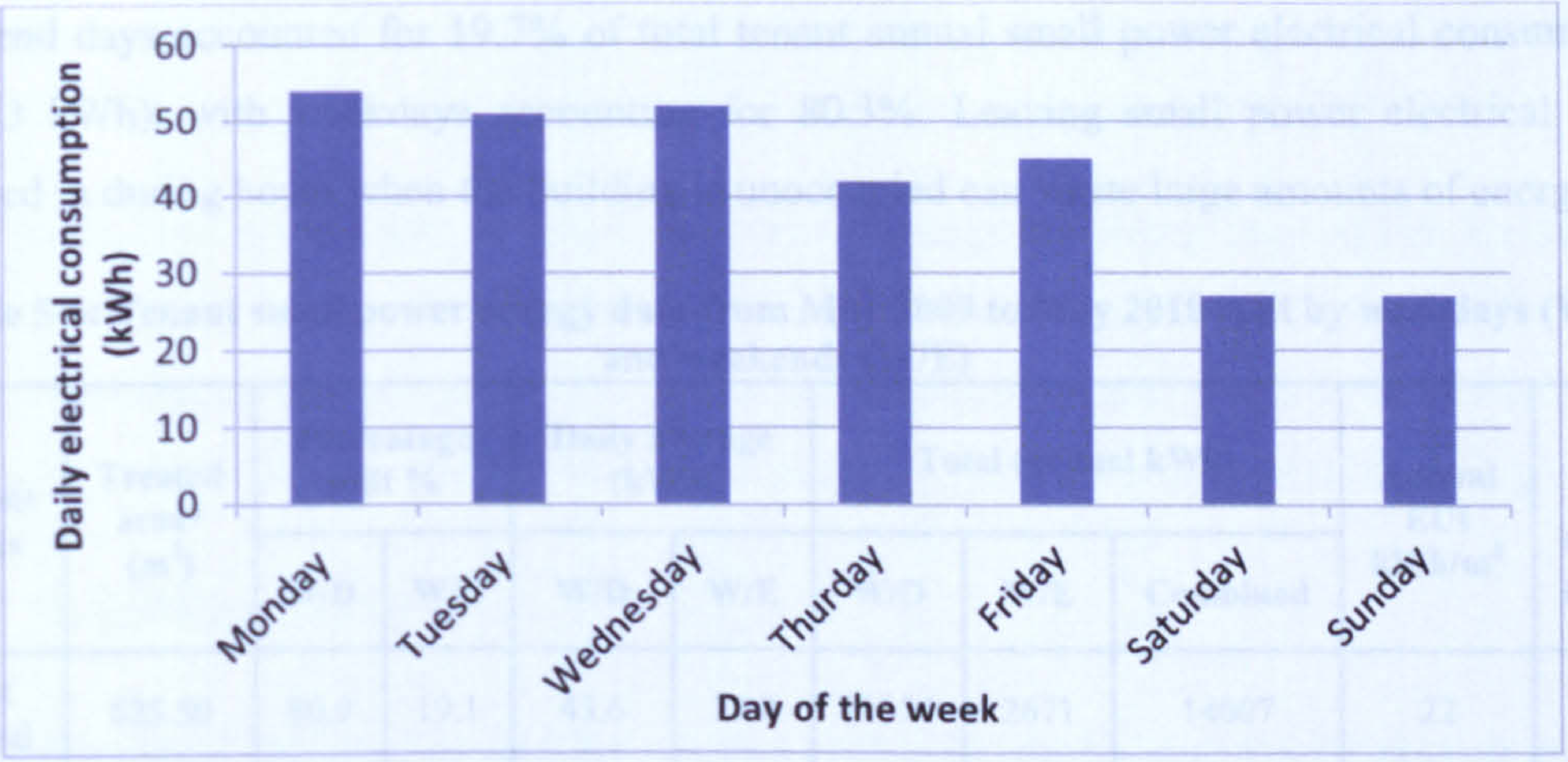


Figure 5-14: A typical pattern of small power consumption over a one week period (15th February 2010) in the east wing ground floor zone

The building is normally occupied from 08:00 to 18:00. Data analysis showed that 32.9% of the total weekday consumption occurred during unoccupied periods. This is shown graphically in Figure 5-15.

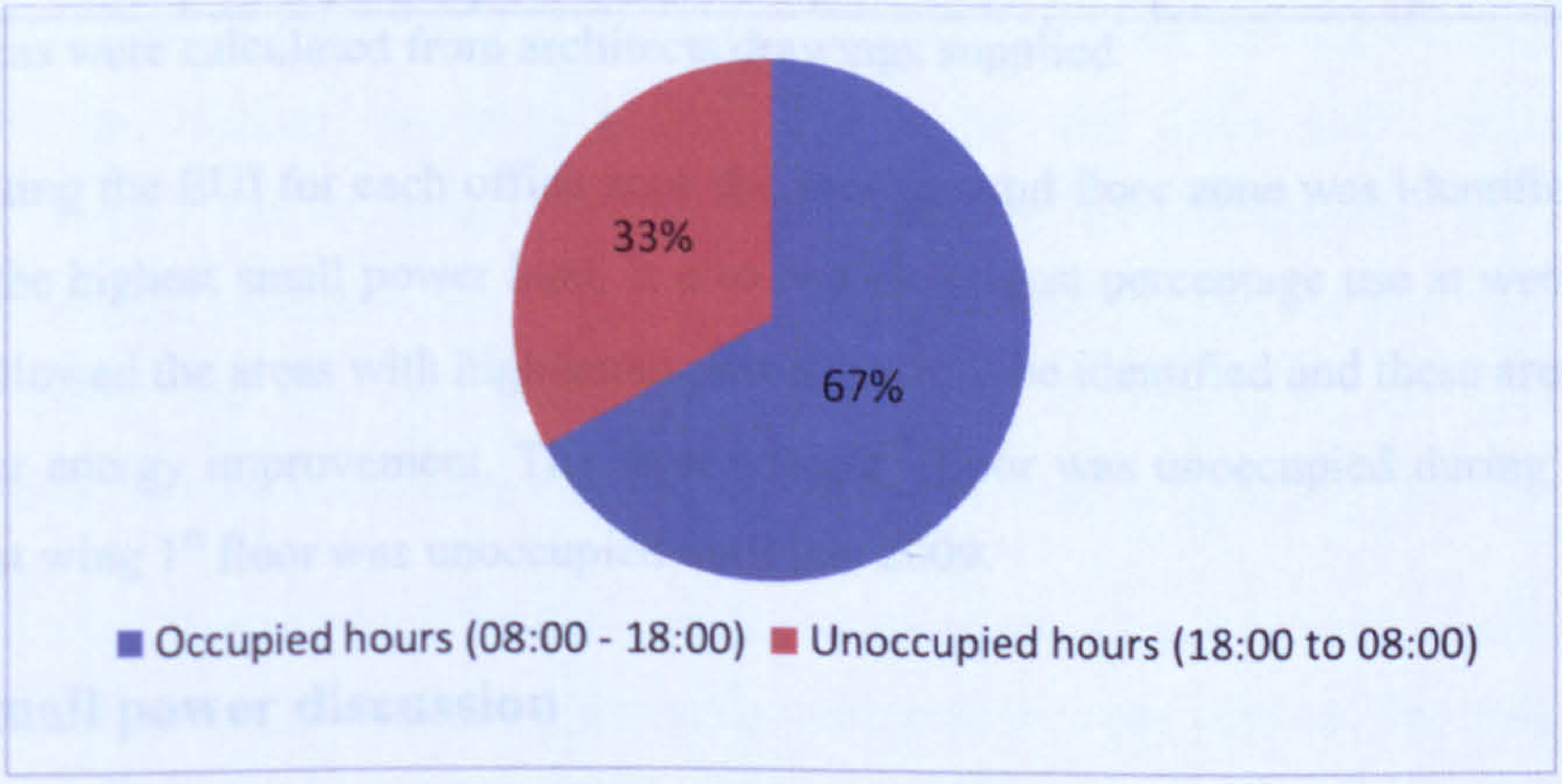


Figure 5-15: A typical pattern of small power consumption over a one week period in the East Wing Ground Floor zone

PROBE 11 (Standeven, Cohen et al. 1997a) found a similar result with 35% of small power energy being consumed at night when the building is unoccupied. This snapshot of small power consumption in one zone during February 2010 described above revealed that approximately one third of the energy was used when the building was empty. This is a significant proportion and one that can be easily reduced with more effective housekeeping.

5.2.7 Summary of annual out of hours small power use

In Table 5-6 the annual small power energy consumptions in all office zones have been divided out for use during weekdays (W/D) and weekends (W/E). Overall this revealed that unoccupied weekend days accounted for 19.7% of total tenant annual small power electrical consumption (97713 kWh), with weekdays accounting for 80.3%. Leaving small power electrical items plugged in during hours when the building is unoccupied can waste large amounts of energy.

Table 5-6: Tenant small power energy data from May 2009 to May 2010 split by weekdays (W/D) and weekends (W/E)

Tenant zones	Treated area* (m^2)	Percentage split %		Daily average (kWh)		Total (annual kWh)			Annual EUI kWh/m^2	% of total tenant power
		W/D	W/E	W/D	W/E	W/D	W/E	Combined		
East ground	625.50	80.9	19.1	43.6	25.2	11336	2671	14007	22	14.4
East 1st	687.36	81.6	18.4	17.1	9.5	4456	1006	5462	8	5.6
West ground	506.10	76.2	23.8	120.4	92.5	31316	9806	41122	81	42.3
West 1st	609.36	84.5	15.5	117.53	52.92	30559	5610	36169	59	37.2
West 2nd	609.36	77.9	22.1	1.06	0.74	275	78	353	1	0.4
AVERAGE		**80.3**	**19.7**	**TOTALS**		**77942**	**19171**	**97113**		**100**

Note: * areas were calculated from architects drawings supplied

By calculating the EUI for each office zone the west ground floor zone was identified to be the area with the highest small power load. It also had the largest percentage use at weekends. The POE has allowed the areas with high small power loads to be identified and these areas could be targeted for energy improvement. The west wing 2nd floor was unoccupied during this period and the east wing 1st floor was unoccupied until late 2009.

5.2.8 Small power discussion

The weekend small power in the office zones use ranged from 15.5% to 23.8% of total weekly use. High electrical loads at weekends were presumably due to occupants leaving small power office equipment on and/or on standby. 32.9% of small power energy was consumed during unoccupied hours (from 18:00 – 08:00). A typical week in February 2010 was investigated and the daily small power consumption for the east wing ground floor zone was investigated. Results showed that almost 20% of the weekly consumption was during Saturday and Sunday.

In summary this analysis of small power use showed the potential to easily save approximately 20% of current small power energy use by switching appliances off during unoccupied weekend periods. This saving increases when the evenings are considered. CIBSE Guide F presents data relating to the power consumption of standard office equipment, leaving a PC and monitor on stand-by has a power consumption of around 30-45W compared to the average power consumption of 120W when in-use. Similarly for a laptop, the stand-by power consumption is around 5-10W compared to the average power consumption in use of 20W (CIBSE 2004).

The results have shown that wasteful amounts of energy are being used in the building by occupants leaving small power appliances (computers and laptops) on overnight. The small power consumption accounted for 29% of total annual electrical energy and 11% of total annual energy, yet it is an end-use that can be easily reduced by more considerate housekeeping.

5.2.9 Lighting energy

The orientation of the building and the use of a central atrium allowed the building to take full advantage of any available natural daylight. A low energy lighting system using T5 luminaries is controlled by light sensitive photoelectric cells which dim down output in response to any natural daylight. The artificial lights are also controlled by presence motion sensors. In a conventional air-conditioned office building, the artificial lighting typically accounts for 24% of the total electrical consumption within a building (Action Energy 2003). Similarly a figure of 21% has been given as good practice.

At the design stage the total electrical demand for all the artificial lighting was predicted to be 75,266 kWh per annum (covering office, corridor, atrium, toilet and ancillary fittings). However, yet again this was based on full occupancy. POE revealed that the total lighting and total tenant lighting accounted for 44% and 13% of electricity use respectively. However, there are uncertainties over the total lighting due the unreliable logging of the 'west landlords lighting' meter. The measured total monthly tenant light energy is shown in Figure 5-16.

The overall trend shows an increase in lighting as occupancy has increased. Seasonal patterns are also evident with reduced lighting demands during the summer months. The 20% increase in occupancy levels between January 2009 and January 2010 brought a 22% increase in tenant lighting energy.

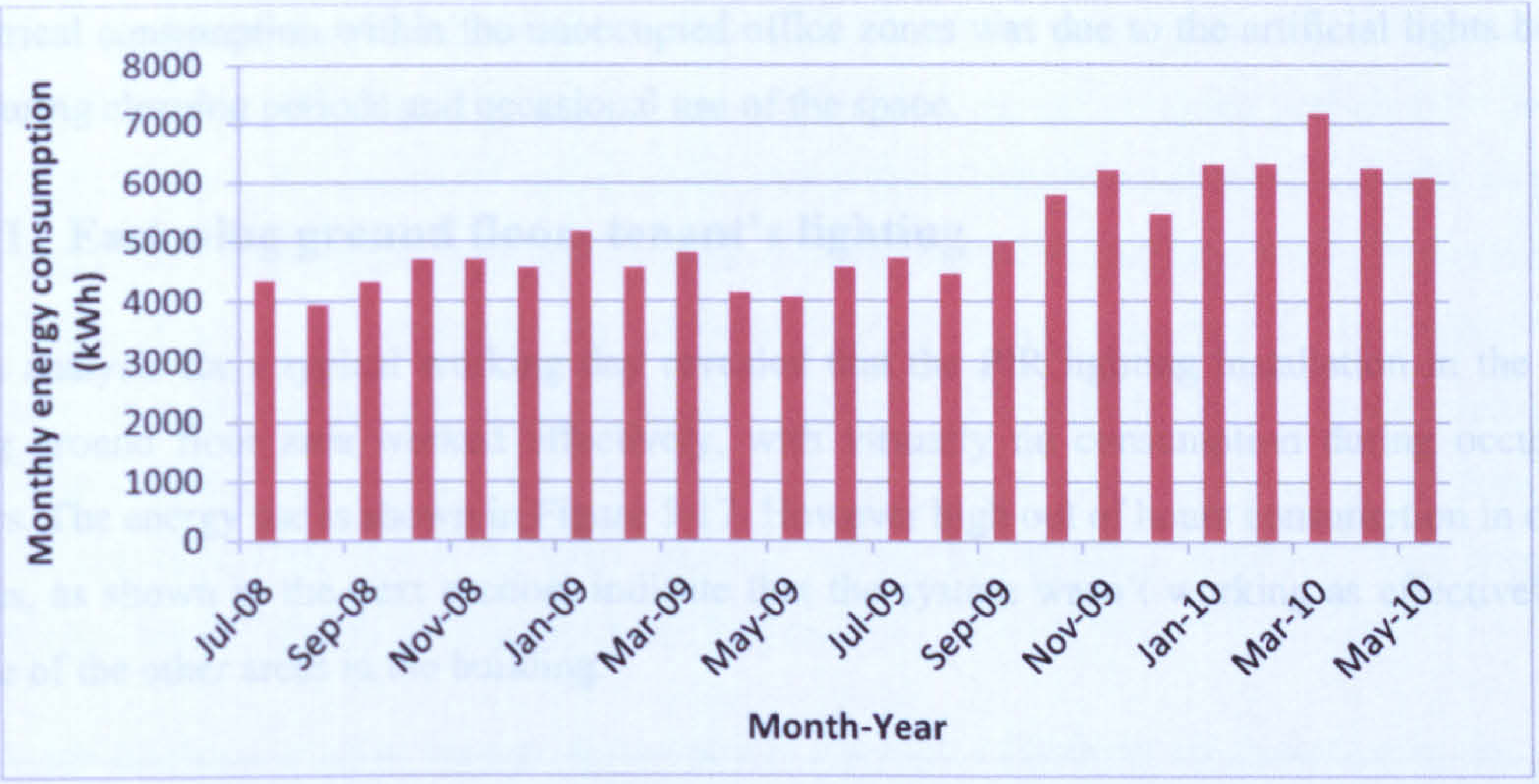


Figure 5-16: Total tenant lighting energy consumption

5.2.10 Comparing predicted and actual lighting energy consumption

Table 5-7 compares the predicted and actual annual artificial lighting energy consumption in the occupied office zones. The predicted amounts were obtained from documentation supplied by the design team and the actual electrical consumption was obtained from energy data measured by the BMS system over a 12 month period (in this case from May 2009 to May 2010).

Table 5-7: Predicted and actual annual lighting electrical consumption

Tenant zones	Treated area* (m^2)	Predicted annual lighting electrical consumption (kWh)	Actual annual lighting electrical consumption (kWh)	Actual EUI ($kWh/m^2/year$)	% increase in actual electrical consumption
East ground	625.50	7045	11664	19	66
East 1st	687.36	5369	544	1	Unoccupied zone
West ground	506.10	6991	13563	27	94
West 1st	609.36	5622	27300	45	386
West 2nd	609.36	4644	894	1	Unoccupied zone
TOTAL	**3037.68**	**29670**	**53965**	18	**82**

Note: * areas were calculated from architects drawings supplied

From Table 5-7 it is clear that the occupied zones, which include the east wing ground floor, west wing ground floor and 1st floor; all consumed far more electricity than was predicted. In these zones, the percentage increase in the actual electrical consumption when compared to the predicted was 66%, 94% and 386% respectively, with an overall average increase of 82%. The electrical consumption within the unoccupied office zones was due to the artificial lights being on during cleaning periods and occasional use of the space.

5.2.11 East wing ground floor- tenant's lighting

Data analysis for a typical working day revealed that the PIR lighting installation in the east wing ground floor area worked effectively, with virtually no consumption during occupied hours. The energy use is shown in Figure 5-17. However high out of hours consumption in other zones, as shown in the next section, indicate that the system wasn't working as effectively in some of the other areas in the building.

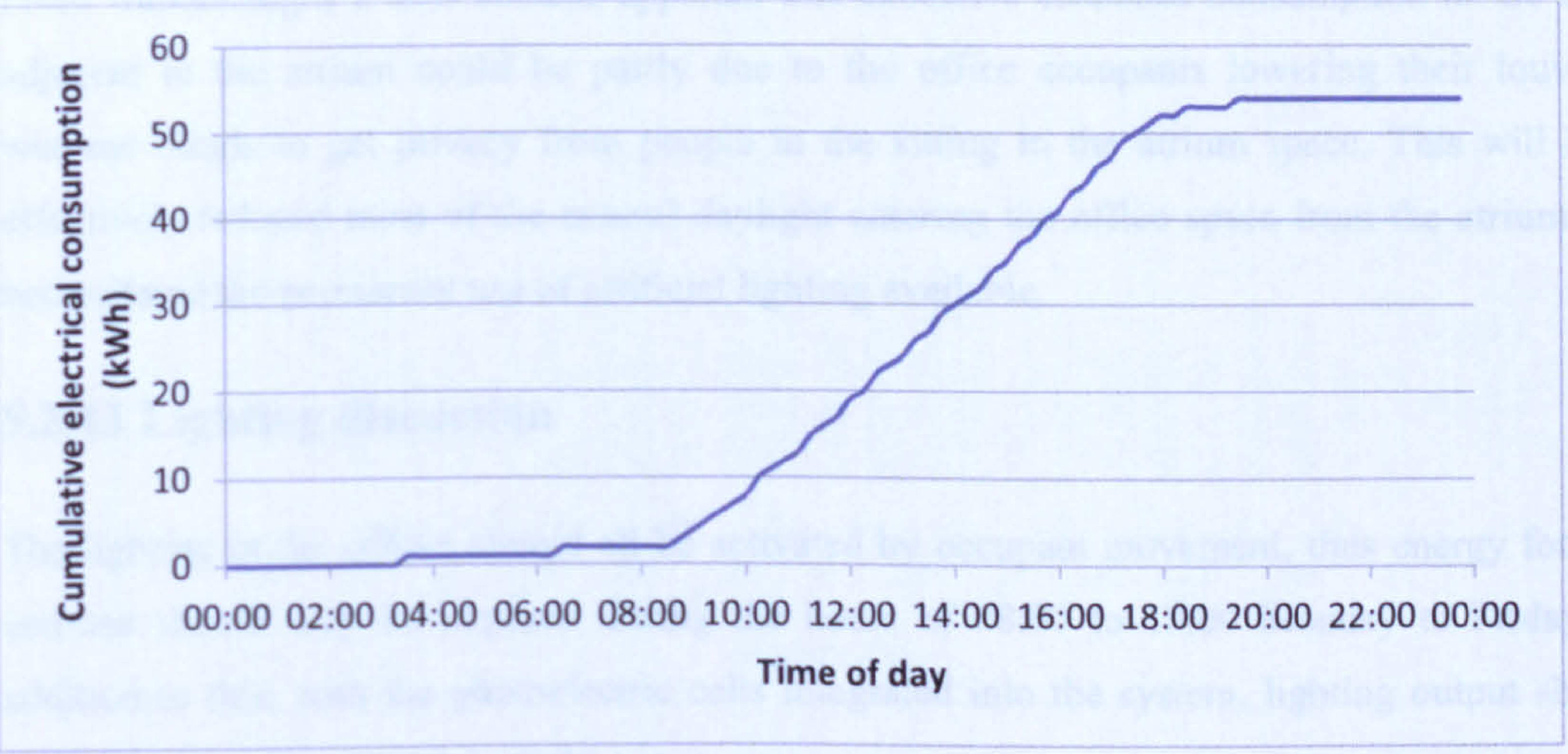


Figure 5-17: Electrical lighting consumption in east wing ground floor over a typical working day

5.2.12 Summary of annual out of hours lighting electricity use

Table 5-8 presents the tenant lighting energy consumption during weekdays and weekends. An average of 12.5% of total tenant annual lighting electrical consumption was calculated during weekends.

Table 5-8: Tenant lighting energy data from May 2009 to May 2010 split by weekdays (W/D) and weekends (W/E)

Tenant's location	Percentage split %		Daily average (kWh)		Total (annual kWh)			% of total tenant lighting
	W/D	W/E	W/D	W/E	W/D	W/E	Combined	
East ground	97.4	2.6	41.3	2.7	10743	290	11033	16.1
East 1st	97.4	2.6	12.3	0.8	3201	85	3286	4.8
West ground	90.8	9.2	58.2	14.4	15142	1526	16668	24.4
West 1st	82.1	17.9	115.5	61.8	30030	6553	36583	53.5
West 2nd	85.4	14.6	2.6	1.1	669	114	783	1.1
AVERAGE	**87.5**	**12.5**	**TOTALS**		**59785**	**8568**	**68353**	**100**

Analysis of electrical consumption data revealed that in all the occupied zones, except the west wing 1st floor, the office lighting appeared to be activated during occupied periods only. In the west wing 1st floor, the electrical consumption was much higher than expected and after analysis of the systems use it became apparent that the motion sensors in this area were not working as expected and on many occasions the artificial lighting would remained on overnight. This explains the high lighting consumption during weekends. Additionally, the occupant satisfaction survey and further discussions revealed that some of the occupants had been given handheld remote controls with which to over-ride the automated lighting controls. The occupant satisfaction survey results are presented in Chapter 8.

From walkthroughs it also became apparent that excessive electrical consumption in the areas adjacent to the atrium could be partly due to the office occupants lowering their louvered window blinds to get privacy from people in the sitting in the atrium space. This will have effectively reduced most of the natural daylight entering the office space from the atrium and necessitated the permanent use of artificial lighting available.

5.2.13 Lighting discussion

The lighting in the offices should all be activated by occupant movement, thus energy for this end-use should only be required during the hours of 08:00 to 18:00 Monday to Friday. In addition to this, with the photoelectric cells integrated into the system, lighting output should vary according the natural daylight.

This appeared to work well in some of the areas in the building as shown in Figure 5-17. An EUI of 19kWh/m^2/year was determined for the east wing ground floor zone which is 65% and 30% better than the EUIs in typical and good practice offices respectively (Best Practice Programme 2003).

However, in other areas of the building lights the lighting system was not working as efficiently. In the west wing 1st floor the energy consumption was 386% more than design expectations and 67% worse than good practice levels, yet still 17% better than typical levels of consumptions in other air-conditioned office buildings. In this zone almost 18% of the annual energy use was during weekends. Maintenance on the lighting system and their controls could easily avoid the lighting operating during these occupied periods. However only from conducting a POE of this type can these problematic areas be identified and targeted for reduced energy consumption.

In terms of overall lighting energy consumption the building's EUI of 18 kWh/m^2/year was 67% and 33% better than typical and good practice in standard air conditioned office buildings. However, the low occupancy within the building was the major reason for this good comparison.

5.2.14 Lifts

The monthly energy consumption per lift is shown in Figure 5-18. Average monthly energy consumption per lift is 128kWh. Lift energy consumption accounted for only 0.7% of the total electricity consumption in the building in 2009. Estimates in the region of 5-10% of total energy have been suggested for the use of lifts in office buildings (CIBSE 2005a). For the case study building the lift energy accounted for 0.3% of total energy. This negligible amount was presumably a result of a low number of storeys and low occupancy. Additionally, currently occupants are currently only located on the ground and first floor and very few use the lift other than for transporting heavy goods to upper/lower levels.

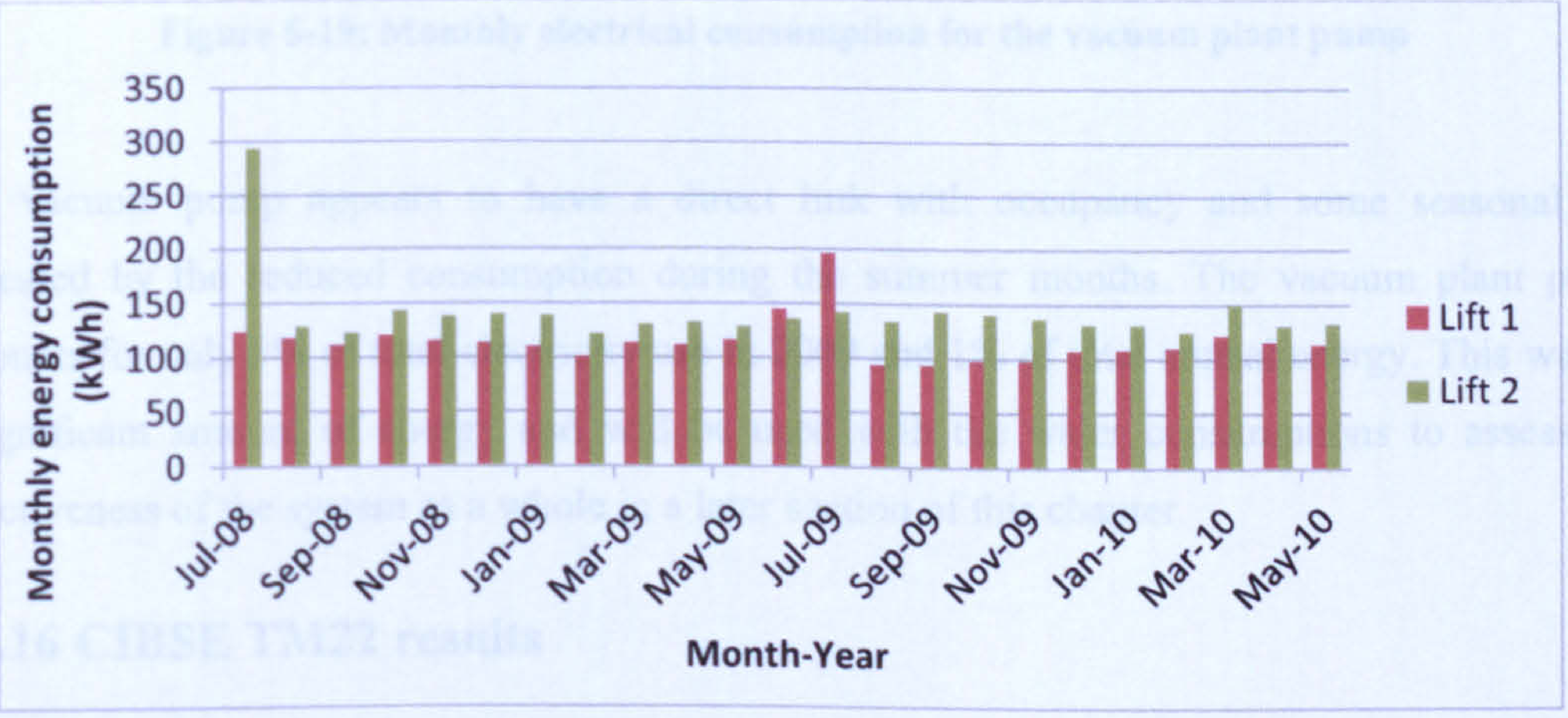


Figure 5-18: Monthly lift energy consumption

5.2.15 Vacuum plant

The installation of the vacuum flush toilet system does have the benefits of reducing water consumption in a building; however the EVAC suction pump has associated energy consumption. Figure 5-19 shows the electrical consumption associated with the pump. During both February 2009 and February 2010 a fault with the system caused excessive use of the EVAC plant. Based on 2009 data, the annual electrical consumption and CO_2 emissions associated with the vacuum point were calculated as 11685kWh and 6356.64kgCO_2 respectively.

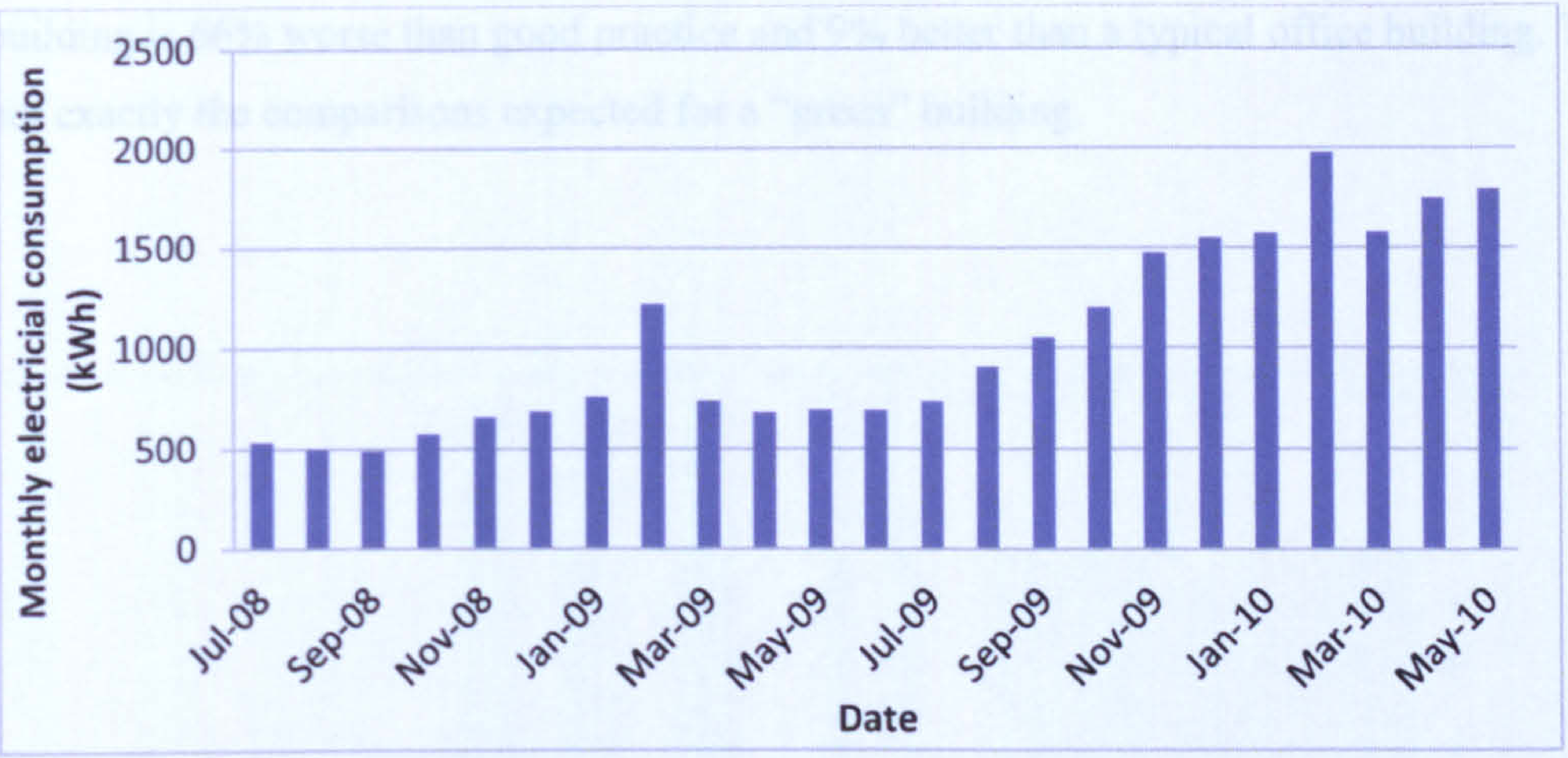


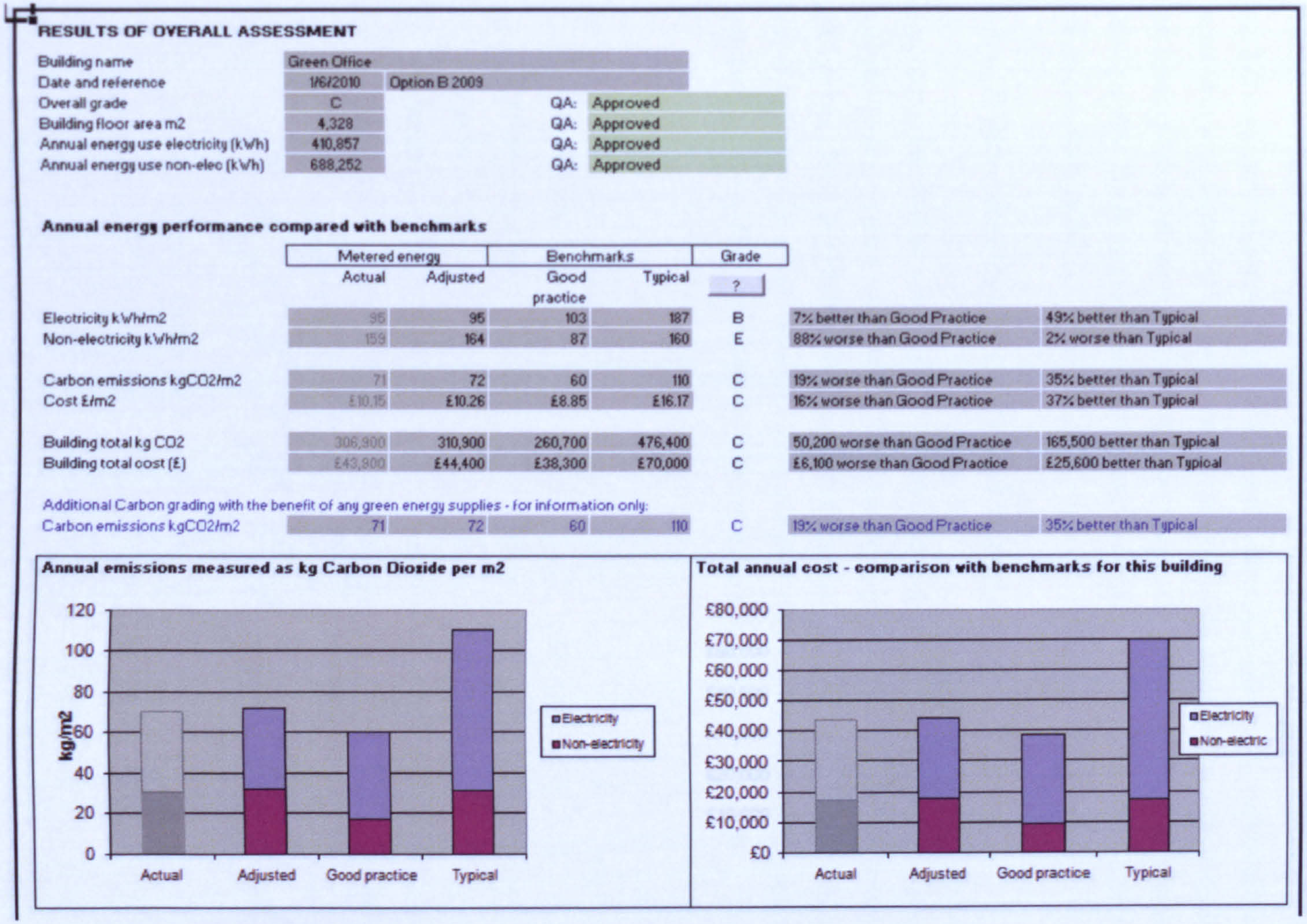
Figure 5-19: Monthly electrical consumption for the vacuum plant pump

The vacuum pump appears to have a direct link with occupancy and some seasonal use indicated by the reduced consumption during the summer months. The vacuum plant pump accounts for only 3% of total electricity use in 2009 and 1% of total annual energy. This was an insignificant amount of energy and will be used with the water consumptions to assess the effectiveness of the system as a whole in a later section of this chapter.

5.2.16 CIBSE TM22 results

The TM22 methodology (CIBSE 2006d) calculates the building energy use compared to benchmarked data for good and typical practice. The carbon emission conversion factors were updated to the 2009 DEFRA figures (Gas- 0.184kgCO$_2$/kWh, Electricity- 0.544kgCO$_2$/kWh). Weather corrections, scheduling and occupied hour adjustments were made to the settings within TM22, to represent those of the case study building. Normalising the data in this way makes comparisons with other buildings much more accurate.

The result from the 'Option B' assessment is shown in Figure 5-20. Based on total floor area, the results show that the annual electrical energy performance of the building was 7% better than good practice and 49% better than a typical office for electrical energy. Similarly for (non-electrical) gas energy consumption it was found to be 88% worse than good practice and 2% worse than a typical office. Upon consideration of these results again it was realised that these do not reflect the unoccupied areas of the buildings. Therefore, the TM22 procedure was repeated using the occupied office spaces only as the base area plus all communal areas. The results are shown in Figure 5-21. In this case the building performance, when compared to the benchmarks, was much less efficient. The performances were 32% worse than good practice and 28% better than typical for electrical energy, and 168% worse than good practice and 46% worse than a typical air conditioned office for gas energy. In terms of building operational costs the building is 66% worse than good practice and 9% better than a typical office building. These are not exactly the comparisons expected for a "green" building.



RESULTS OF OVERALL ASSESSMENT

Building name	Green Office			
Date and reference	1/6/2010	Option B 2009		
Overall grade	C		QA:	Approved
Building floor area m2	4,328		QA:	Approved
Annual energy use electricity (kWh)	410,857		QA:	Approved
Annual energy use non-elec (kWh)	688,252		QA:	Approved

Annual energy performance compared with benchmarks

	Metered energy		Benchmarks		Grade		
	Actual	Adjusted	Good practice	Typical	?		
Electricity kWh/m2	95	95	103	187	B	7% better than Good Practice	49% better than Typical
Non-electricity kWh/m2	159	164	87	160	E	88% worse than Good Practice	2% worse than Typical
Carbon emissions kgCO2/m2	71	72	60	110	C	19% worse than Good Practice	35% better than Typical
Cost £/m2	£10.15	£10.26	£8.85	£16.17	C	16% worse than Good Practice	37% better than Typical
Building total kg CO2	306,900	310,900	260,700	476,400	C	50,200 worse than Good Practice	165,500 better than Typical
Building total cost (£)	£43,900	£44,400	£38,300	£70,000	C	£6,100 worse than Good Practice	£25,600 better than Typical

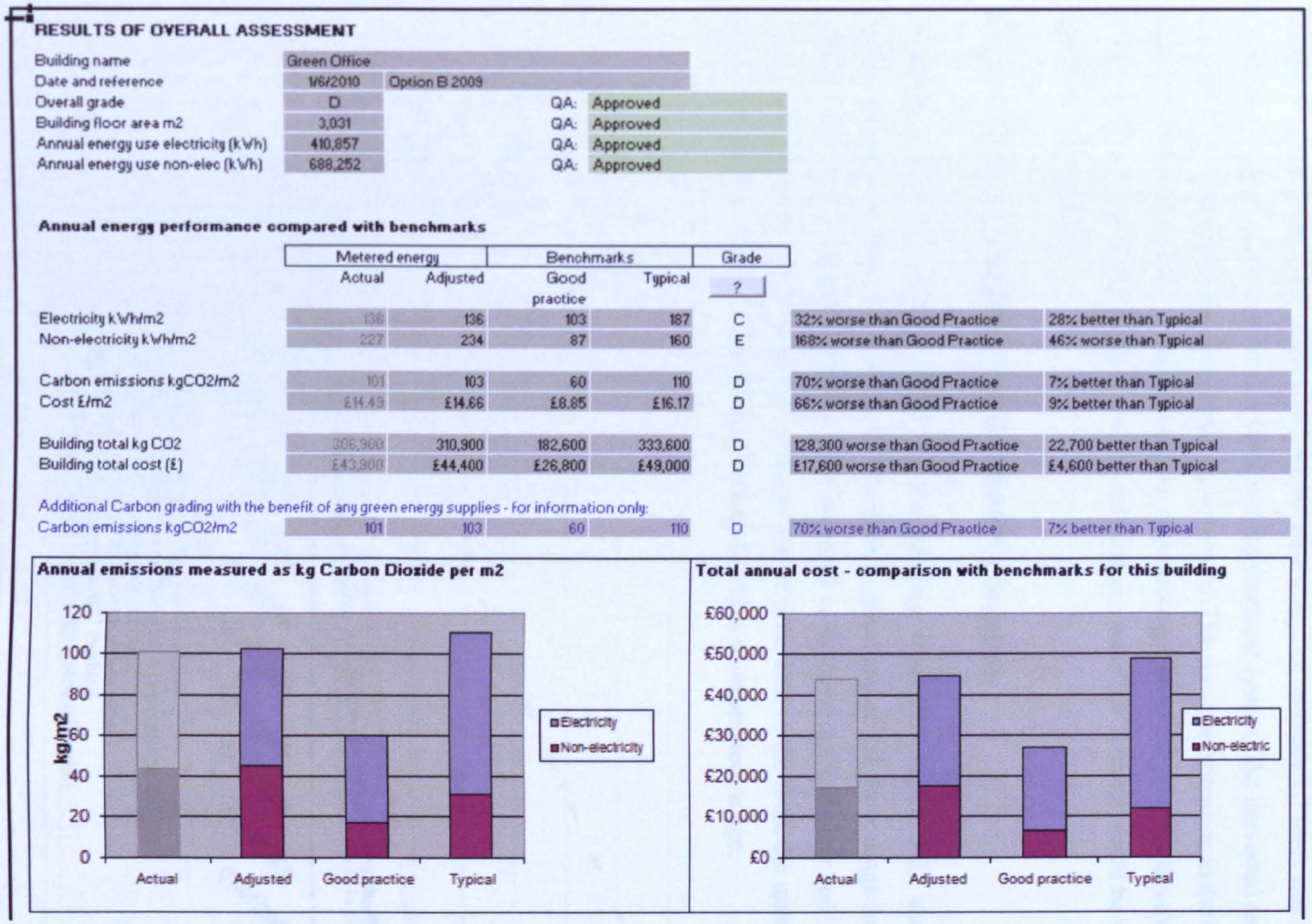
Additional Carbon grading with the benefit of any green energy supplies - for information only:

Carbon emissions kgCO2/m2	71	72	60	110	C	19% worse than Good Practice	35% better than Typical

Annual emissions measured as kg Carbon Dioxide per m2

Total annual cost - comparison with benchmarks for this building

Figure 5-20: CIBSE TM22 Option B assessment result



RESULTS OF OVERALL ASSESSMENT

Building name	Green Office			
Date and reference	1/6/2010	Option B 2009		
Overall grade	D		QA:	Approved
Building floor area m2	3,031		QA:	Approved
Annual energy use electricity (kWh)	410,857		QA:	Approved
Annual energy use non-elec (kWh)	688,252		QA:	Approved

Annual energy performance compared with benchmarks

	Metered energy		Benchmarks		Grade		
	Actual	Adjusted	Good practice	Typical	?		
Electricity kWh/m2	136	136	103	187	C	32% worse than Good Practice	28% better than Typical
Non-electricity kWh/m2	227	234	87	160	E	168% worse than Good Practice	46% worse than Typical
Carbon emissions kgCO2/m2	101	103	60	110	D	70% worse than Good Practice	7% better than Typical
Cost £/m2	£14.49	£14.66	£8.85	£16.17	D	66% worse than Good Practice	9% better than Typical
Building total kg CO2	306,900	310,900	182,600	333,600	D	128,300 worse than Good Practice	22,700 better than Typical
Building total cost (£)	£43,300	£44,400	£26,800	£49,000	D	£17,600 worse than Good Practice	£4,600 better than Typical

Additional Carbon grading with the benefit of any green energy supplies - for information only:

Carbon emissions kgCO2/m2	101	103	60	110	D	70% worse than Good Practice	7% better than Typical

Annual emissions measured as kg Carbon Dioxide per m2

Total annual cost - comparison with benchmarks for this building

Figure 5-21: CIBSE TM22 Option B assessment results- occupied office and all communal spaces

5.3 Water

In an attempt to minimise water use in the building a vacuum drainage system for the WCs, waterless urinals and the low volume fittings in the hand wash basins were all installed. The low volume WCs used rain water harvested from the west wing roof and only 1.2 litres was required per flush compared with around 6 to 9 litres in a conventional system. The harvested rain water is stored in an underground tank and treated prior to use. The water consumption in the building was predicted to be around 1.27m^3/person/year, representing a water usage of 5.0 litres/full time employee/day. It was also predicted that the use of mains water for flushing would be virtually eliminated (King 2007).

5.3.1 Water consumption results and CO_2 impacts

Occupancy information was provided by the building managers. Figure 5-22 shows the predicted (based on the actual number of occupants), typical and actual water usage from May 2008 to May 2009. In February 2009, a fault occurred in the harvested rainwater tank and this caused an increase in mains water use over a period of time. Due to the fault, the mains water data from February 2009 onwards has been extrapolated based on previous usage.

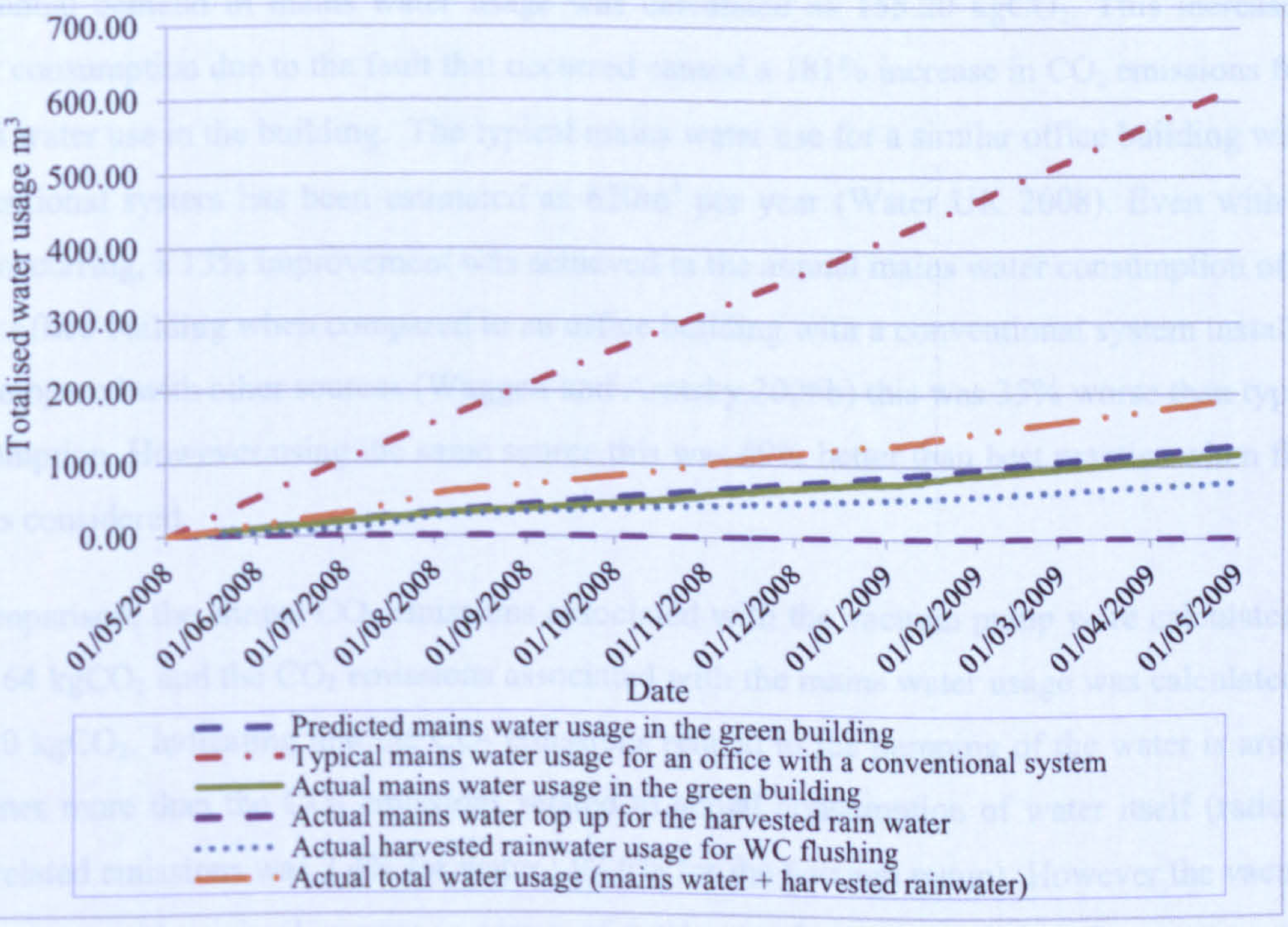


Figure 5-22: Annual predicted, typical (Water UK 2008) and actual water usage in the building

The results indicate that the annual amount of mains water used in the building was only 20% of the mains water used in an office with a conventional flushing system (Water UK 2008) and was around 10% less than the predicted value. No mains water was required to supplement the harvested rain water; therefore the use of mains water for flushing the WCs was eliminated. The total annual water usage for both mains water consumption and the harvested rain water was 30% of the total water used in an office with a conventional flushing system. This reflects the effectiveness of the low volume system and fittings.

Based on the extrapolated data the actual annual mains water consumption in the building was 115.58m^{3}, i.e. 1.15m^{3}/employee/year which is significantly better than best practice figures that have been quoted (Waggett and Arotsky 2006b). With no mains top up required for flushing the WCs and harvested rainwater as 76.71m^{3}. This represents a total water usage as 192.30m^{3}. In terms of CO_2 emissions, the annual demand in mains water usage was calculated as 33.15kgCO_2.

However, as mentioned a fault did occur with the valve in the harvested rainwater tank and this caused an increase in the consumption of mains water use for a period of time. This fault had a significant impact on the water consumption for the duration of the faulty period. The actual annual mains water consumption in the building was calculated as 541.14m^{3}. This in turn relates to 200.19m^{3} of the mains water being required to top-up the harvested rain water. The consumption of harvested rain water was calculated as 300.29 m^{3}. In terms of CO_2 emissions, the annual demand in mains water usage was calculated as 155.20 kgCO_2. This increase in water consumption due to the fault that occurred caused a 181% increase in CO_2 emissions from mains water use in the building. The typical mains water use for a similar office building with a conventional system has been estimated as 620m^{3} per year (Water UK 2008). Even with the fault occurring, a 13% improvement was achieved in the annual mains water consumption of the green office building when compared to an office building with a conventional system installed. Yet compared with other sources (Waggett and Arotsky 2006b) this was 35% worse than typical consumption. However using the same source this was 69% better than best practice when floor area is considered.

In comparison, the annual CO_2 emissions associated with the vacuum pump were calculated as 6356.64 kgCO_2 and the CO_2 emissions associated with the mains water usage was calculated as 155.20 kgCO_2. Indicating that the CO_2 emissions related to the pumping of the water is around 40 times more than the CO_2 emissions related to actual consumption of water itself (ratio for CO_2 related emissions was 2.4% for water : 97.6% for the vacuum pump). However the vacuum pump consumed minimal energy in terms of total annual energy and therefore as a system appears efficient and has potential in future building designs, provided it is well maintained and there is an efficient response to reactive maintenance tasks.

5.4 Internal environment

The internal environment was monitored as part of the study. This included temperature and lighting level investigations. From occupant survey results (presented in a later chapter), it was identified that overheating (and under-heating) were a concern in some of the locations within the building.

5.4.1 Office temperatures and over-heating within the building

The internal temperatures of the office zones have been recorded by the BMS and further measurements were collected using Tinytag data loggers. The zones and labelling convention was described in the methodology chapter. The space temperatures during the occupied hours (between 8am and 6pm Monday to Friday, excluding bank holidays) of the zones which have BMS sensors installed were analysed initially. The analysed data is shown in Table 5-9. These results identified that:

- Temperatures exceeding 28°C were experienced 0% of the occupied hours in the year. CIBSE define a 'hot' threshold at 28°C, and the overheating criterion is 1% occupied hours over 28°C (CIBSE 2005b).
- Temperatures exceeding 26°C were experienced 1% of the occupied hours in the year in zone EWZ1S1 and zone WWZ2S1.
- Temperatures exceeding a CIBSE 'warm' threshold of 25°C were experienced in all of the occupied zones. However, these were all at the 1% level, with the exception of zones WWZ1S2, WWZ2S1, WEZ2S2 and EWZ1S1 where the percentage of occupied hours when the temperature exceeded 25°C were 5%, 8%, 5% and 6% respectively.
- The greatest percentage of occupied hours when the temperatures were below 20°C was in the unoccupied zones.

Table 5-9: BMS data- temperature threshold °C (% of occupied hours measured under various temperature thresholds)

Location			% complete data set (occupancy hours)	Temperature Threshold C (% of occupied hours measured under various temperature thresholds)												
				t<16	t<17	t<18	t<19	t<20	<21	21<t<23	t>23	t>24	>25	t>26	>27	t>28
West West	**Code**	**Occupied?**														
Ground floor	WWZ1S1	Meeting room	86	0	3	9	30	54	78	17	4	1	0	0	0	0
	WWZ1S2	Occupied	86	0	0	0	3	12	25	44	31	15	5	0	0	0
First floor	WWZ2S1	Occupied	86	0	0	0	1	3	13	41	47	23	8	1	0	0
	WWZ2S2	Occupied	86	0	0	0	2	9	27	57	16	6	1	0	0	0
Second floor	WWZ3S1	Unoccupied	86	0	1	16	46	75	90	10	0	0	0	0	0	0
	WWZ3S2	Unoccupied	86	0	1	8	31	61	82	17	1	0	0	0	0	0
West East	**Code**	**Occupied?**														
Ground floor	WEZ1S1	Meeting room	100	0	0	0	1	10	49	47	3	0	0	0	0	0
	WEZ1S2	Occupied	100	0	1	7	14	21	34	33	33	14	5	0	0	0
First floor	WEZ2S1	Unoccupied	100	0	0	0	0	7	42	55	3	1	0	0	0	0
	WEZ2S2	Occupied	100	0	0	1	5	14	30	50	20	7	1	0	0	0
Second floor	WEZ3S1	Unoccupied	100	0	0	0	12	41	75	24	1	0	0	0	0	0
	WEZ3S2	Unoccupied	100	0	2	11	84	57	84	16	0	0	0	0	0	0
East East	**Code**	**Occupied?**														
Ground floor	EEZ1S1	Occupied	87	0	0	2	8	17	33	51	16	5	1	0	0	0
	EEZ1S2	Unoccupied	86	0	3	9	20	30	46	40	14	3	1	0	0	0
First floor	EEZ2S1	Occupied (May 2009)	86	0	1	3	8	28	53	40	6	2	1	0	0	0
	EEZ2S2	Unoccupied	86	15	26	47	71	91	98	2	0	0	0	0	0	0
East West	**Code**	**Occupied?**														
Ground floor	EWZ1S1	Occupied	86	0	0	0	0	0	3	46	51	24	6	1	0	0
	EWZ1S2	Unoccupied (occupied towards the end of 2009	86	0	0	0	0	15	44	43	14	5	1	0	0	0
First floor	EWZ2S1	Unoccupied	85	0	0	1	11	38	69	28	2	0	0	0	0	0
	EWZ2S2	Unoccupied	87	0	0	9	25	54	82	17	1	0	0	0	0	0

The investigations revealed that many of the offices where the BMS temperature sensors area located within were permanently unoccupied or used as occasional meeting rooms. Unfortunately, these unoccupied zones are effectively controlling the temperature in the building. The data in the table above shows poor temperature control as many of the occupied zones experienced temperatures of greater than 25°C for more than 5% of the occupied hours.

Occupied offices within the building which have no BMS sensors located within them were also monitored using Tinytag data loggers. Loggers were installed for a one year period and programmed to log at 15 minute intervals. The temperature conditions were analysed and the results are shown in Table 5-10 below.

Table 5-10: Temperatures in occupied offices with no BMS sensor present

Office ID	% of a full data set	Average	Temperature Threshold °C (% of occupied hours measured under various temperature thresholds)										
			t<17	t<18	t<19	t<20	<21	21<t<23	t>23	t>24	>25	t>26	t>27
1	82	23.6	0	0	0	0	2	36	63	39	8	1	0
2	65	20.8	0	1	10	33	50	41	9	2	1	1	0
3	70	22.6	0	0	0	2	9	36	55	13	3	0	0
4	100	22.8	0	0	0	1	8	40	52	18	6	2	0
5	100	22.6	0	0	2	6	17	26	57	18	6	1	0
6	70	22.0	0	0	0	2	34	12	53	11	0	0	0

This additional analysis confirmed poor control as many of the occupied offices, which have no direct influence on the temperature control, were experiencing greater occasions of higher temperatures. This is discussed in more detail in the following section.

5.4.2 Average VAV group temperatures for plant control

The system monitors the average zone temperature and responds with an action accordingly, whether to heat or cool the particular VAV group. However there are two temperature sensors within each zone, from which the average is obtained. In some areas of the building one, or both of the temperature sensors may fall in two unoccupied offices and therefore suggest that the building requires heating (as these unoccupied zones will be cooler due to the lack of internal heat gains). This in some situations may be causing the system to operate in full heating mode in an attempt to protect and maintain the required temperatures in the offices within the zone; this will result in some of the occupied offices overheating. This is shown in Table 5-10 (see column >25).

Temperatures of the building were collected over the monitoring period and the results are shown in the Figures 5-23 to 5-25. The locations of the associated VAV group and AHU are shown in the Table 5-11.

Table 5-11: VAV groups by AHU and floor

	AHU 1	AHU 2	AHU 3	AHU 4
Ground Floor	EW Z1 Space 1 EW Z1 Space 2*	EE Z1 Space 1 EE Z1 Space 2*	WW Z1 Space 1** WW Z1 Space 2	WE Z1 Space 1** WE Z1 Space 2
First Floor	EW Z2 Space 1* EW Z2 Space 2*	EE Z2 Space 1 EE Z2 Space 2*	WW Z2 Space 1 WW Z2 Space 2	WE Z2 Space 1* WE Z2 Space 2
Second Floor			WW Z3 Space 1* WW Z3 Space 2*	WE Z3 Space 1* WE Z3 Space 2*

Note: Room status as of May 2009, where *= unoccupied office, **=meeting room (mostly unoccupied, with occasional use).

As an example, in the west west zone on the ground floor the WW Z1 Space 1 sensor is located in a meeting room which is unoccupied apart from occasional use and the WW Z1 Space 2 sensor is located in an occupied office. The BMS calculates an average from these two temperature sensors and responds in such that it will provide heating or cooling if required. The graphs shown in Figure 5-23 show the measured temperatures for January, April July and December 2009.

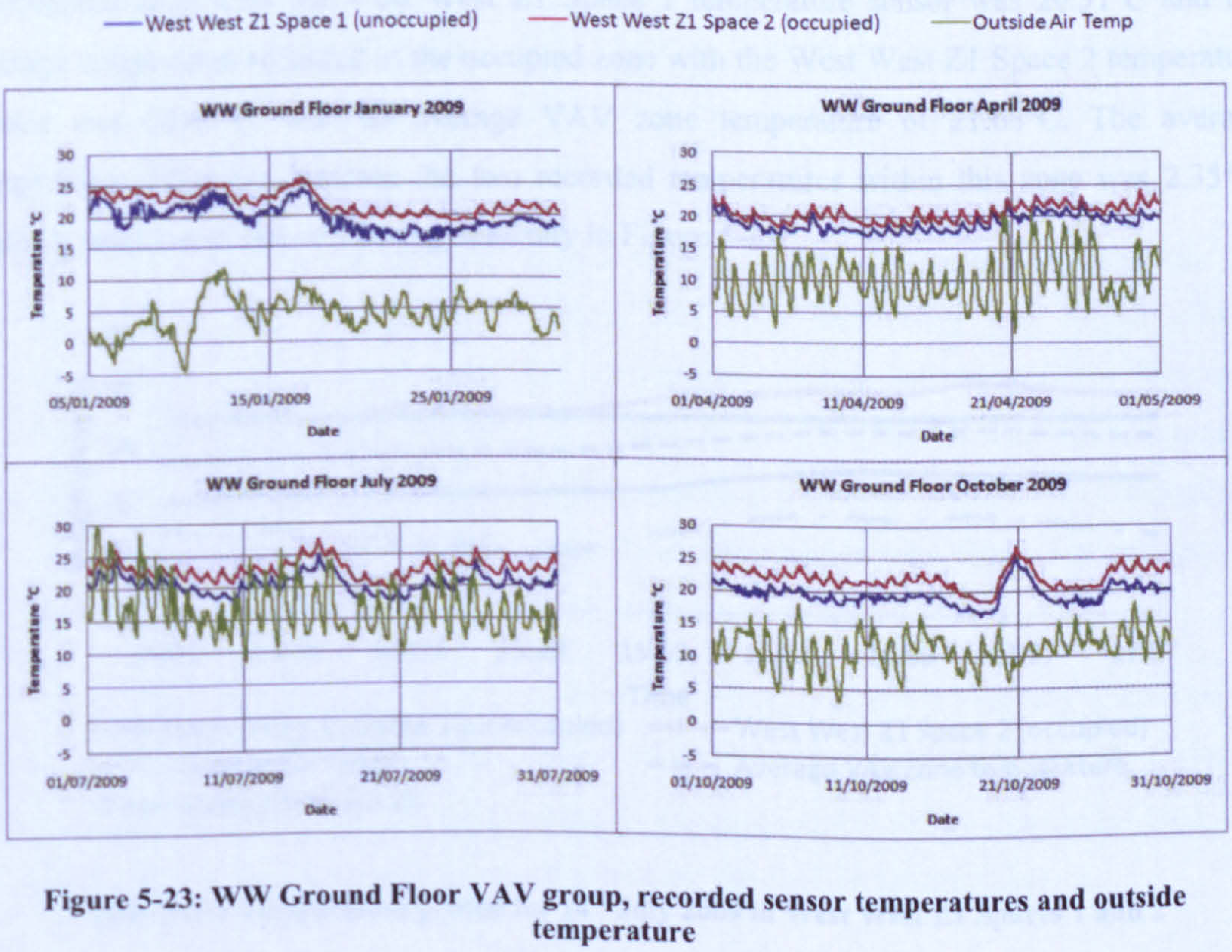


Figure 5-23: WW Ground Floor VAV group, recorded sensor temperatures and outside temperature

In January 2009 average outside temperature was 3.65°C. The average temperature recorded in the unoccupied zone by the West West Z1 Space 1 temperature sensor was 19.68°C and the average temperature recorded in the occupied zone by the West West Z1 Space 2 temperature sensor was 21.99°C, with therefore an average VAV zone temperature of 20.83°C. The average temperature difference between the two recorded temperatures within this zone was 2.31°C. A snapshot of this is shown graphically in Figure 5-24.

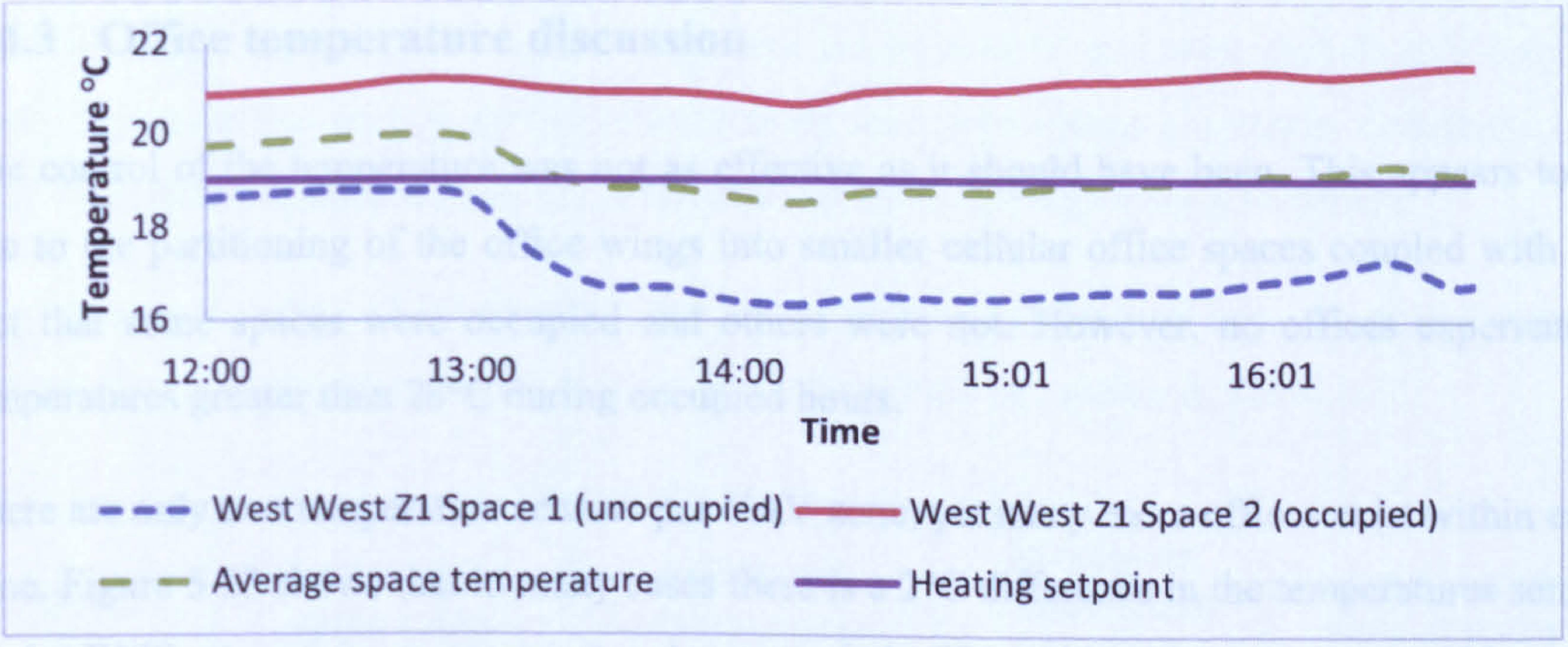


Figure 5-24: Temperature profile on a typical day in January 2009 in West West Z1 Spaces 1 and 2

In July 2009 average outside temperature was 16.62°C. The average temperature recorded in the unoccupied zone with the West West Z1 Space 1 temperature sensor was 20.51°C and the average temperature recorded in the occupied zone with the West West Z1 Space 2 temperature sensor was 22.85°C, with an average VAV zone temperature of 21.68°C. The average temperature difference between the two recorded temperatures within this zone was 2.35°C. Again a snapshot of this is shown graphically in Figure 5-25.

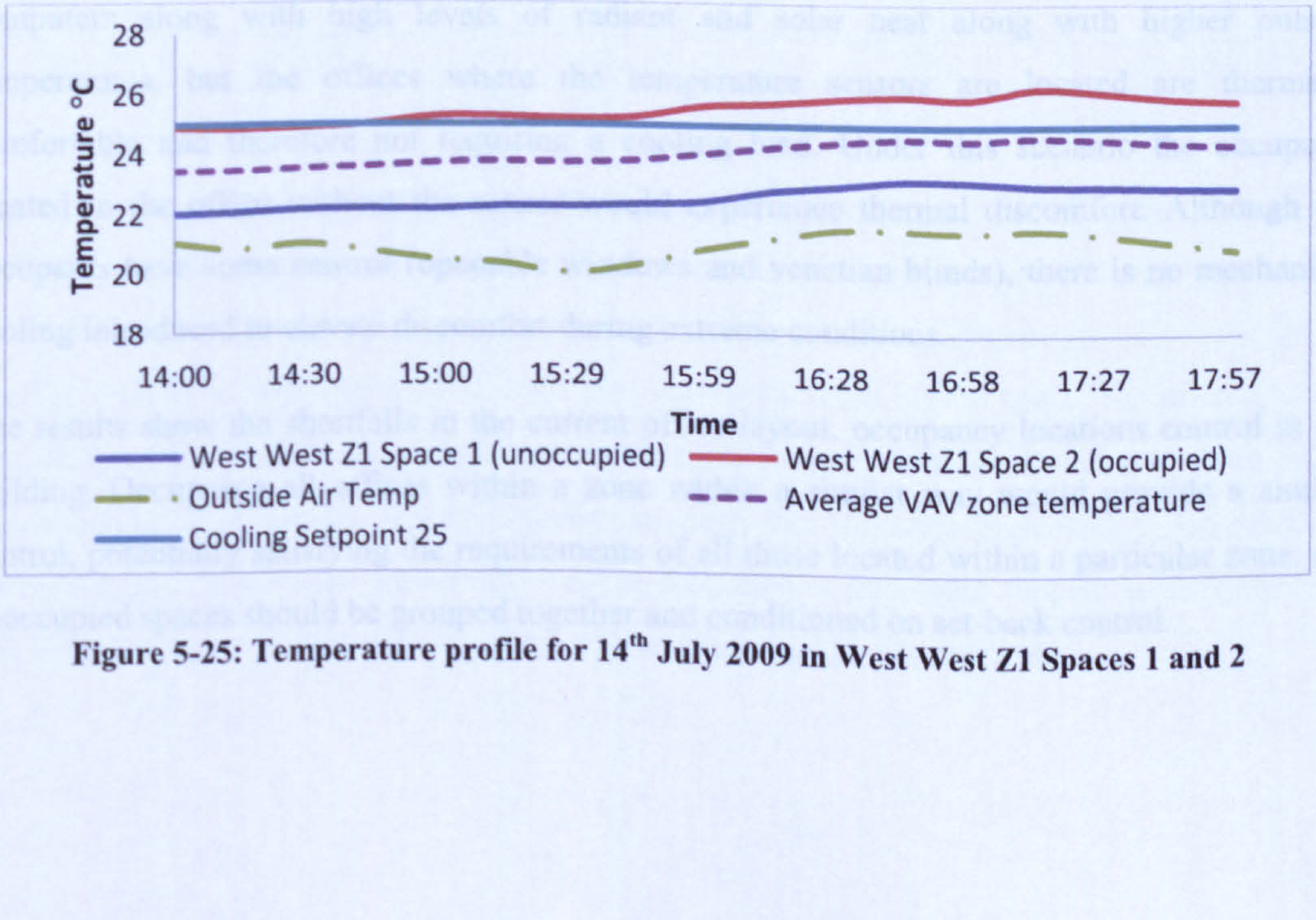


Figure 5-25: Temperature profile for 14th July 2009 in West West Z1 Spaces 1 and 2

The location of the temperature sensors that signal a response via the BMS are in some areas of the building that are almost permanently unoccupied. This has in some situations resulted in over-heating in some occupied areas, in response to the lower average temperatures and potentially under-cooling summer months. This may have impact on the thermal comfort of the occupants within the building. In situations where overheating occurs this can be very wasteful in terms of energy consumption.

5.4.3 Office temperature discussion

The control of the temperature was not as effective as it should have been. This appears to be due to the partitioning of the office wings into smaller cellular office spaces coupled with the fact that some spaces were occupied and others were not. However, no offices experienced temperatures greater than 28°C during occupied hours.

There are only two temperature sensors per VAV zone, yet many more offices exist within each zone. Figure 5-23 shows that in many cases there is a 2°C difference in the temperatures sensed by the BMS sensors in an occupied and unoccupied office within the same zone. If in some cases the sensor is located in an office with low occupancy and the other sensor within that zone is located in an unoccupied area then this may signal the BMS to introduce a heating load into that VAV group. However, if one of the offices situated within that group (which does not have a temperature sensor located within it) has a high occupancy density, and therefore is thermally comfortable with temperatures in the region of 21°C to 23°C then introducing a heating load in this area could cause the area to overheat and the occupants will then experience thermal discomfort.

Likewise in the summer, this area may require cooling as there is a high level of people and computers along with high levels of radiant and solar heat along with higher outside temperatures, but the offices where the temperature sensors are located are thermally comfortable and therefore not requiring a cooling load. Under this scenario the occupants located in the office without the sensor would experience thermal discomfort. Although the occupants have some control (openable windows and venetian blinds), there is no mechanical cooling introduced to elevate discomfort during extreme conditions.

The results show the shortfalls in the current office layout, occupancy locations control in the building. Occupying all offices within a zone within a similar way would provide a similar control, potentially satisfying the requirements of all those located within a particular zone. All unoccupied spaces should be grouped together and conditioned on set-back control.

5.4.4 Analysing the performance of the atrium

A photograph of the atrium is shown earlier in Figure 3-4. The atrium was designed to achieve a temperature of 21°C during the occupied hours and 19°C outside of occupied hours. There are two temperature sensors located in the atrium, an average of the two are used to action a response from the underfloor heating and natural ventilation strategy in place within the atrium. The installed underfloor heating is made up of pipes carrying Low Temperature Hot Water (LTHW). Typically the LTHW of these systems are set at 40°C and often operate on a constant basis. An underfloor heating system relies entirely on convection as a means of transferring the heat. Underfloor heating systems are often ideal solutions for high ceiling buildings.

The concrete floor has a high thermal mass that helps with temperature swings within the space. The average monthly atrium temperatures throughout 2009 are shown in Table 5-12.

Table 5-12: Atrium temperatures

Month-Year	Average atrium space temp temperature (°C)	Minimum atrium space temperature (°C)	Maximum atrium space temperature (°C)	Average outside temperature (°C)
Jan-09	21.83	20.02	23.60	3.65
Feb-09	22.08	20.63	23.76	6.63
Mar-09	22.22	20.60	24.70	7.37
Apr-09	22.07	17.26	25.28	10.13
May-09	22.36	16.99	26.48	12.12
Jun-09	22.07	17.18	25.99	14.53
Jul-09	22.34	17.76	26.65	16.62
Aug-09	22.02	17.22	26.35	17.21
Sep-09	22.23	17.44	25.33	14.19
Oct-09	22.13	18.07	24.61	11.29
Nov-09	21.62	18.33	23.43	7.73
Dec-09	20.77	18.30	23.54	2.94

The atrium is a highly glazed area and there are significant amounts of heat loss through the roof. The control strategy set out to aim for an internal temperature of 21°C during occupied hours and 19°C during unoccupied hours. Constant operation of these types of underfloor heating systems is common as it can take a long time to warm up the space. Maintaining these temperatures, particularly during the night when there is significant heat losses due to the highly glazed atrium roof, results in a high boiler demands and therefore high energy consumption. The graphs in Figure 5-26 present the measured external temperature (shown as the blue line) and the internal space temperatures of the atrium (indicated by the red line).

Figure 5-26: Monthly atrium and external temperatures (January 2009 to December 2009)

Simulation results estimated that half of the space heating consumption is due to maintaining the temperatures of the atrium. The analysis found that the atrium was achieving the space temperatures required, however there was significant gas consumption throughout the evenings when the temperatures dropped but the set point of 19°C during unoccupied hours. This is shown in Figure 5-27. This raises the question of whether potential energy could be saved by lowering the control set point slightly. An intervention during the POE could have tested this to see if this could be an effective way of fine tuning the system.

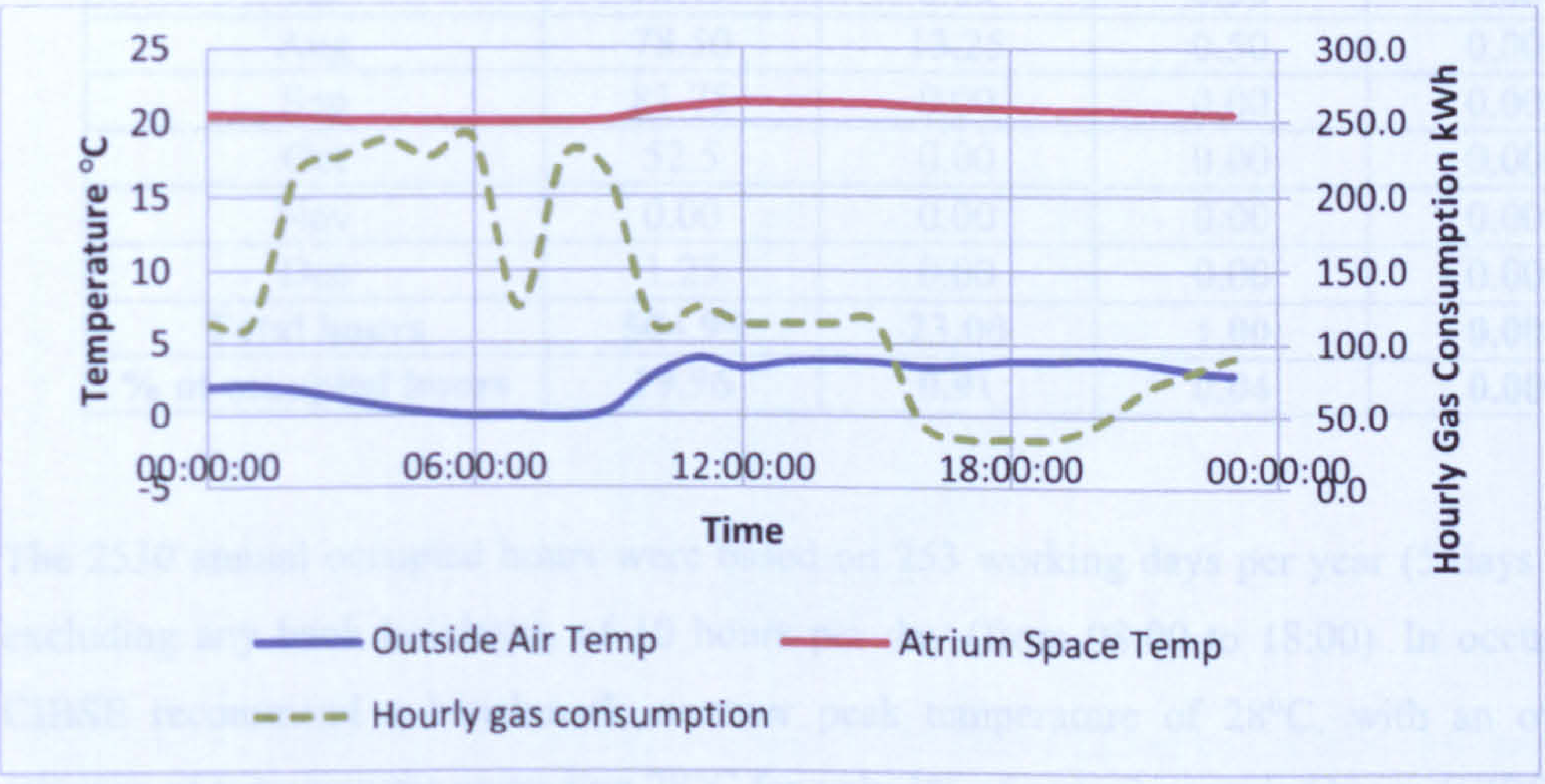


Figure 5-27: Typical atrium and outside temperatures and hourly gas consumptions during December 2009

The occasions when the internal temperature of the atrium exceeds external temperatures are a result of the high levels of glazing and the solar gains. The high levels of internal space temperature are relieved by passive means -natural ventilation within the space utilising two levels of upper windows. Overall the atrium provided high levels of comfort to the occupants within the buildings throughout the year. During the winter months the internal temperatures were achieved.

During occupied hours, the numbers of hours that the atrium temperature exceeded various temperature thresholds were tested and the results are shown in the Table 5-13. There was an incomplete dataset for February 2009 (55% complete) but complete for all other months.

Table 5-13: Overheating hours during occupied hours

Overheating hours during occupied hours	>23°C	>25°C	>26°C	>28°C
Jan	16.25	0.00	0.00	0.00
Feb	25.45	0.00	0.00	0.00
Mar	42.25	0.00	0.00	0.00
Apr	36.25	0.00	0.00	0.00
May	42.25	1.00	0.00	0.00
Jun	54.75	0.75	0.00	0.00
Jul	73.75	8.00	0.50	0.00
Aug	78.50	13.25	0.50	0.00
Sep	81.75	0.00	0.00	0.00
Oct	52.5	0.00	0.00	0.00
Nov	0.00	0.00	0.00	0.00
Dec	1.25	0.00	0.00	0.00
Total hours	**504.95**	**23.00**	**1.00**	**0.00**
% of occupied hours	**19.96**	**0.91**	**0.04**	**0.00**

The 2530 annual occupied hours were based on 253 working days per year (5 days per week, excluding any bank holidays), of 10 hours per day (from 08:00 to 18:00). In occupied areas CIBSE recommend a benchmark summer peak temperature of 28°C, with an overheating criterion of temperatures exceeding 28°C for only 1% of annual occupied hours (CIBSE 2005b). From the analysis carried out, the atrium never exceeded 28°C, and only exceeded 26°C and 25°C by 0.04% and 0.91% respectively during annual occupied hours. The internal temperature exceeded 23°C for 19.96% of annual occupied hours, interestingly 8.5% of these hours were in the winter months of (January, February and March) when this overheating was wasteful and could have caused the lower vents of the BMS to open and introduce an additional load on the boiler to counteract the effects of the vents opening in attempts to lower the internal temperature of the atrium.

5.4.5 Lighting levels

The lighting levels have been measured in terms of both daylight and artificial lighting. The procedure recommended by Littlefair (1993) was used to assess the daylight factors.

Lighting system in the building

The building was designed to exploit natural daylight thus reducing artificial lighting demands. The building comprises of two wings, one two storeys high and the other three, with a central atrium linking the two wings. Within the office spaces, the lighting installation was designed to meet the lighting requirements set out in Code for Lighting (CIBSE 2002a). Low energy T5 compact fluorescent lamp fittings were installed in the office areas. Each light fitting unit consisted of 2 x 2 x 35 W (T5) fluorescent tubes with a PIR sensor to switch on the luminaries in response to detected occupant movement. For additional energy efficiency, the artificial lights were coupled to photoelectric cells which detected the levels of light and automatically dimmed the lighting in response to the available daylight. The lighting units were generally fitted perpendicular to the external wall and mid-way between the windows.

The building's orientation and fenestration is shown in Figure 5-28. With windows located on the east and west facades only, direct sun exposure into the building was limited to the mornings and late afternoon.

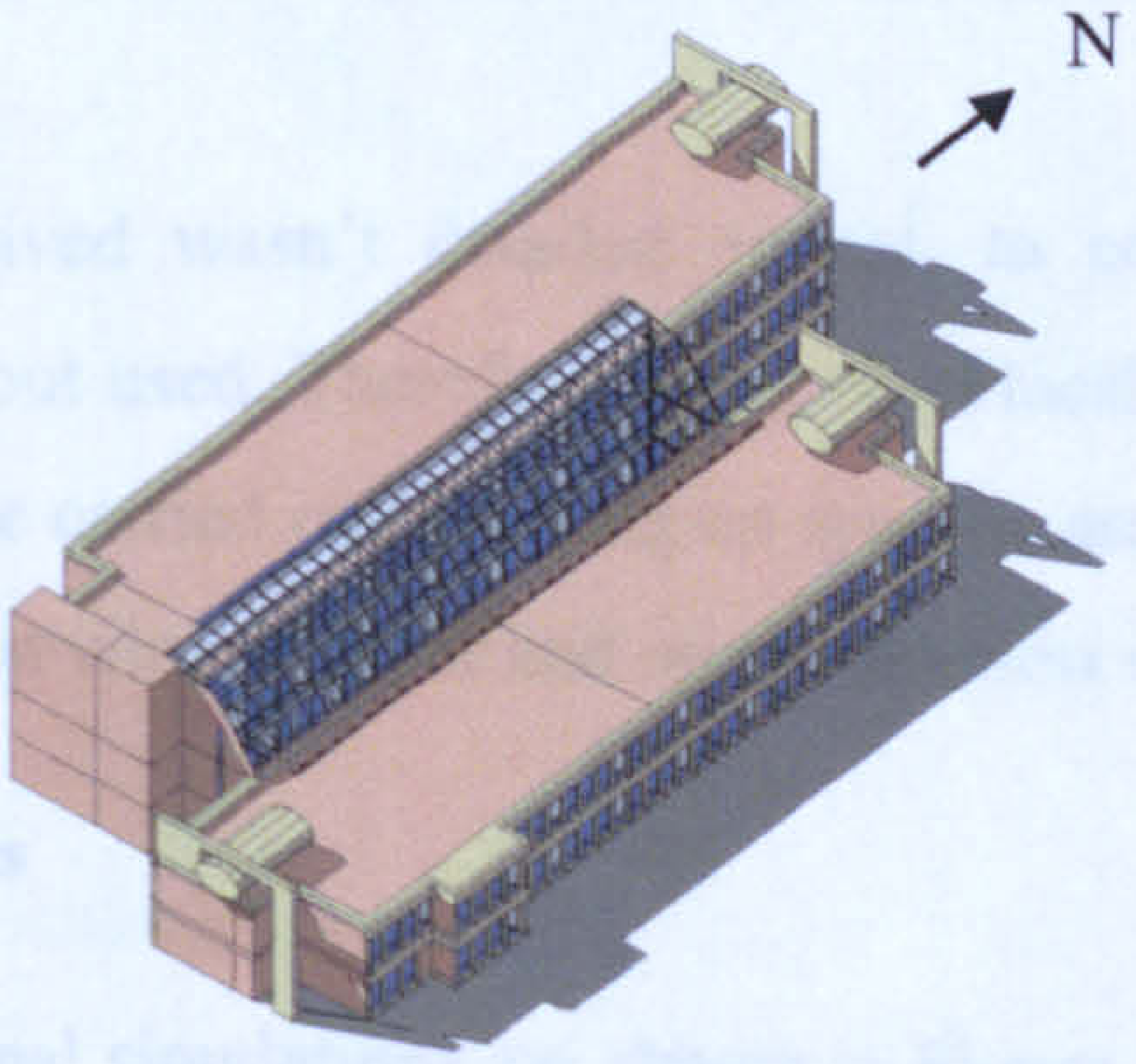


Figure 5-28: Suncast image showing the shadows simulated during late afternoon in mid-summer

A comparison of the designed and actual energy performance of the installed lighting system was presented in an earlier section and is also reported in a recent publication (Birchall and Tinker 2010).

Methodology - physical measurements

The procedure used for carrying out the physical measurements is described in the Methodology chapter.

Methodology – simulation

During design stage, IES<VE> (IES 2010) was used to simulate the energy consumption of the building as well as the daylight factors within the building.

From documentation supplied by the designers only the overall daylight factors of the zones were available and from these it was found that the average daylight factor for the individual office zones was predicted to be 4.18%. These simulated average daylight factors for the various zones are shown in Table 5-14.

Table 5-14: Simulated average daylight factors

Zone	Simulated average daylight factor (%)
East wing ground floor	3.60
West wing ground floor	3.78
East wing 1st Floor	3.78
West wing 1st Floor	4.48
West wing 2nd Floor	5.28
Average	**4.18**

The design information received wasn't detailed enough to compare simulated data with measured data on the grid layout used. Therefore, using the FlucsDL module within IES<VE>, more detailed simulations were carried out focusing on specific areas of the building. The areas selected were the open plan east wing 1st floor and open plan west wing 2nd floor.

Results from simulation tests

The results from these additional simulations are shown in Figure 5-29 (east wing 1st floor) and Figure 5-30 (west wing 2nd floor).

The simulated average daylight factor for the east wing 1st floor was calculated to be 2.1%, with an average illuminance of 257 lux. The daylight factors were simulated for August to be comparable with the measurements taken.

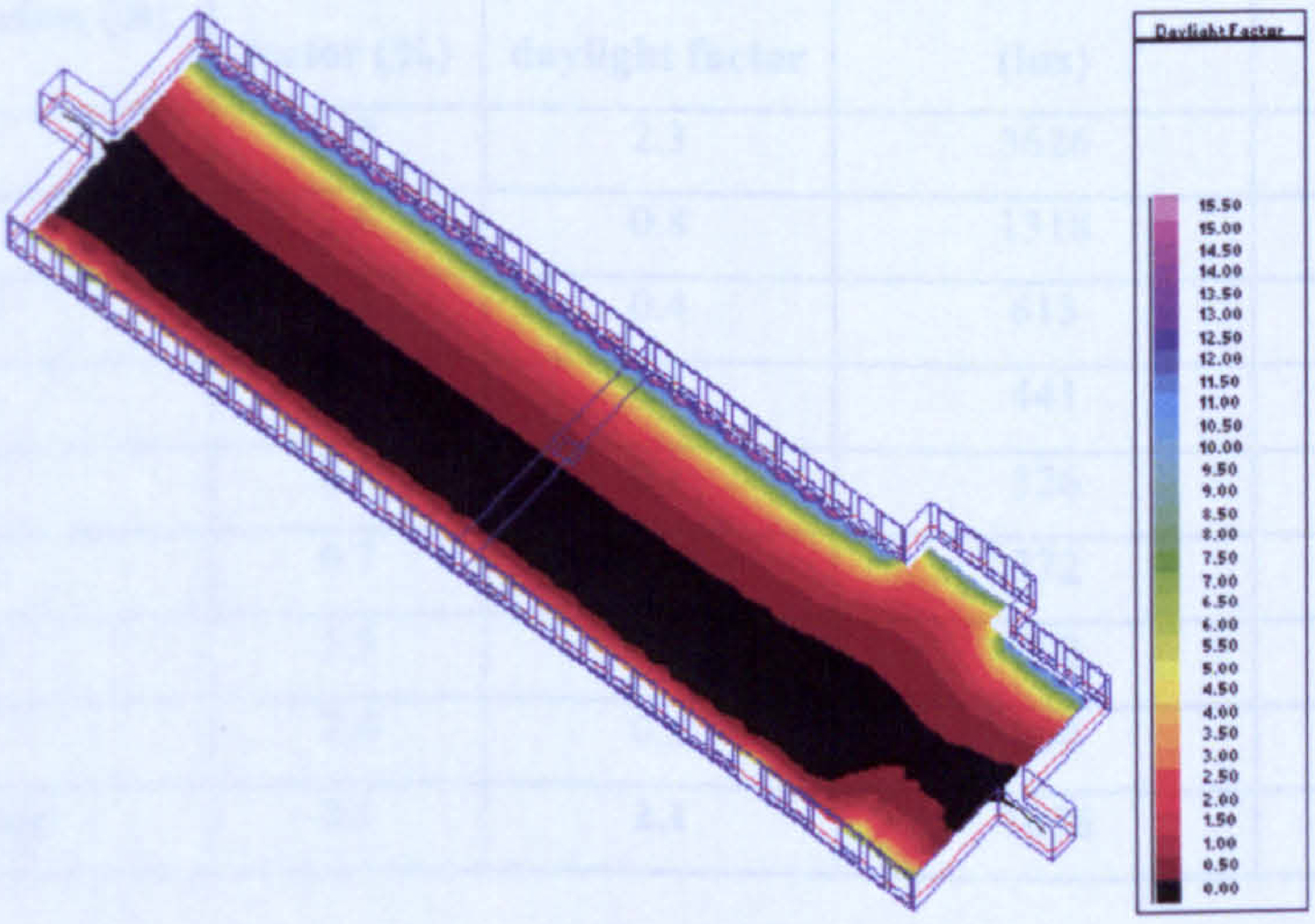


Figure 5-29: Simulated daylight factors for the east wing 1st floor

The simulated average daylight factor for the west wing 2nd floor was calculated to be 3.1%, with an average illuminance of 374 lux. The daylight factors were simulated for September to be comparable with the measurements taken.

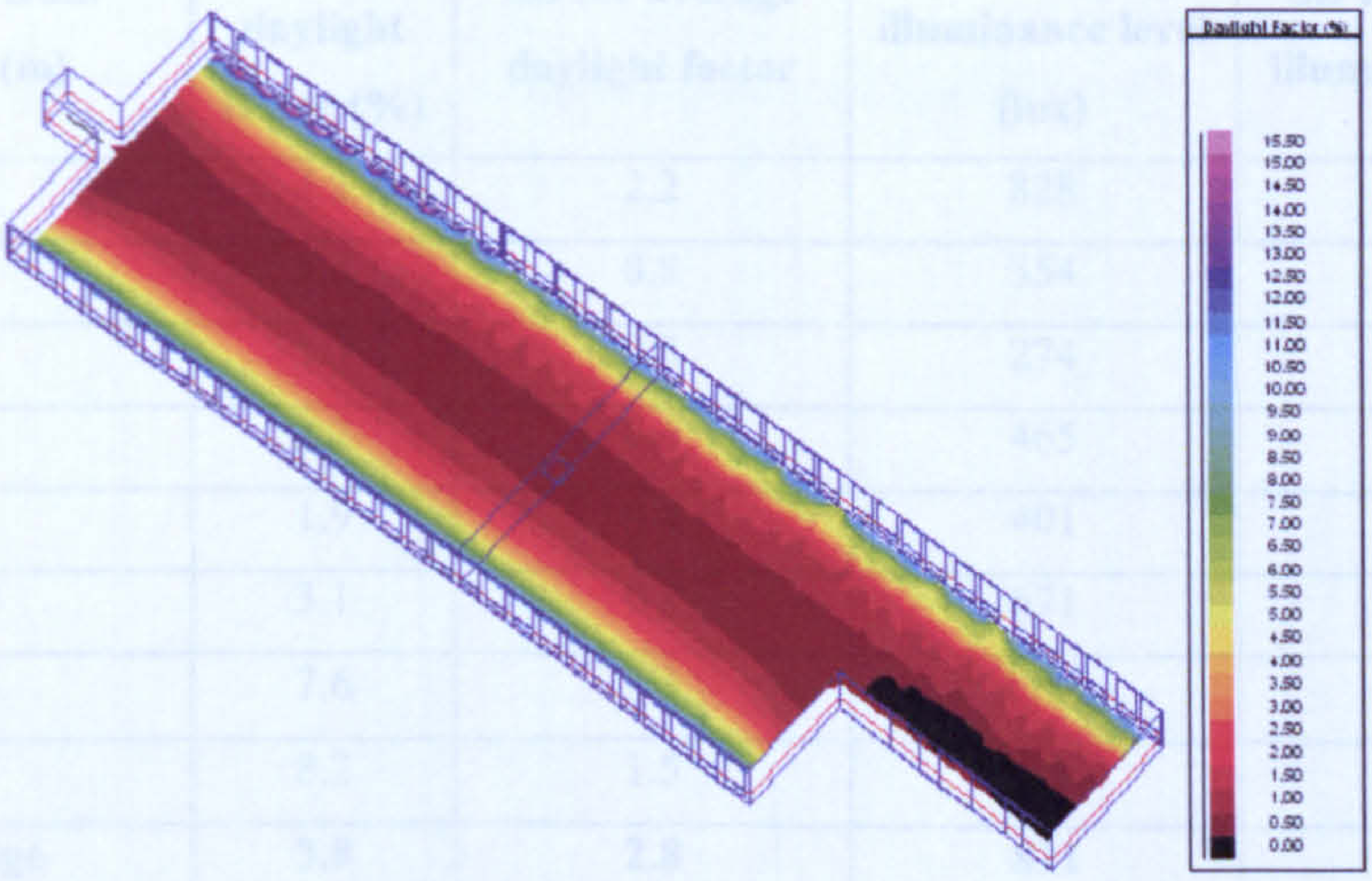


Figure 5-30: Simulated daylight factors for the west wing 2nd floor

Results from physical measurements

The measurements in the east wing 1st floor were carried out at mid-day on 7th August 2009 and are shown in Table 5-15. It was determined that the average daylight factor and illuminance in the room were 2.1% and 1056 lux respectively.

Table 5-15: Measured average illuminance and daylight factors across the east wing 1st floor

Distance from external window (m)	Average daylight factor (%)	SD for average daylight factor	Average illuminance level (lux)	SD for average illuminance level
0.5	6.9	2.3	3626	555.7
2.5	2.6	0.8	1318	234.1
4.5	1.2	0.4	613	106.3
6.5	0.9	0.3	441	53.6
8.5	0.6	0.1	326	70.2
10.5	0.7	0.2	372	112.5
12.5	1.5	0.4	762	249.3
13	2.0	0.9	994	321.1
Average	**2.1**	**2.1**	**1056**	**1056.0**

The measurements in the west wing 2nd floor were carried out at 14:00 on 19th September 2009 and are shown in Table 5-16. It was determined that the average daylight factor and illuminance in the room were 3.8% and 811 lux respectively.

Table 5-16: Measured average illuminance and daylight factors across the west wing 2nd floor

Distance from atrium (m)	**Average daylight factor (%)**	**SD for average daylight factor**	**Average illuminance level (lux)**	**SD for average illuminance level**
0.5	4.2	2.2	828	303.2
2.5	1.8	0.8	354	108.2
4.5	1.3	0.5	274	47.3
6.5	2.2	0.6	465	74.0
8.5	1.9	0.4	401	49.5
10.5	3.1	0.8	671	169.5
12.5	7.6	2.3	1736	873.4
13	8.2	1.5	1759	361.9
Average	**3.8**	**2.8**	**811**	**667.7**

Figure 5-31 shows a cross-section through the building indicating the measured average daylight factors in the east wing 1st floor and west wing 2nd floor. As expected, the factors were the greatest nearest to the windows.

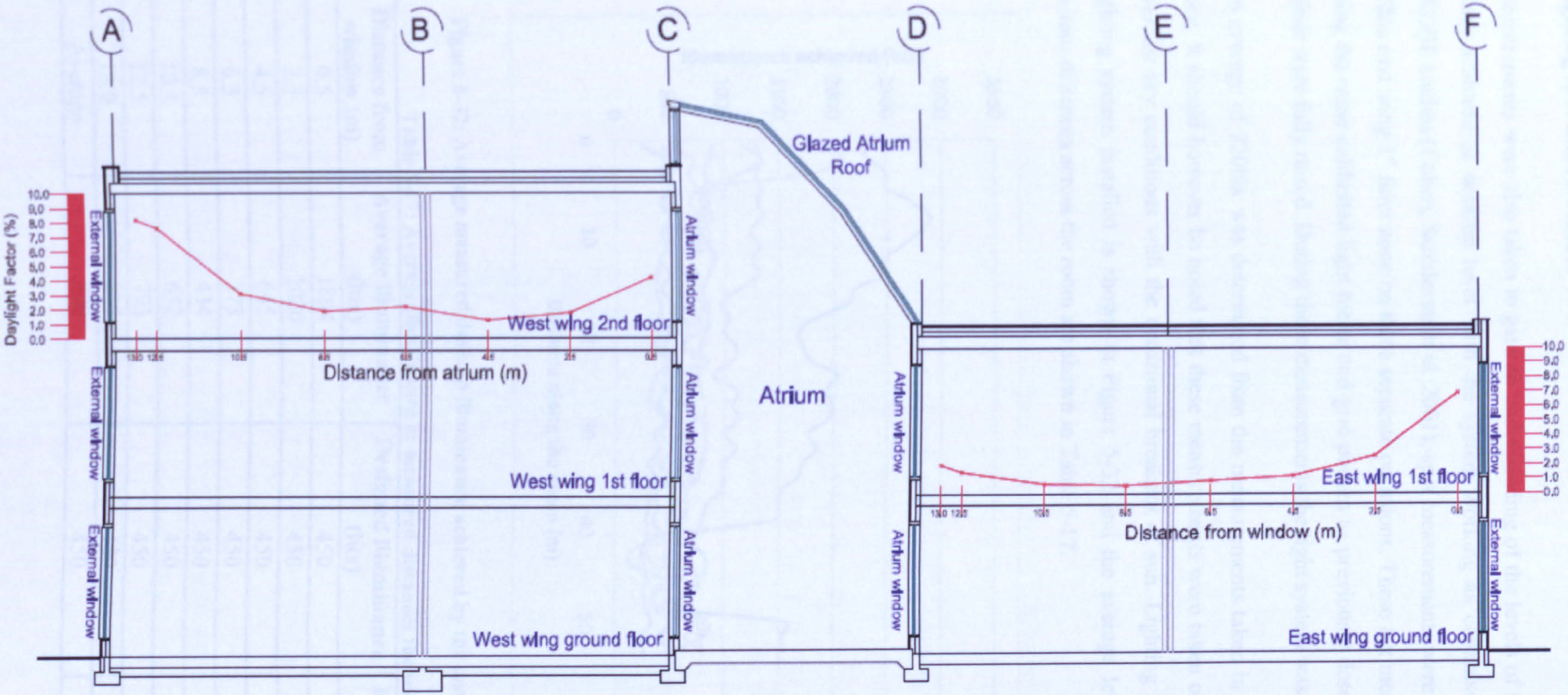


Figure 5-31: Section through the building showing the measured daylight factors for the areas investigated

Lighting spot measurements

Measurements were also taken to gain an understanding of the levels of illuminances that were being achieved at desktop level with the system working as commissioned. Similar to the PROBE studies (Cohen, Standeven et al. 2001), spot measurements were taken in the open plan office east wing 1st floor zone on three separate occasions. These lux measurements were taken using the same calibrated light meter and grid pattern as previously described and the window blinds were fully raised. During these measurements the light system was enabled.

An average of 820lux was determined from the measurements taken in the east wing 1st floor zone. It should however be noted that these measurements were taken on a days with partially overcast sky conditions with the occasional breakout of sun. Lighting levels achieved by the lighting system installed is shown in Figure 5-32 and the average levels of illuminance at various distances across the room are shown in Table 5-17.

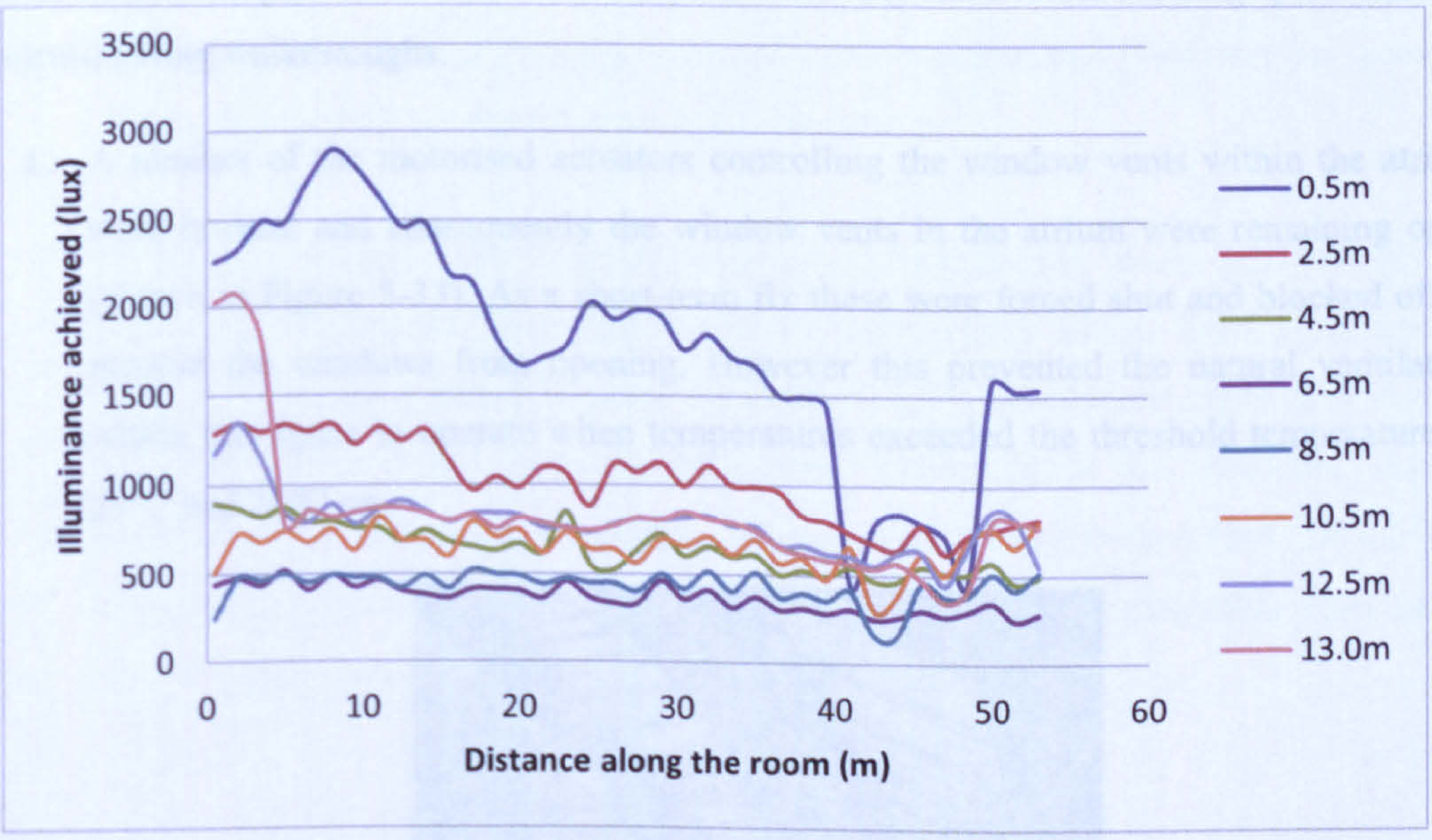


Figure 5-32: Average measured desktop illuminance achieved by the installed lighting system

Table 5-17: Average illuminance at measured distances the window (lux)

Distance from window (m)	Average illuminance (lux)	Designed illuminance (lux)	Required illuminance (lux)
0.5	1804	450	300
2.5	1020	450	300
4.5	645	450	300
6.5	373	450	300
8.5	434	450	300
10.5	652	450	300
12.5	793	450	300
13.0	837	450	300
Average	820	450	300

To minimise disturbance to the occupants in the building measurements were only taken in unoccupied office areas.

The occupied and operational lighting performance of the green office building has been analysed and presented in this section of the thesis. The overall daylight was satisfactory with measured illuminance levels and daylight factors agreeing with those set out in the CIBSE Code for lighting and BS 8206-2:2008. The calculated daylight factors in the east wing 1st floor correlated well with the simulated levels while on the west wing 2nd floor the actual measured values were slightly less than the simulated. In both cases the levels were above the 2% minimum average set out in the relevant codes. The spot measurements showed that the average illuminance levels being achieved were generally above those required and recommended.

5.5 Walkthroughs and other general observations

The notes below report on the most relevant points/issues (related to the buildings performance) observed during walkthroughs.

1. A number of the motorised actuators controlling the window vents within the atrium were broken, and consequently the window vents in the atrium were remaining open (shown in Figure 5-33). As a short-term fix these were forced shut and blocked off to prevent the windows from opening. However this prevented the natural ventilation within this space to operate when temperatures exceeded the threshold temperature of 23°C and 25°C set.

Figure 5-33: Broken actuators in the natural ventilation strategy within the atrium

2. Blinds were often down in the offices over-looking the atrium (as shown in Figure 5-34), presumably as a means of providing additional privacy. However, actions like these would have an adverse effect on the lighting consumption

Figure 5-34: Offices adjacent to the atrium with closed blinds

3. During site visits noise transfer from adjacent offices was very noticeable. Issues surrounding the privacy of telephone conversations and other conversations were therefore a potential problem. The internal partitioning doesn't appear to be adequate enough provide a high enough level of noise dampening. However, no acoustic investigations were conducted as part of this research.

4. Partitioning issues: The impacts caused by partitioning were not thought-out effectively. Partitioning has carried out without seeking advice from a Termodeck Engineer; this has resulted in some offices having an imbalanced ventilation system. The open office layout relies on the central corridor space for ventilation extract, therefore when partitioning takes place extraction holes need to be drilled into the bulk head of the individual office to provide the air extraction. These extraction holes can be seen in Figure 5-35.

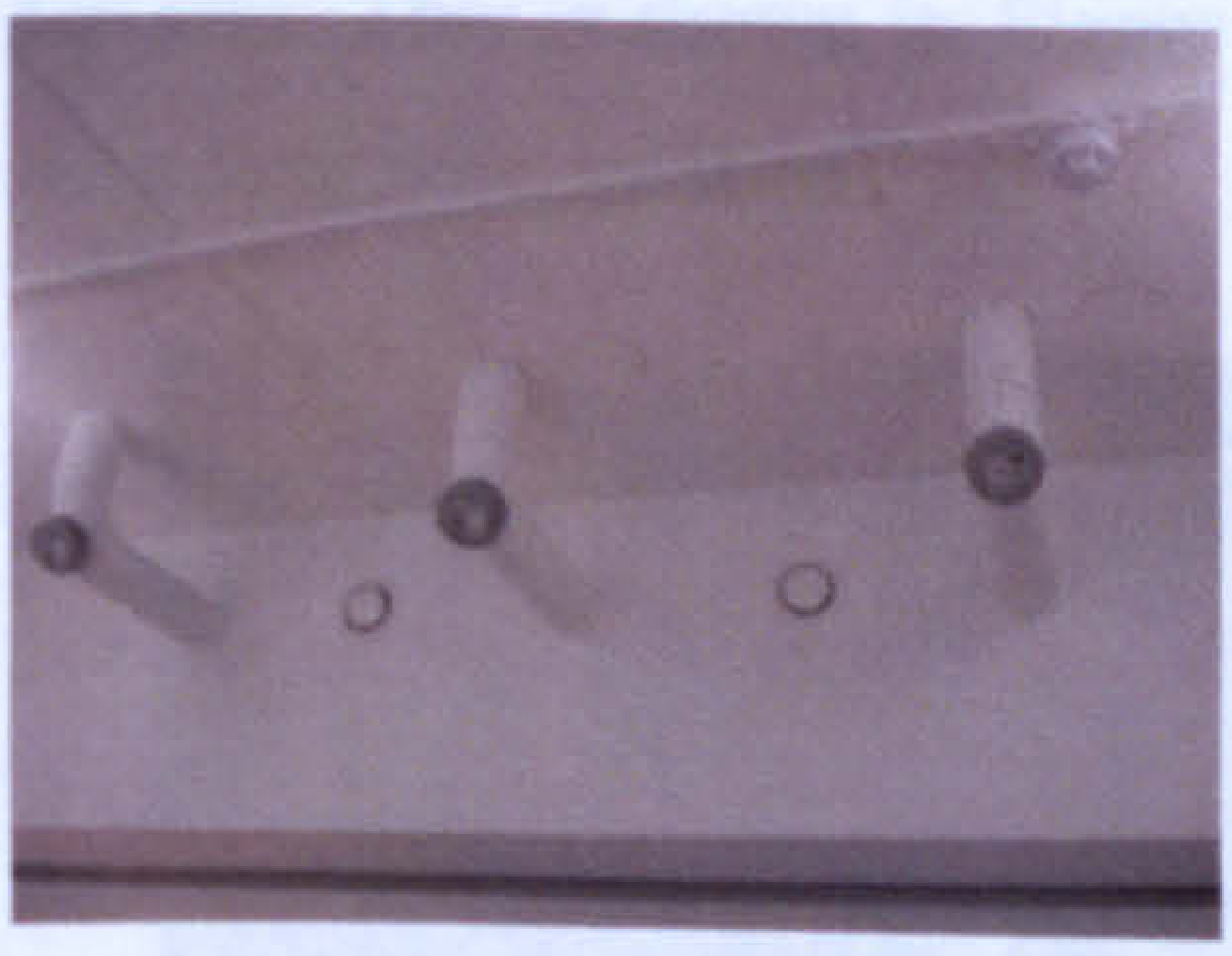


Figure 5-35: Ventilation extract

Figure 5-36: No extract vents within the cellular office

The extent of the problems and the issues became evident as the occupants soon started to complain about the temperature and air conditions in these spaces and upon investigation it was found that there was no extraction within some offices (see Figure 5-36). As a means of coping with the discomfort the occupiers were using a ruler to prop open the window. This is shown in Figure 5-37.

Figure 5-37: Temporary solution by user

Drilling the required extraction vents would have been expensive, therefore as a temporary solution these offices have had grilles fitted in the lower section of the doors to allow for extraction of air into the corridor area. This is shown in Figure 5-38. The occupants are now more satisfied, however this is not a long term solution.

Figure 5-38: Installed grille

5. On both wings there were issues with roof leaks. The leaking was initially identified during visits when thermal imaging was conducted. The leaking caused considerable damage to walls (Figure 5-39) and the carpets within the buildings and has also caused some of the lighting units to rust. As a temporary measure buckets were positioned to reduce the damage to the fabrics (see Figure 5-40).


Figure 5-39: Water damage


Figure 5-40: Temporary measure

6. On numerous site visits the smells from the WC's were noticeable. This was very unpleasant for the occupants and has generated many complaints (as revealed from the occupant survey discussed later in the thesis).
7. Other issues with the EVAC toilets resulted in portable toilets being hired and positioned in the car-park for a short period of time.
8. During summer 2009, some of the occupants were experiencing high levels of discomfort due to the high summer temperatures. Some of them even brought in portable A/C units to provide additional cooling in their office spaces.
9. It was observed that some tenants were given remote controls to increase the output from the luminaries where the lighting levels were inadequate.
10. During monthly meter readings in the plant room the status of the CHP unit was checked. The system has been switched off since 2008 due to the issues with the vibrational plinth.

5.6 BREEAM – comparing the credits attained at design to the results of in-use building performance evaluation

Earlier on in the thesis the credits achieved in the BREEAM assessments were provided. The BREEAM assessment was updated using the results for the energy and water performance measured at the operational stage of the building project. The overall impact this had on the BREEAM score is shown in Table 5-18.

It was also noticed that a credit was mistakenly awarded in the original assessment. In the Health and Well-being section of the BREEAM assessment only 1 out of the 2 possible credits were awarded for 'Daylight and View Out'. The first credit was awarded because the daylighting studies showed an average daylight factor of 2% however, the second credit was not awarded because the central atrium resulted in an obstruction and the view of sky criterion was not attained for all desks. Yet in the overall summary for this section, all possible credits were reported as achieved when this wasn't the case when the report was examined in detail. Therefore this was corrected in the review carried out.

The score significantly reduced from 87.55% to 80.00%. Although there was a 7.55% reduction in the score calculated, the rating was still 'Excellent'. However had a full review of all aspects taken place, it is likely that the score would have achieved at least a 'Very Good' rating.

Table 5-18: Comparison of BREEAM assessment at 'Design and Procurement' stage to a revised version using measured data

		Summary of the results from the BREEAM for Offices 2005 Formal Submission				BREEAM assessment rating summary using the measured data from POE			
Credit allocation	**Available**	**Achieved**	**Percentage %**	**Weighting**	**Score**	**Achieved**	**Percentage %**	**Weighting**	**Score**
Management	10	10	100.00	0.15	15.00	10	100.00	0.15	15.00
Health & well-being	15	15	100.00	0.15	15.00	14	93.33	0.15	14.00
Energy	17	15	88.24			9	52.94		
Transport	14	10	71.43			10	71.43		
Energy & transport sub-total	31	25	80.65	0.25	20.16	19	61.13	0.25	15.28
Water	6	6	100.00	0.05	5.00	4	66.67	0.05	3.33
Materials	12	9	75.00	0.1	7.50	9	75.00	0.1	7.50
Land Use	2	1	50.00			1	50.00		
Ecology	9	9	100.00			9	100.00		
Land use & Ecology sub total	11	10	90.91	0.15	13.64	10	90.91	0.15	13.64
Pollution	12	9	75.00	0.15	11.25	9	75.00	0.15	11.25
TOTAL	139	119		1	**87.55%**	88		1	**80.00%**
RATING					**Excellent**				**Excellent**

5.7 Total CO_2 emissions

The CO_2 emissions from the various resource/fuel consumptions have been analysed and totalised to provide a current estimate of the annual carbon footprint of the building. Based on the actual occupancy for 2009, the annual CO_2 emissions are shown in Table 5-19.

Table 5-19: Breakdown of all annual CO_2 emissions

CO_2 emissions due to...	Annual CO_2 emissions ($kgCO_2$)	% of total CO_2 emissions
Natural gas consumed	133214	37.50
Electricity consumed	221843	62.45
Mains water consumed	155	0.04
Total CO_2 emissions	355212	100.00

Annual CO_2 emissions of 355212 $kgCO_2$ have been estimated for the current use of the building (based on 2009 data). This represents an index of 82.07 $kgCO_2/m^2$/year. This is over 3.5 times the original design estimates. However, this figure is based on the inefficient running of the building, where the buildings HVAC systems are operational 24/7 with all areas conditioned regardless of whether they are occupied or not. Also all of the communal areas of the building remain lit and conditioned regardless of occupancy levels. However other aspects do naturally take account of the lower occupancy levels, such as the small power and office lighting fractions of the electricity usage and the mains water consumption. The electricity consumption accounted for almost two thirds (62.45%) of the annual CO_2 emissions from the operational building. This is mainly due to the higher conversion factor for $kgCO_2$/kWh for electricity compared to gas. The water consumption in the building was minimal (at 0.04%).

The results were an interesting find as the building as mentioned on many occasions is around only 60% occupied in terms of office space and much lower in terms of number of people.

5.8 Simulated performance

The building was originally modelled using IES <VE> building simulation software. The results presented in this section of the thesis are based on the actual performance of the building now it is operational. The occupancy levels of the building have slowly increased throughout the monitoring period but are now at around 60% (July 2010).

At the design stage the building performance was predicted using the building simulation software IES <VE> and calculated on a 100% occupancy basis. As full occupancy didn't occur it is difficult to effectively compare the design predictions and post-occupancy performance data. Consideration and further investigations into this are presented in Chapter Six.

5.9 Chapter summary and discussion

Chapter Five has included the results and findings from the in-use building performance evaluation. The findings included

1. The overall energy performance was over 3 times more than was predicted.
2. Calibration issues were identified, confirming that the commissioning of the building wasn't carried out to a sufficient standard.
3. Energy end uses were reported where data was available, yet it was found that there was unreliable and insufficient sub-metering in the building.
4. High weekend and out-of-hours consumption was found for many end-uses.
5. Internal environment including atrium was analysed. There were issues with the temperature control within the building, yet the atrium provided comfortable target temperatures.
6. Lighting performance was assessed to determine the daylight factors in two zones and reported on desktop illuminance levels. In the areas tested daylight factors were sufficient and the desktop illuminance levels were generally achieved.
7. The water consumption in the building compared well to targets and benchmark data.
8. General observations revealed areas of the building requiring maintenance.

Since 2007, the energy use in terms of both gas and electricity has increased each year. This has not only coincided with increases in occupancy levels but alterations to the BMS. Some early BMS data showed irregular and unreliable data logging and these were later addressed. The data collected via sub metering showed a breakdown of electrical consumption, with some issues reported with the comparison of the totalised electrical sub meters with the overall incoming meter, showing differences of around 30-40%. The west landlord lighting meter was suspected to be over-pulsing. However despite issues being reported to the FM no inspections, alterations or rectifications were made.

The sub metering was not detailed enough, with major plant items being grouped in one meter (i.e. CP1 which included the energy use for all four AHU's fans pumps, controls and the electric chiller). This collective recording of data made the energy use by the individual components difficult to analyse.

On further inspection of the 'CP1' meter it was found that almost 30% of the energy used for this meter was during weekends. Although some energy use during evenings would be expected due to the night cooling strategy, this significant portion of energy was alarming. BMS inspections also found that the building was actually being treated in terms of heating, cooling and ventilation on a 24/7 basis and not as per the settings outlined in the control strategy. Not only was this occurring on continuous basis but the building was also being treated/conditioned in all areas, despite some of the upper zones being permanently unoccupied. However, some earlier screenshots of the BMS show that at commissioning stage the unoccupied areas were running on 'set back' but changes were made by managers early in the monitoring stages and never reverted to the original settings.

As the building became occupied it was split into individual office spaces to suit the needs of the individual tenants. However the occupancy levels were not consistent throughout the building. This appeared to cause some issues over temperature control within each VAV zone. There are two temperature sensors located within each VAV zone (each VAV zone is approximately 54mx6m) and these sensors are located within only two of the cellular offices within that zone.

Low occupancy appears to impact on temperature control in the building, as many of the BMS temperature sensors were located in unoccupied spaces, resulting in many of the occupied zones overheating. Temperatures exceeding 25°C were experienced in WWZ1S2, WWZ2S1, WEZ2S2 and EWZ1S1 zones for 5%, 8%, 5% and 6% of annual occupied hours respectively.

Many of the other offices within the VAV group do not have any sensors located within it. It is suspected that had all zones been occupied in a similar manner, temperature control would have been more effective. However due to the patterns of location that have occurred, some places have suffered from insufficient temperature conditions. This highlights the need for effective commissioning, arrangement and management during fit-out to ensure that the control is adequate.

The atrium was effective at providing a thermally comfortable, usable and informal space for the occupants. Data analysis showed that temperatures in the atrium exceeded 25°C for less than 1% of occupied hours. For almost 20% of occupied hours, temperatures of 23°C or greater were experienced. The control settings of the underfloor heating resulted in internal temperatures of 21°C during occupied hours and 19°C during unoccupied hours being achieved. The graphs presented in Chapter Five demonstrate the temperature differences between the internal atrium and external temperatures, suggesting the large amounts of heating required to maintain the required conditions within the atrium. Although comfortable conditions in the atrium were achieved, by reducing the set point by a degree during unoccupied hours may reduce the heat demand during the winter month evenings. Yet this would require further investigations.

For the five office zones, weekend small power use ranged from 15.5% to 23.8% of total weekly use. High electrical loads were seen at weekends, presumably due to occupants leaving small power office equipment on or on standby. Focusing on a highly occupied zone within the building, detailed analysis for weekdays in February 2010 showed that approximately one third of small power energy within this zone was during unoccupied hours (between 18:00 – 08:00).

The small power use analysis identified a potential to easily save 20% of this energy by switching appliances off during unoccupied weekend periods. This saving increases further when the evenings are considered. CIBSE Guide F presents data relating to the power consumption of standard office equipment, leaving a PC and monitor on stand-by has a power consumption of around 30-45W compared to the average power consumption of 120W when in-use. Similarly for a laptop, the stand-by power consumption is around 5-10W compared to the average power consumption in use of 20W (CIBSE 2004).

The energy consumed by the two lifts located within the building was found to be negligible, accounting for 0.7% of total annual electrical building consumption. In this particular building, the floors that are currently occupied include the ground and first floors only. The use of lifts were found to be minimal and mainly used when needed to transport goods on trolleys or for heavy loads.

The CHP unit was non-operational for the majority of the monitoring period. This was due to issues with missing vibration dampening on the base of the unit. Unfortunately as a result of this, the CHP unit was permanently switched off to reduce the disturbance to the occupants within the building. Therefore the building has solely relied on the two high efficiency 75 kW boilers to provide all the heat for hot water and space heating.

Lighting energy consumption for all occupied zones were greater than the levels predicted at the design stage, with an overall increase of 82%. The lighting EUI performances in the three occupied areas were 18.65kWh/m^2/year, 26.80kWh/m^2/year and 44.8kWh/m^2/year. The first two EUIs reported compared well to those given for a good practice air conditioned office (27kWh/m^2/year) and the EUI of 44.8 kWh/m^2/year was around 17% better than the typical lighting EUI for a standard air conditioned office. Energy consumption for a heavily occupied area was analysed and results showed that the lighting system was operating as expected with lighting energy consumption during occupied periods only, triggered by the PIR sensors.

The analysis of lighting energy data showed that high levels of weekend consumption in the west wing 1st floor zone existed, with almost 18% of the total annual lighting energy consumption for this zone being used at weekends. Night visits to site confirmed that lights were being left on in one area in particular and consequently being responsible for around 50% of the total tenant light energy in the building. Contributing to this, the photoelectric control within the lighting system results in full lighting output during the evenings when no daylight is available.

The lighting levels in two zones of the building were measured and expressed both in terms of daylight factors and illuminance on the working plane. The daylight factors were measured on days when overcast sky conditions were experienced. These daylight factors calculated were satisfactory, agreeing with those set out in the relevant codes and standards. In terms of comparisons with the simulated daylight factors, the measured results correlated well for the east wing first floor zone and were slightly less for the west wing 2^{nd} floor zone.

The spot measurements carried out with the lighting system enabled found that lighting levels were adequate with 820 lux average measured on the working plane in a zone (measuring 13m x 54m) that was investigated, with greater illuminance towards the external windows and towards the atrium as expected.

In terms of water consumption early performance of the system was excellent; however a fault occurred on the valve in the grey-water storage tank and resulted in 'calls' for large amounts of water. Firstly based on the early performance, the data was extrapolated to give a reflection of potential annual performance. This showed that providing the system is working effectively, there is no mains water required to supplement the harvested rain water for flushing. The total annual harvested rain water and mains water used in the building was 30% of the total water used in a typical office with a conventional flushing system. 60% of the total water used was actually mains water and this was all required for washing purposes only. The other 40% of the total water was harvested rain water used for flushing.

However, during the monitoring period a fault did occur on the valve and resulted in a constant 'call' for top-up water with overflow into the pond. This was not detected straight away and resulted in an annual mains water consumption of $541.14m^3$ with 37% of this being used for 'top up' to the rainwater tank for flushing purposes. This constant call for water actually filled the tank to the required level and meant that the water was forced to flow into the overflow pond located outside of the building. In terms of CO_2 emissions the mains water consumption was equivalent to 155.20 $kgCO_2$/year- a 181% increase on the annual CO_2 emissions had the fault not occurred. However, despite the fault, the actual annual mains water was 13% better than an office building with a conventional system. The results demonstrate the consequences that can occur when assets fail. Overall this system has the real potential to perform well, yet planned maintenance should be implemented. Careful management and monitoring of assets are important to avoid unnecessary use of resources and the associated costs.

The low volume flushing system requires a vacuum pump that also has an energy consumption associated with it. The annual energy consumption measured for the vacuum plant system was

11685 kWh/year and this equates to 6356.64 $kgCO_2$ per year. This was itself an interesting find as it showed that the CO_2 associated with using a low volume vacuum system within an office building was 40 times more than the CO_2 emissions associated with the use and treatment of the mains water (with a ratio of 2.4% for water to 97.6% for the vacuum pump).

It is evident that the in-use energy performance of the building is much greater than the design intentions and even benchmark data. The analysis of the operational "green building" has shown up many issues. Design, build, commissioning and on-going facility management shortfalls have come together to limit its ability to perform to its specified design potential. Only once these problematic areas have been identified (through a POE activity) can actions be put in place to target them and improve efficiency of a building.

Greater awareness, team integration, feedback, and attention to detail would better allow sensible operating assumptions, design and control setting for all credible future operating environments and modes of operation.

Chapter Six - Investigating the building energy performance associated with partial occupancy using simulation techniques

6.1 Introduction

A principle objective of this study was to investigate, using a Dynamic Thermal Model (DTM), how partial occupancy and building management affect energy performance, specifically:

a) To simulate the building performance at the current level of occupancy and compare this with measured data.
b) To investigate the impact internal heat gains have on the energy performance of the building.
c) To investigate the building's energy consumption when partial occupancy exists.
d) To evaluate the potential environmental and economic savings resulting from the implementation of effective management strategies when partial occupancy exists.

To meet these objectives, this chapter investigates how occupancy levels and the management of a building with low occupancy can impact a building's energy performance; an area where very little research has been carried out.

The current operational settings on the building's BMS are not in line with those set out in the control philosophy manual. Alterations were made to the BMS on a regular basis by the managers at site, and this has resulted in the building operating on a 24/7 basis. Although issues were highlighted to the Facilities Manager on several occasions, modifications to align the settings back to the original control strategy did not occur. Therefore, the building's energy performance resulting from 24/7 operation with partial occupancy has also been investigated.

The chapter also compares the simulated results to those for a building with efficient management control at the same occupancy conditions. This allowed the amounts of wasteful energy, money and CO_2 that have resulted from the under-occupied building managed without full consideration to be calculated.

6.2 Background to the software

Building characteristics affecting heat transfer processes include: climate, building orientation, thermal insulation, building dynamics and thermal mass, properties of the glazed elements, shading devices, solar gains, casual heat gains, air tightness, ventilation (both natural and mechanical) and installed systems (HVAC and mix-mode) (IES 2008). IES<VE> provides a tool for detailed modelling that takes account of the factors listed.

IES<VE> software is made up of 4-tiers, including VE-Ware (free analysis tool for energy and carbon analysis), VE-toolkits (a useful analysis tool at the early stages of a design project), VE-Gaia and VE-Pro, which respectively increase in complexity. VE-Pro selected for this study is the most powerful of the options available and is made up of modules including:

- ModelIT: for specifying the building geometry and construction elements.
- SunCast: for investigating the impacts of solar gains in a building.
- ApacheSim: simulates the dynamic thermal processes between the building, internal heat loads, the external climate and building systems. Weather files are included to allow for full year simulations at the appropriate geographical location.
- FlucsDL: calculates the daylight factors and illuminance levels around the building.
- Radiance: used to generate rendered images of luminance and illuminance. Radiance provides an analytical tool for daylight, artificial lighting and the levels and occurrence of glare.
- MicroFlow: simulates air movement.
- ApacheHVAC: allows specific HVAC equipment and control systems to be defined.

6.3 Methodology using simulation techniques

At the design stage of the case study building IES<VE> was used as the building energy simulation tool. The building was originally modelled by IES Consulting Ltd using IES<VE> version 5.2.

Early in the monitoring phase it became apparent that occupancy uptake in the building was low and transitional, and that the full occupancy may not be achieved.

The simulation results used in the design calculations were based on 100% occupancy, therefore carrying out comparative analyses between the design and measured performances at the 50%-60% occupancy levels became questionable until the full extent of how varying occupancy can affect building performance was understood.

With this in mind a member of the design team provided the original IES model so the required changes to occupancy levels could be made. Unfortunately, with the updates in more recent releases of the software and compatibility issues, the supplied model would not simulate and therefore results matching those at the design stage could not be regenerated. This may have been due to rebuild changes when updating the model into a newer version of the software. As a result, considerable work to the HVAC network was required to rebuild the model so that simulations would run. Once this was carried out the appropriate data and templates were assigned.

6.4 Model description, HVAC system and controls assigned

A full description of the building was given in Chapter 3. The IES<VE> model used was created to test the building design. The building's geometry, orientation, fenestration, materials and basic system were obtained from the original model supplied by the design team.

A new ApacheHVAC network was created to enable a plug-in link to the ApacheSim module within the software. Figure 6-1 shows the IES ApacheHVAC network created to mimic those systems installed at the building. In Figure 6-1 the system flow for the various floors are shown in green, the system controllers are shown in red and the air flow path is shown in blue.

Adjustments were made to the Macroflo openings so that atrium windows were in an open state when the indoor temperature within the atrium exceeded 23°C. The previous control set in the model received from the designers (after 'rebuild'- which enabled the model to open in a more recent version of the software) appeared to show that the atrium windows were open almost continuously, hence resulting in a large heating load during initial tests. The slab zoning/configurations were also changed to more closely match the VAV zones they are actually supplying. In the original model network no night time cooling was applied (although from design documentation this was intended), therefore night time cooling controls were also created in this updated design model.

An 'as built to run' model was then created with installed boiler efficiencies updated and the underfloor heating system defined. Office occupant density was changed from 6.5m^2/person to 7.5m^2/person- as per design documentation.

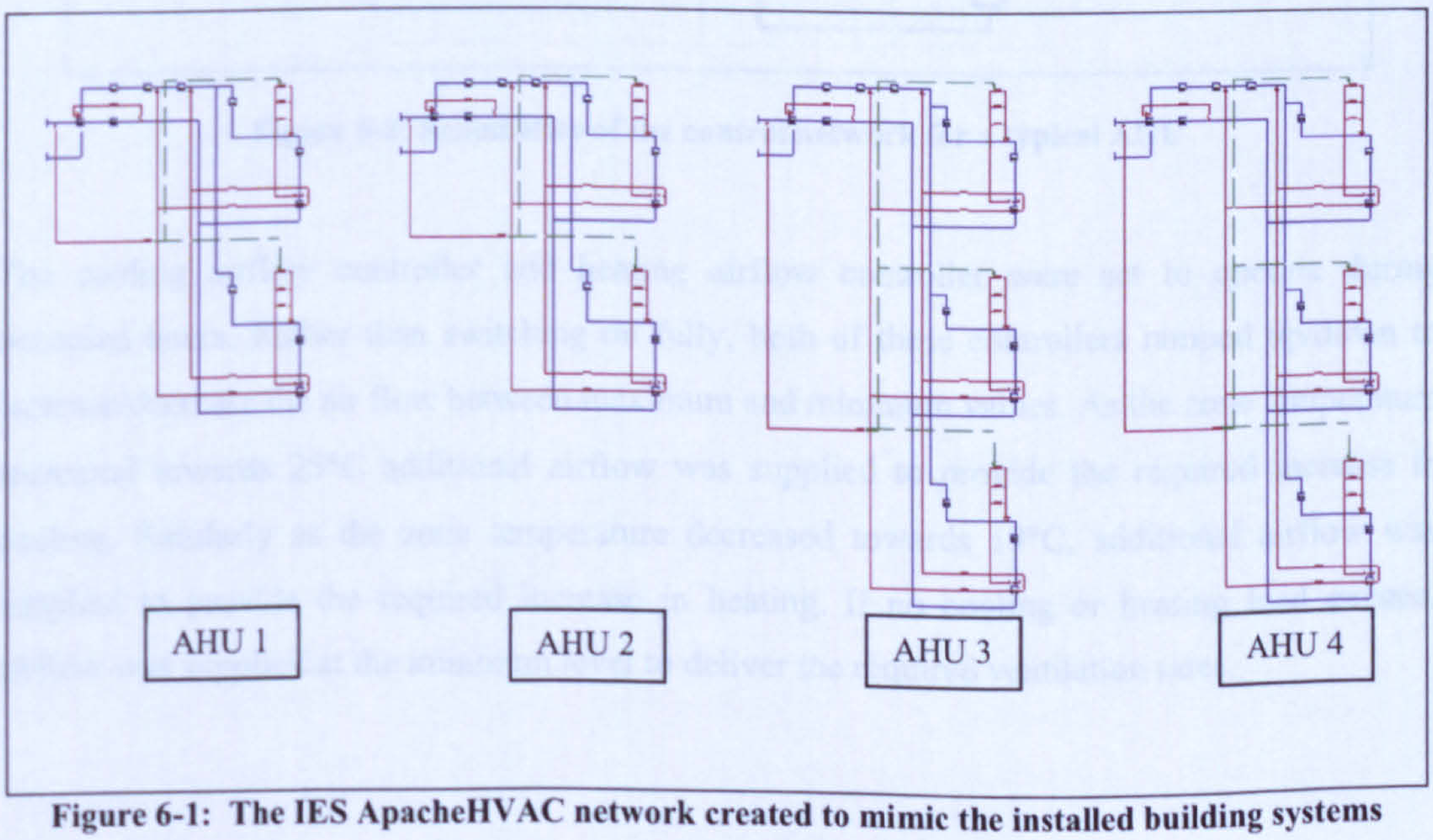


Figure 6-1: The IES ApacheHVAC network created to mimic the installed building systems

The HVAC network created was broken down to the separate AHUs and therefore much more representative of the plant system that is actually set up. Figure 6-2 shows the control network for one of the AHUs. The colour coding in Figure 6-2 is the same as that used in Figure 6-1. The green box contains a number of multiplexed zones. The network specified the night ventilation controller to operate outside occupied hours so that if the average room temperature of the VAV group exceeded 21°C, the night time ventilation was switched on at the fixed flow rates. If the indoor temperature went below 21°C the night-time ventilation was off. Night purging was set to only occur when temperatures were less than 20°C outside. By using this idea of 'free' night cooling the cooling demands were significantly reduced.

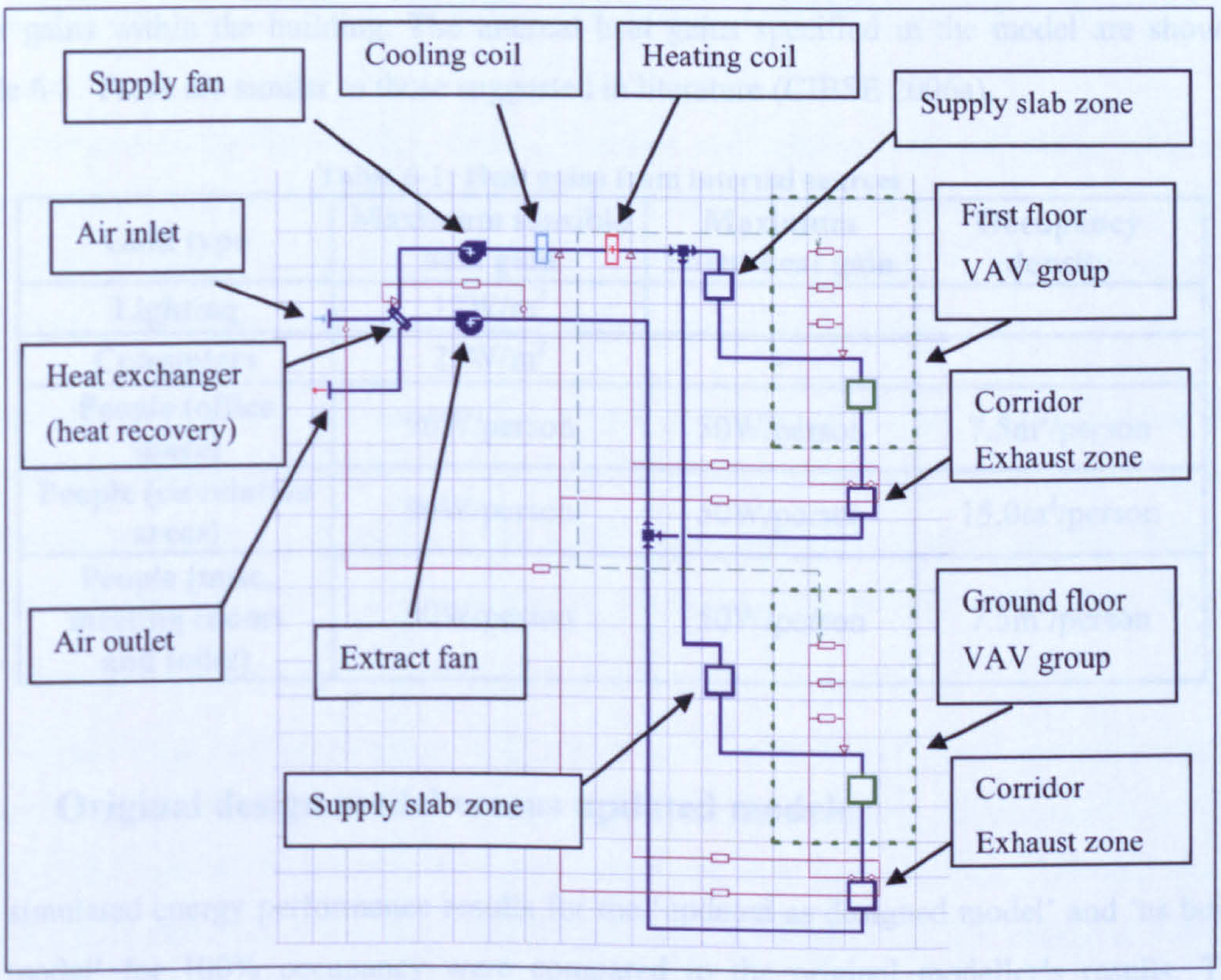


Figure 6-2: Schematics of the control network for a typical AHU

The cooling airflow controller and heating airflow controller were set to operate during occupied hours. Rather than switching on fully, both of these controllers ramped up/down to increase/decrease the air flow between maximum and minimum values. As the zone temperature increased towards 25°C additional airflow was supplied to provide the required increase in cooling. Similarly as the zone temperature decreased towards 19°C, additional airflow was supplied to provide the required increase in heating. If no cooling or heating load existed, airflow was supplied at the minimum level to deliver the required ventilation rates.

The heating coil controller assessed the average VAV group temperature. If the room temperature dropped to 19°C, the heating coil would be activated and supply air at 28°C. With a 2°C deadband, the heating coil would remain activated until a room temperature of 21°C was sensed. In a similar manner, the cooling coil controller assessed the average VAV group temperatures. If the room temperature increased to 25°C, the cooling coil would be activated and supply air at 14°C. Again with a 2°C deadband, the heating coil would remain activated until a room temperature of 23°C was sensed. The heat exchanger controller activates exhaust heat recovery whenever the exhaust air is less than 21°C.

To maintain some consistency with the original model, the SheffieldEWY.fwt weather file was used. The Suncast simulations were performed prior to the thermal modelling to account for solar gains within the building. The internal heat gains specified in the model are shown in Table 6-1. These are similar to those suggested in literature (CIBSE 2006a).

Table 6-1: Heat gains from internal sources

Gain type	Maximum sensible heat gain	Maximum latent heat gain	Occupancy density
Lighting	$12W/m^2$	-	
Computers	$25W/m^2$	-	
People (office space)	90W/person	50W/person	$7.5m^2$/person
People (circulation areas)	90W/person	50W/person	$15.0m^2$/person
People (misc, meeting rooms and toilet)	90W/person	50W/person	$7.5m^2$/person

6.5 Original design model versus updated models

The simulated energy performance results for the 'updated as designed model' and 'as built to run model' for 100% occupancy were compared to the original modeller's results. These comparisons are shown in Table 6-2.

Table 6-2: Comparing annual energy use for design and as built models

Annual energy Use	Original design model (kWh)	Updated as designed model (kWh)	% difference from original	As built to run model (kWh)	% difference from original	% difference between 'as built to run' and 'updated as designed'
Heating (excluding hot water)	104095	102495	-2	99102	-5	-3
Cooling	65408	10277	-84	8030	-88	-22
Fans and pumps	101011	95087	-6	92071	-9	-3
Humidification	0	0	0	0	0	0
Lighting	75266	82427	10	82427	10	0
Total	**345780**	**290286**	**-16**	**281630**	**-19**	**-3**

The predicted energy for heating, fans and pumps and lighting were all within 10% of the original model. The cooling energy was 84% less in the 'updated as designed' model compared to the original model. By applying night time ventilation and utilising the thermal mass to store the 'coolth', cooling demands were reduced in the 'updated as designed' model.

Overall there was a 16% difference in the original and 'updated design' model. Updated boiler efficiencies, consistent heat recovery settings and underfloor heating system were set up in the 'as built to run' model. Overall there was a 19% difference in the original and the 'as built to run' model and a 3% difference between the 'as built to run' and the 'updated as designed' model.

The original model predicted annual CO_2 emissions total of 22 $kgCO_2/m^2$, yet the model was based on the assumption that both an electric chiller and an absorption chiller combined with the use of a CHP unit would be used. As shown earlier, the POE found that the CHP unit was non-operational for the most part of the monitoring period. The amount of CHP generated power (of which was intended to power the lighting and small power requirements of the building) was negligible and faults also occurred on the absorption chiller. For this reason, in the model it was assumed that the electric chiller would provide all cooling needs and all lighting and equipment demands were electrically powered. CO_2 emissions of 28 $kgCO_2$ /m^2 were calculated for the 'as built to run' model; 27% more than the original design.

The 'as built to run' model is hereafter used as the benchmark and is referred to as 'as built hr21' model- i.e. as built to operate with a set point of 21°C for the heat recovery device. The results for 100% occupancy are given in Table 6-3.

Table 6-3: Energy performance of the building with 100% occupancy for 'as built hr 21'

Energy end-use	Annual energy (kWh)
Space heating	99102
Space cooling	8030
Annual Fans and pumps	100101
Lights	82427
Equipment	202216
System gas	99102
System electricity	100102
Total system (kWh)	199203

Note hr= heat recovery

6.6 Occupancy and the impact on energy consumption

The exceptional levels of insulation were expected to result in the internal heat gains (from the people, lighting and computers) providing most of the required heat in the building (King 2007).

Quantifying the contributions the heat generated from the internal heat gains make in terms of off-setting the heating energy demand is something that has seldom been investigated and reported on in research literature.

In this section the 'as built hr 21' model is used as the benchmark, with the building fully occupied. To evaluate the contribution the internal heat gains from people make towards offsetting the heating demand, and also the overall affect this has on building energy, the model was re-simulated with internal heat gains from the people removed but all other thermal loads and settings remaining the same. The energy consumptions results for the various end uses under these tests are shown in Table 6-4.

Note that: 'Total system energy' = heating + cooling +fans, pumps and controls energy consumption, 'Total energy' = total system energy + lighting + equipment energies and 'Equipment' = computers energy consumption.

Table 6-4: Annual energy performance at different conditions for internal heat gains (kWh)

Condition	Heating	Cooling	Fans, pumps and controls	System energy	Lights	Equipment
100%	99102	8030	92071	199203	82427	202216
No people	124332	2717	84559	211608	82427	202216

The results show that the internal heat gains from people in the fully occupied building bring a 25230kWh (20%) annual energy saving in the heating consumption compared to the building's heating demands at zero occupancy. The internal heat gains from people in the fully occupied building increase the cooling energy by 5313kWh (196%) compared to the results when the building is unoccupied. For the fans, pumps and controls energy, the internal heat gains from people in this fully occupied building increase this energy by 9% compared to consumption when the building operating unoccupied.

The results found that the presence of the occupants (i.e. their metabolic heat gains) bring a 6% reduction in total energy for heating, cooling, fans, pumps and controls, i.e. total system energy.

The energy associated with the presence of the other individual heat gains including lighting and computers in the office zones were also investigated. However, in offices the computer/equipment and also lighting energy consumption are generally dependent upon occupancy; therefore the model was re-simulated with the people, equipment/computers and artificial light thermal templates removed but all other settings in the model remaining the same. The building's energy consumption resulting from the absence of people, equipment/computers and lights in the office areas, both individually and collectively are shown in Table 6-5. This is also shown graphically in Figure 6-3.

Table 6-5: Annual energy use as a function of internal heat gains (kWh)

Condition	Heating	Cooling	Fans, pumps and controls	Lights	Equipment	Total system energy	Total energy
100%	99102	8030	92071	82427	202216	199203	483846
No people	124332	2717	84559	82427	202216	211609	496253
No computers	170688	366	77195	82427	4399	248249	335075
No lights	117361	6010	88640	24747	202216	212011	438974
No people, computers or lights	257343	0	77005	24747	4399	334348	363493

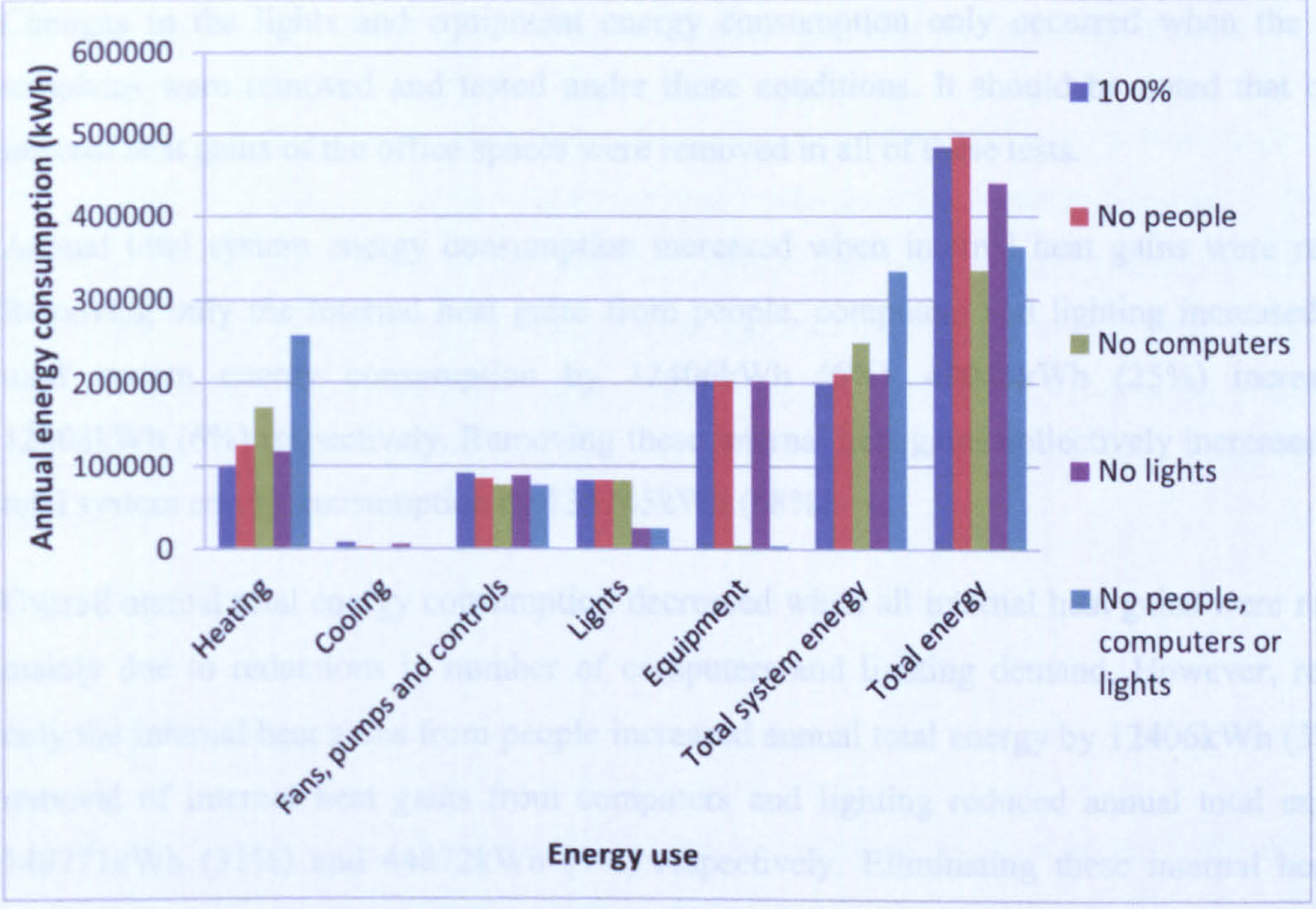


Figure 6-3: Impacts internal heat gains have on annual building energy use

In terms of total energy for heating, cooling, fans and pumps (i.e. system energy), there was overall an increase in consumption when internal heat gains in the building were removed. Heating demand was most heavily influenced by the removal of the internal heat gains from people, computers/equipment and artificial lighting.

The removal of internal heat gains from people, computers and lighting increased annual heating energy consumption by 25230kWh (25%), 71586kWh (72%) and 18259Wh (18%) respectively. Removing all these internal heat gains collectively increased annual heating energy by 158241kWh (160%).

The removal of internal heat gains from people, computers and lighting reduced annual cooling energy consumption by 5613kWh (66%), 7664kWh (95%) and 2020kWh (25%) respectively. Removing these internal heat gains collectively reduced annual cooling energy consumption by 8030kWh (100%).

Annual fans, pumps and controls energy consumption decreased when internal heat gains were removed. The removal of internal heat gains from people, computers and lighting reduced annual fan, pumps and controls energy consumption by 7512kWh (8%) , 14876kWh (16%) and 3431kWh (4%) respectively. Removing these internal heat gains collectively reduced annual fans, pumps and controls energy consumption by 15066kWh (16%).

Changes in the lights and equipment energy consumption only occurred when the thermal templates were removed and tested under those conditions. It should be noted that only the internal heat gains of the office spaces were removed in all of these tests.

Annual total system energy consumption increased when internal heat gains were removed. Removing only the internal heat gains from people, computers and lighting increased annual total system energy consumption by 12406kWh (6%), 49046kWh (25%) increase and 12808kWh (6%) respectively. Removing these internal heat gains collectively increased annual total system energy consumption by 135145kWh (68%).

Overall annual total energy consumption decreased when all internal heat gains were removed, mainly due to reductions in number of computers and lighting demand. However, removing only the internal heat gains from people increased annual total energy by 12406kWh (3%). The removal of internal heat gains from computers and lighting reduced annual total energy by 148771kWh (31%) and 44872kWh (9%) respectively. Eliminating these internal heat gains collectively reduced annual total energy by 120353kWh (25%).

The impacts internal heat gains have on the annual total system energy and total building energy of the case study office are shown graphically in Figure 6-4.

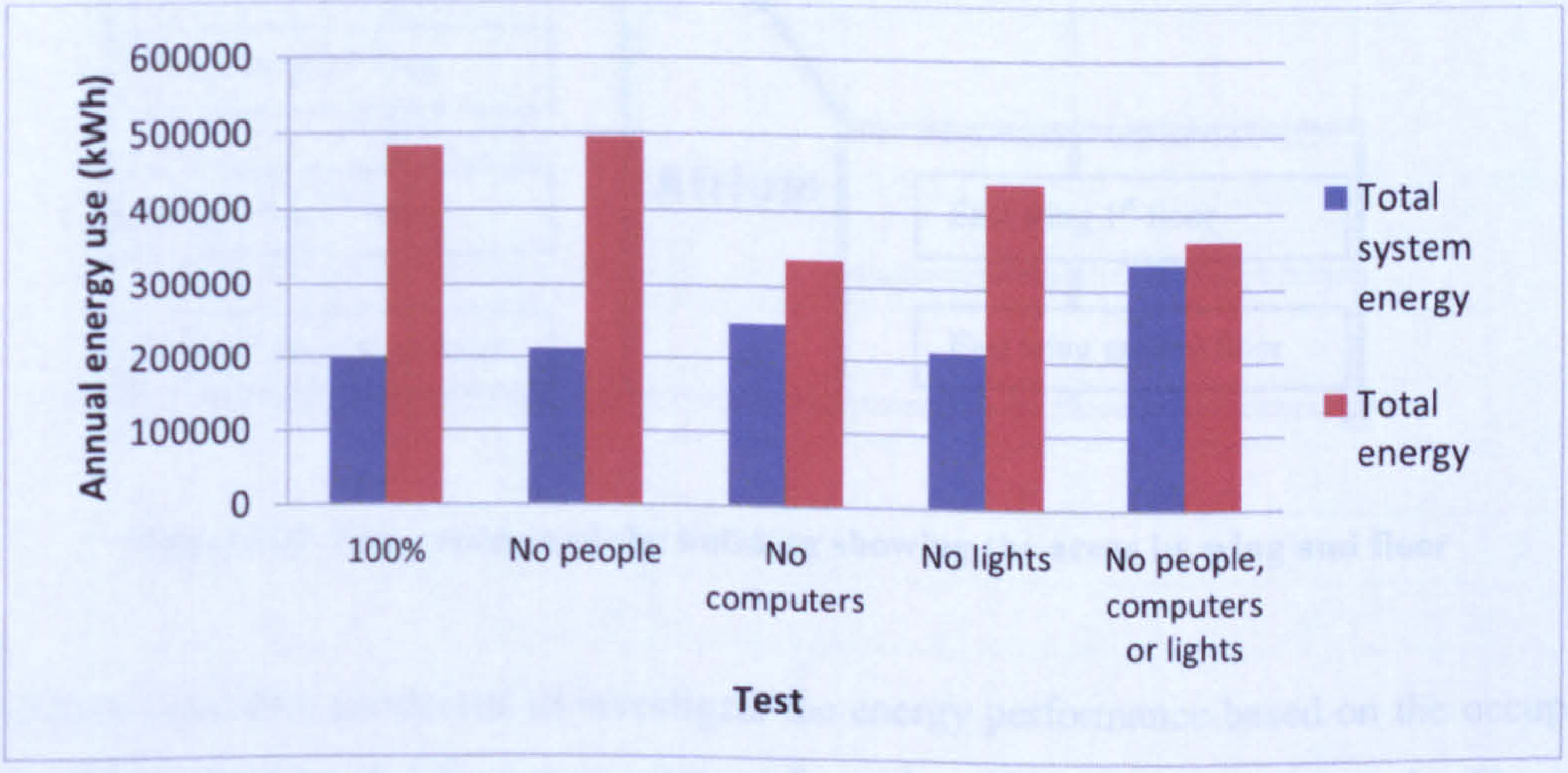


Figure 6-4: Impact on system energy and total energy due to internal heat gains

The collective presence of internal heat gains from people, computers and lights reduce the system energy requirements in the building by 68%.

The analysis presented shows the impacts on various energy uses in the building due to the internal heat gains. The effect each internal heat gain has on reducing the heating has been investigated, and computers were found to contribute the most in off-setting this demand (i.e. 72%).

6.7 Building energy performance when partial occupancy exists

The previous section investigated the impacts on a building's energy performance resulting from the absence/presence of heat gains but didn't take account of partial occupancy. The nature of multi-tenant commercial office buildings means that the occupancy rarely reaches 100% (Hayward 2011) and may vary significantly throughout the lifetime of the building. As a result of BMS control setting inspections it has been identified that the systems in the building have been operating as though the building is fully occupied despite being around only 50%-60% occupied.

6.7.1 Methodology

The occupancy uptake in the building appears to be based on floor zones (with reference to Figure 6-5, west wing ground followed by east wing ground, west wing 1^{st}, east wing 1^{st} and then west wing 2^{nd}).

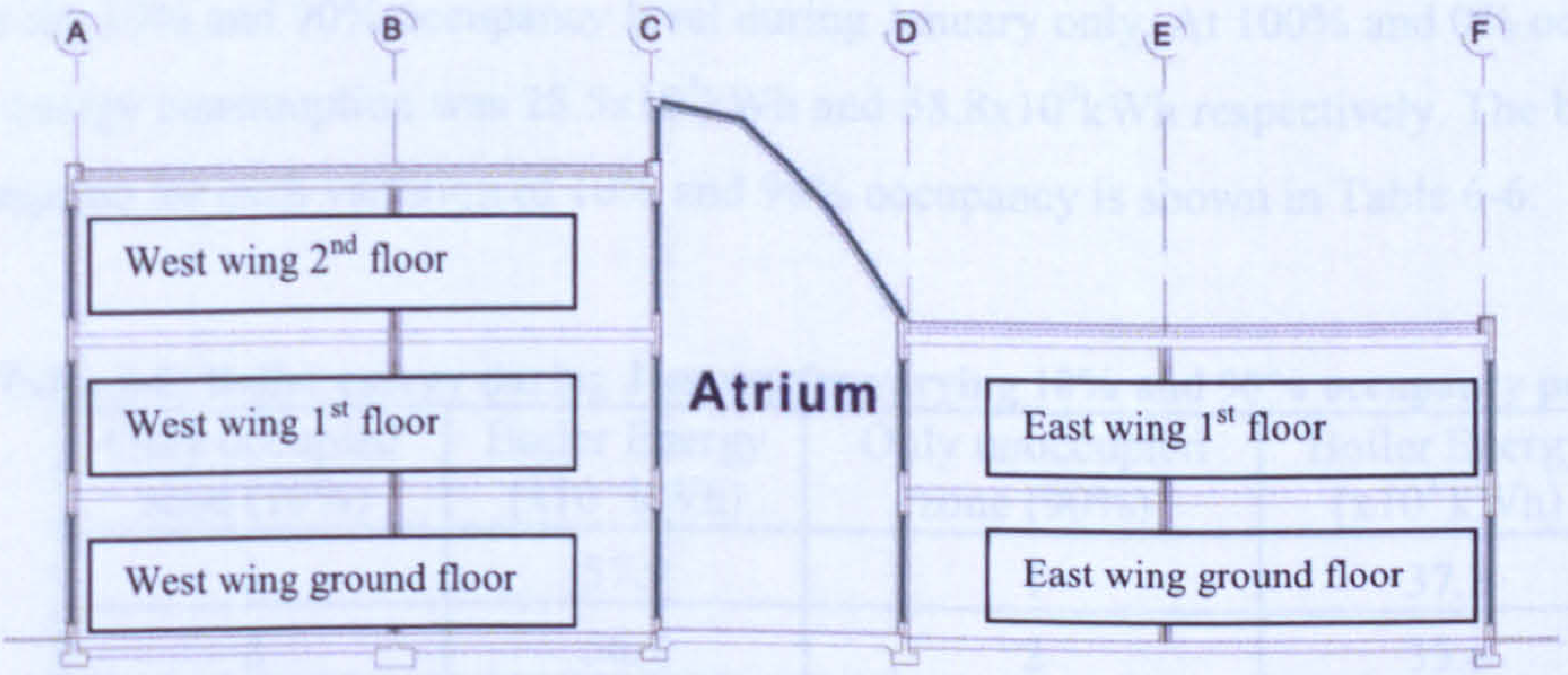


Figure 6-5: Cross section of the building showing the areas by wing and floor

Simulation tests were conducted to investigate the energy performance based on the occupancy uptake that has occurred. These tests were performed at 10% occupancy intervals. The zones within the building are numbered in Figure 6-6: 0% occupancy (zones 1+2+3+4+5+6+7+8+9+10 unoccupied), 10% occupancy (zones 1+2+3+4+5+6+7+8+9 unoccupied), 20% occupancy (zones 1+2+3+4+5+6+7+8 unoccupied), 30% occupancy (zones 1+2+3+4+5+6+7 unoccupied), 40% occupancy (zones 1+2+3+4+5 unoccupied), 50% occupancy (zones 1+2+3+4 unoccupied), 60% occupancy (zones 1+2+3 unoccupied), 70% occupancy (zones 1+2+3 unoccupied), 80% occupancy (zones 1+2 unoccupied), 90% occupancy (zone 1 unoccupied) and 100% occupancy (all zones occupied). This sequence of occupancy uptake is here after referred to as 'sequence 1'. A thermal template to represent unoccupied spaces was created and appropriately assigned.

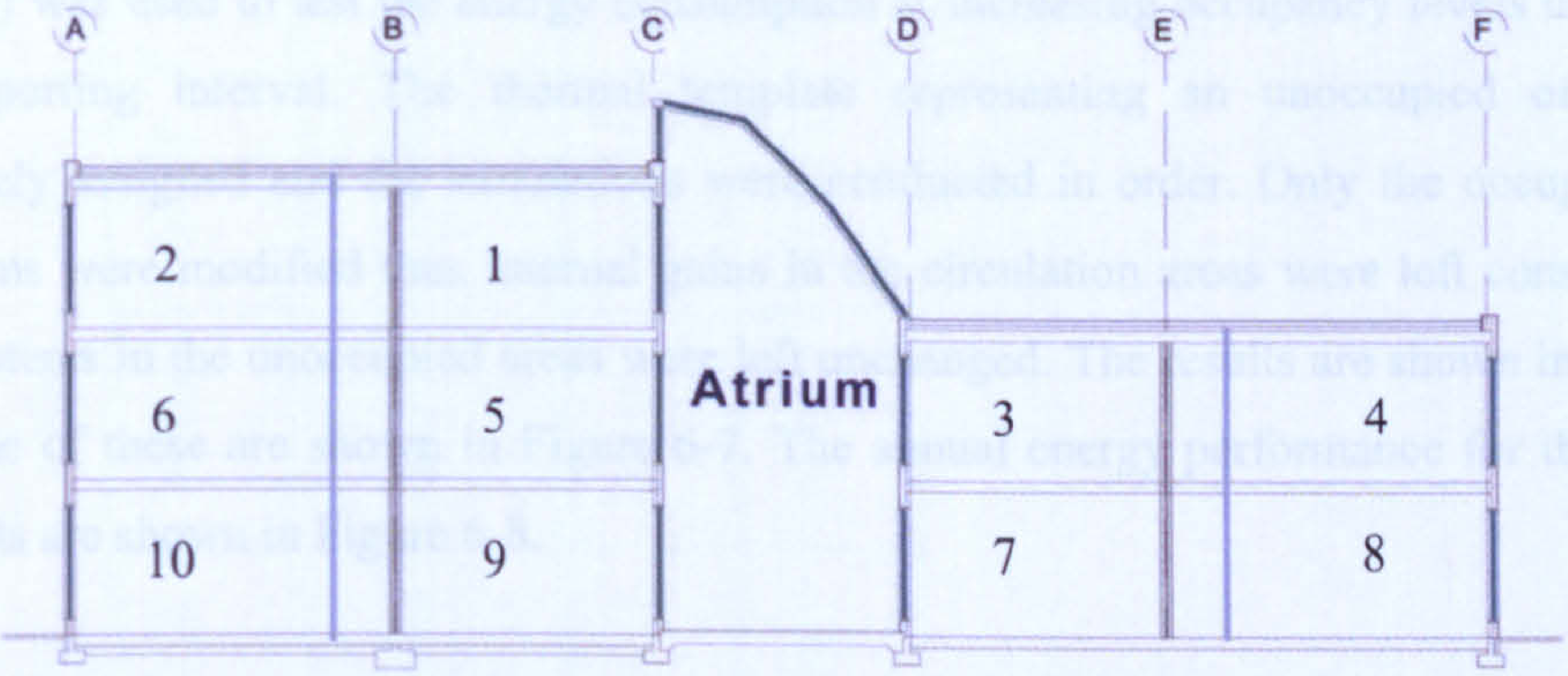


Figure 6-6: Numbered zones in the building

6.7.2 Model validation

To ensure that the model's settings were responding as expected, validation tests were carried out for the 10% and 90% occupancy level during January only. At 100% and 0% occupancy the boiler energy consumption was $28.5\text{x}10^3$kWh and $58.8\text{x}10^3$kWh respectively. The boiler energy consumption for each variation of 10% and 90% occupancy is shown in Table 6-6.

Table 6-6: Boiler energy during January for varying 10% and 90% occupancy patterns

Only occupied zone (10%)	Boiler Energy ($\text{x}10^3$ kWh)	Only unoccupied zone (90%)	Boiler Energy ($\text{x}10^3$ kWh)
1	57.9	1	37.3
2	56.7	2	33.6
3	56.0	3	33.0
4	56.7	4	31.7
5	55.8	5	36.3
6	56.4	6	33.3
7	55.1	7	35.2
8	56.4	8	31.8
9	55.6	9	38.7
10	56.3	10	34.6

Each 10% occupancy increase tested gave a decrease in boiler energy demand when compared to the 0% occupancy. Similarly, each 90% occupancy test resulted in an increase in boiler energy demand when compared to the energy use at 100% occupancy. Therefore this simple validation test showed that the model responded as expected when rooms became occupied and unoccupied.

6.7.3 Simulation results- building energy consumption at varying occupancy

The 'as built hr 21' model (which represents the building operating as intended at full occupancy) was used to test the energy consumption at increasing occupancy levels using 10% as the reporting interval. The thermal template representing an unoccupied office was appropriately assigned and the simulations were conducted in order. Only the occupancy for office rooms were modified thus internal gains in the circulation areas were left constant. The HVAC systems in the unoccupied areas were left unchanged. The results are shown in Table 6-7 and some of these are shown in Figure 6-7. The annual energy performance for the system components are shown in Figure 6-8.

Table 6-7: Energy performances at varying occupancy levels with the rest of building operating as intended (sequence 1 hr 21)

Occupancy	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Space heating energy	257343	245616	239090	228473	220152	241808	258557	230114	203730	155320	99102
Space cooling energy	0	4294	4459	4836	5058	6896	7485	7802	8068	7847	8030
Annual Fans and pumps energy	77005	79264	83051	84985	85909	88700	93297	94119	95816	95875	92072
Lights	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
Equipment	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
System gas energy	257343	245616	239090	228473	220152	241808	258557	230114	203730	155320	99102
System electricity energy	77005	83558	87510	89821	90967	95596	100782	101921	103884	103721	100102
Total system energy (kWh)	334348	329174	326599	318293	311119	337403	359339	332035	307613	259041	199203

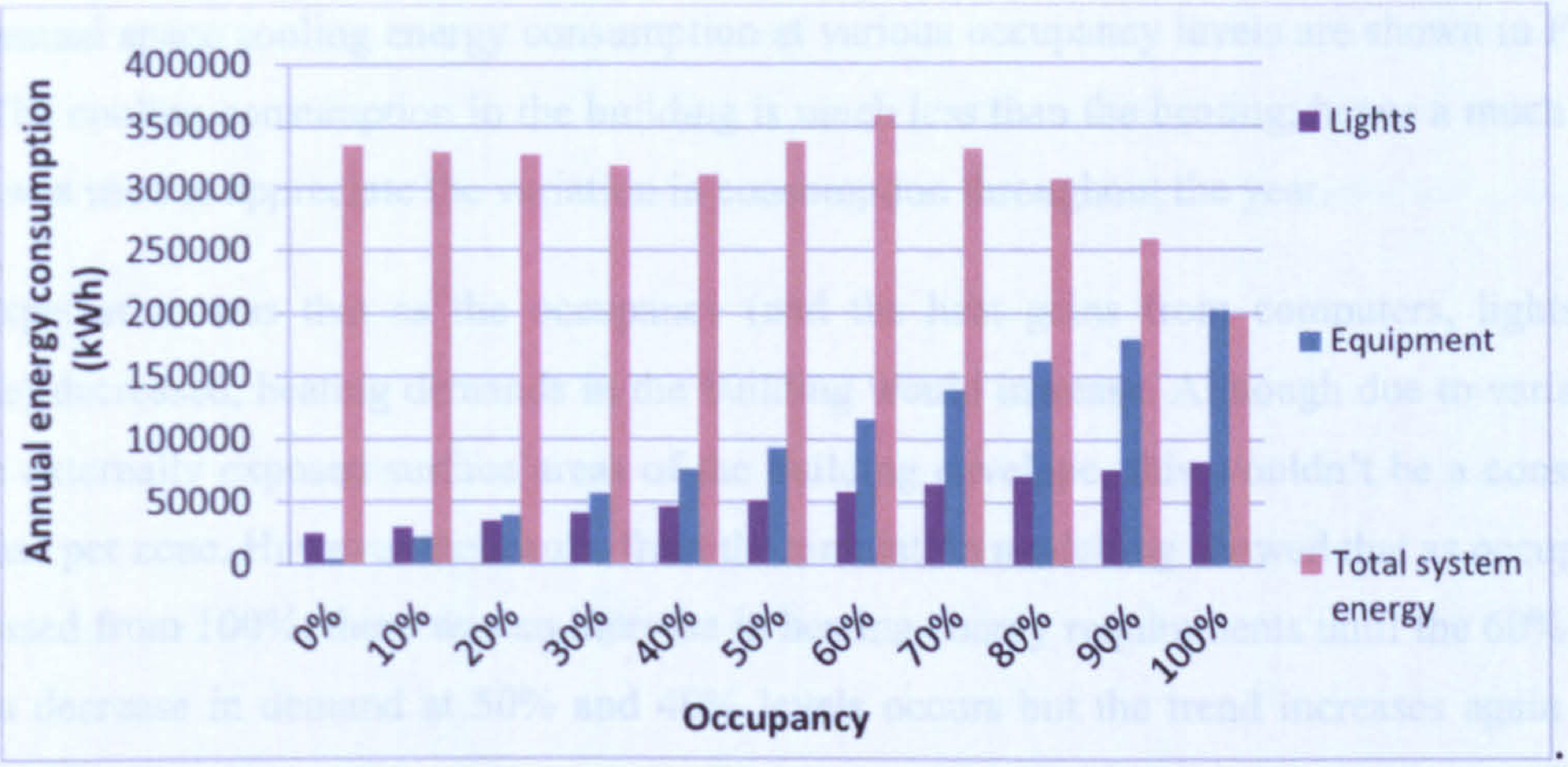


Figure 6-7: Energy performance at varying occupancy levels (sequence 1 hr 21)

The individual components of the total system energy are shown in Figure 6-8.

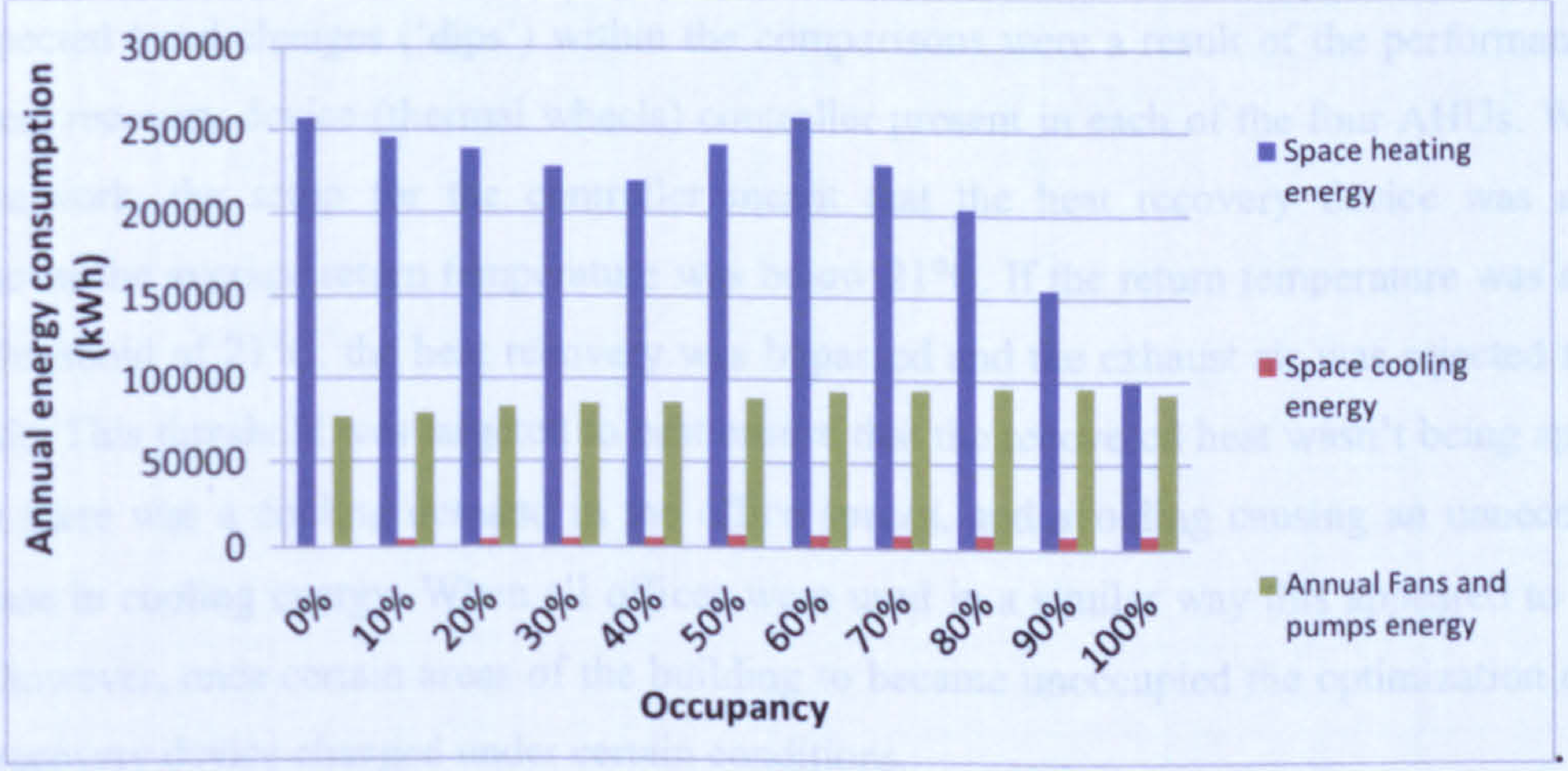


Figure 6-8: The energy performance of the system components at varying occupancy levels (sequence 1 hr 21)

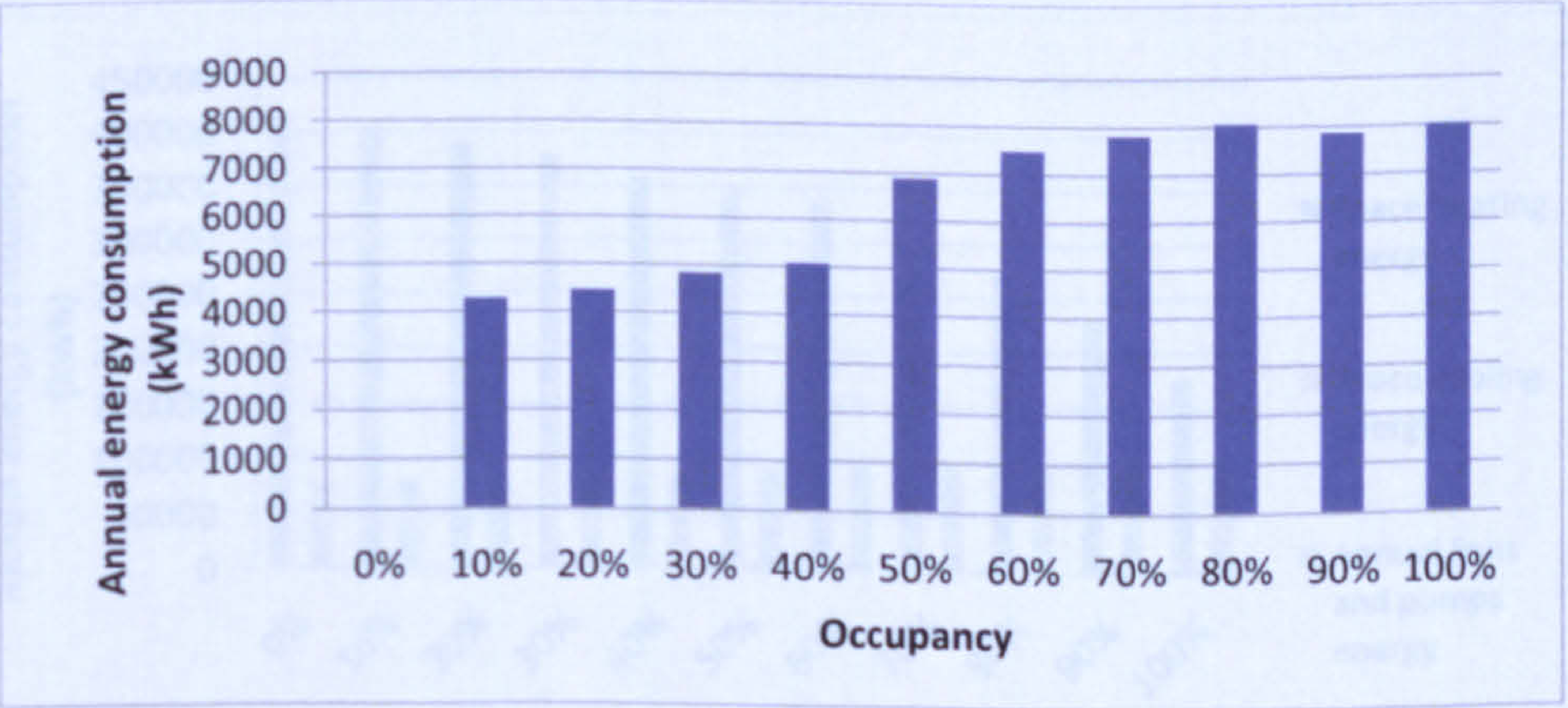


Figure 6-9: The space cooling energy demands under a range of occupancy levels (sequence 1 hr 21)

The annual space cooling energy consumption at various occupancy levels are shown in Figure 6-9. The cooling consumption in the building is much less than the heating; hence a much finer scale was used to appreciate the variation in consumption throughout the year.

An expectation was that as the occupancy (and the heat gains from computers, lights and people) decreased, heating demands in the building would increase. Although due to variations in the externally exposed surface areas of the building envelope, this wouldn't be a consistent increase per zone. However the results from the simulation modelling showed that as occupancy decreased from 100%, there was an increase in heating energy requirements until the 60% level then a decrease in demand at 50% and 40% levels occurs but the trend increases again from 30% to 0% occupancy. This can be seen in Figure 6-8. These results were initially identified as suspicious and potential anomalies.

These suspected anomalies in the annual energy demands were investigated using sensitivity analysis and detailed findings are presented in Chapter 7. The investigation identified that the unexpected trend changes ('dips') within the comparisons were a result of the performance of the heat recovery device (thermal wheels) controller present in each of the four AHUs. Within the network, the setup for the controller meant that the heat recovery device was active whenever the average return temperature was below 21°C. If the return temperature was above this threshold of 21°C, the heat recovery was bypassed and the exhaust air was rejected to the outside. This threshold was targeted to best ensure that the recovered heat wasn't being applied when there was a cooling demand in the office spaces, and avoiding causing an unnecessary increase in cooling energy. When all offices were used in a similar way this appeared to work well however, once certain areas of the building to became unoccupied the optimization of the heat recovery device changed under certain conditions.

Figure 6-10 shows the results from a tests similar to the previous ones but with all heat recovery devices disabled.

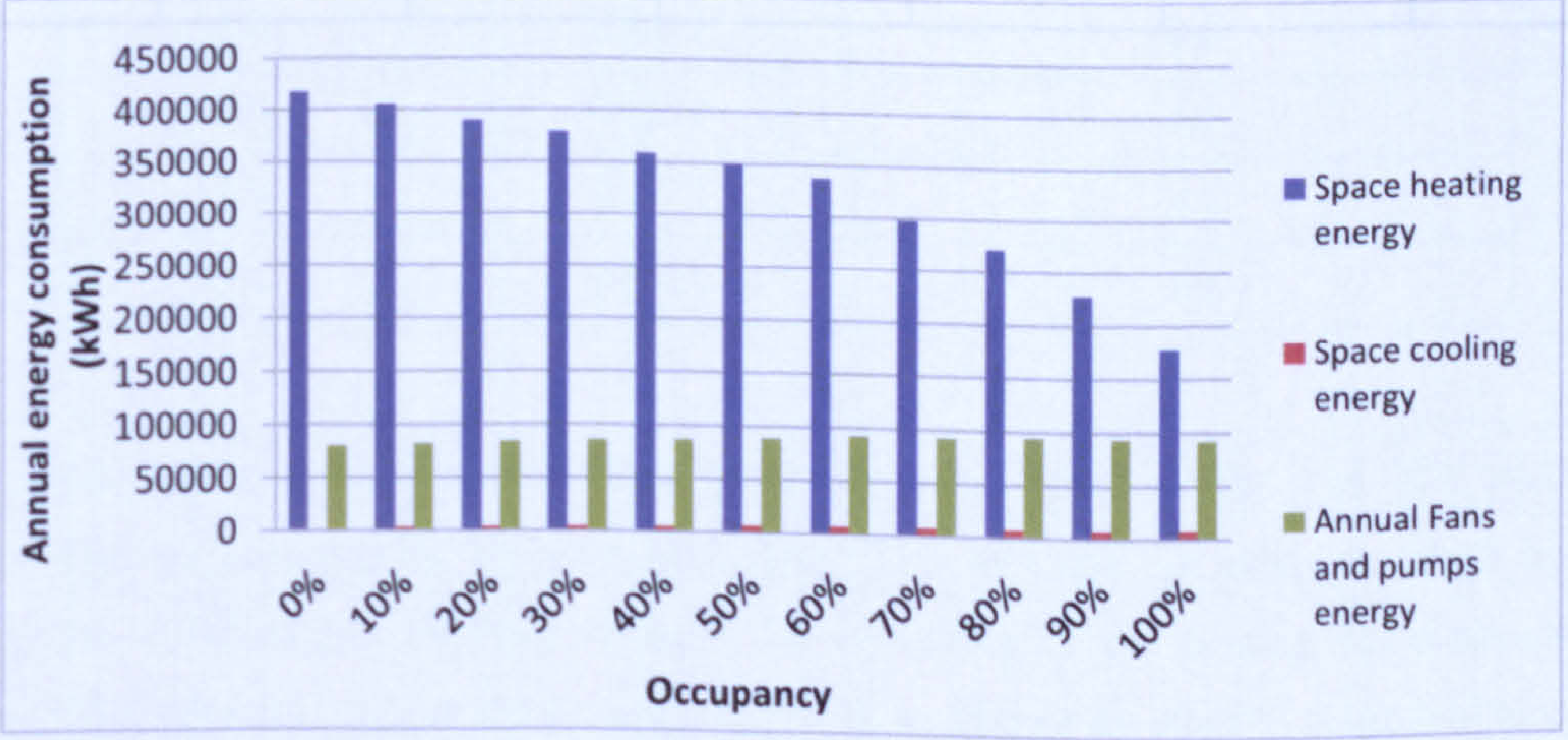


Figure 6-10: Energy performance at varying occupancy levels (sequence 1) with no heat recovery

As shown in Figure 6-10, with no heat recovery there is a continuous decrease in heating energy as the occupancy increases. This is a result of the reduction in internal heat gains. The sensitivity analyses presented in the Chapter 7 investigates these originally suspected anomalies in more detail.

At this point the focus will again return to the 'as built to run' model with heat recovery set at 21°C and the HVAC system fully operational. Tables 6-8, 6-9 and 6-10 compare the energy performances at lower occupancies to those at 100% occupancy (+ represents a percentage increase and - indicating a percentage decrease in energy use).

Table 6-8: Comparing annual space heating, space cooling and fan and pumps energy at varying occupancy levels to consumption at full occupancy

Occupancy	Annual space heating energy (kWh)	% difference in space heating energy from 100%	Annual space cooling energy (kWh)	% difference in space cooling energy from 100%	Annual fans and pumps energy (kWh)	% difference in fans and pumps energy from 100%
100%	99102	0	8030	0	92072	0
90%	155320	57	7847	-2	95875	4
80%	203730	106	8068	1	95816	4
70%	230114	132	7802	-3	94119	2
60%	258557	161	7485	-7	93297	1
50%	241808	144	6896	-14	88700	-4
40%	220152	122	5058	-37	85909	-7
30%	228473	131	4836	-40	84985	-8
20%	239090	141	4459	-45	83051	-10
10%	245616	148	4294	-47	79264	-14
0%	257343	160	0	-100	77005	-16

Table 6-9: Comparing annual lighting and equipment energy at varying occupancy levels to consumption at full occupancy

Occupancy	Annual lighting energy (kWh)	% difference in lighting energy from 100%	Annual equipment energy (kWh)	% difference in equipment energy from 100%
100%	82427	0	202216	0
90%	76039	-8	179648	-11
80%	71071	-14	162095	-20
70%	64682	-22	139526	-31
60%	58030	-30	116027	-43
50%	51641	-37	93459	-54
40%	46672	-43	75906	-63
30%	41337	-50	57057	-72
20%	34684	-58	39504	-81
10%	29715	-64	21952	-89
0%	24747	-70	4399	-98

Table 6-10: Comparing annual system energies at varying occupancy levels to consumption at full occupancy

Occupancy	Total system energy (kWh)	% difference in total system energy from 100%
100%	199203	0
90%	259041	30
80%	307613	54
70%	332035	67
60%	359339	80
50%	337403	69
40%	311119	56
30%	318293	60
20%	326599	64
10%	329174	65
0%	334348	68

The annual system energy consumed at lower occupancy levels is between 30% and 80% greater than the consumption at 100% occupancy. This indicates the extent to which internal heat gains in buildings contribute towards the off-setting of the heating requirements and suggests that system energy at lower occupancy is less efficient by 30-80% compared to a fully occupied building when there is inefficient building management control. However, the increases in occupancy will also increase lighting and small power consumption, and when this is considered the pattern changes. Table 6-11 shows the total energy at the various occupancy levels tested.

Table 6-11: Comparing total energy at various occupancy levels to consumption at full occupancy

Occupancy	Total energy (excluding hot water)	% difference in total energy from 100%	Total energy (including hot water)	% difference in total energy from 100%
100%	483847	0	503847	0
90%	514729	6	532729	6
80%	540778	12	556778	11
70%	536243	11	550243	9
60%	533395	10	545395	8
50%	482504	0	492504	-2
40%	433697	-10	441697	-12
30%	416687	-14	422687	-16
20%	400788	-17	404788	-20
10%	380841	-21	382841	-24
0%	363493	-25	363493	-28

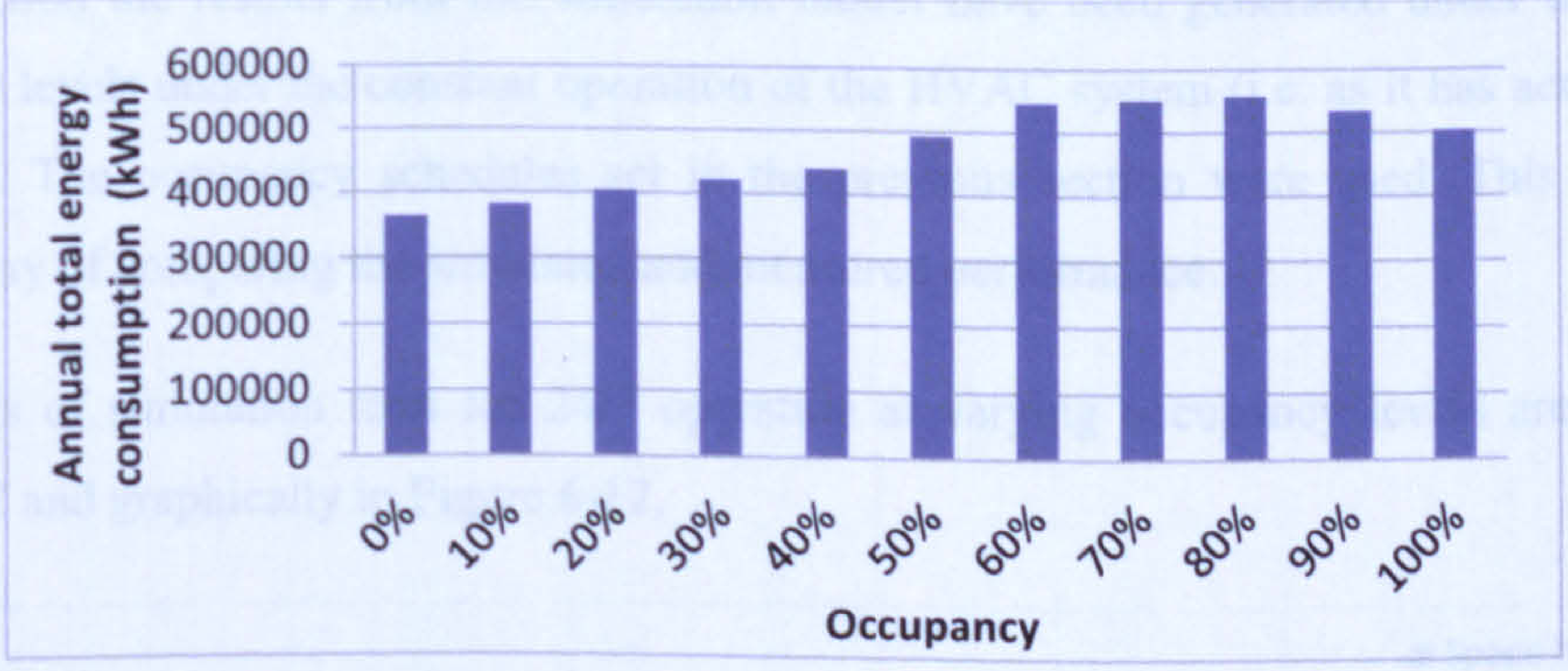


Figure 6-11: Total energy (including hot water) at various occupancy levels

Figure 6-11 shows the building's energy consumption when unoccupied zones are operating as 'occupied'. Therefore this inefficient BMS management has resulted in the total energy performance at 60% occupancy to be 8% more than the energy performance had the building been fully occupied at 100%.

This total energy includes hot water demands, lighting and small power consumption and suggests that under the management strategy currently being used the building would have actually consumed less energy if it had been 100% occupied as opposed to 90%, 80%, 70% or 60%.

These investigations have highlighted the impacts that varying occupancy can have on building performance. Reduced occupancy can actually cause increased energy consumption operational settings are not modified to reflect low occupancy. Such impacts should be made aware to designers, facility managers and other building operators. Later in this chapter the potential energy savings from the implementation of more effective management is calculated.

6.8 Results for partial occupancy with 24/7 HVAC

As previously mentioned inspection of the BMS control settings identified that the current occupancy scheduling were resulting in the HVAC plant system (HVAC is used here to describe the mechanical ventilation and comfort cooling strategy) operating 24 hours a day, 7 days a week. In addition to this, the occupancy schedules have not been carefully set/programmed to account for the low occupancy levels and the zones that are unoccupied are being heated, cooled and ventilated as though they are fully occupied when in fact they are not. System controls have been altered by the management team in attempts to satisfy their clients' needs and resolve any reported issues of discomfort. As will be later seen, these types of changes have consequently resulted in wasteful energy consumption.

In this section the results from the simulation model have been generated under the varying occupancy levels under the constant operation of the HVAC system (i.e. as it has actually been operating). The occupancy schedules set in the previous section were used. This is a more realistic way of comparing the simulated and measured performance.

The results of simulation tests for 24/7 operation at varying occupancy levels are shown in Table 6-12 and graphically in Figure 6-12.

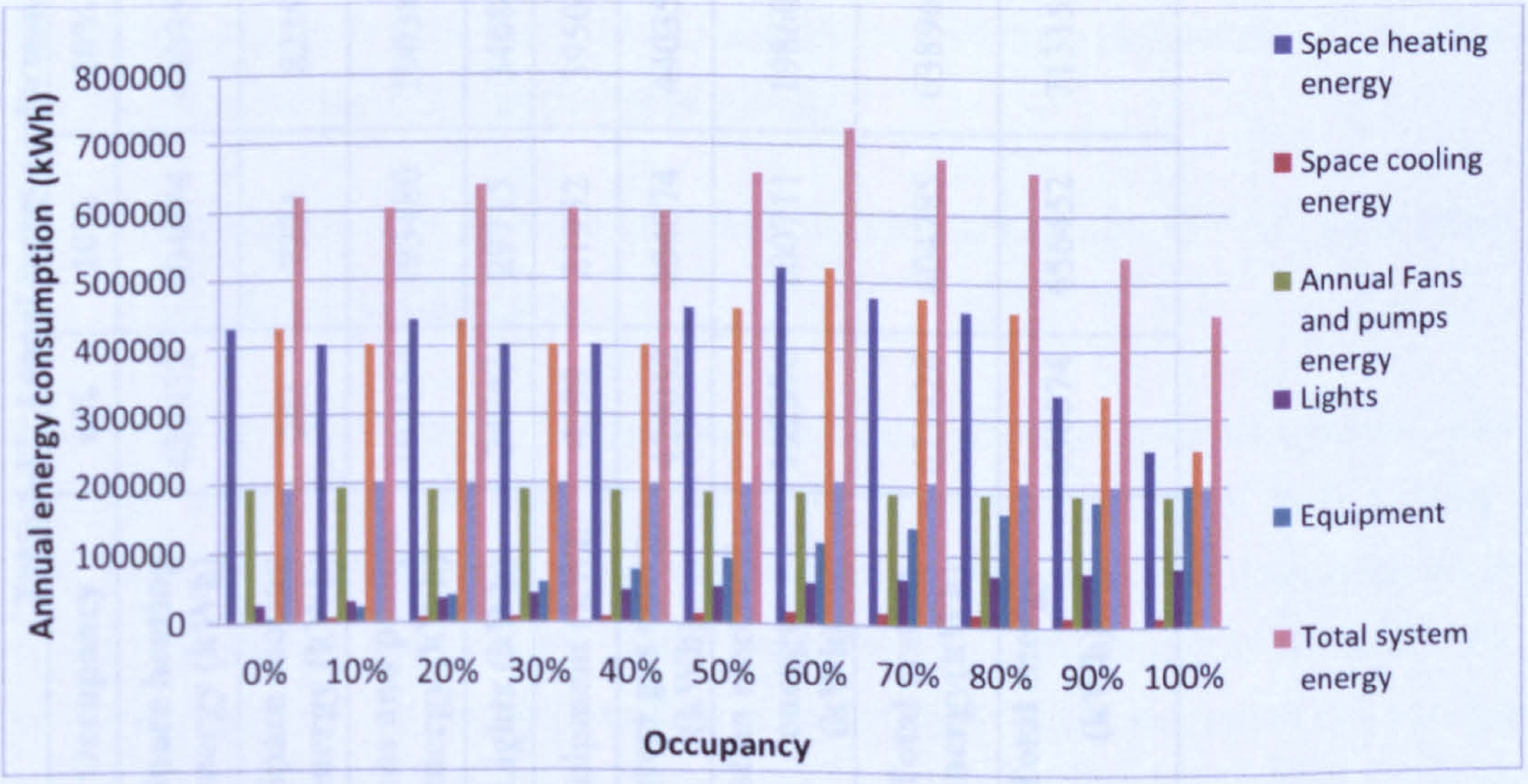


Figure 6-12: Annual energy performance (kWh) at varying occupancy levels with 24/7 HVAC operation (seqence 1 hr 21)

Table 6-12: Annual energy performance (kWh) at varying occupancy levels with 24/7 HVAC operation (seqence 1 hr 21)

Occupancy	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Space heating energy (kWh)	429032	404074	440359	403815	404070	458334	520547	477624	457202	337048	254673
Space cooling energy (kWh)	241	7231	8219	8761	9220	13383	16665	16866	17260	13652	12274
Fans and pumps energy (kWh)	192154	193480	190389	190902	188204	187753	188701	188659	189104	188160	185923
Lights (kWh)	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
Equipment (kWh)	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
System gas energy (kWh)	429032	404074	440359	403815	404070	458334	520547	477624	457202	337048	254673
System electricity energy (kWh)	192396	200711	198609	199663	197424	201136	205366	205526	206365	201812	198197
Total system energy(kWh)	621428	604785	638967	603478	601494	659470	725914	683150	663567	538860	452870
Total energy (kWh)	650574	656452	713155	701872	724072	804570	899971	887358	896733	794547	737513

As shown in Table 6-13, the total system energy under 24/7 operation is greater than the 100% occupancy performance for all reduced occupancy levels. The greatest increase was again seen at the 60% occupancy level. In terms of total energy, analyses showed that under the current 24/7 control, the building would have actually consumed less energy has it been 100% occupied than at the lower levels down to 50% occupancy.

Table 6-13: Comparing annual system and total energies at varying occupancy levels to consumption at full occupancy with 24/7 HVAC operation (seqence 1 hr 21)

Occupancy	Total annual system energy (kWh)	% difference in total system energy from 100%	Annual total energy	% difference in total energy from 100%
100%	452870	0	737513	0
90%	538860	19	794547	8
80%	663567	47	896733	22
70%	683150	51	887358	20
60%	725914	60	899971	22
50%	659470	46	804570	9
40%	601494	33	724072	-2
30%	603478	33	701872	-5
20%	638967	41	713155	-3
10%	604785	34	656452	-11
0%	621428	37	650574	-12

This indicates the amounts of wasteful energy that can occur in unoccupied buildings that are inefficiently managed. In the next section these results from these simulation tests are compared to those for a building with effective management.

6.9 Simulated energy with effective management and HVAC operating only in occupied areas

It has been seen that Facilities Management has been inefficient. BMS management has been poor and reasons for this include financial difficulties and a lack of both training and understanding of the systems in place. This section investigates potential improvements in the energy performance delivered by efficient and effective management of the BMS. As the occupancy uptake of the building has been slow and significantly lower than was anticipated, informed and effective management would have resulted in adjustments being made to the operation of the HVAC systems to minimise inefficient energy performance.

Energy performance resulting from energy efficient management is investigated in this section and the results are compared to those for the current running of the building. The HVAC system and night cooling is controlled in zones, mainly by east and west and by floor level.

In these tests the model's control settings at each occupancy level were adjusted to account for the unoccupied office spaces in the building. Unoccupied offices were put on 'set-back' control. The uptake of occupancy was based on 'sequence 1' described earlier. The results are presented in the Table 6-14.

Table 6-14: Annual energy performance (kWh) of a well-managed system at varying occupancy levels (sequence 1 hr21)

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Space heating energy	166913	154430	147770	143017	131999	122993	116670	111213	107688	102155	99102
Space cooling energy	294	2755	3089	3494	3551	5497	5786	6279	6537	7689	8030
Annual Fans and pumps energy	1215	9517	20282	28999	37794	45202	55499	64260	75114	82053	92071
Lights	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
Equipment	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
System gas energy	166913	154430	147770	143017	131999	122993	116670	111213	107688	102155	99102
System electricity energy	1558	12289	23380	32502	41353	50701	61285	70540	81651	89743	100102
Total system energy	168470	166719	171150	175519	173352	173693	177955	181752	189339	191897	199203
Total energy	197616	218385	245339	273913	295931	318794	352012	385960	422504	447584	483847

Some of the end-use energy consumptions at the various occupancy levels tested are shown graphically in Figures 6-13 to 6-17. Reductions in energy use as occupancy decreases are seen with the expected exception to space heating where there is a continuous increase in usage as occupancy decreases.

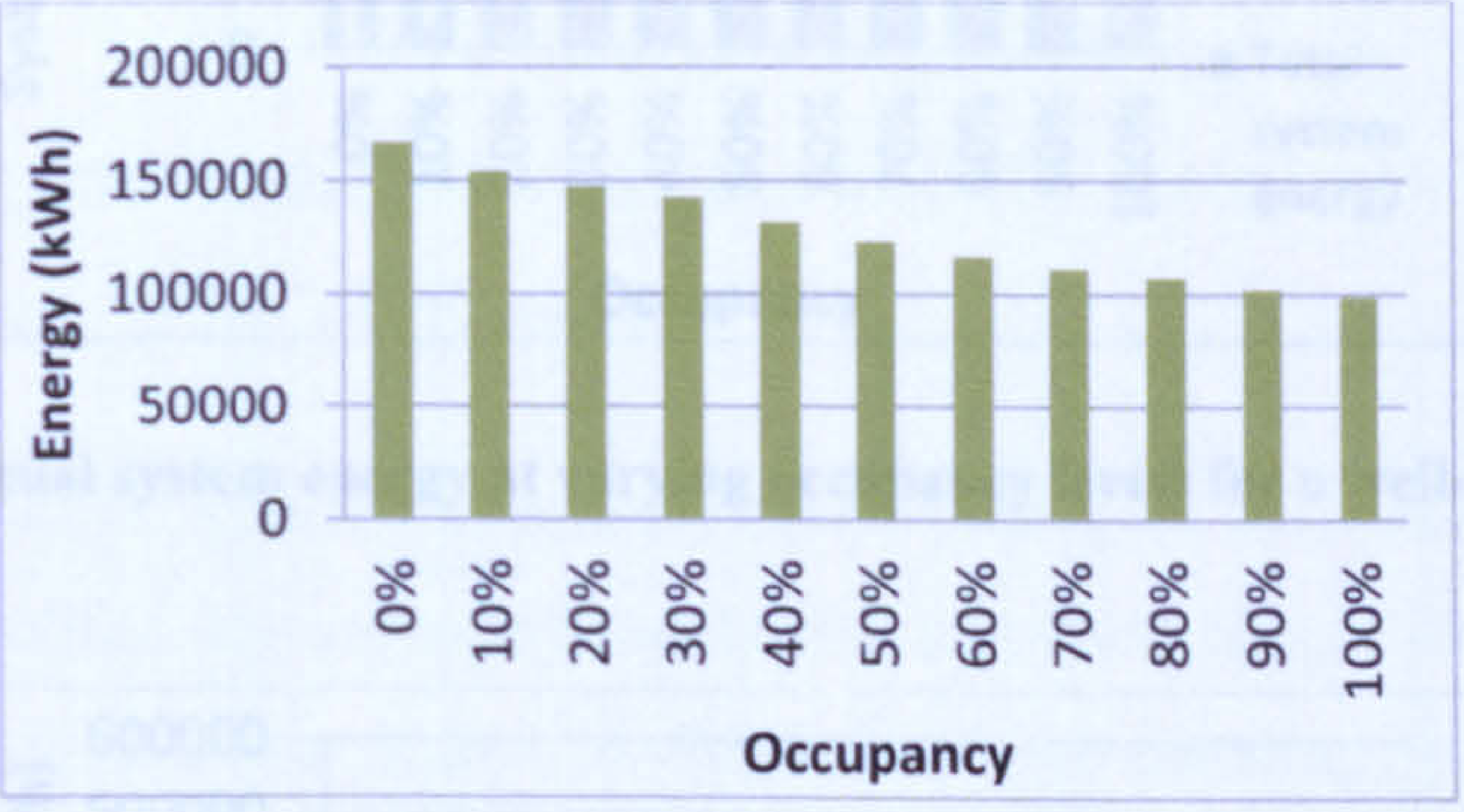


Figure 6-13: Annual space heating at varying occupancy levels for a well-managed system

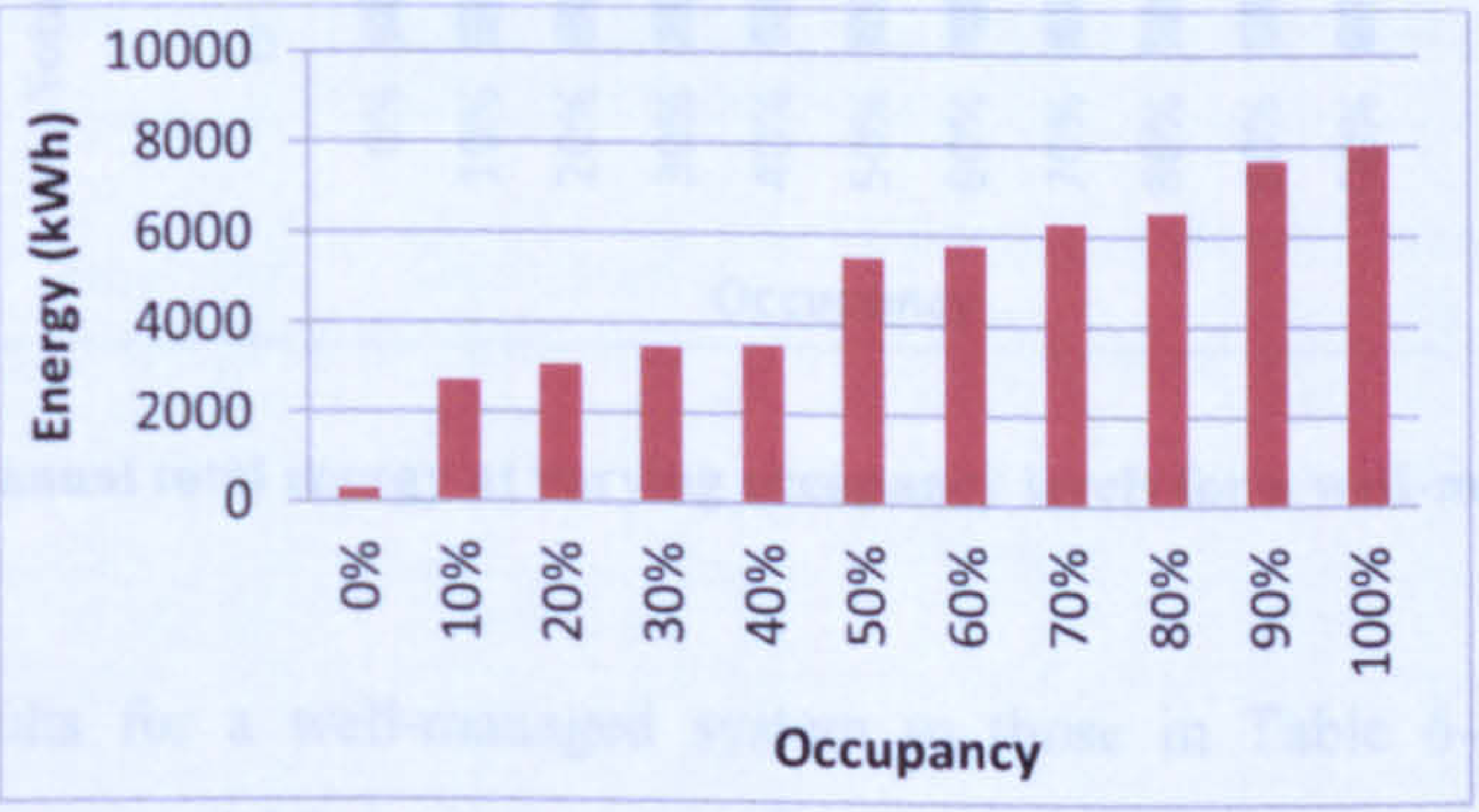


Figure 6-14: Annual space cooling at varying occupancy levels for a well-managed system

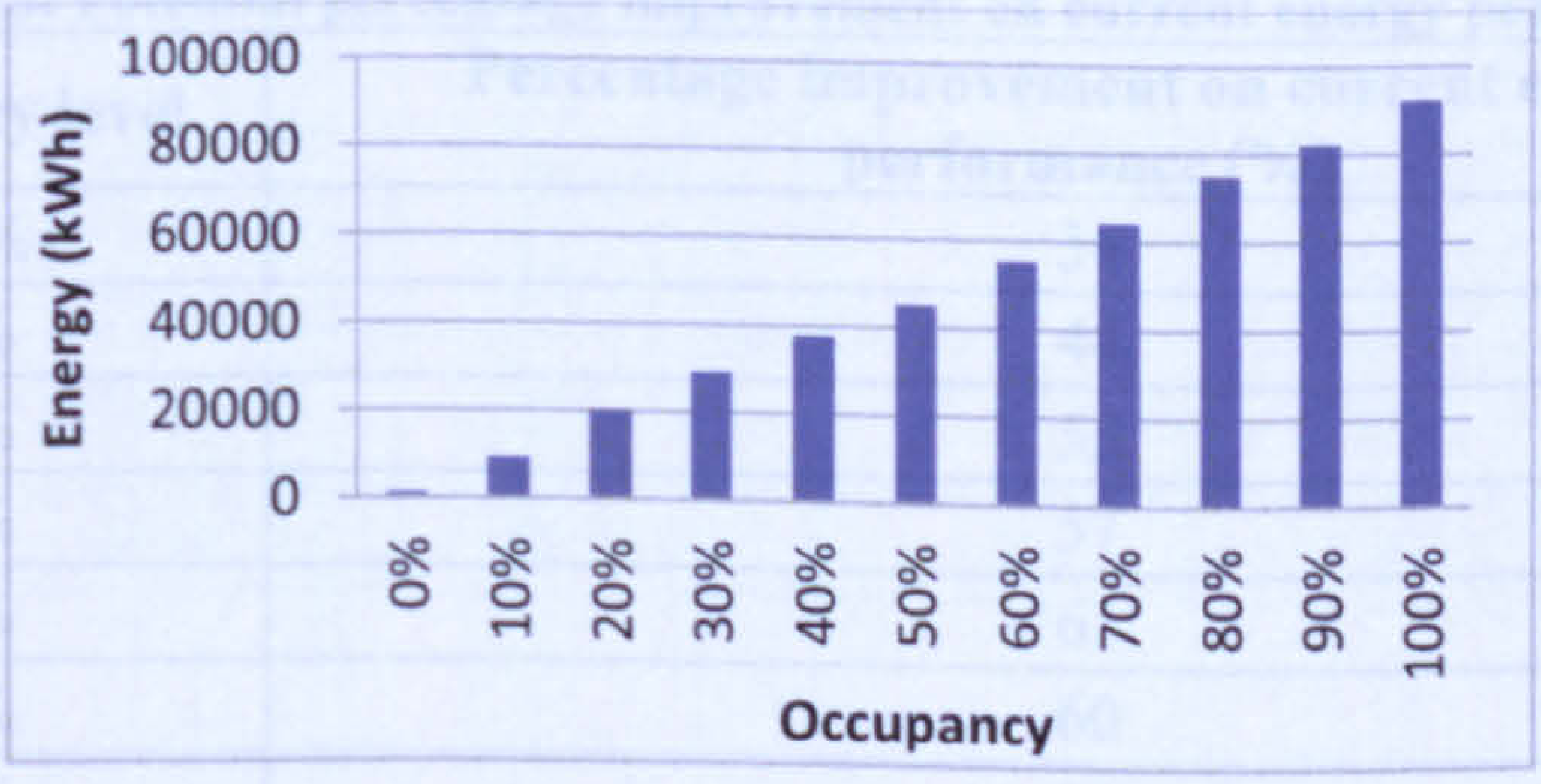


Figure 6-15: Annual Fans and pumps at varying occupancy levels for a well-managed system

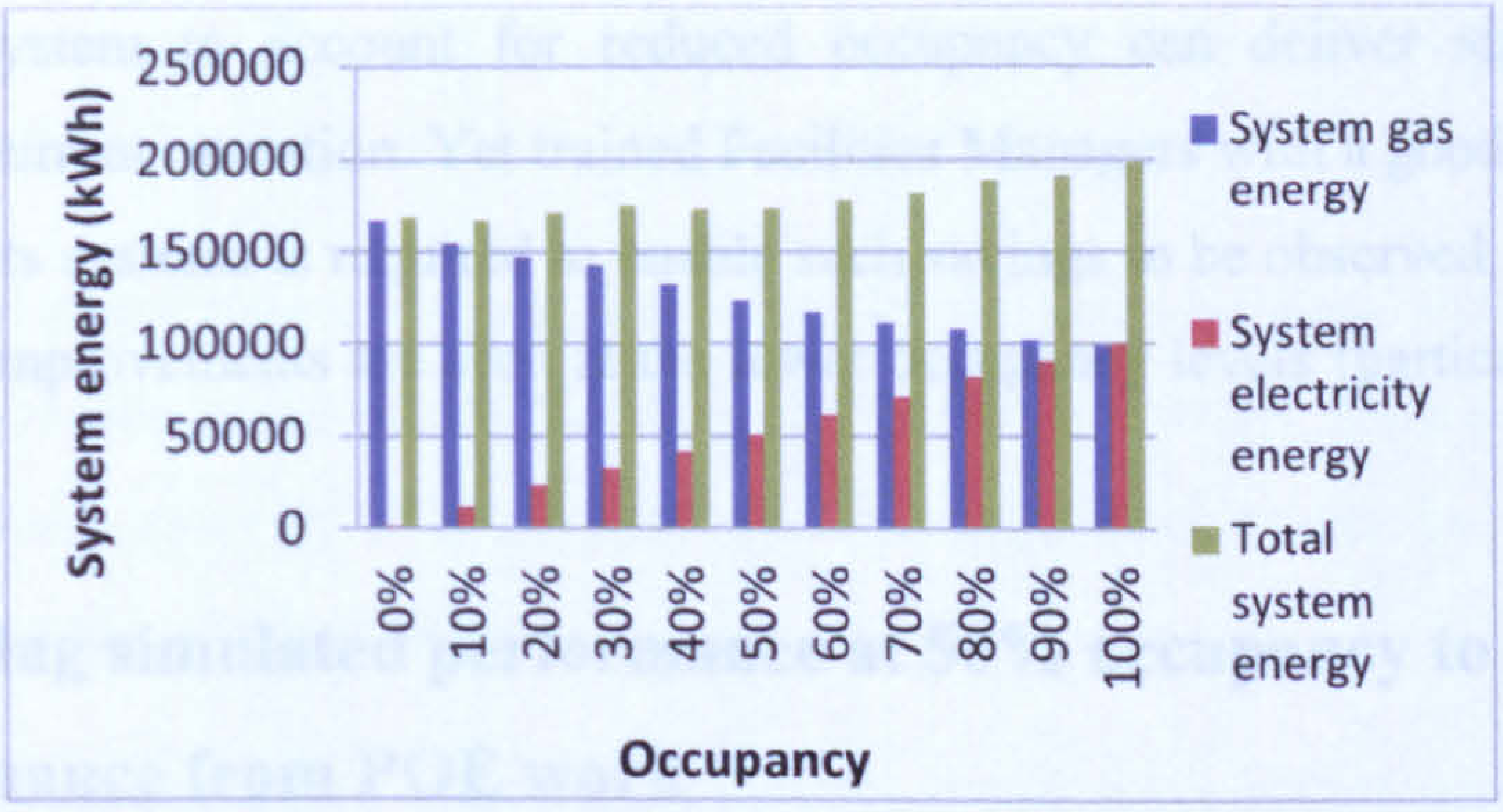


Figure 6-16: Annual system energy at varying occupancy levels for a well-managed system

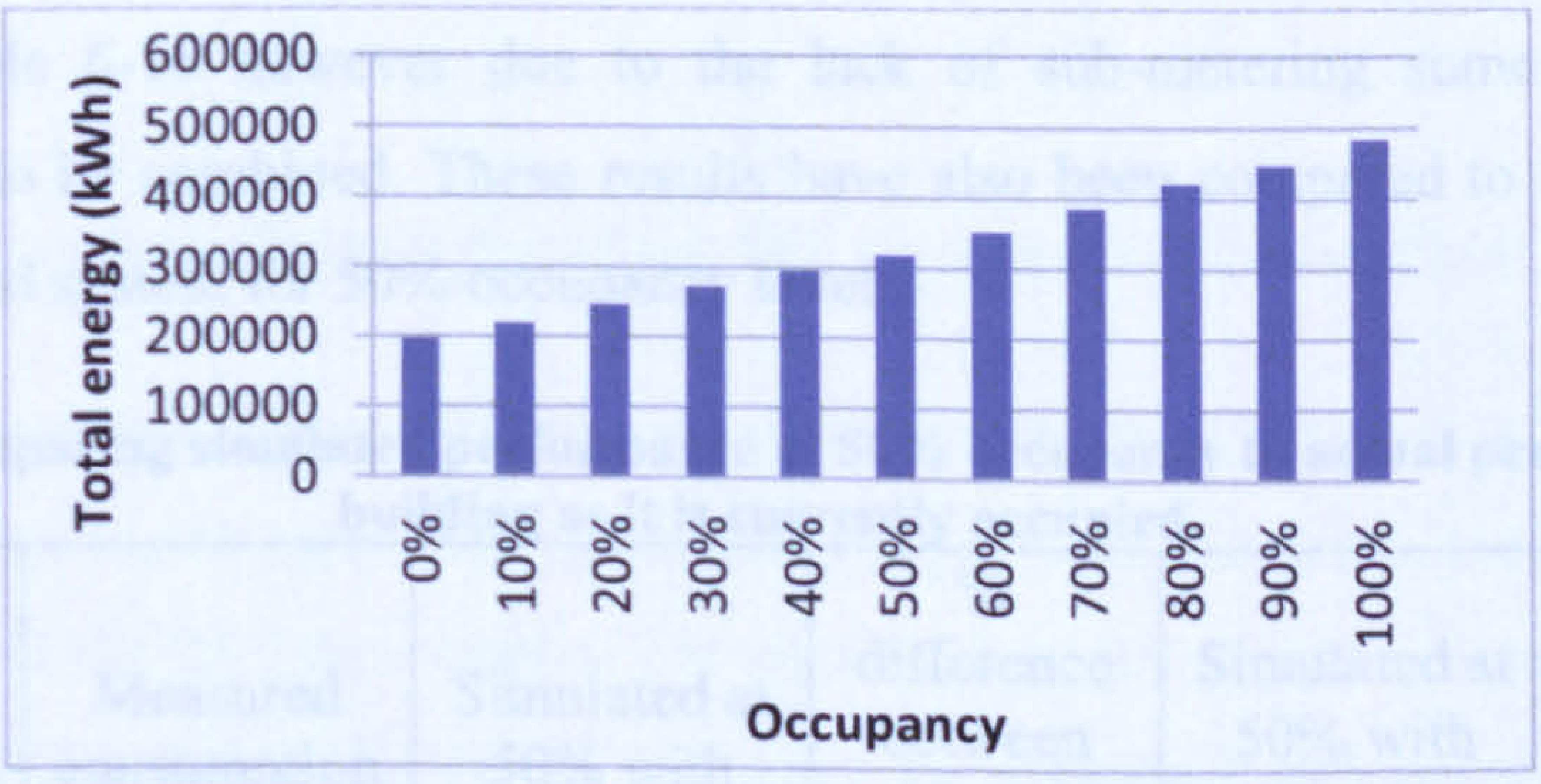


Figure 6-17: Annual total energy at varying occupancy levels for a well-managed system

Comparing the results for a well-managed system to those in Table 6-12 (as it has been managed) allows the potential improvements to be calculated. Table 6-15 shows the potential percentage improvement on current performance at various occupancy levels.

Table 6-15: Potential percentage improvement on current energy performance

Occupancy level	Percentage improvement on current energy performance (%)
100%	34
90%	44
80%	53
70%	57
60%	61
50%	60
40%	59
30%	61
20%	66
10%	67
0%	70

Modifying the system to account for reduced occupancy can deliver significant savings compared to the current operation. Yet trained Facilities Managers with a good understanding of the building and its systems is required to enable such savings to be observed. The results show that the greatest improvements are seen at the lower occupancy levels (particularly at 10% and 20%).

6.9.1 Comparing simulated performance at 50% occupancy to measured performance from POE work

In this section the results from the simulation model with 50% occupancy levels set and the system operating inefficiently are compared to the measured energy use for 2009. This is presented in Table 6-16 however due to the lack of sub-metering some of the system's components had to be combined. These results have also been compared to simulation results for a well-managed system for 50% occupancy levels.

Table 6-16: Comparing simulated performance at 50% occupancy to actual performance of the building as it is currently occupied.

Annual energy(kWh)	Measured consumption (kWh)	Simulated at 50% with HVAC 24/7	% difference between measured and simulated	Simulated at 50% with effective management	% difference between measured and simulated
Space heating	434556	458334	-5	122993	253
Space cooling		13383		5497	
Fans, pumps and controls		187753		45202	
Space cooling + fans, pumps and controls	211514	201136	5	50699	317
Lights	61017	51641	18	51641	18
Equipment	118399	93459	27	93459	27
System gas	434556	458334	-5	122993	253
System electricity	211514	201136	5	50701	317
Total system	646070	659470	-2	173693	272

Overall, the actual total system energy consumption at 50% occupancy is 2% less than the simulated energy results for 24/7 operation. The space heating energy is 5% less than the simulated, space cooling energy and annual fans, pumps and controls energy is 5% more than the simulated by the model. The actual energy consumed due to lighting demands was 18% more than the model simulated however; this measured figure includes some landlord lighting needs. Likewise, the equipment energy included all the landlord small power sockets including the cafe in the atrium area. The similar results for both the measured and simulated data show that the model is reliable to perform comparative analysis.

Comparing the measured data to the simulated data for the same building with a more effective management system quantified the inefficiency of the current settings. Measured annual system energy was 3.7 times more or 272% greater than the simulated results for the building with effective management is implemented.

There is great potential for the building to operate much more efficiently than the current operation. Management need to instigate actions to rectify the settings on the BMS to enable the building to operate much more efficiently.

6.9.2 Comparing simulation weather file to measured weather data

In the original design the example weather year file for Sheffield, which is closest to the Leeds area, was used. To remain consistent with the design work the same file was used in this research. The SheffieldEWY.fwt weather file data used in the simulation tests is compared to the measured weather data in Table 6-17. Overall the measured temperatures were generally slightly higher than the ones used in the simulation tests. There was an overall difference of 1.48°C in annual average temperatures between the two sets of data. These differences should be considered when making comparisons between simulated and measured energy consumption.

Table 6-17: Comparing simulation weather file and measured weather data

Month	Statistic	Simulation weather file Dry-bulb temperature °C	Measured outside air temperature °C	Difference °C
Jan	Mean	0.99	3.65	2.66
	Max.	10.40	11.66	1.26
	Min.	-10.10	-4.41	5.69
Feb	Mean	3.62	6.63	3.01
	Max.	14.30	11.93	-2.37
	Min.	-7.80	-2.5	5.30
Mar	Mean	3.99	7.37	3.39
	Max.	12.50	15.12	2.62
	Min.	-4.10	-1.38	2.72
Apr	Mean	9.69	10.12	0.43
	Max.	20.80	20.47	-0.33
	Min.	2.10	1.75	-0.35
May	Mean	9.76	12.12	2.37
	Max.	22.00	26.24	4.24
	Min.	-0.20	3.54	3.74
Jun	Mean	12.38	14.53	2.15
	Max.	25.40	26.45	1.05
	Min.	3.00	5.17	2.17
Jul	Mean	15.76	16.62	0.85
	Max.	26.50	29.73	3.23
	Min.	8.20	8.59	0.39
Aug	Mean	15.24	17.21	1.97
	Max.	26.50	28.92	2.42
	Min.	5.50	9.76	4.26
Sep	Mean	13.14	14.19	1.05
	Max.	21.20	23.95	2.75
	Min.	3.20	9.08	5.88
Oct	Mean	10.23	11.29	1.06
	Max.	19.80	17.97	-1.83
	Min.	-1.20	3.31	4.51
Nov	Mean	7.43	7.73	0.31
	Max.	15.10	14.98	-0.12
	Min.	0.40	1.51	1.11
Dec	Mean	6.00	2.94	-3.06
	Max.	14.30	11.13	-3.17
	Min.	-2.30	-6.26	-3.96
Year	Mean	9.04	10.52	1.48
	Max.	26.50	29.73	3.23
	Min.	-10.10	-6.26	3.84

6.10 Quantifying the amounts of wasteful energy consumed from current building management and control settings

As seen, the building has been inefficiently managed and many of the controls have been left to run on a 24/7 basis. The current building operation has been wasteful in environmental and economic terms. To quantify this, the three models with different management strategies have been produced and the results have been compared.

6.10.1 Models used for alternative management strategy analysis

The three models are:

a) As built, as managed: The 'as built, as managed' model represents the building as it has actually been managed, with the HVAC system operating on a 24/7 basis in all areas regardless of them being occupied or not. Results from the as 'built, as managed' model have been generated for different occupancy levels. In this model, the building is not benefiting from the night cooling ventilation as it is being conditioned throughout the night.

b) As built, inherited management: The 'as built, inherited management' model represents the building performance as it has would have been operating had the controls not been changed to operate 24/7. Although the HVAC system is not operating on a 24/7 basis and instead is performing as it was designed to (as per control strategy, during occupied periods and with the night cooling in place), in this version the unoccupied areas are still being conditioned as though they are occupied.

c) As built, good management: The 'as built, good management' model has been created to simulate the energy performance of the building if more efficient management strategies had been implemented in response to lower occupancy levels. In the areas that are unoccupied this model has been managed to operate on set back control, with a set point of 12°C and set-back trickle ventilation. The set-back controls are important to protect the builds fabric from damage.

Each model (a, b and c above) has been simulated at various occupancy levels. The same occupancy uptake (sequence 1 as described earlier) in the building has been used in these simulations as the one that has actually occurred.

6.10.2 Wasteful energy in terms of energy units

Tables 6-18 to 6-20 show the annual total system energy and total energy consumption for these three models at various occupancy levels. Similar tables of results for the individual components of energy use are found in Appendix A.

Table 6-18: Total system energy (kWh)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	621428	604785	638967	603478	601494	659470	725914	683150	663567	538860	452870
As built, inherited management	334348	329174	326599	318293	311119	337403	359339	332035	307613	259041	199203
As built, good management	168470	166719	171150	175519	173352	173693	177955	181752	189339	191897	199203
Energy difference between good management and as managed (kWh)	-452957	-438067	-467817	-427959	-428141	-485777	-547958	-501397	-474228	-346962	-253667

Table 6-19: Total energy (kWh)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	650573	656452	713156	701872	724072	804570	899970	887358	896732	794547	737514
As built, inherited management	363493	380841	400788	416687	433697	482504	533395	536243	540778	514729	483847
As built, good management	197616	218385	245339	273913	295931	318794	352012	385960	422504	447584	483847
Energy difference between good management and as managed (kWh)	-452957	-438067	-467817	-427959	-428141	-485777	-547958	-501397	-474228	-346962	-253667

Table 6-20: Total energy including hot water demands (kWh)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	650573	658452	717156	707872	732072	814570	911970	901358	912732	812547	757514
As built, inherited management	363493	382841	404788	422687	441697	492504	545395	550243	556778	532729	503847
As built, good management	197616	220385	249339	279913	303931	328794	364012	399960	438504	465584	503847
Energy difference between good management and as managed (kWh)	-452957	-438067	-467817	-427959	-428141	-485777	-547958	-501397	-474228	-346962	-253667

In terms of total system energy, at 50% occupancy levels the 'as built, as managed' model uses 1.95 times more energy than the 'as built, inherited management' model and 3.70 times more energy than the 'as built, good management model'. In terms of units of energy this is 322067kWh and 485777kWh respectively. If the building had been managed more efficiently, the current total system energy consumption could have been reduced by 73.66%.

In terms of total energy, at 50% occupancy levels the 'as built, as managed' model uses 1.67 times more energy than the 'as built, inherited management' model and 2.52 times more energy than the 'as built, good management model'. The current total energy consumption could have been reduced by 60.38% had the building been managed efficiently.

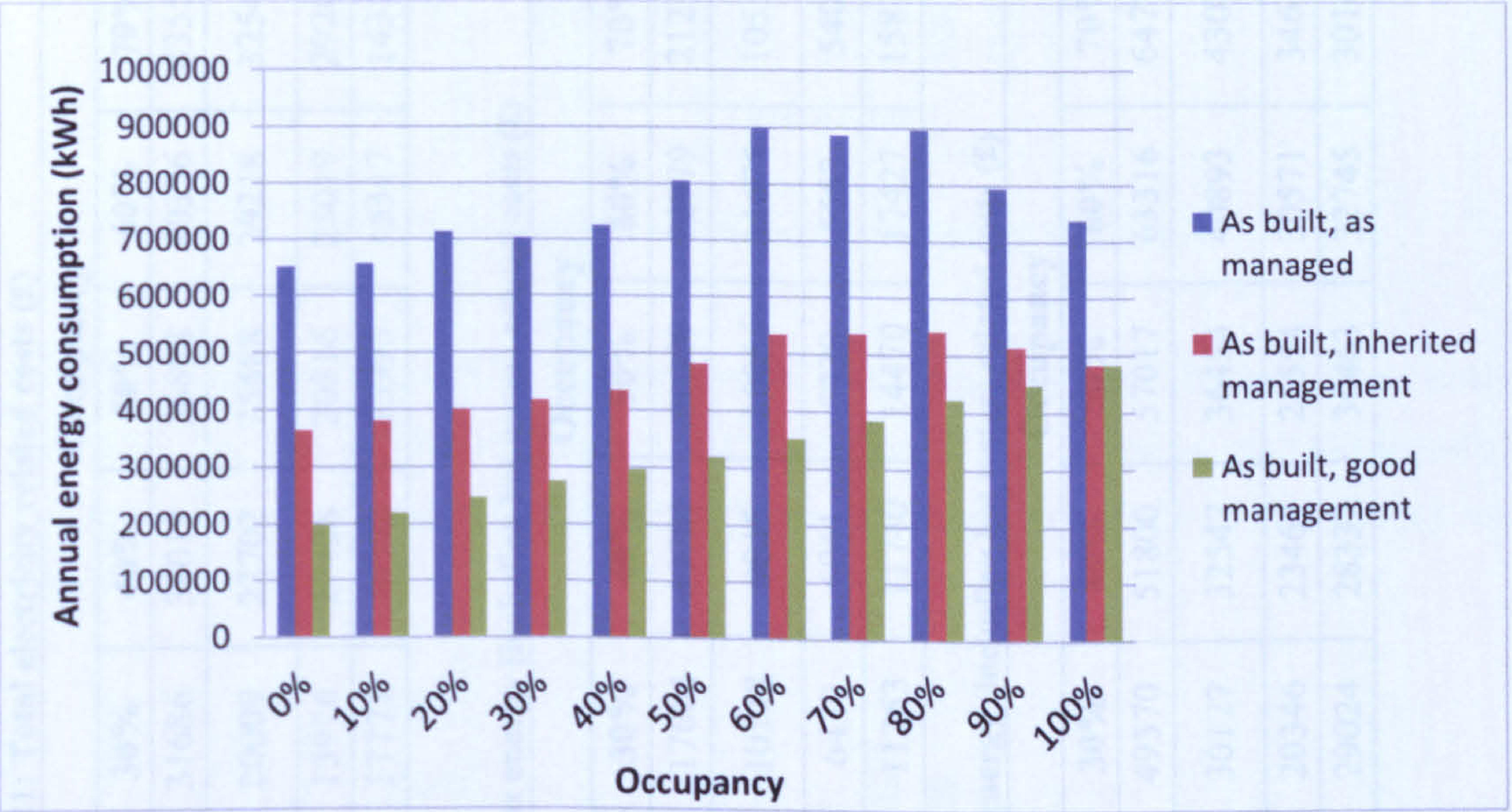


Figure 6-18: Total energy associated with the three management scenarios

6.10.3 Wasteful energy in economic terms

Under the current control setting of the BMS, it has been highlighted that the building has been performing much less efficiently than it potentially could have been. Converting the amounts of wasteful energy into monetary terms (pounds and pence) can demonstrate the amounts of wasteful money that has been spent on utility bills due to inefficient control and operation of the building's BMS. A rate of 4.3 pence/kWh was assumed for gas and 10.3 pence/kWh for electricity. These figures were derived from inspection of the utility bills at site. The results are shown in Tables 6-21 to 6-23.

Table 6-21: Total electricity related costs (£)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	23552	26830	29001	31686	34019	36808	40336	43559	46726	48637	51331
As built, inherited management	11285	14376	17190	20009	22702	25588	29218	32545	35832	38209	40902
As built, good management	3264	6799	10372	13916	17428	20816	25019	29208	33468	36723	40902
Potential annual savings (£)	20288	20031	18629	17771	16592	15993	15317	14350	13258	11914	10429

Table 6-22: Total gas energy (including hot water) related costs (£)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	18513	17522	19174	17684	17781	20209	22979	21214	20419	15320	11852
As built, inherited management	11104	10685	10489	10118	9845	10866	11675	10534	9481	7479	5139
As built, good management	7202	6750	6549	6430	6041	5739	5552	5403	5337	5185	5139
Potential annual savings (£)	11310	10772	12625	11253	11740	14470	17427	15811	15082	10136	6713

Table 6-23: Total energy (including hot water) related costs (£)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	42065	44352	48175	49370	51800	57017	63316	64772	67145	63957	63183
As built, inherited management	22389	25060	27679	30127	32547	36454	40893	43078	45313	45687	46042
As built, good management	10466	13549	16921	20346	23469	26554	30571	34611	38805	41907	46042
Potential annual savings (£)	31598	30803	31254	29024	28332	30463	32745	30161	28340	22050	17141

In terms of total electricity utility bills, had the system been operating more efficiently than it has currently been, then at 50% occupancy £15,993 could have been saved on electricity bills annually. The potential savings at other occupancy levels are also shown in Table 6-21.The savings are shown in Figure 6-19.

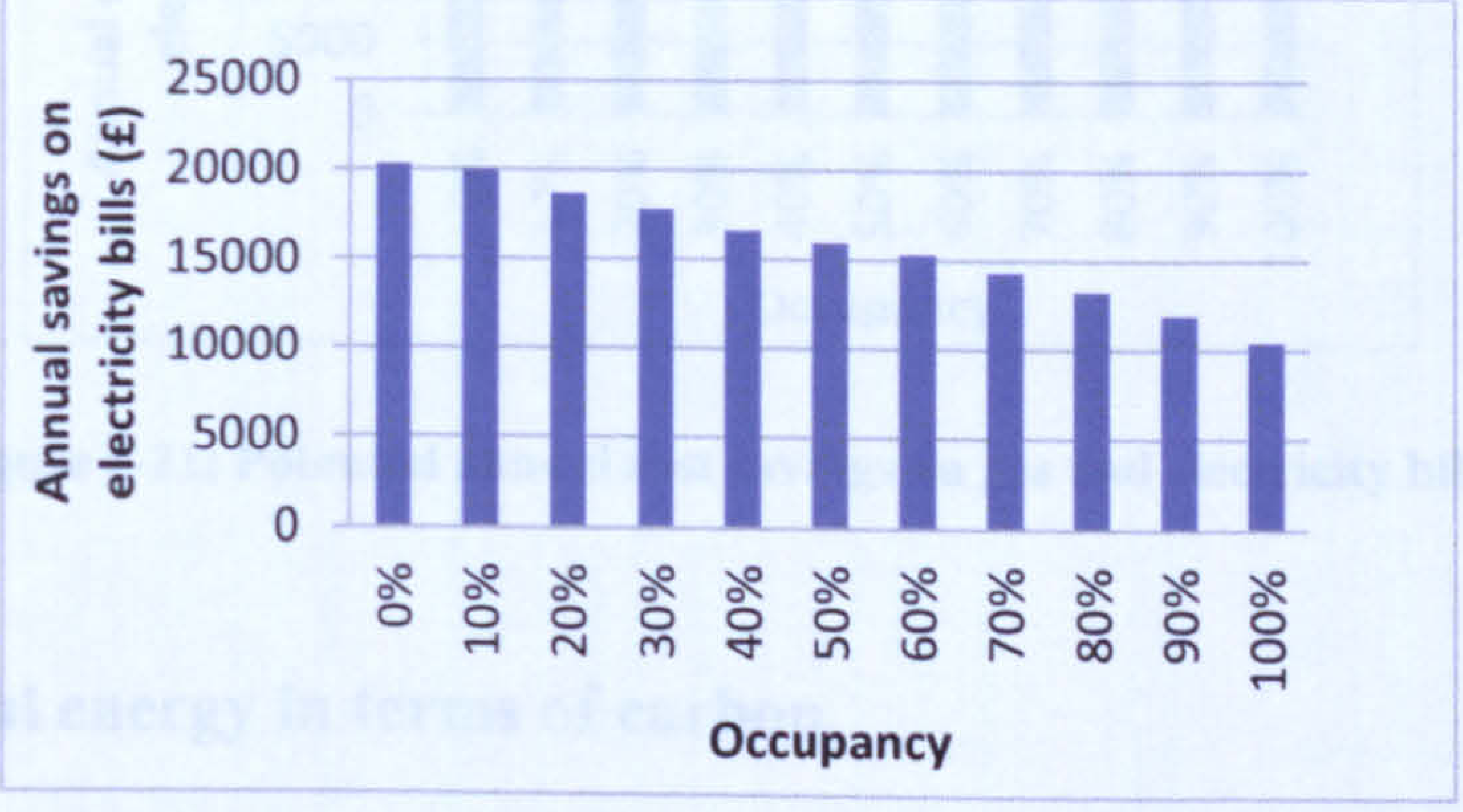


Figure 6-19: Potential annual cost savings on electricity bills

In terms of total gas utility bills, had the system been operating more efficiently than it has currently been, then at 50% occupancy £14,470 could have been saved on gas bills annually. The potential savings at other occupancy levels are also shown in Table 6-21. The savings are shown in Figure 6-20.

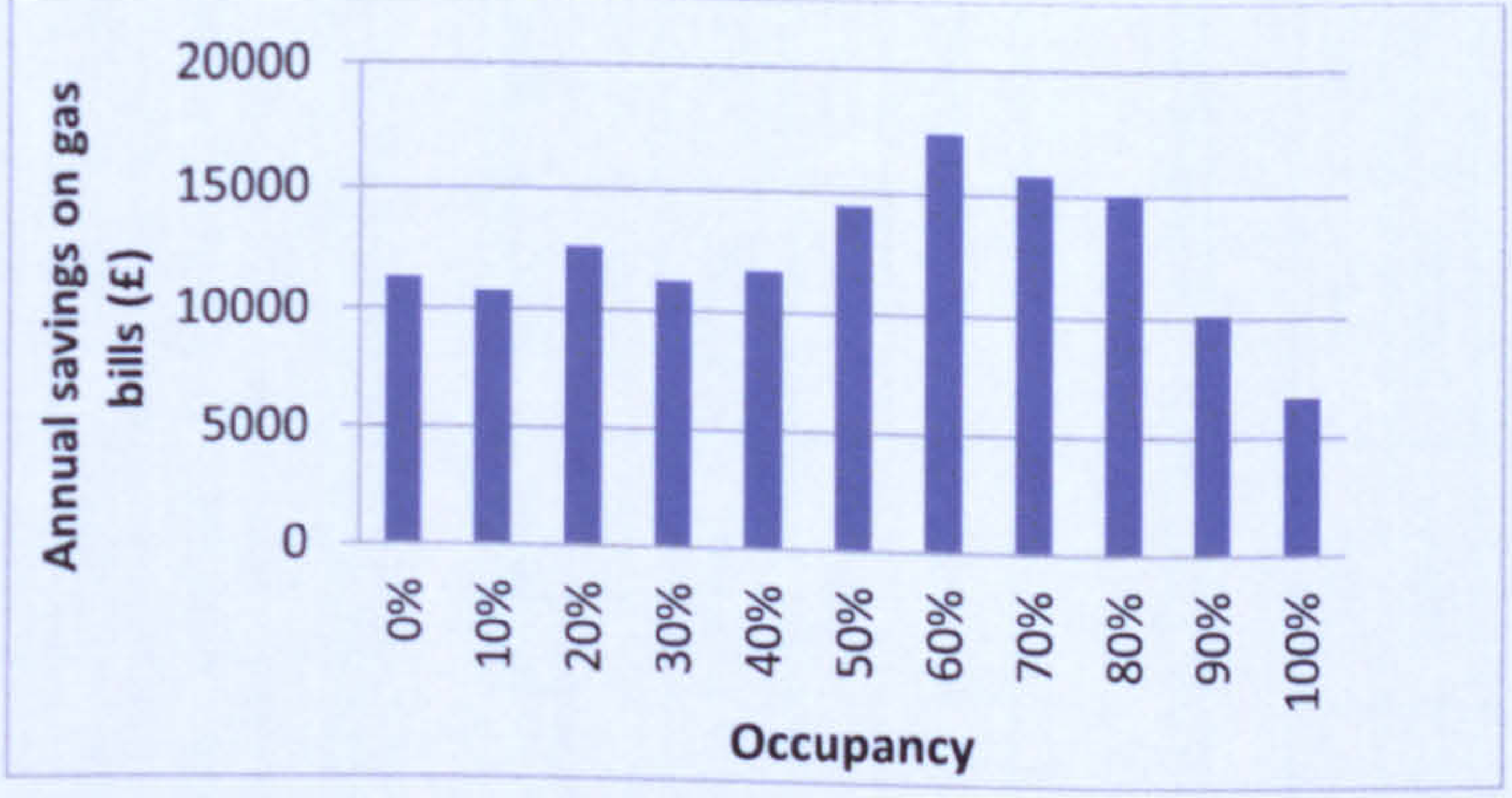


Figure 6-20: Potential annual cost savings on gas bills

In terms of total building energy (including all system energy, lighting needs, equipment energy and hot water demands), had the system been operating more efficiently than it has currently been, then at 50% occupancy £30,463 could have been saved on utility bills annually. The potential savings at other occupancy levels are also shown in the Table 6-23. The savings are shown in Figure 6-21.

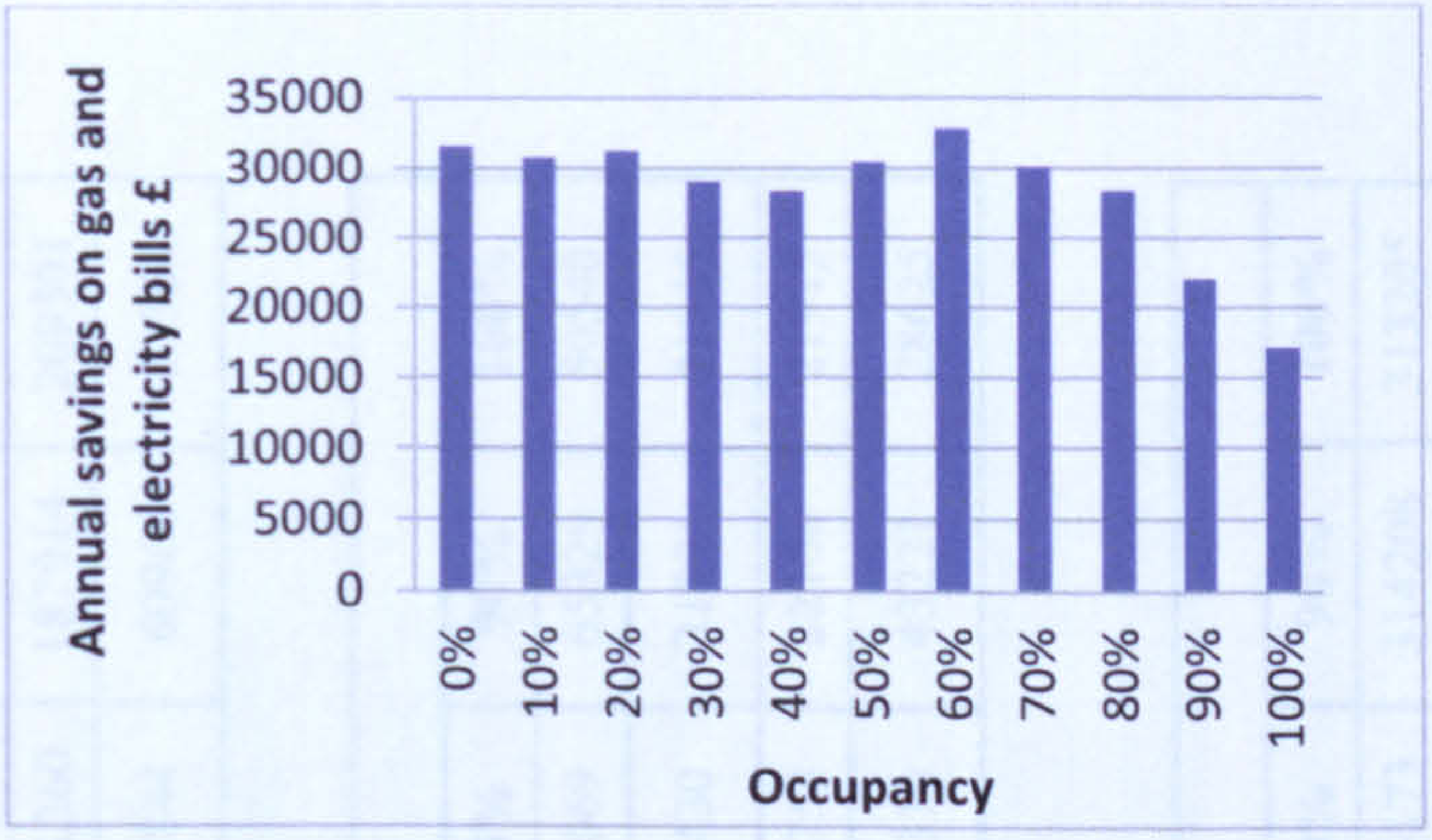


Figure 6-21: Potential annual cost savings on gas and electricity bills

6.10.4 Wasteful energy in terms of carbon

The 2009 DEFRA/DECC carbon conversion factors were used to calculate the amounts of CO_2 emissions due to the wasteful amount of energy consumed. A conversion factor of $0.184kgCO_2/kWh$ was used for natural gas and $0.544kgCO_2/kWh$ used for electricity (AEA 2009). These results are shown in Tables 6-24 to 6-26.

Table 6-24: Total electricity related carbon emissions ($kgCO_2$/year)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	120519	137294	148402	162143	174081	188352	206406	222895	239104	248879	262666
As built, inherited management	57746	73562	87964	102389	116169	130938	149512	166534	183354	195518	209301
As built, good management	16702	34792	53077	71207	89179	106516	128026	149463	171260	187914	209301
Potential annual savings ($kgCO_2$)	103816	102502	95324	90936	84903	81837	78380	73432	67844	60966	53364

Table 6-25: Total gas (including hot water) related carbon emissions ($kgCO_2$/year)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	78942	74718	81762	75406	75821	86173	97989	90459	87069	65329	50540
As built, inherited management	47351	45561	44728	43143	41980	46333	49782	44917	40430	31891	21915
As built, good management	30712	28783	27926	27419	25760	24471	23675	23039	22759	22108	21915
Potential annual savings ($kgCO_2$)	48230	45935	53836	47987	50061	61702	74314	67420	64310	43221	28625

Table 6-26: Total energy (including hot water) related carbon emissions ($kgCO_2$/year)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	199460	212011	230164	237549	249902	274526	304395	313354	326173	314208	313205
As built, inherited management	105097	119124	132692	145532	158148	177271	199295	211451	223785	227409	231216
As built, good management	47414	63575	81003	98626	114939	130986	151701	172502	194018	210022	231216
Potential annual savings ($kgCO_2$)	152046	148436	149161	138923	134963	143540	152694	140852	132155	104186	81989

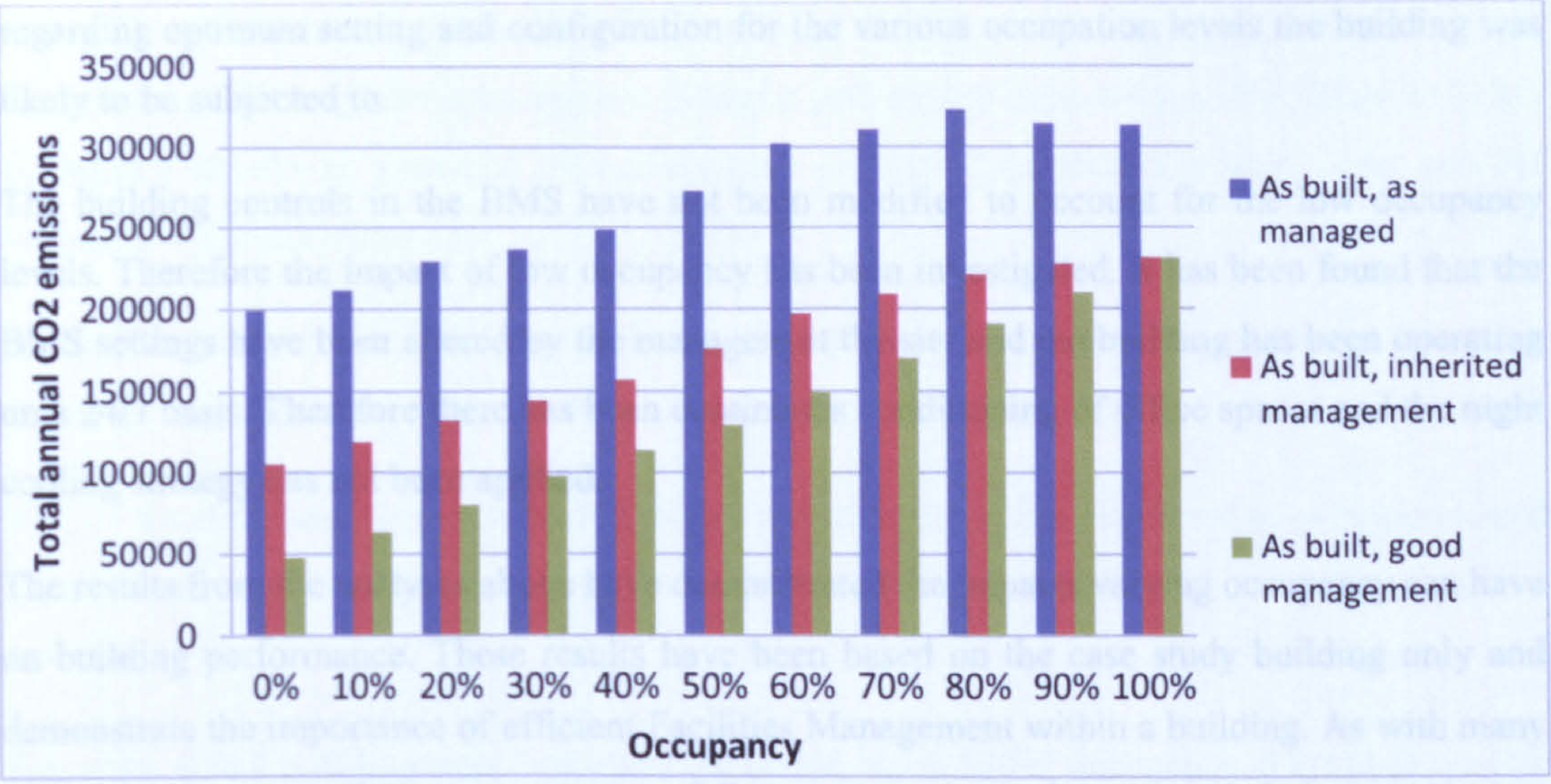


Figure 6-22: Total annual CO_2 emissions (including hot water)

The associated CO_2 emissions at all the occupancy levels tested are shown in Figure 6-22. Comparing how the building has actually been managed to one effectively managed at the 50% occupancy level shows that 143540 $kgCO_2$ annual has been wasted- representing 33.17 $kgCO_2/m^2$/year.

6.11 Chapter discussion and conclusion

The impact of occupancy on building performance has been investigated in this chapter. The model was updated to be more representative of the building and its systems. The updated model did not exactly match those predicted by the original designer. However, the main purpose of this section of the study was to investigate the impacts low occupancy (and the associated low internal heat gains resulting from this reduced occupancy) have on the energy consumption of the building. The changes in occupancy levels have the most significant effect on the heating demand of the building.

Effective facilities management should be implemented in all commercial buildings. If areas of a building are unoccupied, particularly for a long period of time, the Facility Manager should respond to this by switching the BMS plant controls (or other appropriate controls) to operate at set-back control. In those areas where lower occupancy levels are experienced than the controls are set to provide, ventilation rates should be reduced to provide more energy efficient performance whilst not compromising on occupant comfort in those areas that are occupied or in use. Unfortunately this didn't occur in the case study building.

The significant shortfalls in the building performance was largely due to the FM being unable or unwilling to correct plant failures, together with lack of experience and clarity from design regarding optimum setting and configuration for the various occupation levels the building was likely to be subjected to.

The building controls in the BMS have not been modified to account for the low occupancy levels. Therefore the impact of low occupancy has been investigated. It has been found that the BMS settings have been altered by the managers at the site and the building has been operating on a 24/7 basis. Therefore there has been continuous conditioning of office spaces and the night cooling strategy has not been applied.

The results from the analyses above have demonstrated the impacts varying occupancy can have on building performance. These results have been based on the case study building only and demonstrate the importance of efficient Facilities Management within a building. As with many office developments that rent out space, full occupancy is rarely achieved. It is important to fully understand the effect that the occupancy can have on the energy consumption. As indicated, effective management must be demonstrated to enable the building to operate as energy efficiently as possible. Also the interference from untrained managers altering the control setting of the BMS resulted in 24/7 operation.

Intelligent facility management or review can ensure challenge and clarity on the set and control point setting and base assumptions associated. Ideally management and available knowledge should be such to recognise when the control system mode operating may be compromised by the current or pending future operating environment.

This chapter has shown that occupancy levels in a building can, under certain conditions, significantly affect the performance of a building. These conclusions have been based on the case study building, and the magnitude of affects the occupancy levels have on the energy performance will depend on the buildings systems, controls, layout and fabric so will not be the same for other buildings.

This study highlights the general lack of understanding of the potential impacts of reduced occupancy and how best to design for and manage it. Relating this awareness to designer, operators and people involved in POE studies will best ensure potential conditions for inefficiencies and recognise further consideration. This is one of the major recommendations of this study.

It should also be noted that the results shown in this chapter have been based on the constant density of 7.5m^2 per person within the office spaces. In reality this constant density has not been found throughout the building and further work would include the impact of varying occupancy densities.

Using Dynamic Thermal Modelling Chapter 6 has investigated occupancy, management and control, in a building where occupancy is lower than design expectations. Buildings with low occupancy should be managed effectively and considered to reduce energy, costs and the associated CO_2 emissions.

At the beginning of this chapter a number of specific objectives were outlined. These are discussed and concluded below.

a) To simulate the performance of the building at the current level of occupancy and compare this with measured data

The case study building was originally modelled with 100% occupancy. However as low occupancy was found once the building became operational, the DTM was modified to test the energy performance at lower levels of occupancy.

Some differences were found between the results from the original designer's model and updated models, with a total energy percentage difference of 16%. The biggest differences were seen in the cooling energy requirements due to the changes in the night cooling and use of thermal mass. The 'as built to run' model presented slight improvements compared with the design model. This was due to the alterations to the underfloor heating system. The 'as built to run' model represented the settings as per design control philosophy, however it has been identified that the building has in fact been left to operate on a 24/7 basis in many areas. This appears to be due to changes made by management.

Overall, the actual total system energy consumption at 50% occupancy was 2% less than the simulated energy results for 24/7 operation. The similar results for both the measured and simulated data show that the model is reliable to perform comparative analysis.

Measured annual system energy was 3.7 times more or 272% greater than the simulated results for the building with effective management is implemented.

Hence, the differences in the designed and measured perform is largely due to the behaviour of people and the management over controls once a building becomes operational. If uncertain of the basis for control the Facility Management should instigate a review by suitably qualified people to ensure significant changes from base design and control conditions are properly considered.

b) To investigate the impact internal heat gains have on the energy performance of the building

The impacts on energy performance due to internal heat gains were investigated. In the first instance these were considered in the sense of being present (therefore 100%) or absent (i.e. 0%). The internal heat gains of people, computers and lighting were tested individually and also collectively. All other settings within the model remained unchanged. A number of impacts were identified from doing this:

1) The removal of people (and therefore their associated heat gains) brought with it a 20% increase in space heating energy, a 196% decrease in cooling energy and a 9% decrease in fan, pumps and controls energy. In terms of total annual system energy this translated to a 6% increase when the internal heat gains of people are removed.
2) The removal of computers had the most significant impact of all the individual internal heat gains, with an increase of 72% in space heating energy, although it reduced the cooling space energy by 95% and brought a 25% increase in total system energy and a 31% reduction in total energy.
3) The removal of the internal heat gains from lighting found an 18.9% increase in space heating energy, a 25% decrease in space cooling energy, a 6% increase in total system energy and a 9% decrease in total energy.
4) Assessing the energy performance when all internal heat gains (i.e. people, computers and artificial lights) are removed, found a 160% increase in space heating energy, a 100% decrease in cooling energy, a 68% increase in total system energy and a 25% decrease in total energy.

These tests showed that occupancy does contribute towards off-setting the space heating energy in a building, and this is most heavily influenced by the heat gains from computers. The metabolic heat gains from people alone, off-set heating demands by 20%. When other heat gains are also considered this figures increases to 160%.

c) To investigate the building's energy consumption when partial occupancy exists

The impacts varying occupancy has on building energy performance were investigated using the 'as built hr 21' model. The energy use at the varying occupancy levels were simulated and revealed interesting findings, anomalies and potential flaws in the control and setting.

As occupancy (including people, lighting and computers) decreased from 100% (with no changes made to the BMS controls in terms of space conditioning to account for this) the heating energy generally increased. However, this was not consistent and simulation results identified an increase in heating energy from 100% down to 60% occupancy with a trend change or reduction in energy at 50% and 40%, then a gradual increase again after 40% occupancy. These results suggested that more space heating was required at 60% compared to 40%- contradicting the overall expected trend. In terms of space cooling under the same conditions, there was a general overall decrease in energy required as occupancy decreased from 100% down to 0% as expected due to the reduction in internal heat gains (although again there was a slight 'dip' in the results at the 90% occupancy level).

In terms of fan and pumps energy there was little variation in the energy requirements at the occupancy levels tested. The lighting and equipment energy showed expected decreases as occupancy levels reduced.

What was interesting from the simulation results generated was that in terms of system energy it appears to be the most efficient to have the building 100% occupied, with the least energy efficient occupancy level being at 60% (this is based on the sequence found at post-occupancy and therefore used in the model). Even more interestingly, when considering total energy (i.e. system energy, lighting energy and small power energy) and also total energy with hot water demands included, the results show that the total energy is actually less at 100% occupancy than at 60% occupancy even after factoring in the lighting and small power energy consumption. From a business perspective, the serviced office business potentially (based on the running settings tested) would have used less energy if the building was fully occupied compared to the 60% occupancy level and therefore actually saved money had they let this extra space with no rental charge.

At first these unexpected trend changes in the heating energy were treated as potential anomalies. However once investigated the trend changes in energy use were identified as a consequence of the heat recovery device performance, the set-points and average voting for control under varying occupancy levels. The detailed report for this conclusion is shown in Chapter Seven.

The case study building has been inefficiently managed at the post occupancy stage with not only the areas that are unoccupied being treated/conditioned as though they are occupied but also many areas being controlled and treated on a 24/7 basis. Similar trend changes in the data were seen, but overall consumption was much greater. This 24/7 simulation was a more realistic set of results to use when comparing the simulated results at 50% against the actual performance that was measured. Total system energy was calculated as 2% more in the simulated model than the measured data identified, and lighting and small power were 18% and 27% less respectively.

These investigations raise the awareness of reduced occupancy in buildings, showing that there needs to be full consideration to the control of the building when low occupancy exists as this can have an adverse effect on performance. Designers should provide effective operational guidance. If low occupancy does occur, FMs should then be able to better understand appropriate control set points thus ensure efficient performance under these conditions.

d) To evaluate the potential environmental and economic savings resulting from the implementation of effective management strategies when partial occupancy exists

The performance of the building with more efficient management was then evaluated. This was modelled in such a way that the unoccupied areas of the building were conditioned on 'set back' to provide the adequate means of maintaining the building fabric. Three base models were simulated and the results were compared. These models are referred to and described as:

1. 'As built, as managed': this is effectively the 'HVAC 24/7 hr 21' model described earlier.
2. 'As built, inherited management: this described the model based on the settings set out in the control philosophy manual for the building but with no alternations made to account for reduced occupancy, i.e. 'As built hr 21' model described earlier.
3. 'As built, good management': this is the as built model with effective management incorporated so that the areas that are unoccupied were controlled under 'set back' control.

The results for these various models were generated for various occupancy levels, and reported and compared in terms of energy, money and carbon savings annually. A number of conclusions can be drawn from the results produced.

a) In terms of total system energy at the 50% occupancy level the 'as built, as managed' was most inefficient, consuming 1.95 times and 3.80 times more energy than the 'as built, inherited management' and the 'as built, good management' models respectively. Had the building been managed more efficiently system energy savings of 73.66% could have been achieved. In terms of total energy this could have been a reduction of 60.38%.
b) In monetary terms, had the building been managed more efficiently at the 50% occupancy level then savings of almost £16,000 could have been made annually on the electricity utility bills and approximately £14,500 on annual gas utility bills. Based on the 50% occupancy that occurred this equates to approximately £30,500 per year.
c) In a similar way the CO_2 emission savings that could be delivered with more efficient management at the current levels of occupancy translates to 143540 $kgCO_2$ per year, equating to 33.17 $kgCO_2/m^2$ per year of savings. These savings alone are more than the original running CO_2 emissions estimated for the building at the design stage.

In conclusion there are considerable environmental and financial savings that could be made with improved operation and Facilities Management of the building at reduced occupancy levels.

Chapter Seven - Potential anomalies due to control set-point sensitivity

7.1 Introduction

The results for certain conditions and control set points indicate that heat recovery may not have been set to operate at the optimum settings. The simulation results presented in Chapter Six identified that unexpected trend changes (or 'dips') were occurring. This caused significant heartache and consideration in the analysis. These trend changes were evident, particularly in terms of heating and cooling related energy consumption, when changes in the occupancy levels occurred but room controls were left to run in the original occupied control mode. The heat recovery device has a strong influence on the energy performance at all occupancy levels and the extents of these effects are tested in this section.

Analysing the results generated from the simulation model, it appears that the building's HVAC system's heat recovery device and its set-point control are so finely balanced that the changes in occupancy can result in the average exhaust air to change and result in the heat recovery device switching in and out of use.

Indeed, with the set-point being very close to target upper room temperature, this switching may have been occurring at full occupancy levels (for certain conditions, such as time of year). On rooms sequentially becoming unoccupied, the potential lower average room extract temperature resulted in the heat recovery being more fully utilised, hence explaining the trend change in heat requirements under certain occupancy change scenarios. A balance must be struck, as later tests show that a moderate increase in set-point creates the potential for an increase chiller load.

The sensitivity analysis presented later in this section has helped support the general assumptions/analysis made above. To clarify, it is important that the bypass set-point for the thermal wheel is carefully set to ensure that optimum and effective heat recovery takes place. If the bypass set-point temperature of the heat recovery device is too high then there is a danger that too much heat be recovered and thus cause an increase in the chiller demand. However set too low and heat that could have been used is wastefully rejected out of the system. This is further complicated by control being based on the average room temperature from multiple rooms and one or more of these may be unoccupied. It appears that sometimes rooms can be compromised by this method.

In the HVAC system network created, if the average VAV group temperature sensed drops to 19°C the heating coil will be activated. When the zone is in heating mode, the system is set to supply air at 28°C and maintain a room temperature of around 20°C and 23°C. Once the average VAV group temperature sensed reaches 21°C (based on room temperature) the heating coil in the AHU is switched off. The AHU serve the building in vertical blocks as shown in Figure 6-1 (in Chapter 6). However, as there is a heating (and a cooling) controller for each VAV group, if there is a heating demand in any of the rooms then the heating coil is activated.

Each AHU has its own heat recovery device; in this case it is a thermal wheel (identified as the label 'heat exchanger' in Figure 6-2) and this is controlled by room exhaust air temperature. The heat recovery is bypassed when the exhaust gas form the areas in the respective AHU is greater than the set point of 21 °C (design set figure). This may be the cause of many of the potential inefficiencies. As indicated it has the potential to be by-passed when useful heat can be gained during heating required periods. Set too high, it can result in adding heat it is not required, thus unnecessarily engaging chilling systems. The study shows it to be finely balance and certainly needing full consideration during the design and commissioning stages and in any POE assessment. This study highlights and recommends detailed attention during these processes.

The numbered zones, as previously defined in Chapter Six, are shown again in Figure 7-1. Figure 7-2 shows the VAV groups, including those groups which are served by which AHU.

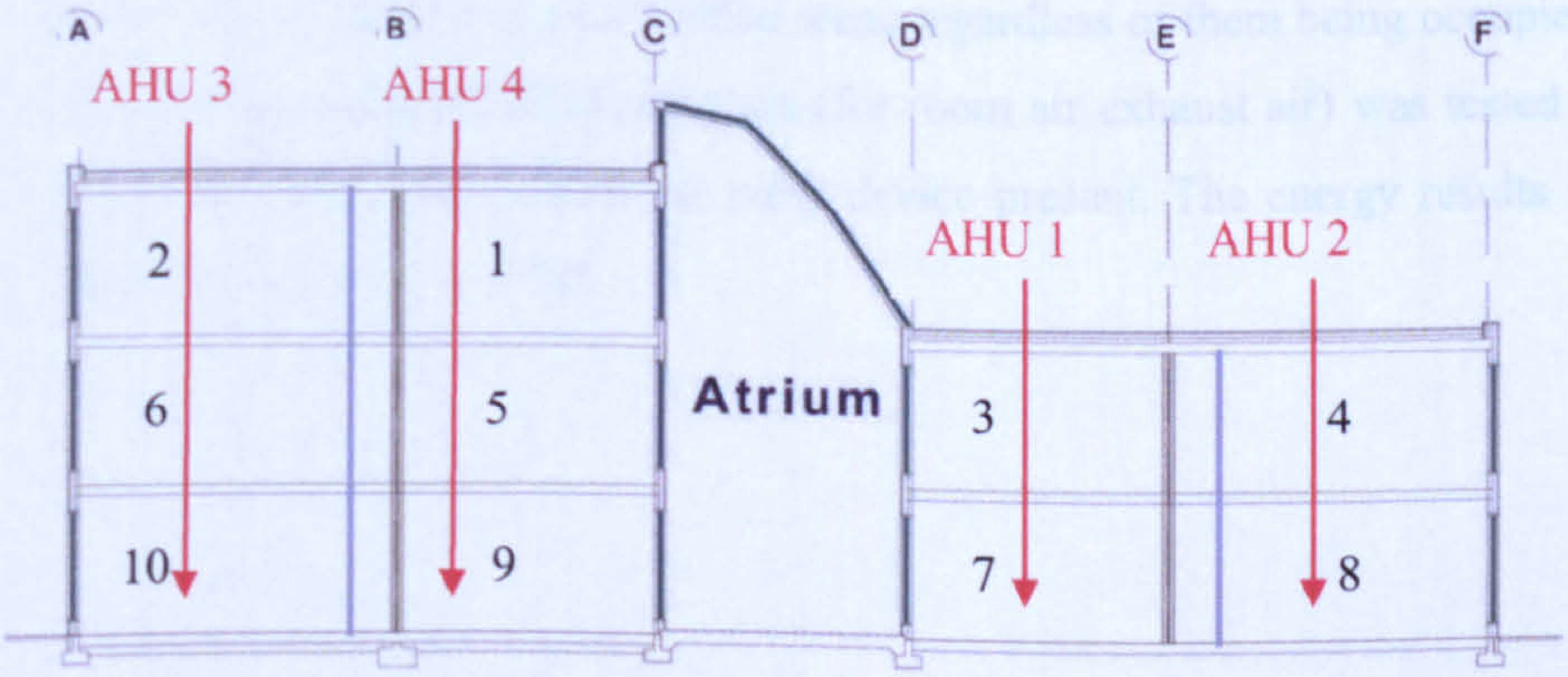


Figure 7-1: Numbered zones in the building

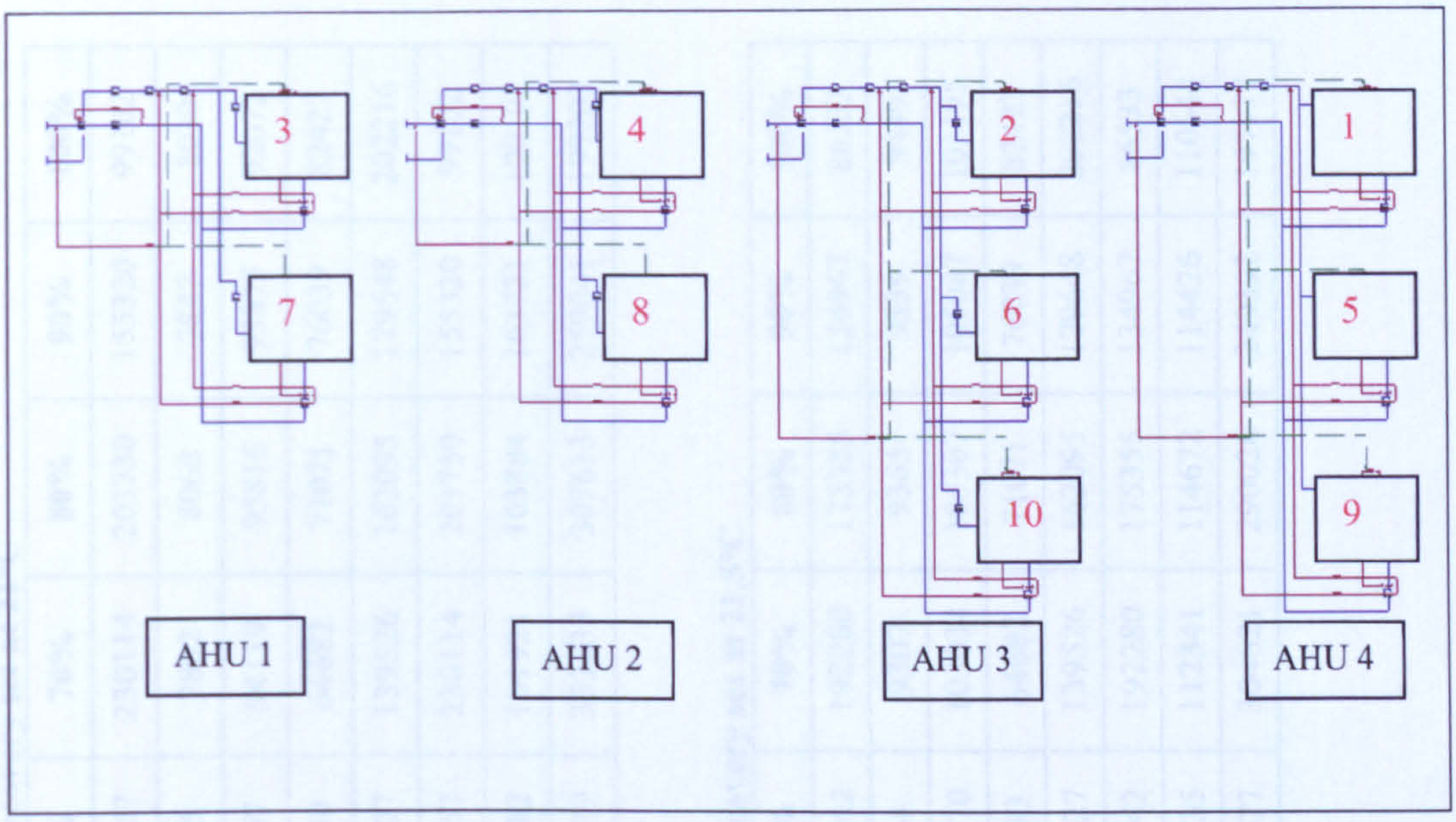


Figure 7-2: The VAV groups within the system network

7.2 Description of the sensitivity tests performed and results simulated

A number of simulations were carried out to test the sensitivity of the heat recovery device on the energy consumption of the building. This was tested at 10% occupancy intervals, with the building's HVAC system operating in all office areas regardless of them being occupied or not. The heat recovery bypass threshold temperature (for room air exhaust air) was tested at 21°C, 21.5°C, 22°C, 22.5°C and with no heat recovery device present. The energy results for these tests are presented in Tables 7-1 to 7-5.

Table 7-1: Annual energy performances at varying occupancy levels with heat recovery set at 21°C

Occupancy	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Space heating energy	257343	245616	239090	228473	220152	241808	258557	230114	203730	155320	99102
Space cooling energy	0	4294	4459	4836	5058	6896	7485	7802	8068	7847	8030
Annual Fans and pumps energy	77005	79264	83051	84985	85909	88700	93297	94119	95816	95875	92072
Lights	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
Equipment	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
System gas energy	257343	245616	239090	228473	220152	241808	258557	230114	203730	155320	99102
System electricity energy	77005	83558	87510	89821	90967	95596	100782	101921	103884	103721	100102
Total system energy (kWh)	334348	329174	326599	318293	311119	337403	359339	332035	307613	259041	199203

Note under sequence 1 with the rest of building operating hr 21

Table 7-2: Annual energy performances at varying occupancy levels with heat recovery set at 21.5°C

Occupancy	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Space heating energy	253160	237210	223294	205858	188166	192058	215942	192280	175355	134967	86533
Space cooling energy	0	6009	5947	6483	6585	8881	8764	9307	9365	9339	9449
Annual Fans and pumps energy	83812	84493	88682	90284	92474	95187	101970	103034	105307	105087	101195
Lights	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
Equipment	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
System gas energy	253160	237210	223294	205858	188166	192058	215942	192280	175355	134967	86533
System electricity energy	83812	90502	94629	96768	99059	104069	110735	112341	114672	114426	110644
Total system energy (kWh)	336972	327712	317923	302626	287225	296127	326677	304621	290026	249392	197177

Note under sequence 1 with the rest of building operating hr 21.5

Table 7-3: Annual energy performances at varying occupancy levels with heat recovery set at 22°C

Occupancy	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Space heating energy	252497	235944	219145	200237	179813	171461	181929	160164	144884	115530	78104
Space cooling energy	1	8454	8353	9111	9244	12195	11646	12614	12665	12355	12209
Annual Fans and pumps energy	91322	93587	95446	99018	100371	103852	112877	115827	118933	118899	116262
Lights	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
Equipment	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
System gas energy	252497	235944	219145	200237	179813	171461	181929	160164	144884	115530	78104
System electricity energy	91323	102040	103799	108129	109615	116047	124523	128441	131598	131255	128473
Total system energy (kWh)	343821	337984	322943	308366	289428	287508	306452	288605	276482	246785	206577

Note under sequence 1 with the rest of building operating hr 22

Table 7-4: Annual energy performances at varying occupancy levels with heat recovery set at 22.5°C

Occupancy	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Space heating energy	252179	235736	218277	199381	178603	167164	159711	138005	121182	101219	73475
Space cooling energy	11	9855	11649	12701	13110	16679	15348	16200	16417	14874	14442
Annual Fans and pumps energy	94692	96981	100871	105332	107594	110868	120274	124218	127790	128575	128575
Lights	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
Equipment	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
System gas energy	252179	235736	218277	199381	178603	167164	159711	138005	121182	101219	73475
System electricity energy	94702	106836	112520	118033	120704	127547	135622	140418	144207	143450	143016
Total system energy (kWh)	346882	342572	330797	317414	299307	294710	295332	278423	265390	244669	216492

Note under sequence 1 with the rest of building operating hr 22.5

Table 7-5: Annual energy performances at varying occupancy levels with no heat recovery

Occupancy	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Space heating energy	416586	404183	389416	379008	358518	350120	337139	298621	272251	228089	177580
Space cooling energy	0	3801	4262	4639	4878	6759	7418	7718	7995	7525	7765
Annual Fans and pumps energy	80641	82462	84351	85957	87053	89515	92662	93025	94876	93698	92159
Lights	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
Equipment	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
System gas energy	416586	404183	389416	379008	358518	350120	337139	298621	272251	228089	177580
System electricity energy	80641	86263	88613	90596	91931	96274	100080	100743	102871	101224	99924
Total system energy	497227	490446	478029	469604	450450	446394	437219	399364	375123	329313	277504

Note under sequence 1 with the rest of building operating with no hr

At all occupancy levels the space heating energy consumption decreased as the heat recovery bypass temperature increased from 21°C to 22.5°C as waste heat in the exhaust air had more opportunity to be recovered and utilised again within the system. This can be seen in Figure 7-3. Those tests with no heat recovery enabled showed the biggest annual boiler (heating) consumption. At heat recovery bypass temperatures of 21°C, 21.5°C and 22°C, the trend change in heating energy was evident as occupancy decreased from 100% down to 0%. With a heat recovery bypass threshold temperature of 22.5°C and when no heat recovery is present this 'trend' change was no longer evident, however resulted in a cooling demand increase and wasteful energy consumption respectively.

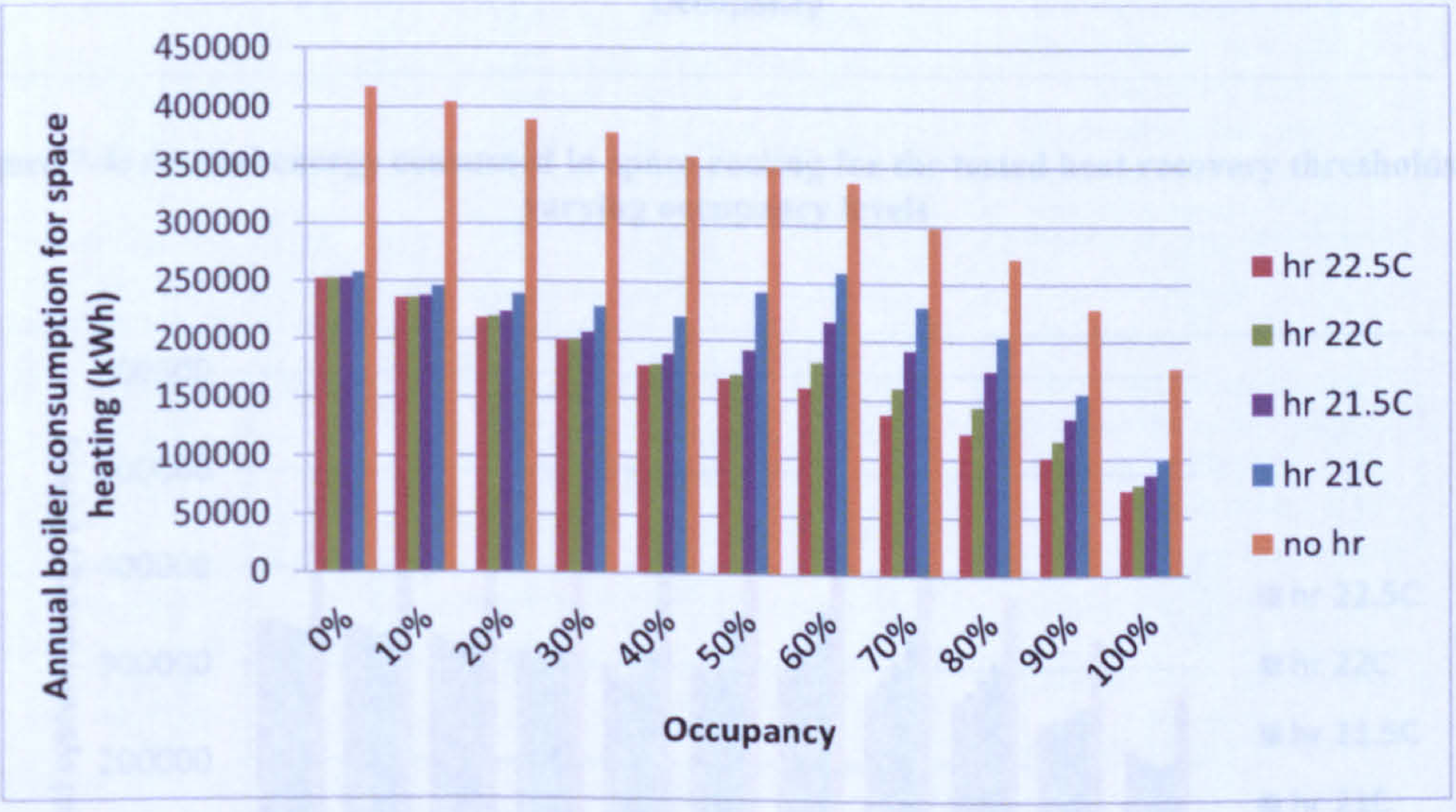


Figure 7-3: Annual energy consumed in space heating for the tested heat recovery thresholds at varying occupancy levels

From Figure 7-4 it can be concluded that at all occupancy levels the demand for space cooling energy increases as the heat recovery bypass temperature increases from 21°C to 22.5°C. This is due to the increased demand from the chiller to reduce the temperature to the required comfort temperature. When no heat recovery was enabled the annual chiller consumption was at its lowest.

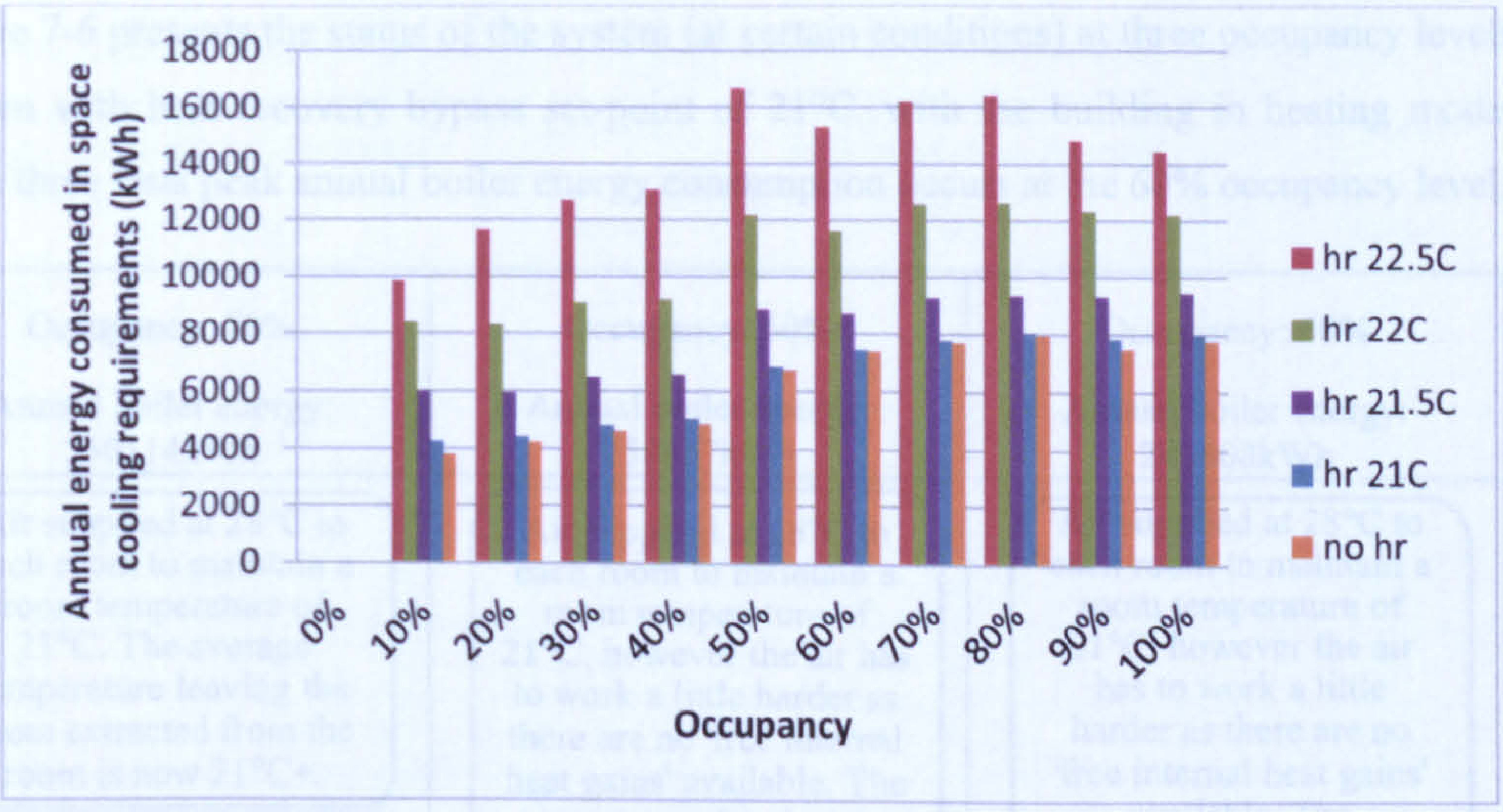


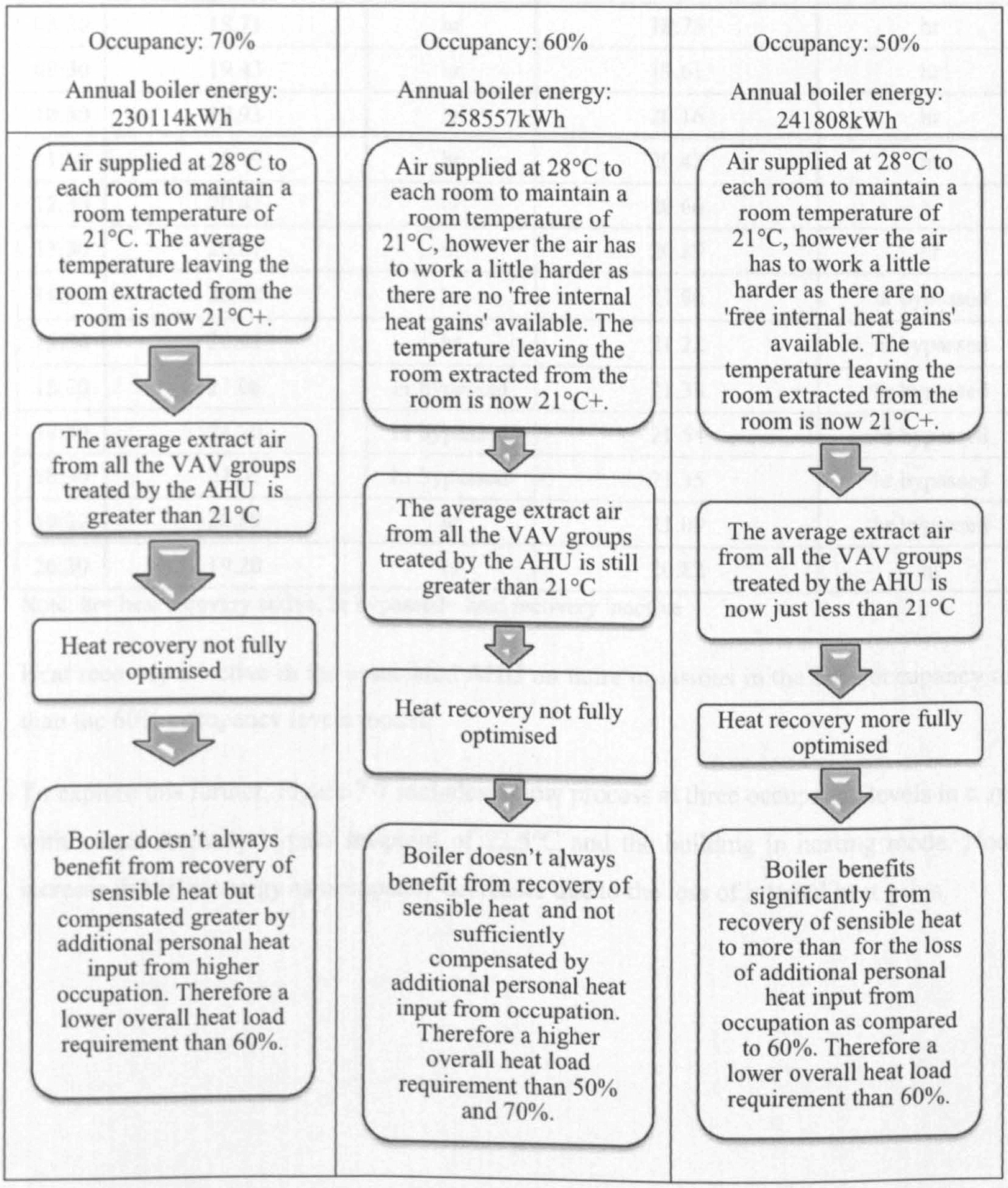
Figure 7-4: Annual energy consumed in space cooling for the tested heat recovery thresholds at varying occupancy levels

Figure 7-5: Annual system energy for the tested heat recovery thresholds at varying occupancy levels

As indicated in Figures 7-3 to 7-5, the heating demands most heavily influence total system energy consumption, although the cooling and fan and pump energy also have an impact. At 100% occupancy the heat recovery bypass temperature of 21.5°C is marginally more efficient than at 21°C. However, at mid occupancy 22°C and 22.5°C become more efficient set-points. At lower occupancy levels 21°C becomes the most efficient set-point. Although note this is against a poorly managed system. It does however show how optimum settings can change with occupancy levels, yet this depends on the building management implemented.

The local area monitoring and voting system for control is contributing to this and is hence a potential area for improvement in control design and operation.

Figure 7-6 presents the status of the system (at certain conditions) at three occupancy levels in a system with heat recovery bypass set-point of 21°C, with the building in heating mode. For these three tests peak annual boiler energy consumption occurs at the 60% occupancy level.



Occupancy: 70%

Annual boiler energy: 230114kWh

Air supplied at 28°C to each room to maintain a room temperature of 21°C. The average temperature leaving the room extracted from the room is now 21°C+.

The average extract air from all the VAV groups treated by the AHU is greater than 21°C

Heat recovery not fully optimised

Boiler doesn't always benefit from recovery of sensible heat but compensated greater by additional personal heat input from higher occupation. Therefore a lower overall heat load requirement than 60%.

Occupancy: 60%

Annual boiler energy: 258557kWh

Air supplied at 28°C to each room to maintain a room temperature of 21°C, however the air has to work a little harder as there are no 'free internal heat gains' available. The temperature leaving the room extracted from the room is now 21°C+.

The average extract air from all the VAV groups treated by the AHU is still greater than 21°C

Heat recovery not fully optimised

Boiler doesn't always benefit from recovery of sensible heat and not sufficiently compensated by additional personal heat input from occupation. Therefore a higher overall heat load requirement than 50% and 70%.

Occupancy: 50%

Annual boiler energy: 241808kWh

Air supplied at 28°C to each room to maintain a room temperature of 21°C, however the air has to work a little harder as there are no 'free internal heat gains' available. The temperature leaving the room extracted from the room is now 21°C+.

The average extract air from all the VAV groups treated by the AHU is now just less than 21°C

Heat recovery more fully optimised

Boiler benefits significantly from recovery of sensible heat to more than for the loss of additional personal heat input from occupation as compared to 60%. Therefore a lower overall heat load requirement than 60%.

Figure 7-6: Heat recovery performance- bypass set-point of 21°C, building in heating mode.

The data presented in Table 7-6 identifies a situation under certain conditions when this switch may occur. This is shown using IES model data on Monday 24th February 08:30 to 20:30 for the hr21 model at 50-60% occupancy.

Table 7-6: Heat recovery (hr) status for 50 and 60% occupancy levels

Time	Air temperature (°C) before heat exchanger	hr status	Air temperature (°C) before heat exchanger	hr status
	50%	50%	60%	60%
08:30	18.71	hr	18.75	hr
09:30	19.43	hr	19.61	hr
10:30	19.93	hr	20.16	hr
11:30	20.19	hr	20.42	hr
12:30	20.42	hr	20.66	hr
13:30	20.61	hr	20.87	hr
14:30	20.78	hr	21.06	hr bypassed
15:30	20.92	hr	21.22	hr bypassed
16:30	21.06	hr bypassed	21.38	hr bypassed
17:30	21.20	hr bypassed	21.54	hr bypassed
18:30	21.05	hr bypassed	21.35	hr bypassed
19:30	20.89	hr	21.09	hr bypassed
20:30	19.20	hr	20.82	hr

Note: hr= heat recovery active, hr bypassed= heat recovery inactive

Heat recovery is active in the associated AHU on more occasions in the 50% occupancy model than the 60% occupancy levels model.

To explore this further, Figure 7-7 includes a flow process at three occupancy levels in a system with a heat recovery bypass set-point of 22.5°C and the building in heating mode. Note the increase in boiler energy as occupancy decreases due to the loss of internal heat gains.

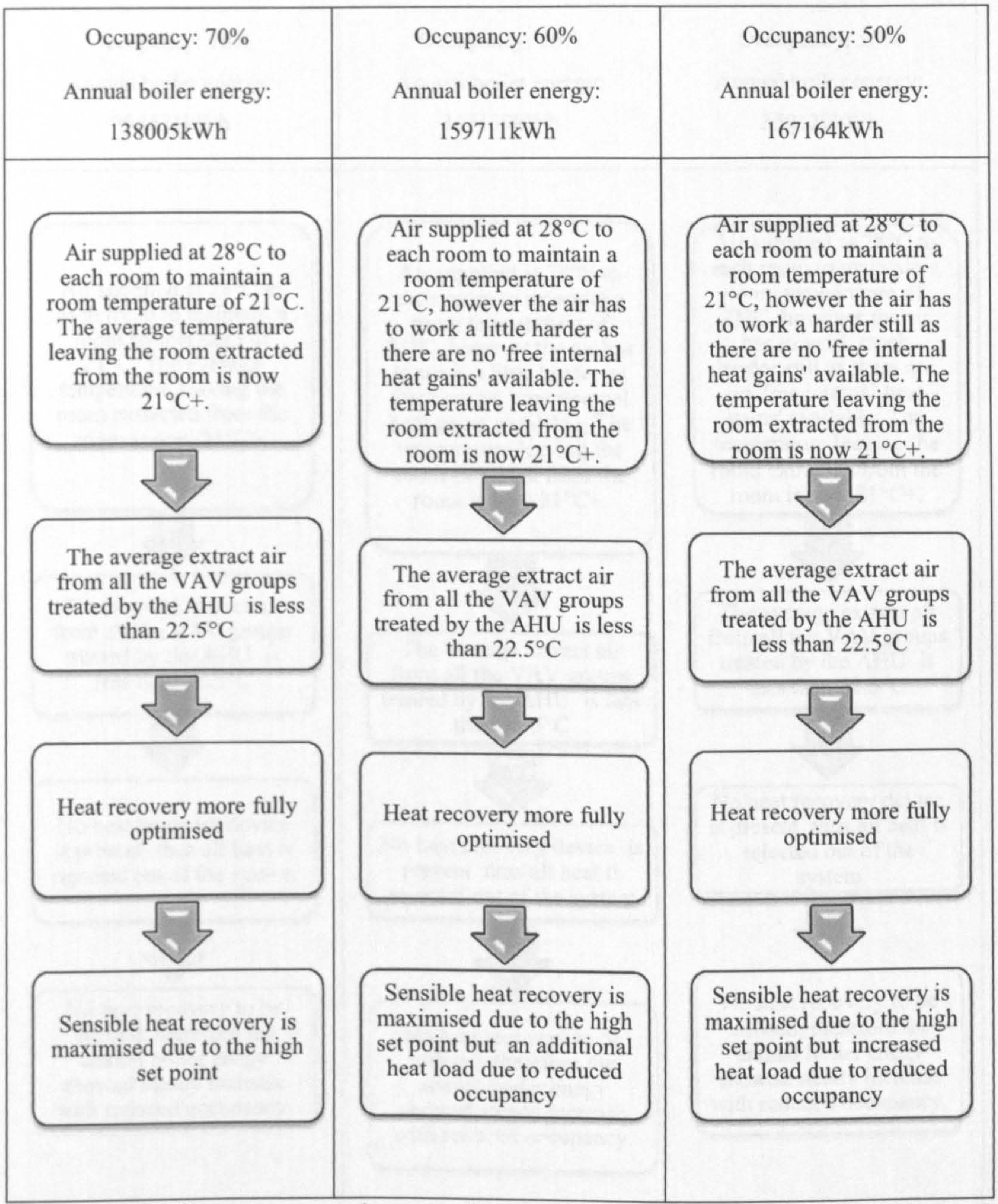
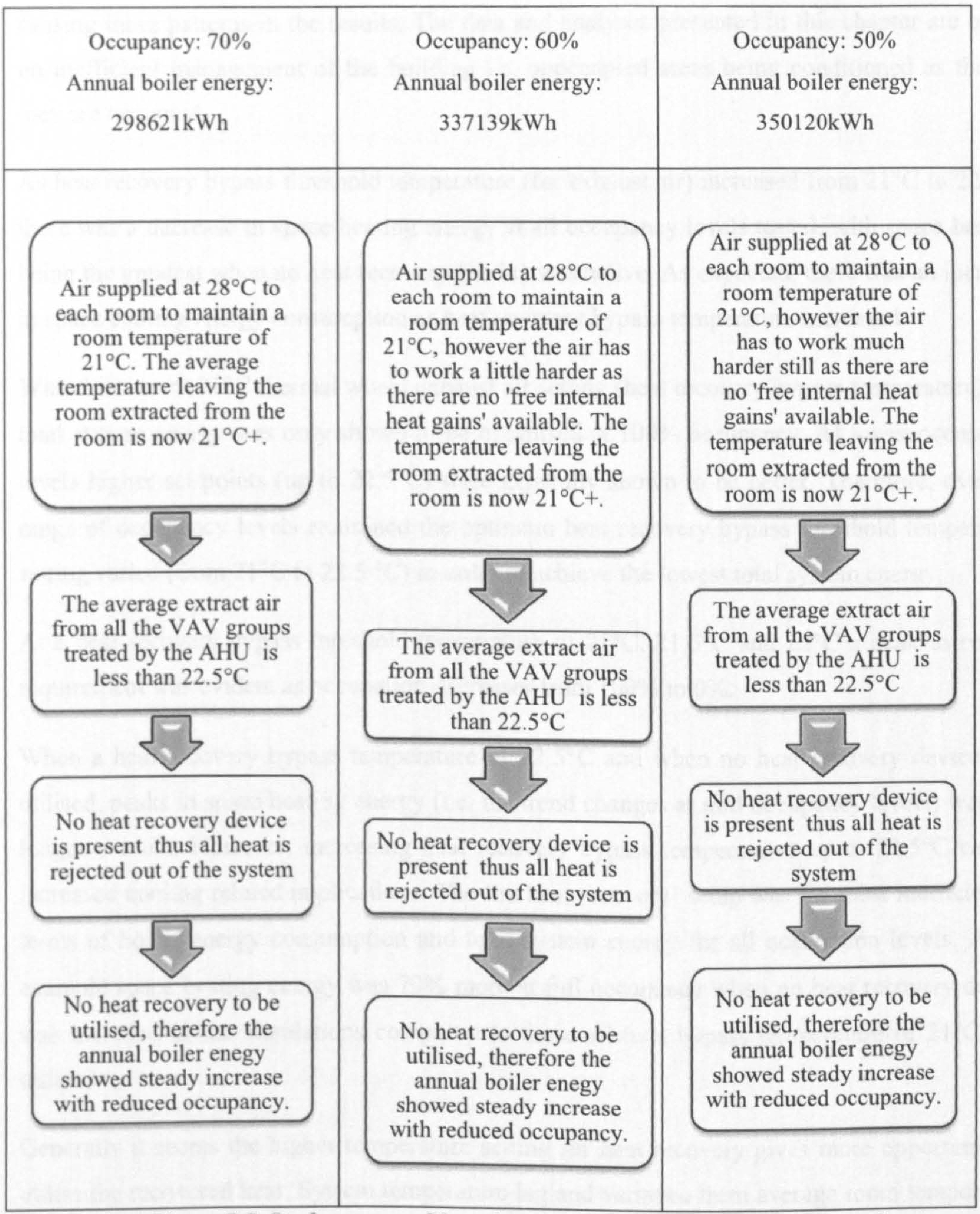


Figure 7-7: Heat recovery performance- bypass set-point of 22.5°C, building in heating mode

However with the heat recovery device set at 22.5°C there is the chance that too much heat is now being recovered and causing the chiller to now operate to counteract this increase in temperature; a result of too much heat being recovered.

Figure 7-8 shows a flow process at three occupancy levels in a system with no heat recovery and if the building is in heating mode. Note that in this scenario there is again an increase in boiler energy consumption as the occupancy decreases, but the magnitudes of the energy consumption are much greater.



Occupancy: 70% Annual boiler energy: 298621kWh	Occupancy: 60% Annual boiler energy: 337139kWh	Occupancy: 50% Annual boiler energy: 350120kWh
Air supplied at 28°C to each room to maintain a room temperature of 21°C. The average temperature leaving the room extracted from the room is now 21°C+. The average extract air from all the VAV groups treated by the AHU is less than 22.5°C No heat recovery device is present thus all heat is rejected out of the system No heat recovery to be utilised, therefore the annual boiler enegy showed steady increase with reduced occupancy.	Air supplied at 28°C to each room to maintain a room temperature of 21°C, however the air has to work a little harder as there are no 'free internal heat gains' available. The temperature leaving the room extracted from the room is now 21°C+. The average extract air from all the VAV groups treated by the AHU is less than 22.5°C No heat recovery device is present thus all heat is rejected out of the system No heat recovery to be utilised, therefore the annual boiler enegy showed steady increase with reduced occupancy.	Air supplied at 28°C to each room to maintain a room temperature of 21°C, however the air has to work much harder still as there are no 'free internal heat gains' available. The temperature leaving the room extracted from the room is now 21°C+. The average extract air from all the VAV groups treated by the AHU is less than 22.5°C No heat recovery device is present thus all heat is rejected out of the system No heat recovery to be utilised, therefore the annual boiler enegy showed steady increase with reduced occupancy.

Figure 7-8: Performance with no heat recovery, building in heating mode

7.3 Chapter discussion and conclusions

Chapter 7 presented the results from the sensitivity analyses carried out to support the results generated from simulation investigations in Chapter 6.

In the previous chapter trend changes in energy consumption were seen as occupancy decreased. These trend changes were initially suspected as potential anomalies in the model, however sensitivity analyses identified that the heat recovery devices (thermal wheels) were causing these patterns in the results. The data and analyses presented in this chapter are based on inefficient management of the building i.e. unoccupied areas being conditioned as though they are occupied.

As heat recovery bypass threshold temperature (for exhaust air) increased from 21°C to 22.5°C there was a decrease in space heating energy at all occupancy levels tested, with space heating being the greatest when no heat recovery (no hr) was active. As expected, there was an increase in space cooling energy consumption as heat recovery bypass temperature increased.

With the current 21°C thermal wheel exhaust air setting (heat recovery bypass temperature), the total system energy was only shown to be optimised at 100% occupancy. At lower occupancy levels higher set points (up to 22.5°C) were generally shown to be better. Therefore, over the range of occupancy levels examined the optimum heat recovery bypass threshold temperature setting varied (from 21°C to 22.5 °C) in order to achieve the lowest total system energy.

At a heat recovery bypass threshold temperature of 21°C, 21.5°C and 22°C a peak in energy requirement was evident as occupation decreases from 100% to 0%.

When a heat recovery bypass temperature of 22.5°C and when no heat recovery device was utilised, peaks in space heating energy (i.e. the trend changes at mid-occupancy levels) were no longer evident. However, increasing heat recovery bypass temperatures up to 22.5°C caused increased cooling related implications. The 'no heat recovery' setup was the most inefficient in terms of boiler energy consumption and total system energy for all occupation levels. As an example space heating energy was 79% more at full occupancy when no heat recovery device was included in the simulations compared to those when a bypass temperature of 21°C was utilised.

Generally it seems the higher temperature setting for heat recovery gives more opportunity to utilise the recovered heat. System temperature lag and variance from average room temperature and differences in room to exhaust temperature may be the main drivers in taking benefit from any additional heat recovery. There are other possible mechanisms that may be relevant such as step changes in room heating loads. It is evident from the results that the balance of all these factors is changing as the occupation levels vary and the different rooms/areas come in and out of play, hence resulting in unexpected peaks and troughs with occupation change.

Possible physical factors at play relate to ducting loses and poor room ventilation from partitioning or poor location of inlet and extract points.

It should be noted that:

- Essentially room temperature decides if the boiler is required (hence gas used).

- Room exhaust air temperature decides if the heat recovery device is utilised or bypassed.

Discrepancies between room temperature and exhaust temperature can exist due to many issues associated with the building temperature control and ventilation system, poor ducting and partitioning, preferred or temporary air flow paths, average temperature control together with the effects of step changes in room loads. These anomalies can have a bearing on the control set point and hence its use of heat recovery in conjunction with room heating and cooling.

The analysis above shows how sensitive the heat recovery set-point temperature and the associated target room temperatures are. For the system settings used, there is a very fine balance around 21°C, such that the return exhaust temperature from the room can cause heat recovery to switch in and out with imposed changes of room extract temperature with changes in occupancy. However, moderate increases in set-point can introduce chiller loading. With such sensitivity the optimum value can change with the climate temperature profiles applied and the step change in occupancy. Hence, the ideal value should be set on commissioning and adjusted through plant life when the true additional loads such as pipe losses are determined.

Essentially the investigations performed in this section have explained the unexpected trend changes in the comparisons of energy performance at varying occupancy. The results show the fine balance between room set-point temperatures and heat recovery bypass temperatures.

The sensitivity analysis suggested that a heat recovery set-point of 21.5°C may have been a more appropriate setting, however due to the points made above further refinement was not undertaken. The results assisting in analysis and appreciation would best ensure true plant setting and adjustment during commissioning and use. As a result the set-point of 21°C was maintained as the base set-point.

In practice the temperatures and performance may not exactly match those considered for heat recovery in design and modelling. For example, exhaust air heat and temperature losses in the duct work may occur in reality which may not be accurately accounted for the design/modelling.

The results from the sensitivity analyses reinforce the importance of careful room control selection and isolation capability in design. It supports the need for careful and effective management, commissioning and continual commissioning should occupancy levels change. It highlights the potential for poor assumptions in design and the general awareness needed throughout the design, commissioning and operating stages to the possible effects of occupation changes.

Consequently, for the study building and typically for other buildings base recommendations are:

- The heat recovery device should be seasonally commissioned and adjusted so that during the heating season the set point is increased to allow for more heat recovery. During the summer months the set point should be reviewed to prevent any unnecessary additional chilling resulting from heat recovery.
- Grouping of rooms/ zones in the control package could be configured better to increase heat recovery when beneficial. This is an important design consideration and recommendation for close control in design, commissioning and POE.

The main message from this investigation is that systems can be finely balance and with changes (setting or occupational) can give unrealised shortfalls. Blind reliance on control and set point configurations can be very costly. It is important to have suitably skilled and informed facility management who can identify anomalies and request further investigation or reassessment as/if required. Equally POE should identify inefficient operations provided they are done with full awareness and consideration to all factors including design, and current operating strategies together with current and future operating environments that may impose. Without good control a so called "green buildings" will not operate to its full potential.

Chapter Eight - Social performance

8.1 Introduction

In the previous chapters, energy aspects have been evaluated. Although the energy efficient performance of the building is important, acceptable levels of occupant comfort are crucial. This is particularly true in office buildings as many previous studies have investigated how building environments can have psychological impacts as well as productivity effects (Leaman 1995).

In order to verify if the building was a success in terms of occupant satisfaction and comfort a survey was conducted. The survey and the procedure were described in Chapter Four - Methodology. In Chapter Eight the results are analysed, discussed and compared to other buildings.

8.2 Overall results from Building Use Studies (BUS) survey

There were 85 occupants (sample size) in the building on the day of the survey and a 67% response rate was achieved. Of the respondents, 52% were male and 48% were female. The ratio of occupants 'under 30 years old' to '30 years old or older' was 23:77. 58% had worked in the building for one year or more. The building was regarded as the normal base for work for all the occupants.

On average the occupants worked 4.5 days a week, spending 8.43 hours per day in the building with 7.58 hours spent at their desks and 7.15 hours per day looking at the VDU. The layout of the offices varied in size for the different companies. 5% of the respondents normally occupied their office space alone, 14% shared with 1 other person, 30% shared with 2-4 others, 32% shared with 5-8 others and 18% shared with more than 8 others. It was found that 56% of occupants were located next to a window.

8.3 More detailed findings

Similar to previous studies (Baird 2010) the average scores for each of the survey questions are presented in Table 8-1. The perceived responses from the occupants are compared to the benchmark and/or scale mid-point of the other buildings that have been surveyed using the BUS methodology and exist within the BUS dataset.

With regards to Table 8-1:

- Worse = aspect score compared poorly against the BUS benchmark and/or scale mid-point.
- Similar = aspect score was comparable to the BUS benchmark and/or scale mid-point.
- Better = aspect score compared well against the BUS benchmark and/or scale mid-point.

Also with reference to Table 8-1, a score of 7 is the 'best' unless otherwise noted with a subscript $_4$ or $_1$. In these cases, a score of 4 is 'best' if noted with a subscript $_4$ and a score of 1 is 'best' if noted with a subscript $_1$. In the control factors section of Table 8-1, the percentages represent those respondents that considered control over the particular aspect as important (Baird 2010).

Results in Table 8-1 have shown that out of the 46 aspects, 14 of them performed considerably worse, 19 had similar scores and 13 were considerably better than the benchmark score within the BUS dataset.

Table 8-1: Average scores and comparison for each of the survey questions (similar layout to Baird 2010)

Aspects		Average score	Standard deviation	Worse	Similar	Better
Operational Factors						
Image to visitors		6.14	1.076			*
Space in Building		5.32	1.223			*
Space at desk - too little/too much $_4$		4.89	1.090	*		
Furniture		5.61	1.123			*
Cleaning		4.56	1.680		*	
Availability of meeting rooms		5.81	1.029			*
Suitability of storage arrangements		5.04	1.428			*
Facilities meet work requirements		5.54	1.135			*
Safety		6.02	0.954			*
Environmental Factors						
Temp in Winter						
Temp in winter overall		3.79	1.641	*		
Temp - too hot/too cold $_4$		4.65	1.436	*		
Temp- stable/variable $_4$		4.80	1.546	*		
Air in Winter						
Air - still/draughty $_4$		3.33	1.588	*		
Air – dry/humid $_4$		3.32	1.234		*	
Air - fresh/stuffy $_1$		4.07	1.369		*	
Air - odourless/smelly $_1$		3.77	1.674		*	
Conditions in winter overall		4.09	1.380		*	
Temp in Summer						
Temp in summer overall		3.59	1.525	*		
Temp - too hot/too cold $_4$		3.77	1.436		*	
Temp- stable/variable $_4$		4.80	1.539	*		

Aspects (continued....)		Average score	Standard deviation	Worse	Similar	Better
Air in Summer						
Air - still/draughty $_4$		3.04	1.414		*	
Air – dry/humid $_4$		3.83	1.257		*	
Air - fresh/stuffy $_1$		4.20	1.369		*	
Air - odourless/smelly $_1$		3.43	1.803		*	
Conditions in summer overall		4.15	1.406		*	
Lighting						
Lighting overall		4.49	1.947		*	
Natural light - too little/much $_4$		3.98	1.094			*
Sun & Sky Glare - none/too much $_1$		3.77	1.793		*	
Artificial light - too little/much $_4$		3.85	1.235	*		
Artificial light glare - none/too much $_1$		3.31	1.399			*
Noise						
Noise overall		4.57	1.524			*
From colleagues - too little/too much $_4$		4.45	1.143	*		
From other people - too little/too much $_4$		4.6	1.180	*		
From inside - too little/too much $_4$		4.12	1.103		*	
From outside - too little/too much $_4$		4.00	0.981			*
Interruptions - none/frequent $_1$		3.27	1.672			*
Control factors	**Imp.**					
Heating	44%	1.67	1.200	*		
Cooling	40%	1.84	1.207	*		
Ventilation	37%	3.07	1.624		*	
Lighting	25%	2.25	1.607	*		
Noise	23%	1.95	1.156	*		

Aspects (continued....)		Average score	Standard deviation	Worse	Similar	Better
Satisfaction Factors						
Design		5.39	1.236			*
Needs		4.98	1.458		*	
Overall Comfort		4.60	1.568		*	
Productivity %		-1.88	1.241		*	
Health		3.88	0.955		*	
Total Aspects				**14**	**19**	**13**
Additional questions						
Sustainability issues		5.07	1.465	N/A		
WCs		3.77	1.618	N/A		

In Figure 8-1, the overall variables results of the survey are shown on the 7 point scale either by a diamond shape (indicating an aspect that performed considerably worse than the BUS benchmark score), a circle (indicating an aspect that performed similar to the BUS benchmark score) or a square (indicating an aspect that performed considerably better than the BUS benchmark score).

Figure 8-1: BUS survey results, overall variables (Building Use Studies 2009)

Temperature was the most disappointing and problematic aspect revealed from the overall variables of the building. The building is automatically controlled by the BMS and the occupants have little control over the internal environment other than being able to open windows and control the window blinds within their office space.

The overall dissatisfaction with the general lack of control over the indoor temperature during both the summer and winter was evident and the occupant's response fell below the critical range. The occupants were not only dissatisfied with the overall temperature control in both the winter and summer periods, but also with the variations and stability of these temperatures which caused severe discomfort issues with the occupants.

Most other parameters including the air quality, lighting, comfort and health etc. all fell within the critical design range (i.e. comparable to the BUS benchmarks and/or scale mid-point). The artificial lighting in particular appeared to not be well received by the occupants. The more positive findings included the design and aesthetics within the building, the image the building conveys to visitors and the low noise intrusion from outside. The occupants were however unhappy about internal noise transfer and particularly the poor noise control through the office partitions.

The BUS survey graphs for the individual questions can be found in Appendix B.

The poor thermal result for the building suggests that Termodeck is not properly 'tuned' to occupancy. It identifies that the Termodeck is out of phase, as many aspects look unstable. These findings support the temperature problems discussed in Chapter 5. The findings from the PROBE studies suggest that many buildings have problems with the BMS. Even with the Elizabeth Fry building, a well-known and proven low energy building, it was only after the BMS programming was examined that the team got the Termodeck performing properly (Standeven, Cohen et al. 1998b). The issues mentioned earlier regarding occupancy patterns and system controls should be used in conjunction with this as evidence that the BMS should be re-commissioned.

By incorporating additional questions into the survey feedback on specific features of the building could be gathered and it was possible for the respondents to record additional comments. These revealed positive support for the amount of natural daylight admitted into some of the office spaces and into the atrium. The more negative comments were about poor temperature control in the building (also seen in many other studies including PROBE 1), smells from the vacuum flush WC's, annoyances associated with the artificial lights switching off after a period without movement, artificial lighting levels being too low and poor control of their automatic 'dimming down'. The kitchen areas were also criticised for being too small.

Based on the 7 point scale (1 being not at all important and 7 being very important), when asked "how important are sustainability issues to you?" an average score of 5.07 was calculated, with a standard deviation of 1.465. With a score greater than 4, this suggests there is some evidence that the occupants do have an interest in sustainable issues, but having no comparable data, conclusive remarks cannot be made. Again based on the 7 point scale (this time 1 being 'not at all' and 7 being ' a lot'), when occupants were asked if they like the WC system an average score of 3.77 was determined, with a standard deviation of 1.618. Again an average score of less than 4 suggests that there is some dissatisfaction with the low vacuum flush system and comments made by occupants on the completed survey enhances this evidence. When asked 'do you use the recycle bins located in your office space?'; 89% do 'frequently', 9% do 'sometimes' and 2% 'never' do.

BUS methodology determines various indices to aid in the comparisons and evaluation of a building. The indices are calculated to put variables on a common scale with a mean of 0 and a standard deviation of 1.

The building's results in terms of BUS comfort and BUS satisfaction indices are shown in Figures 8-2 and 8-3 respectively. The overall result for the building is represented by the shaded circle, and the diamond, triangle and square superimposed on the figure represent results from other surveys done on UK 'green' office buildings.

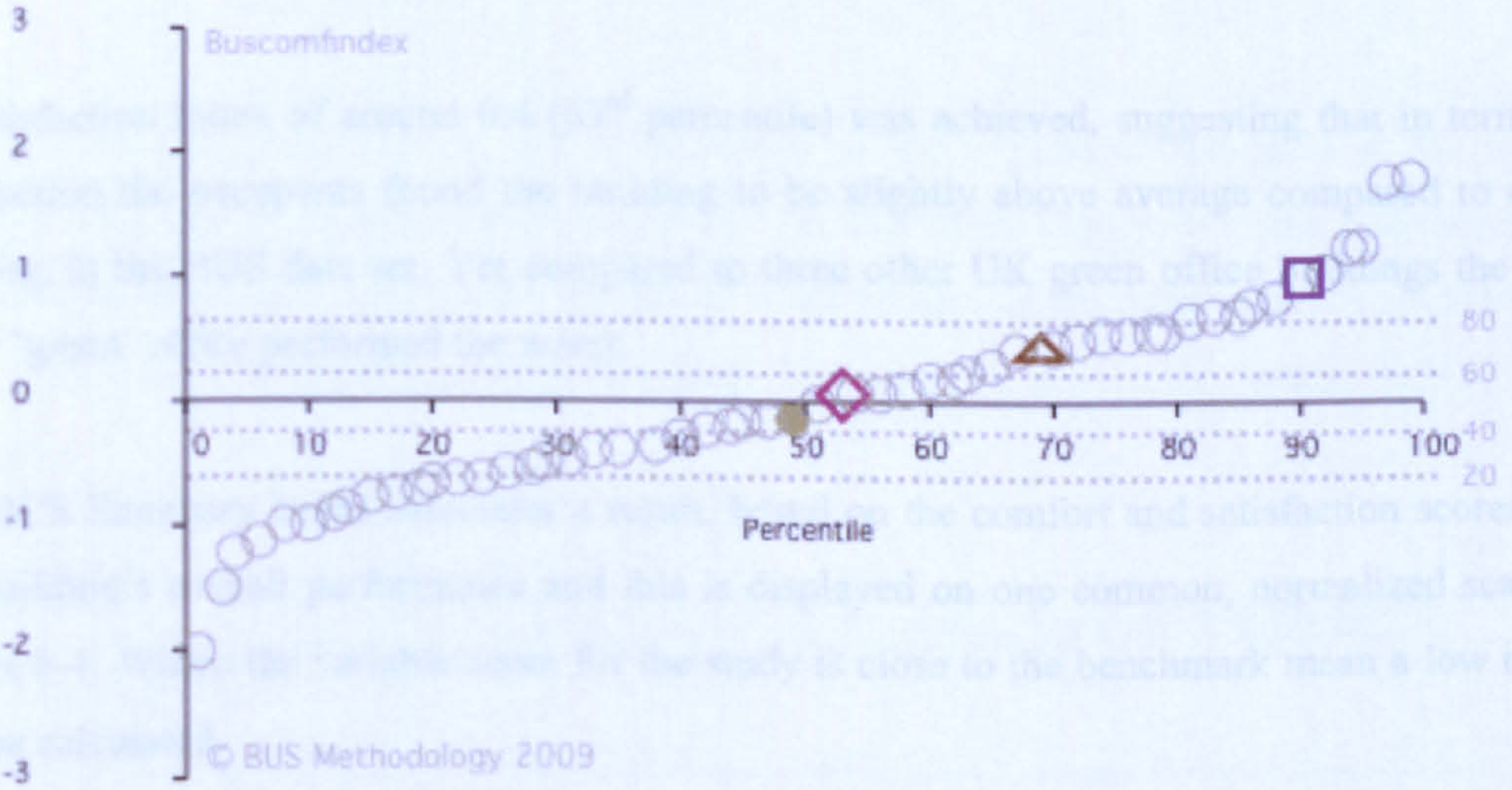


Figure 8-2: BUS Comfort Index

The case study office has a Comfort Index of just below zero (49th percentile) suggesting that the comfort is average compared to other buildings that have been surveyed using the BUS methodology. However, compared to three other green office buildings in the UK it had the worst comfort performance.

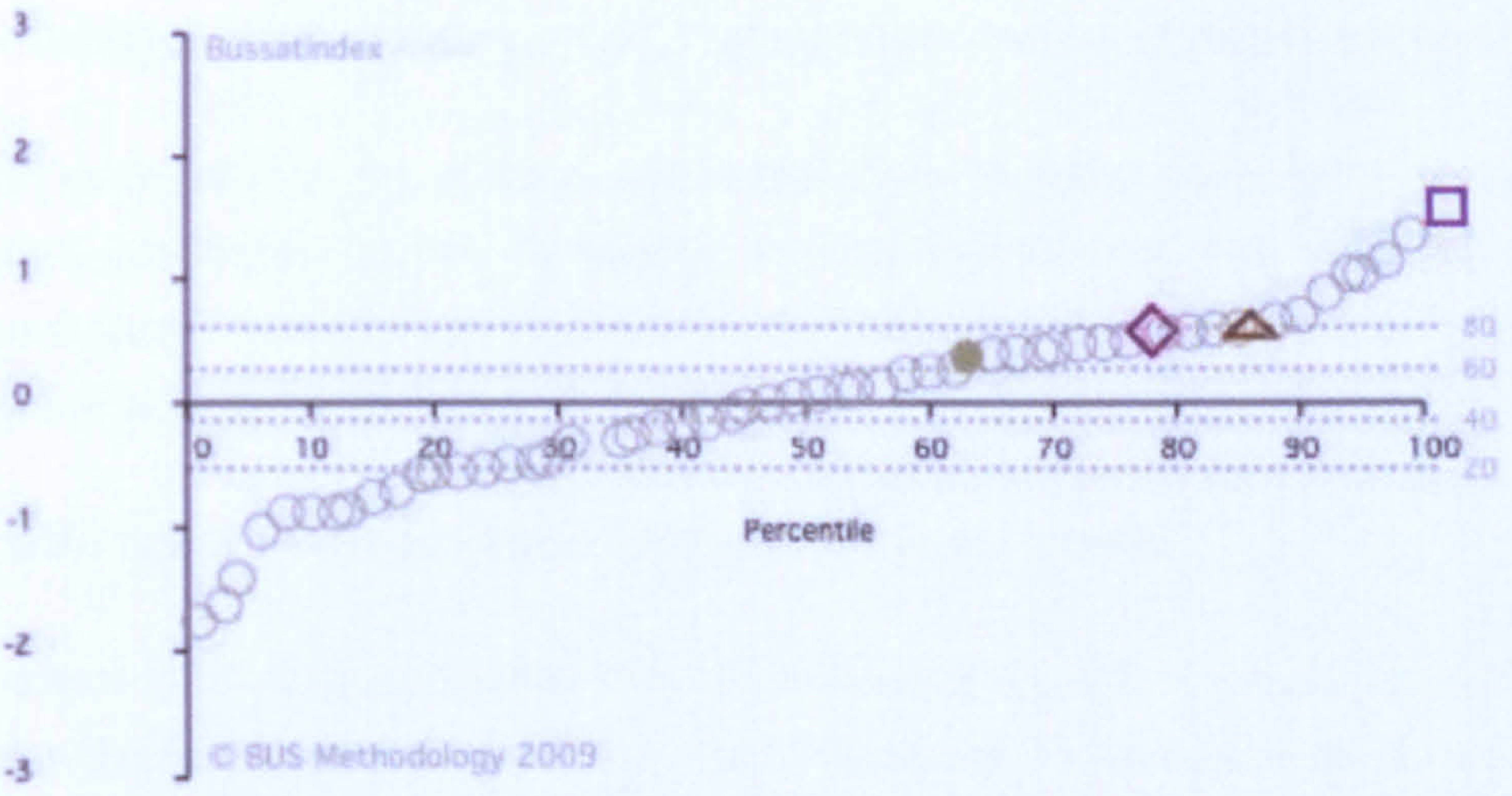


Figure 8-3: BUS Satisfaction Index

A Satisfaction Index of around 0.4 (63rd percentile) was achieved, suggesting that in terms of satisfaction the occupants found the building to be slightly above average compared to other building in the BUS data set. Yet compared to three other UK green office buildings the case study 'green' office performed the worst.

The BUS Summary Index calculates a result, based on the comfort and satisfaction scores, for the building's overall performance and this is displayed on one common, normalized scale in Figure 8-4. Where the variable score for the study is close to the benchmark mean a low index will be calculated.

The overall result for the building is again represented by the shaded circle, and the diamond, triangle and square superimposed on the figure represent results from other surveys done on UK 'green' office buildings. Within the existing benchmark data set it can be seen that the result for the building is in the 57th percentile (with a summary index of just above zero at 0.1) and the occupant satisfaction result for the building was average overall.

The indices suggest that compared to other buildings within the BUS dataset, the building was performing around average in terms of comfort and occupants slightly more satisfied with aspects such as the design of the building, needs, health and productivity. On the whole the summary index suggests that the building is performing 7% better than the average score for the dataset.

However when compared to the other 'green' office buildings surveyed the building was again the worst performing.

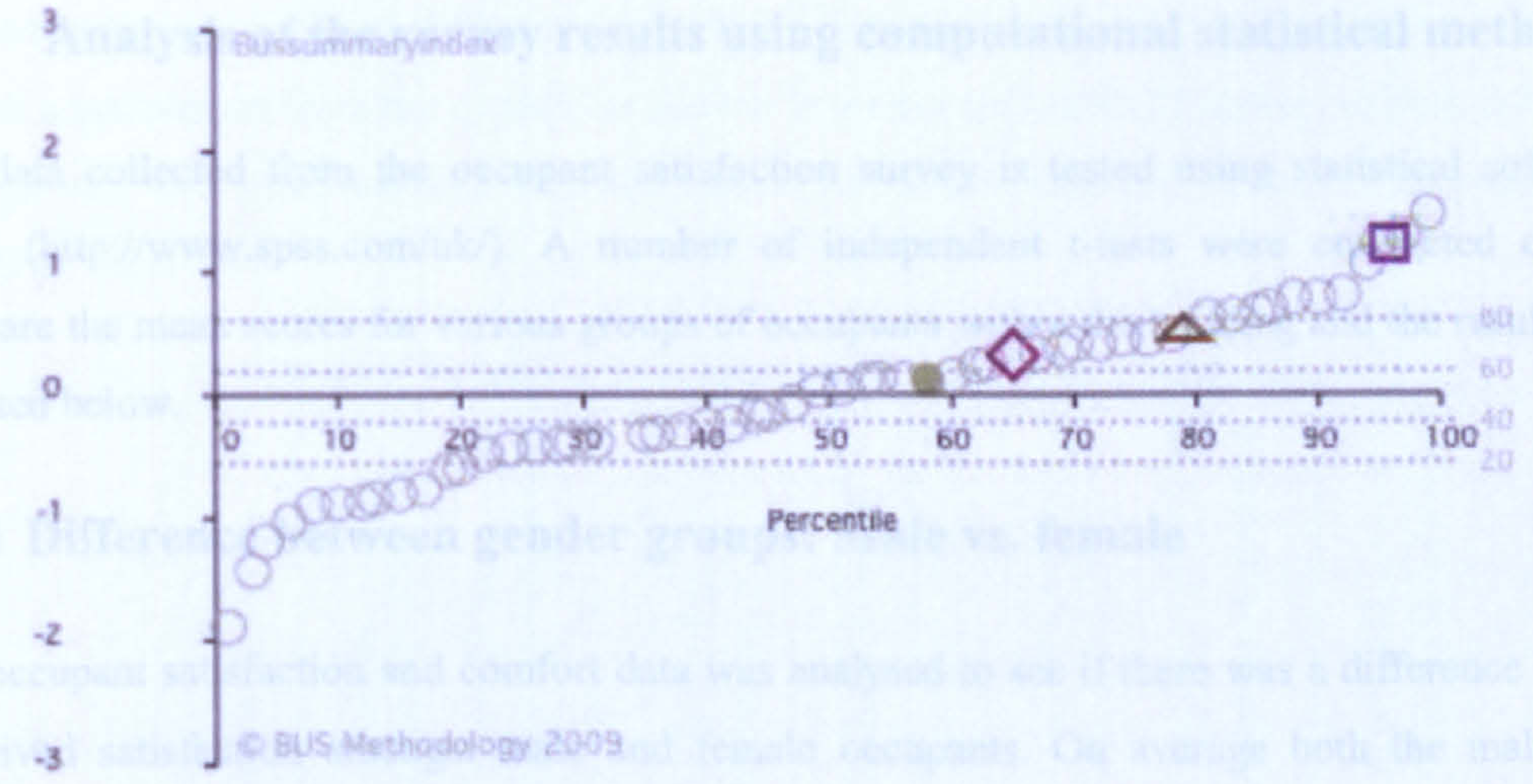


Figure 8-4: BUS Summary Index

The Forgiveness index is a measure of tolerance of the occupants calculated as the overall comfort over the average summary variables. As shown in Figure 8-5, the building has a Forgiveness index of 1 in the 62nd percentile; suggesting that the occupants have a tolerance 12% more than that for the average building. This may be due to the 'green' ethos of the building.

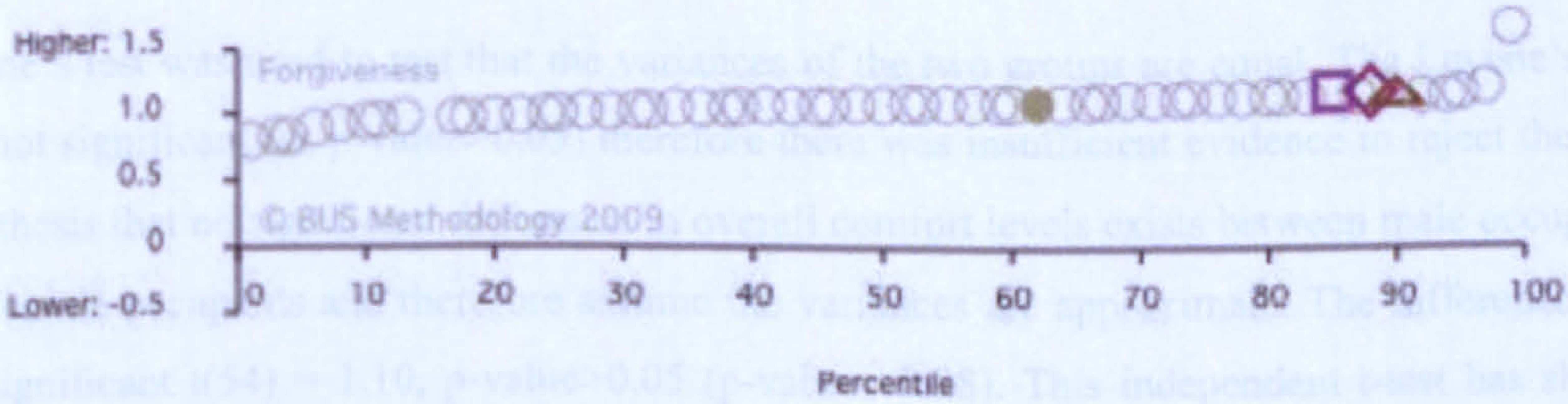


Figure 8-5: BUS Forgiveness Index

The advantage of using the BUS survey is that it provides a means to which the results can be compared to benchmarked data, therefore giving some meaning to how the average results compare to the performance of other buildings. Overall the building score was slightly above the average building within the BUS dataset however when compared to three other green office buildings the score was the worst.

Temperature is one of the most important factors in thermal comfort for occupants, yet scored poorly in the survey. If the temperature control within the building was improved it is expected that the results would improve.

8.4 Analysis of the survey results using computational statistical methods

The data collected from the occupant satisfaction survey is tested using statistical software SPSS (http://www.spss.com/uk/). A number of independent t-tests were conducted out to compare the mean scores for various groups of occupants within the building and the results are reported below.

8.4.1 Difference between gender groups: Male vs. female

The occupant satisfaction and comfort data was analysed to see if there was a difference in the perceived satisfaction amongst male and female occupants. On average both the male and female occupants perceived comfort levels slightly satisfactory (in both sets the average overall comfort was greater than 4). The overall comfort levels were higher for male occupants (M = 4.79, SE = 0.30) than for female occupants (M = 4.33, SE = 0.30). The two hypotheses are:

H_0 (null hypothesis): No significant difference in overall comfort levels exists between male occupants and female occupants.

H_1 (alternative hypothesis): A significant difference in overall comfort levels exists between male occupants and female occupants.

Levene's test was used to test that the variances of the two groups are equal. The Levene's test was not significant (as p-value>0.05) therefore there was insufficient evidence to reject the null hypothesis that no significant difference in overall comfort levels exists between male occupants and female occupants and therefore assume the variances are approximate. The difference was not significant t(54) = 1.10, p-value>0.05 (p-value= 0.28). This independent t-test has shown that there is no significant difference between the overall comfort levels of male and female occupants. Similar tests were conducted for the aspects listed in Table 8-2.

Table 8-2: Building aspects

Aspects for statistical testing
Building design overall
Temperature winter comfortable
Temperature winter hot
Conditions winter overall
Temperature summer comfortable
Temperature summer hot
Conditions summer overall
Noise overall
Lighting overall
Overall comfort

Statistically, no significant difference was found between the two gender types for all other overall aspects apart from the overall conditions in winter and overall lighting. In both cases the male gender was more satisfied with the current conditions than the females. The results are shown in Table 8-3.

Table 8-3: Difference between gender groups: Male vs. female

	Male Mean	Male SE	Female Mean	Female SE	Levene's test for Equality of Variances, p	Equal variance assumed?	t	df	t-test for Equality of means, p	Is p>0.05?	Difference
Building design overall	5.48	0.23	5.25	0.24	0.74	Yes	0.67	54	0.51	Yes	Not significant
Temperature winter comfortable	4.00	0.29	3.52	0.41	0.08	Yes	0.97	44	0.34	Yes	Not significant
Temperature winter hot	4.32	0.28	5.05	0.30	0.85	Yes	-1.75	45	0.09	Yes	Not significant
Conditions winter overall	4.44	0.27	3.60	0.30	0.94	Yes	2.09	43	0.04	No	Significant
Temperature summer comfortable	3.74	0.29	3.39	0.34	0.69	Yes	0.80	48	0.43	Yes	Not significant
Temperature summer hot	3.67	0.26	3.88	0.32	0.45	Yes	-0.53	50	0.60	Yes	Not significant
Conditions summer overall	4.33	0.27	3.92	0.28	0.96	Yes	1.05	50	0.30	Yes	Not significant
Noise overall	4.86	0.30	4.33	0.28	0.80	Yes	1.28	53	0.21	Yes	Not significant
Lighting overall	5.07	0.32	3.96	0.39	0.46	Yes	2.21	54	0.03	No	Significant
Overall comfort	4.79	0.30	4.33	0.30	0.71	Yes	1.10	54	0.28	Yes	Not significant

8.4.2 Differences between age groups: Under 30 vs. 30 or over

The differences in comfort and satisfaction levels for occupants of two age groups (under 30 years old and over 30 years old) have also been tested. Using similar hypotheses the comfort/satisfaction levels for the overall aspects listed in Table 8-2 were tested. The independent t-tests revealed that no significant difference was found between the two age groups for all overall aspects listed in Table 8-2. The results from the tests are shown in Table C-1 in Appendix C.

8.4.3 Differences between wings: East wing vs. west wing

Similarly the differences in comfort and satisfaction levels of occupants by wing location were tested.

Apart from overall conditions in the summer, no significant difference was found between the overall comfort/satisfaction levels (for all aspects shown in Table 8-2) for occupants located in the east compared to those in the west wing. The Levene's and independent t-test show that there is a significant difference in how occupants in the east wing perceive their satisfaction levels with the overall conditions in the summer months compared to occupants in the west wing. The occupants in the west wing were generally more satisfied. The results from this test are shown in Table C-2 in Appendix C.

8.4.4 Differences between floors: Ground floor vs. 1st floor

Similarly the differences in comfort and satisfaction levels of occupant location by floor were tested- in this case the ground floor vs. the 1st floor.

Levene's and independent t-test did show significant differences in levels of satisfaction with temperature in winter months in terms of comfort (uncomfortable/comfortable), temperature in winter months in terms of (too hot/ too cold), overall comfort conditions in the winter, temperature in the summer months (too hot/ too cold) and overall lighting between the two floor levels. No other significant differences were found between the occupants located on the two floor levels for other aspects shown in Table 8-2. The results from this test are shown in Table C-3 in Appendix C.

Generally, occupants located on the upper floors have not been in the building for as long as the ground floor. Where a significant difference has been found between the occupants located on the two floors, overall the levels of satisfaction are greater for the occupants on the ground floor than the 1st floor. A factor of this may be that the occupants on the ground floor have become more tolerant of the building. Conversely, the satisfaction with the overall lighting was greater for the occupants located in the 1st floor than those located on the ground floor. This may have been a result of lower lighting levels or the lowering of blinds in those offices adjacent to the atrium to provide greater levels of privacy.

8.4.5 Difference of time spent: Less than a year vs. more than a year

Levene's test was used to test that the variances of the two groups are equal. The independent t-test have shown that there is a significant difference between the overall comfort levels of occupants who have been in the building for less than a year and occupants who have been in the building for a more than a year however this as p=0.045 this is only very marginal.

The Levene's and independent t-test also identified significant differences in levels of satisfaction with temperature in summer months (uncomfortable/comfortable), overall comfort conditions during the summer and overall satisfaction with noise. The results from this test are shown in Table C-4 in Appendix C.

No other significant differences were found between the occupants who had occupied the building for less than a year and more than a year for other aspects tested as shown in Table 8-2.

The overall comfort levels for occupants who have been in the building for less than a year was higher than that of occupants who had been in the building for more than a year. This may be a result of the occupants having not experienced significant discomfort during the extreme weather months. Yet it contradicts the earlier comment that occupant's tolerance levels increase with time in the building.

8.4.6 Difference of sitting next to a window: Sitting next to a window vs. not sitting by a window

No significant difference was found between the groups of occupants located next to a window and not next to a window for all other overall aspects shown in Table 8-2. The results from these tests are shown in Table C-5 in Appendix C. However, when the lighting aspects were more closely inspected (see Table 8-4) a significant difference in the satisfaction levels with lighting quality for glare from natural light was found between the two groups. The Levene's and independent t-test showed that there is a significant difference in how occupants in the east wing perceive their satisfaction levels for glare from natural light. There is a greater level of satisfaction with glare from natural light (sun/sky) for the occupants who are located not next to a window.

Table 8-4: Difference in lighting comfort/satisfaction for sitting next to a window vs. not sitting by a window

	Next to window mean	Next to window SE	Not next to window Mean	Not next to window SE	Levene's test for Equality of Variances, p	Equal variance assumed?	t	df	t-test for Equality of means, p	Is p>0.05?	Difference
Lighting overall	4.91	0.33	3.96	0.39	0.90	Yes	1.86	55	0.07	Yes	Not significant
Natural light	4.13	0.83	3.80	0.27	0.01	No	1.05	92	0.30	Yes	Not significant
Glare from natural light	4.38	0.30	3.00	0.30	0.74	Yes	3.19	55	0.00	No	Significant
Artificial light	3.87	0.17	3.83	0.33	0.02	No	0.12	33	0.90	Yes	Not significant
Glare from artificial light	3.58	0.24	2.96	0.30	0.15	Yes	1.66	53	0.10	Yes	Not significant

8.5 Comfort levels and the effects on productivity and health

Measuring productivity can be relatively straight forward in buildings such as factories where a rate of product output can be determined. However, in offices it is not as straight forward. In this case the occupants were asked to self-rate their productivity. This should be taken with care due to the subjective nature. Correlation can be used to measure how variables are related to each other. Previous research has shown that higher comfort levels can deliver improvements in terms of productivity (Leaman 1993). The data collected for the surveyed building supports this notion; however the relationship is not very strong. Some positive linear correlation exists for the analysed data with the, coefficient of determination, $R^2 = 0.2698$ based on all occupants surveyed (see Figure 8-6). From statistical tests, it was found that productivity is positively related to overall comfort with a Pearson Correlation coefficient of $r=0.519$ and a significance value of less than 0.01. Therefore there is confidence that there is a genuine relationship between overall comfort and productivity.

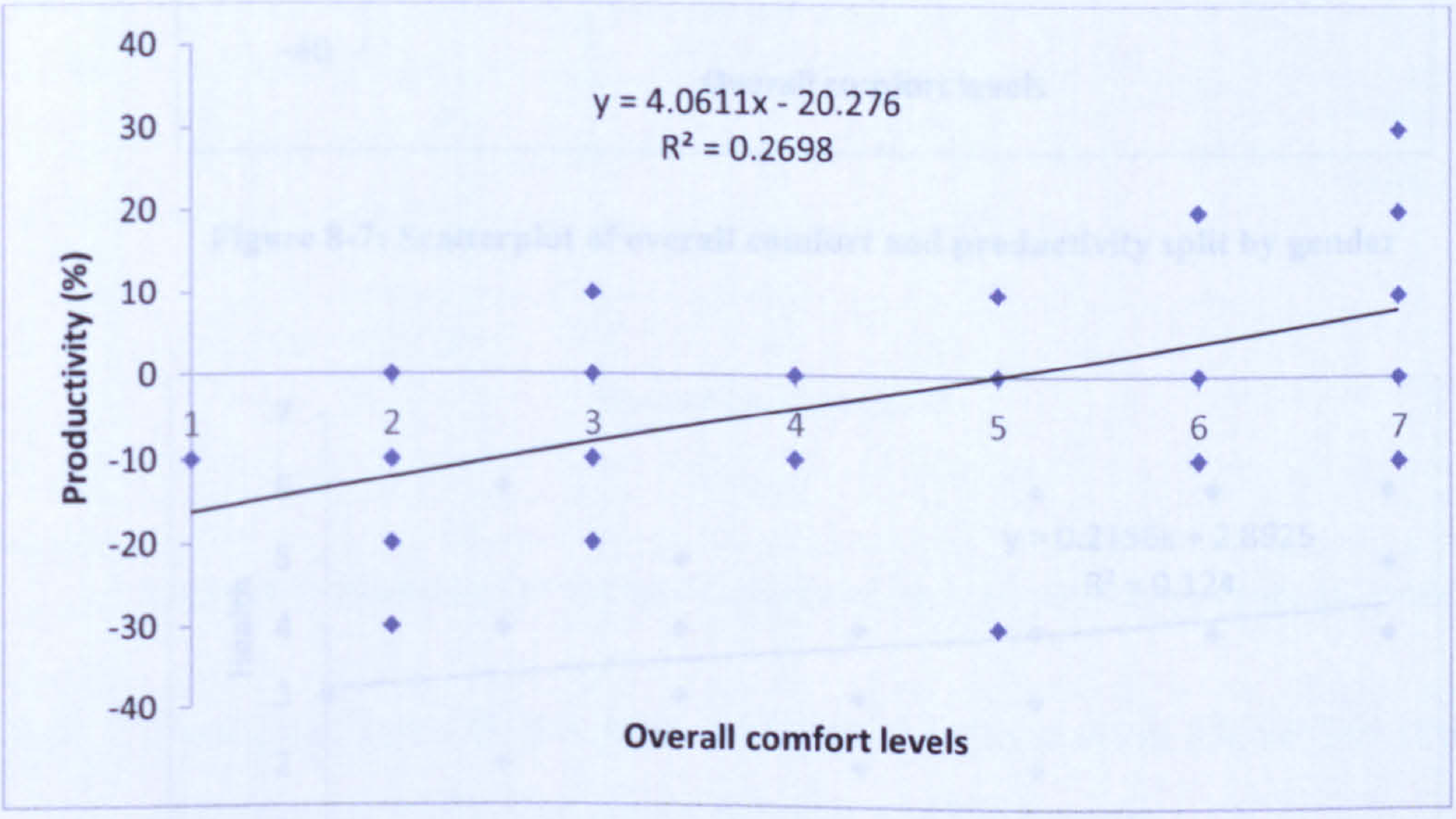


Figure 8-6: Scatterplot of overall comfort and productivity for all occupants

For all occupants, on average the productivity levels were perceived to have slightly decreased by the environmental conditions in the building (indicated by average score= 4.81). When split by gender, the average perceived productivity levels are higher by male occupants (average score= 5.11, a slight increase in productivity) than by female occupants (average score= 4.48, a slight decrease in productivity) and the average overall comfort levels are also higher for male occupants (average score= 4.79) than for female occupants (average score= 4.33). However, it can be concluded that there is a relationship between overall comfort levels and productivity, and this appears slightly stronger for the female gender ($R^2= 0.2901$) than the male gender ($R^2= 0.2179$). This is shown in Figure 8-7. Therefore productivity appears to be more affected by overall comfort levels for the female gender than the male gender. By use of the split command in SPSS the significance was tested to see if this difference in male and females was meaningful or not. The correlations of these independent samples were r_{male}=0.467 and r_{female}= 0.539, with z_r (males) = 0.220 and z_r(females)= 0.261 a value of z (-0.151) was determined with a one-tailed probability of 0.440. From this it can be confirmed that the correlation between the comfort levels and productivity levels is not significantly different in male and female genders.

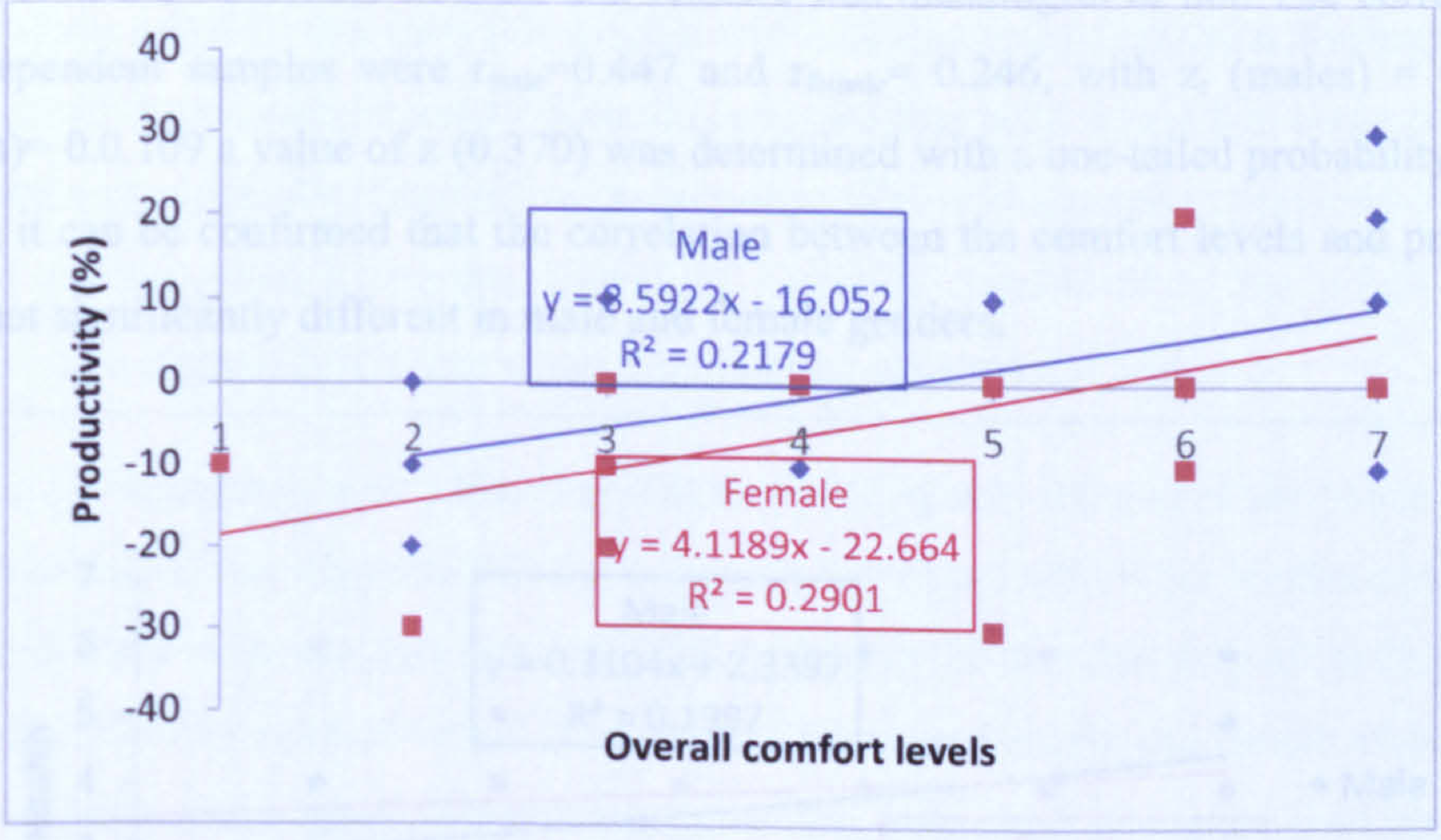


Figure 8-7: Scatterplot of overall comfort and productivity split by gender

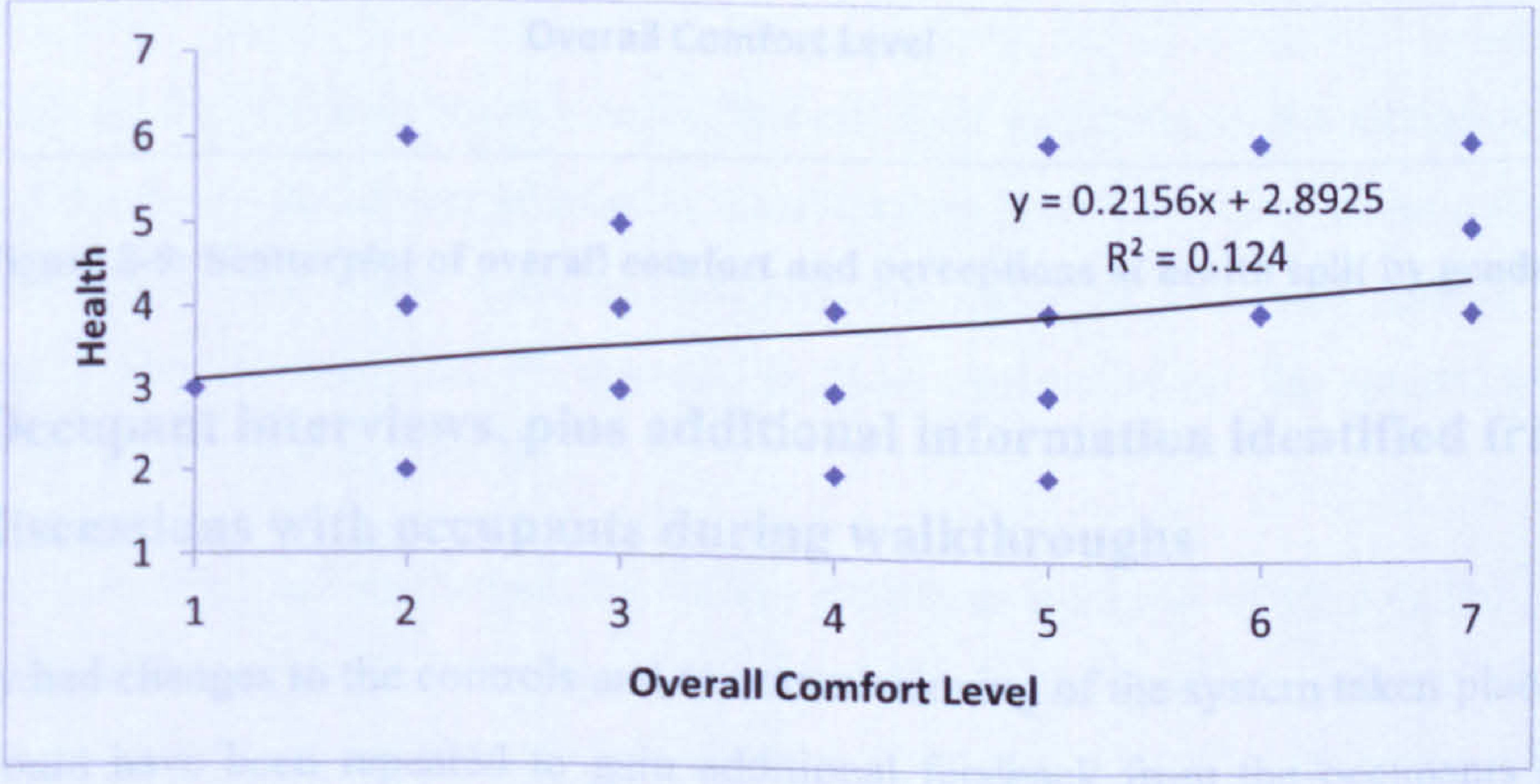


Figure 8-8: Scatterplot of overall comfort and perceptions of health

A weak positive linear correlation exists between the comfort levels and health as shown in Figure 8-8 (coefficient of determination R^2 = 0.124). From statistical tests it was found that perceived health is positively related to overall comfort, with a Pearson Correlation coefficient of r=0.352 and a significance value 0.004, hence there is confidence that there is a small positive relationship between overall comfort and perceived health.

On average perceived health levels of all occupants were rated as 3.87 which is slightly below the neutral score of 4.0. When split by gender, the average perceived productivity levels are slightly lower for male occupants (average score= 3.83) than for female occupants (average score= 3.92) and the average overall comfort levels are higher for male occupants (average score= 4.79) than for female occupants (average score= 4.33). However, it can be concluded that the relationship between overall comfort levels and health is very weak in both genders, with it being slightly stronger for the male gender (R^2= 0.1997) than the female gender (R^2= 0.0607). This is shown in Figure 8-9. By use of the split command in SPSS the significance was tested to see if this difference in male and females was meaningful or not. The correlations of these independent samples were r_{male}=0.447 and r_{female}= 0.246, with z_r (males) = 0.209 and z_r(females)= 0.0.109 a value of z (0.370) was determined with a one-tailed probability of 0.356. From this it can be confirmed that the correlation between the comfort levels and productivity levels is not significantly different in male and female genders.

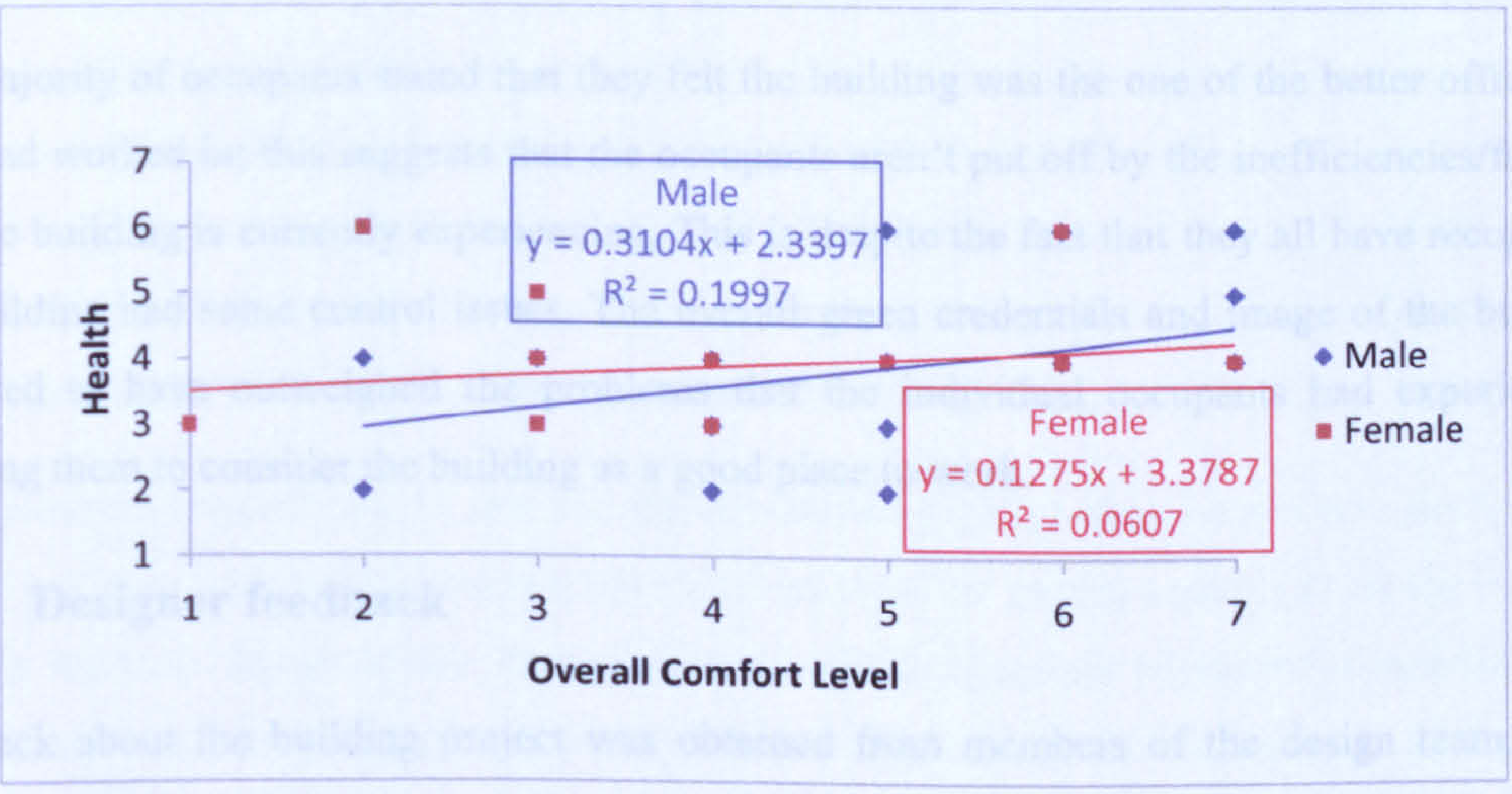


Figure 8-9: Scatterplot of overall comfort and perceptions of health split by gender

8.6 Occupant interviews, plus additional information identified from discussions with occupants during walkthroughs

Originally had changes to the controls and re-commissioning of the system taken place then the survey would have been repeated to gain additional feedback from the occupants under the modified conditions. However, as no improvements were made to the settings within the BMS and other in-operative plant equipment (i.e. the CHP unit) it seemed that little would be gained by repeating this again. A number of occupant interviews were conducted instead. Samples of the responses during occupant interviews are shown in Appendix D.

The interviews identified that the aspects that caused individual occupants discomfort and the level of discomfort experienced differed depending on the location in the building that they were situated. The two main complaints made by the occupants related to temperature, either being too hot or too cold, and/or the smells of the vacuum toilets. This feedback is consistent with the monitoring finding of previous chapters as irregularities with the temperature control were evident throughout the building, potentially due to sensor positioning/controls and the ventilation system being compromised by new partitions.

Those interviewed confirmed that the green credentials were a big influence as to why they decided to take space in the building; it gives off a good image to their clients and positive environment to work in. The atrium and amount of natural light it provides was highlighted as an aspect of the building that they felt worked well. As was true of previous findings (Bordass and Leaman 1995), all occupants questioned confirmed that they would feel more comfortable if they could more control of their office environment. Yet as discussed in previous chapters the amount of control given to tenants should be carefully considered to not result in energy inefficiencies, as evident in the overwriting the lighting controls in Chapter 5.

The majority of occupants stated that they felt the building was the one of the better office that they had worked in; this suggests that the occupants aren't put off by the inefficiencies/failings that the building is currently experiencing. This is despite the fact that they all have recognised the building had some control issues. The overall green credentials and image of the building appeared to have outweighed the problems that the individual occupants had experienced, allowing them to consider the building as a good place to work.

8.7 Designer feedback

Feedback about the building project was obtained from members of the design team. Each member of the design team was emailed a questionnaire which included some questions that were 'open-ended' and more specific questions in order of obtaining useful feedback. Unfortunately not all members of the design team responded to the questionnaire. The responses are shown in Appendix E.

The design team feedback confirmed that design principles were not effectively fed-forward to the end user which has resulted in some of the down falls in the building systems. All members of the design team that answered the questionnaire had recognised this: identifying it as being due (in part) to a lack of communication both between the design team, the client and the end users, despite the fact that efforts were made by the design team to re-engage with the new owners.

The apparent reason for this breakdown in communication suggested by the design team was due to the Design & Build procurement route which created too much distance between original designers and the building occupiers and the question of who should pay for rectifications.

As the contractual link between the design team and the client does not directly exist in Design and Build contracts this could hinder the communication between them. Yet as long as the main contractor effectively facilitates information back to the client from the design team then this should not become an issue. It is therefore not inherently due to the selected procurement that information was not fed-forward, as suggested by the building service manager, it is the failings of adequate communication between the design team and the main contractor or between the main contractor and the client.

All respondents felt that the building was successful up until the occupants took control of the building; when a lack of information being fed-forward or understood by the owners/ building managers led to the buildings controls not working as designed. The importance of POE was therefore recognised by all, yet there was not a general census of who should pay for POE to take place.

The fact that the BMS contracts engineer states how the strategy of the building was 'very complex and took quite a while to work through' and that the minimal training given to the end user was not successfully received indicates why the BMS system was not running efficiently during occupancy. It highlights the question of whether this was this due to the BMS system being too complex or because the new owner failed to appreciate the importance/ consequences of having an appropriate training member of staff controlling it.

The questionnaire identifies the fact that the new building owner turned down both the building service engineer's proposal to oversee the rectification of the system controls to set the building back to work as designed and discontinued the BMS contracts engineers' appointment to maintain the site, which could have resolved the control issues/inefficiencies that the building experienced. Yet it is unknown whether this was due to cost implications, a lack of understanding of why these appointments would be beneficial or the complexity of the building systems.

8.8 Management feedback

Interviews and discussions were held with the Centre Managers at the case study building (with Client Services Manager and Centre Manager). The Client Services Manager had worked there since February 2008 (for two and a half years at the time the discussion took place) and the Centres Manager had worked there for just less than one year.

When asked about their overall satisfaction with the building and how in their opinion the building could have been improved the responses were of mixed opinion. Generally they were satisfied with the amount of lighting in the building, and felt there is a lot of natural light and believed the atrium works well and in their office the perforated blinds also work well. They liked the positioning of the building and think that aesthetically the building looks very good. The design improvements suggested by the Management team was the noise transmission between floor and adjacent rooms and the vacuum flush toilet system was an on-going problem that should be improved or left out of future design projects. The team felt that the building was too big and there maintenance costs were too high.

Since handover and the end of the defect liability period, they highlighted that problems have occurred including the CHP unit, EVAC toilet (it was said that they were also considering putting the urinals on a water system to eliminate the issues they had been experiencing with the vacuum flush system), heating problems (BMS) and the problems that occurred on the grey-water tank.

It was evident that in they found the building very difficult to manage in terms of FM. The managers had been given very little in terms of training for controlling and managing the BMS system and other pieces of plant/equipment control. At handover, the previous Centre Manager, did receive some basic training regarding how to change the temperature and open the windows in the atrium. However, the new management team have received no official training and have "just picked things up as they have gone along". Noting that as time as gone by they have learnt more about how external temperatures affect the indoor temperature. Also mentioning that as the response time of the thermal mass is very slow, they now look at the weather reports and if they know it is going to be cold in a few days they will prepare for this and change the BMS settings in preparation.

The Management team found that the Operation and Maintenance manuals were not straight forward. They find them too complicated and are not easy to follow or understand.

It was said that a new FM company will soon be contracted and will have remote control over the BMS and the plan was to rectify many of the issues identified.

When asked "what would you have like to have done differently or seen done differently during handover and the first year of operation had you had the chance?" the response was "to have received more thorough training and more advice on how to run the building".

Finally when asked if they had any additional comments it was said that the 'green' aspects are not worth it, and they were even thinking of taking the 'green' features out of the building. One of the members of the management team said that it is 'all singing and dancing in terms of selling the building" but the benefits in terms of running are just not worth it'.

The main points taken away from the interview was that training on the system is crucial to making the building run efficiently and at the moment there is little knowledge and true understanding of the system due to absent facilities management.

8.9 Chapter discussions and conclusions

An objective of the study was to evaluate the social-related aspects of the building's performance. This included:

a) Investigating the comfort and satisfaction levels of the occupants in the 'green' office building and make comparisons with similar buildings
b) Evaluating how these perceived levels of satisfaction vary amongst different groups of people within the building

As a means of collecting the required data to investigate the objectives, the BUS methodology was selected survey. The results supporting each objective are discussed below.

a) Investigating the comfort and satisfaction levels of the occupants in the 'green' office building and make comparisons with similar buildings

The BUS methodology uses a one off survey that captures data relating to perceived comfort and satisfaction levels of the users/occupants.

The response rate for the survey was good, at 67%. The occupant survey revealed a lot of useful information about the satisfaction and comfort levels within the building. These results were then compared against BUS benchmark figures within the BUS database. Occupant comfort and satisfaction levels were poor for the aspects relating the temperature.

The results from the survey have shown that the building has overall provided a comfortable and satisfactory environment. The building on the whole performed well when compared to other buildings within the BUS database, however compared to three other 'green' buildings the performance was overall poor. The main issue that came out of the survey was the dissatisfaction with temperature and the levels of control given to the occupants.

The building achieved good results for the questions relating to operational factors. The image of the building to visitors scored very well, with a score significantly better than both the scale midpoint and the benchmark score, placing it within the top 32% of buildings within the BUS database.

In terms of space in the building, furniture, availability of meeting rooms, suitability of storage areas and safety, the building scored better than the scale midpoint and benchmark. Overall too much desk space was assessed by the occupants, resulting in the score being worse than the benchmark and scale midpoint. Cleaning scored around the same as the benchmark but a slight improvement on the scale midpoint.

The environmental factors were perceived as the most disappointing aspect of the building. Many comments were made by the occupants regarding issues with temperature in both summer and winter months. The score for overall temperature in the summer and winter were placed in the bottom 37% and 24% respectively of the buildings within the BUS dataset.

In winter, overall scores for temperature and air were poor. Temperatures were perceived as slightly too cold in the winter and slightly uncomfortable, performing worse than both the respective scale midpoint and benchmarks. Temperatures in the winter during the day were judged to be on the variable side with a study mean score of 4.8, a score worse than both the benchmark and scale midpoint. In the summer overall scores were again disappointing, although not as poorly perceived by the occupants as those in winter. The temperature (hot/cold) had a scale midpoint of 4 and the benchmark score was slightly less than this, a study mean of 3.77 was calculated- a value between the benchmark and the scale midpoint. For both overall temperature and temperature stability in the summer, the study scores were worse than both their respective scale midpoints and benchmarks. Suggesting that the conditions are slightly uncomfortable and temperature is variable during the summer months.

Overall air in the winter was comparable to both the benchmark and scale midpoint, with a result in the top 42% of buildings within the BUS dataset. In terms of humidity, the air in the winter was around the same as the benchmark and slightly towards the dry side of the scale midpoint. Similarly, in terms of freshness and odours the building was comparable to both scale midpoint and benchmark.

Overall air in the summer was again comparable to the scale midpoint and benchmark, with a result within the top 39% of buildings within the BUS database. For other air related aspects of building performance the users regarded the air in terms of; odour/smell, still/dry, fresh/stuffy and dry/humid, all fairly neutral and comparable to the benchmark and/or scale midpoint. With the air perceived as being very slightly towards the still, dry, odourless and stuffy side of the scale.

Noise was an interesting aspect in terms of perceived performance. With an average score of 4.57, overall noise was assessed better than both the scale midpoint and benchmark. This placed the building in the top 30% of those within the BUS database. The case study building also performed better than the respective benchmarks and scale midpoints for noise from outside and unwanted interruptions. This may be a result of the low occupancy as found in (Bordass, Leaman, et al. 1996). There does however appear to be issues with too much noise from colleagues and other people. This was supported by comments made on the survey by some of the respondents. The offices are cellular and the noise transferred between the adjacent spaces was very poor in terms of performance, and occupants found issues with hearing conversations form adjacent rooms and privacy with telephone conversations.

For overall lighting an average score of 4.49 was achieved. This was better than the scale midpoint but slightly lower, yet comparable to the benchmark. This placed the building in the bottom third of buildings within the BUS dataset. Users were very satisfied by the natural light within the building and results suggest the users assessed that the levels of glare from the sun and sky were adequate. With regards to artificial lighting, the occupants assessed the building as having poor light (also found in (Standeven, Cohen, et al. 1995)) suggesting that the lighting system is not providing enough illuminance on the working plane. Yet measured lighting levels in Chapter Five suggest lighting was sufficient. The occupants experienced no issues with glare from the artificial lighting system.

In terms of personal control, the responses mirrored many of the issues over the levels of satisfaction and comfort with temperature, lighting and noise previously identified. Comparing the personal control factors for heating, cooling, lighting and noise to the scale midpoint and /or benchmarks within the BUS database, the results were poor. This has also been found in other studies (Bordass and Leaman 1995). Control over heating was believed to be the most important factor, with 44% of respondents highlighting this in the survey. This was reflected with the 1.67 average score for perceived level of control. Similarly for cooling a control average of 1.84 was calculated, with 40% of occupants believing that control over cooling was important to them. Scores for ventilation were slightly better with results similar to the scale midpoint and/or benchmark, presumably due to the openable windows within the office windows. 37% of respondents assess control over ventilation as important to them. Control over lighting and noise was regarded as important by 25% and 23% of occupants respectively. However the scores 2.25 and 1.95 for perceived control in lighting and noise respectively showed that the building performed worse than the midscale point and benchmark.

Similar to the image rating the design of the building scored well, with an average score of 5.39. When asked "if the facility meets your needs", the users assessed the building as average. Overall comfort was rated as fairly neutral, with an average score of 4.6. This score was higher than the scale midpoint and very similar to the benchmark. In terms of productivity the study score was in the 43rd percentile. On average a 1.88% decrease in productivity levels were perceived, a comparable figure to the benchmark. Many other studies have found productivity losses greater than this (Ashbridge and Cohen 1996) (Standeven and Cohen 1996b). However this is disappointing. In terms of perceived health, again a similar score towards the upper limit of the benchmark was calculated.

71% of occupants have in the past requested for changes to the heating, lighting, ventilation and cooling within the building. Some 12% were completely satisfied, with 32% neither satisfied nor unsatisfied with the speed and effectiveness of the response. 0% and 7% respectively were completely unsatisfied with the speed and effectiveness of the response to any request for changes. Some additional questions were included to tailor the survey slightly more to the building in question. When asked if the occupant like the vacuum flush WC's a 3.77 average score was received (where 7 is a positive response), suggesting that there is some dislike towards this system. To support this many comments were made by the occupants regarding the unpleasant smells from the WC's.

When asked "how important are sustainability issues to you", again based on a 7 point scale where 7 is important and 1 is not important at all, an average score of 5.07 was achieved. This suggests that the occupants have more than average concerns over issues relating to sustainability. As these questions were included for this study only, no comparisons could be made between the responses obtained and other surveyed buildings. It was also found that 89% of occupants frequently use the recycle bins.

As the building has many green credentials, a question of how aware the occupants were of these aspects came to mind. The percentage of occupants aware of these features, are detailed in the Table 8-5.

Table 8-5: Occupant awareness of sustainable features within the building

Feature	**Percentage of occupants aware of the feature (%)**
Building's sustainable construction	72
Grey water flush WCs	91
'Green' roof	81
Combined heat and power system	58
'Termodeck' system	49
Low energy lighting	82

Interestingly the feature with the lowest percentage of occupants aware of its installation in the building was the Termodeck system, which of course is supplying the heating and cooling to the spaces. This begs the question whether raising the awareness through better education would create a greater level of forgiveness on the occupants' behalf.

A total of 226 written comments were received from the respondents. These comments were split into 3 categories; positive, neutral and negative responses. Of the 226, 17% were positive, 8.5% were neutral and 74.5% were negative. This is shown in Table 8-6.

Table 8-6: Overview of the comments made by occupants

Aspect for comment	Positive	Neutral	Negative
Changed behaviour because of conditions in the building	1	0	15
Comfort overall	2	2	6
Design	4	3	11
Health (perceived)	3	1	2
Needs	1	1	20
Lighting	1	1	14
Noise	1	1	14
Productivity	2	1	6
Meeting rooms	2	1	4
Things that hinder work			32
Things that work well	18		
Request for changes			21
Storage	0	6	3
Space at desk	3	2	7
Sustainability issues	1	0	13

From examining the occupants' comments a number of issues became evident and therefore should be addressed or at least considered to enhance the levels of comfort and satisfaction. These include:

- Kitchen space extended (this has actually already taken place)
- BMS temperature control should be re-commissioned (to iron out the fluctuation in temperature) as there were many reports of request for changes to temperature and poor results were obtained in the survey.
- Toilet system should be better maintained as there were many complaints regarding smells.
- Occupants would like toilets on both sides of the building.
- Lighting system should be re-commissioned in some locations. Some occupants have even been given handheld remotes to provide an overriding means.
- Feedback suggested there is an issue with noise transfer, therefore reverberation tests should be carried out to examine this.
- Occupants generally like the amounts of light as it provides a "pleasant and light environment to work" and there were many positive comments about the atrium and the amount of space in the building.

b) Evaluating how these perceived levels of satisfaction vary amongst different groups of people within the building

Statistical methods were used to see if the satisfaction/comfort levels were significantly different between various groups of people. This was tested for the overall variables within the survey.

The results showed that for all overall comfort and satisfaction levels tested, no significant differences were found between male and females with the exception of overall conditions in winter and lighting overall. In both cases the male gender was found to be more satisfied than the female. No significant differences in the overall variables were found between age groups split by 'under 30' and 'over 30 years old'.

In terms of location within the building a number of significant differences were found. Occupants on the east wing were more satisfied with overall comfort conditions in the summer compared to those occupants located in the west wing. For all other overall conditions, no significant differences were found between occupants located in the east wing compared to those in the west wing. In terms of location by floor level many significant differences were found. The occupants on the ground floor were more satisfied/ comfortable than the occupants on the first floor. The variables with significant differences were temperature in winter (uncomfortable/comfortable), temperature in winter (too hot/too cold), overall conditions in winter, temperature in summer and overall lighting.

When comparing occupants who had been in the building for less than a year to those that have been in the building for more than a year, significant differences in the comfort levels in the summer (uncomfortable/ comfortable), conditions in summer overall and noise overall were found with higher levels of satisfaction/ comfort for those who have been in the building for a year or less. A factor relating to this could be that these occupants have not experienced the same levels of discomfort due to the little time they have been in the building.

Investigations into the overall comfort levels of occupants who sit next to a window compared to those that don't were carried out to see if there were any significant differences in perceived levels. Looking at the overall variables no significant differences were found. However, when lighting was examined more closely significant differences in levels of glare from natural light were found, with too much glare for those who sit next to the window.

Previous research has found significant benefits in productivity can be brought about through higher overall comfort levels (Leaman 1995). This relationship was evident from the data collected. Although this relationship was weak ($R^2 = 0.2698$) there was still a genuine relationship. When split by gender type no significant difference was found in terms of the impacts increased comfort levels have on productivity levels.

In terms of how increases in overall comfort levels affect perceived health, the results showed that a weak positive relationship does exist and this again is not significantly different between the gender types.

The results presented in this chapter are in many ways subjective but they do however provide information on how the occupants perceive satisfaction and comfort levels in the building. Obtaining this sort of feed-back is important as it allows the aspects in which occupants are dissatisfied with to be addressed and actions can be made to improve the working environment.

Chapter Nine - Summary of work, conclusions and recommendations for further work

9.1 Overview

This final chapter concludes on the findings of this research and reviews the project as a whole including areas of further work.

The thesis has presented the results from the study's POE of an award winning BREEAM 'Excellent' office building in the North East of England. This case study office, despite having been open since February 2007, isn't fully occupied and as of July 2010 the occupancy was approximately 60%. The POE has investigated the energy, water and other physical aspects of building performance and compared the results to benchmarked data, the BREEAM assessment, design predictions made using simulation techniques and calculations during the design stage of the project. The social aspects of building performance have been evaluated through occupant surveys, interviews, discussions and general observations.

Generally the activity of POE is still rarely carried out. There are case studies presented in literature, such as the PROBE studies during the 1990's, however none of these studies have evaluated detailed occupancy variations and the impacts it can have on the energy performance of a building.

This study went beyond a typical POE as it has included investigations into how the occupancy variations and management strategies applied under these conditions can impact on building energy performance through the use of simulation modelling techniques. This is an area where very little research has previously been carried out. The interesting and original contribution this work makes is presented in Chapters 6 and 7.

As highlighted in Chapter One, the original tenants of the case study building (Innovate Office Ltd) went into administration in June 2008. In October 2008 a new company bought the serviced office business out of administration. This had a significant impact on the original aims of the research presented here. Over the course of the monitoring period the planned interventions to improve performance could not take place. The lack of effective facilities management has had a disastrous impact on the post-occupancy performance of the building. The high level of design that was put into this building could not follow through into the post occupancy stage due to lack of funds and lack of facilities management. Overall the "green building" status was severely weakened.

9.2 Overall conclusions and summary of key findings

The study aims and objectives were set out in Chapter One. A number of interesting findings and shortfalls in design, commissioning and facility management processes were reported on in the thesis presented. Conclusions drawn from the research findings are summarised in the sections below.

Credibility gaps between the actual and predicted performance, like many other buildings, existed in the case study building. Energy use was over three times that predicted at design. Similarly CO_2 emissions resulting from the use of gas and electricity were over three and a half times more than those estimated at the design stage. Given the lower than designed for occupancy levels experienced, this should not have been the case. However the low occupancy levels combined with poor management of the building, as a whole resulted in disappointing building performance; certainly so for a building with such high ambitions and numerous 'green' features incorporated into it. The study outlined a fully joined up approach, understanding and implementation for modern multi-system controlled buildings was generally found to be missing.

The research has highlighted and investigated the issues surrounding building performance that can occur. To carry out effective POE data must be logged reliably, with adequate sub-metering so that individual end uses can be accounted for.

Comparing fuel usage, the gas consumption far outweighed the electricity consumption. In terms of electricity, the fan pumps and electric chiller accounted for the largest portion (51%). This was followed by lighting requirements (13% tenant lighting, 31% landlord lighting), then small power equipment (29%). The vacuum pump energy accounted for 2% and the lift energy accounted for 1% of the total electrical energy usage.

A lack of sub-metering made the HVAC end-uses difficult to determine. However for the fans, pumps and electric chiller consumption was 82% more than was predicted at design. High levels of consumption were partly due to the 24/7 operation which was a result of inexperienced (and untrained) staff making changes to the control settings.

Well trained staff is vital. Inefficient management of systems, as mentioned, can lead to inexperienced and unnecessary altering of the BMS which in turn leads to an increase in energy consumption (i.e. operating the BMS on a 24/7 control setting). There should be regular skills audits, toolbox talks, training plans for each individual as well as new staff training plans to improve knowledge and understanding for those using such systems.

Energy monitoring is important as wasteful consumption can be identified and addressed. High levels of small power consumption were consumed during unoccupied hours. This is something that can be easily addressed through effective housekeeping. Small power energy consumption during unoccupied weekday hours accounted for around one third of total small power consumption. Weekend small power consumption ranged from 15.5% to 23.8% of the total weekly use. However, small power usage compared well to benchmark figures, mainly due to the low occupancy experienced in the building.

Lighting consumption in all occupied office zones was also greater than the design predictions. It was found that although most of the lighting controls were operating as intended, in one of the zones this was not the case and resulted in wasteful consumption during unoccupied hours. This reinforces the need for POE and effective maintenance.

When operating effectively the vacuum pump worked efficiently with the low volume flush grey-water WC system. However, this system was not well received and many complaints were reported in the occupant satisfaction survey.

Water consumption within the building was generally good and compared well to the design and benchmark figures.

Temperature control appeared to be an issue in the building. The temperature sensors reporting information back to the BMS were often located in unoccupied offices and consequently caused some overheating issues in the building. However, the offices did not experience temperatures above the CIBSE 'hot' threshold of 28°C.

The lighting levels were investigated and measurements indicated adequate lighting in those areas tested. However, many complaints from occupants were received as shown in the occupant survey results

The BREEAM assessment conducted at the design stage was revisited and updated using the measured energy and water data determined from the POE. As a result the score was reduced by 7.55%, yet a rating of 'Excellent' was still achieved. However if additional aspects were reviewed it is expected that this rating would certainly drop into at least the 'Very Good' category.

Total annual CO_2 emissions of 82.07 $kgCO_2/m^2/year$ were estimated for the current use of the building- a figure 3.5 times the original design estimates.

To improve the performance of the building the following recommendations can be made:

1. In order to get a better understanding of where energy is being used in the building additional sub-meters should be installed including a meter on the electric and absorption chiller and use of fans within each AHU.

2. Thorough re-commissioning of the BMS should take place to allow areas to be initially aligned (and any changes qualified) with the settings laid out in the control strategy. These conditions can then be checked to see if they are satisfactory for the occupants.
3. Based on the findings in Chapter Six, consideration should be given to put all unoccupied areas on set-back control.
4. Consider relocating some of the occupants so that more zones can be put on set-back control.
5. For this particular green building project, although financial difficulties have prevented the repair of the CHP unit, at the soonest possible time this should be rectified so that the building can benefit from the tri-generation system. However, this should be also be monitored to see if the use of this unit is commercially viable particularly given the low occupancy levels experienced.
6. Suitably qualified and experienced personal at all stages are required to ensure green design and potential are realised for the range of possible and likely building and plant uses. If the facility management have shortfall in knowledge to conduct an effective energy efficiency and use review, external support or review should be sought.

Investigating how low occupancy levels within a building can affect building performance was carried out using simulation techniques. At the design stage designers should consider how occupancy can impact on the energy performance. This can be tested in a similar way to the approach shown in the research presented. There should be consideration as to how office buildings, like the case study building, take up occupancy.

The simulations carried out showed that:

1. Without the people present a 20% increase in heating requirements, together with a 196% and 9% decrease in cooling energy and fan, pump and controls energy respectively was observed. In terms of total system energy this was a 6% increase. Therefore, suggesting that the internal heat gains from people offset total system energy by 6%.
2. The absence of people will also translate into an absence of small power usage and also lighting. When simulations were carried out without all these present, there was a 160% increase in heating requirements and 100% decrease in cooling requirements. In terms of total system energy this was a 68% increase.

The results have shown that when inefficient FM of a building occurs low occupancy levels can actually increase energy use. Under current management strategies the building would actually perform more efficiently in terms of total annual energy at the 100% occupancy compared to the 60% levels where efficiency was at its lowest.

Heat recovery efficiency can influence the energy performance of a building when occupancy is low. The results from the sensitivity analyses support the need for careful and effective management, commissioning and continual commissioning should occupancy levels change. The potential sensitivity to the heat recovery control set-point was shown. Seasonal commissioning should be carried out to improve the running performance during the various seasons throughout the year.

Careful planning can allow for systems to be varied or controlled on set-back when appropriate, and therefore can save energy, operating costs and CO_2 emissions. Locating occupants in areas that are all conditioned by the same plant should be considered. Continual commissioning and maintenance including consideration to occupants and their locations and densities within a zone or space should take place. Also, it is vital that seasonal commissioning of plant assets and their control occurs (to ensure that operation is at a more energy efficient level). Substantial savings can be made when systems are fine tuned to perform more efficiently, for example in the case study building, a better managed system could bring annual savings of 60.3% in total energy, £30,500 on utility bills and 33.1 $kgCO_2/m^2$ in environmental savings.

Additionally to reduce the reactive maintenance costs, conditioned based monitoring and/or planned preventative maintenance should be included in future FM contracts.

The occupant survey revealed that many aspects of the building were not well received, particularly the overall temperature and temperature consistency control, in both summer and winter. Noise from other people in the building, artificial lighting, personal control, air in winter and space at desks were also perceived to be unsatisfactory. In terms of image design, natural light and space the building was rated very highly. Overall noise was also highly rated despite the disappointing result for some of the individual noise related aspects. There were many negative comments about the temperature control, vacuum flush WC's, noise and lighting made by respondents.

The aspects of the design that were well received by the occupants should be considered in future design of buildings; included in this is the atrium. The users all appeared to like this space as it provided an informal and light spacious area to have a coffee/meeting. However, the energy required to maintain the required temperatures within this space are considerable so this should be taken into account. Additionally, the atrium provides a buffer to reduce the heat losses from the adjacent offices.

When considering overall comfort aspects, the comfort index shows that the building result was in the 49th percentile. In terms of satisfaction, the index fell within the 63rd percentile. These combined results give a summary index with a result in the 57th percentile. This indicates that overall the building is in the top 43% of those within the BUS database and therefore slightly better than average. Yet when compared to other 'green' office buildings the result was disappointing.

It appears that the building has the potential to perform much more efficiently. If the issues relating to temperature and lighting are addressed then the levels of comfort and satisfaction may rise, thus improving the performance of the building which in turn will improve the perceived performance by the occupants.

The study has highlighted how management, human and building behaviour can impact on energy use and supports the need for routine POE.

9.3 Recommendations, lessons learnt and closing the feedback loop

The lessons learnt from POEs are important as they can be applied and fed into the design and operation of future buildings (and even existing buildings).

Following this study a number of recommendations can be made in terms of the design, operation and management of the building (and indeed may apply to other buildings).

Recommendations to the management at site:

- Commissioning is often rushed at the end of a project. BMS needs to be re-commissioned and better managed. It is no good just putting a BMS system into a building. People must understand how to use the systems and therefore maximise functionality. BMSs have the potential to save energy but it is important to meter, monitor and manage the systems.
- Close off unused/unoccupied areas of the building to reduce wasteful energy use.
- Facilities management needs to be more effective to not only reduce the energy efficiency but to improve comfort levels for its occupants.
- Continual monitoring of the BMS should occur and also reviewed when significant change occurs.
- Seasonal commissioning should take place to improve the building performance during the various seasons.
- If possible, relocate some of the occupants in the building to allow for the AHUs in unoccupied zones to be shut off (put on set-back control).
- Adequate and more technical training given to the staff but at a level that is easy to understand.
- Educate the occupants more to help them better understand the building and the ethos behind it.

- To a large extent occupant behaviour can have a significant influence on the performance of the building. Energy consuming ways in which occupants can influence energy use includes leaving equipment on overnight and (where control permits) leaving lights on. Many electrical items are being left on overnight and this is wasteful. Raising awareness would be of benefit.

POE is important to allow design teams to learn from the buildings they are designing and to become aware of what design approaches actually work well once a building becomes operation and what doesn't.

Recommendations and lessons for designers:

- Focusing particularly on the building selected for this study, a number of design features were not utilised effectively nor efficiently, begging the question as to whether or not should they have been installed in the first place.
- Bill Bordass often says "Don't over-complicate buildings, keep them simple and do it well". If designers kept buildings simple without unnecessary complexity then building managers and occupants would have a better understanding of the controls and how to manage the building as a whole.
- Provide clear, concise O&M manuals that are easy for the users and building managers to understand. The Managers in the case study building found the O&M manuals at site complicated.
- Follow up on after Practical Completion: learn lessons from any mistakes and apply successful aspects to future design projects. Consider the 'Soft Landings' (as discussed in the literature review) approach to all future projects.
- Consider occupancy levels in the design and also highlight, in the O&M documents, the importance of careful building management and routine reviews.
- Carry out sensitivity analysis to the control set points for the possible variations in the operating environment and full range of possible building occupation uptake. Any operating mode or control set-point changes that would better suit a particular operating environment should be made very clear in the operating manuals and to those who manage the building.
- Ensure time for effective commissioning and hand-over. This is often squeezed in to meet the handover deadline.
- Allow for continual review and seasonal commissioning.
- Achieving a high result from a BREEAM assessment at the design stage doesn't mean that the building will be performing effectively at the operating stage.

- As post occupancy studies increase in number and more widespread data becomes available, designers should challenge and utilise this information to fill in the performance prediction knowledge gaps and to ensure all aspects are fully considered.
- Let's learn more from the buildings procured as a means of improving the future building stock. Also with the large amounts of existing stock, routine building performance evaluations should be conducted to identify areas of a building that are consuming large amounts of wasteful energy and reduce these to help towards achieving targets of reducing CO_2 levels by an 80% by 2050.

9.4 Future work

Sadly the lack of improvement in the operation and management of the building over the period of this work eliminated the opportunity for some of the further monitoring and feedback that was hoped for.

Possible further work related to the research presented may include more detailed investigations into how occupancy can affect performance and focus this work on occupancy density.

If the issues with the BMS and CHP unit were to be rectified, it would be interesting to return to the building and repeat the monitoring, and also investigate what improvements (if any) in comfort levels would have resulted from the changes in the system and the control settings.

POE should be a continual process to ensure there is efficient operation of a building. This is required to not only reduce the amounts of wasteful energy and environmentally damaging emissions, but also to ensure that the comfort and satisfaction levels of the occupants remain high and a productive environment is maintained. With health and safety approval, an out-of-hours evening and weekend walkthrough would be beneficial to confirm usage.

Further investigations into the building fabric would have been interesting to evaluate the success of the construction itself. This may include more detailed thermography and/or U-value testing using heat flux sensors.

Making comparisons with other buildings is always difficult as there are many factors that can affect the performance as a whole including; location, plant equipment, size, occupancy patterns and building use. The work presented in this thesis has mainly been based on one case study building. In reflection, had more green offices (and even buildings without any green credentials) also been monitored this would have provided more comparative analysis, especially in terms of the energy. Had more access to the Nottingham office been granted, this could have provided a more 'like for like' comparison as both buildings are of similar size and are managed by the same company providing the same professional services.

The occupancy related research presented raises awareness and opens up further potential for understanding the issues. In the building used in this research, control set-points and the locations of occupants offices as occupancy uptake occurs could have an impact on the performance. Locating the occupants by 'AHU block' as opposed to 'ground-up' may have presented significant savings. With this layout, unoccupied blocks would then be able to operate on set-back control. Also the energy efficiency related to the density of occupied areas provides scope/opportunity for substantial research to take place.

The scope of the research work and results presented here has focused on the in-use performance of the case study building. There are other energy and CO_2 related issues associated with buildings including the materials used to construct the building, the construction process itself, also the demolition and after life of a building. At a time when the environmental and financial climates are in crisis and high on agendas it is important, especially in the design and operation of commercial office buildings, that the energy use is efficient. The maintenance costs should not escalate as a result of a low carbon product. Time, resources and data permitted, future studies to expand on this work could include conducting life cycle analyses involving the calculation and comparison of the building's life-cycle carbon and life-cycle costs. This type of analysis could investigate if the delivery of a low energy/carbon zero building brings high life-cycle costs, both in carbon and monetary terms. Although it wasn't highlighted in the main text of this research, discussions with the management team later on in the monitoring phase of the project revealed that the maintenance costs of the case study building were high and this itself brings question to the overall sustainability of such a building.

Knowing that there have been financial difficulties related to the delay in the remediation work, Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) could be an interesting exercise to carry out as a way forward at this point. Two stages of LCC could potentially be explored. The first could be the LCC related to the initial build and if the green aspects installed were in fact commercially viable. The other LCC that could be explored may be the costs at the occupancy stage and if the investments in the re-commissioning of the building would be good for the business. This could include using a base-case scenario and some other alternative(s). A base-case may be to carry on the way things are and leave the building operating as it is. One alternative may include investing the money to put the CHP in operation and also carry out a re-commissioning of the BMS. Another alterative may be to strip out all the 'green' aspects that are currently failing and replace them with 'non-green' items. These scenarios would be calculated over a 25 year study period and include the operational costs, maintenance costs, repair costs, fuel costs and capital expenditure. The LCCs for each scenario would be calculated to suggest the most appealing way forward for the business. However a LCA could also be conducted to compare these scenarios from an environmental aspect so that the optimum balance can be struck to suggest the best way forward at this point.

9.5 Closing remarks

Building occupation can have a very significant effect on operational costs. How significant will depend on the awareness of those concerned with the design, commissioning and operation of the plant. There are potential issues, factors and changes that may be influential as to what allowances and actions they take. This study has highlighted the need for this general awareness and the possible affects resulting from the lack of this awareness.

POE is something that is required to ensure that optimised building performance is achieved. Identifying areas that are not performing as well as they should, by comparing them to benchmarked data and design data, can identify inefficient aspects.

POE is an activity that requires impartial judgement and reporting of the findings. Therefore should (arguably) not be carried out by the design team as they may be biased and expectant rather than open minded with the truth, due to concerns and pressures that any unwanted findings could damage the reputation of the company. However, a good relationship is required with the POE practitioner and the design team, as clear understanding of design intentions and how aspects of the building are meant to operate is important. Also the designer should stay involved so that lessons can be learnt to benefit future designs.

Facilities Management is an area of expertise that has gained more attention over recent years. Post Occupancy Evaluations allows Facilities Managers to identify areas where potential savings in energy, money and CO_2 can be made. It can also bring improved comfort levels through identification of dissatisfaction by means of occupant surveys; thus improving the satisfaction levels for the occupants who are ultimately the end users. Particularly within offices, the occupant's satisfaction levels must come first and be maintained at a high level so that the clients don't take their business and operations elsewhere. With the feedback and feed-forward aspects of POE designers, architects and engineers can all learn from their designs and implement successful aspects into future designs or improve on aspects of their design that did not perform as well as expected in both terms of energy and occupant satisfaction.

Many may envisage a green future with low-carbon buildings, but as this research has identified, the aspirations at the design stage rarely match what happens in reality. For this reason, the field of POE (and BPE) must gain more creditability. The identifications made during such a process can be used to fine-tune a building so it performs more efficiently.

As mentioned in the opening chapter, buildings are responsible for a large proportion of the generated CO_2 emissions. There is definitely the potential to improve the operational performance of all buildings in some way to enable, although maybe not at the full reduction required but at least help somewhat, a more sustainable future for future generations.

Appendices

Appendix A

Table A-1: Space heating energy (kWh)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	429032	404074	440359	403815	404070	458334	520547	477624	457202	337048	254673
As built, inherited management	257343	245616	239090	228473	220152	241808	258557	230114	203730	155320	99102
As built, good management	166913	154430	147770	143017	131999	122993	116670	111213	107688	102155	99102

Table A-2: Space cooling energy (kWh)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	241	7231	8219	8761	9220	13383	16665	16866	17260	13652	12274
As built, inherited management	0	4294	4459	4836	5058	6896	7485	7802	8068	7847	8030
As built, good management	294	2755	3089	3494	3551	5497	5786	6279	6537	7689	8030

Table A-3: Fan, pumps and controls energy (kWh)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	192154	193480	190389	190902	188204	187753	188701	188659	189104	188160	185923
As built, inherited management	77005	79264	83051	84985	85909	88700	93297	94119	95816	95875	92072
As built, good management	1215	9517	20282	28999	37794	45202	55499	64260	75114	82053	92071

Table A-4: Lighting energy (kWh)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
As built, inherited management	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427
As built, good management	24747	29715	34684	41337	46672	51641	58030	64682	71071	76039	82427

Table A-5: Equipment energy (kWh)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
As built, inherited management	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216
As built, good management	4399	21952	39504	57057	75906	93459	116027	139526	162095	179648	202216

Table A-6: Space heating related costs (£)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	18513	17436	19001	17425	17436	19777	22462	20609	19728	14544	10989
As built, inherited management	11104	10598	10317	9859	9500	10434	11157	9929	8791	6702	4276
As built, good management	7202	6664	6376	6171	5696	5307	5034	4799	4647	4408	4276

Table A-7: Space cooling related costs (£)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	26	769	874	931	980	1423	1772	1793	1835	1451	1305
As built, inherited management	0	457	474	514	538	733	796	829	858	834	854
As built, good management	31	293	328	371	377	584	615	668	695	817	854

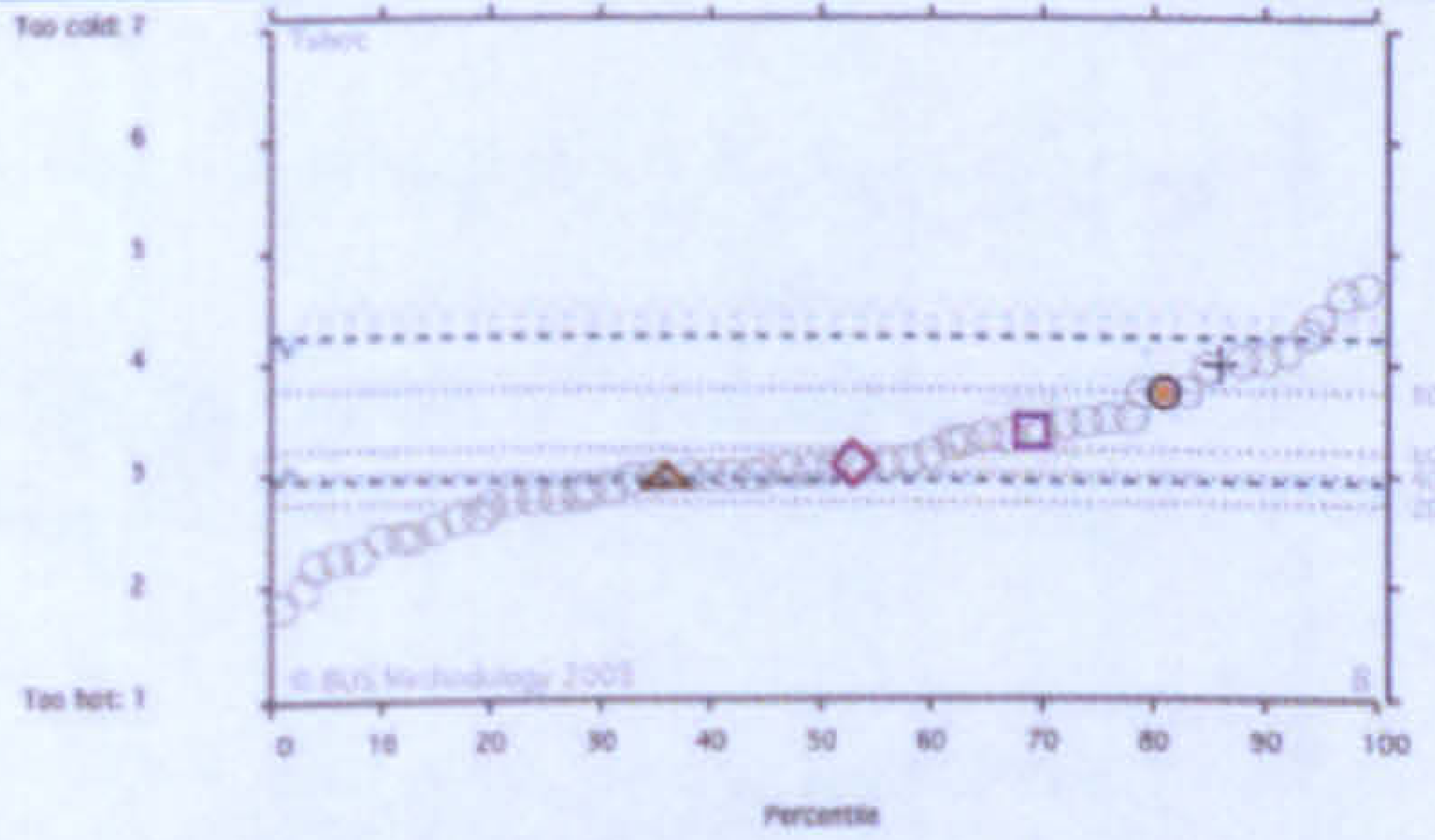
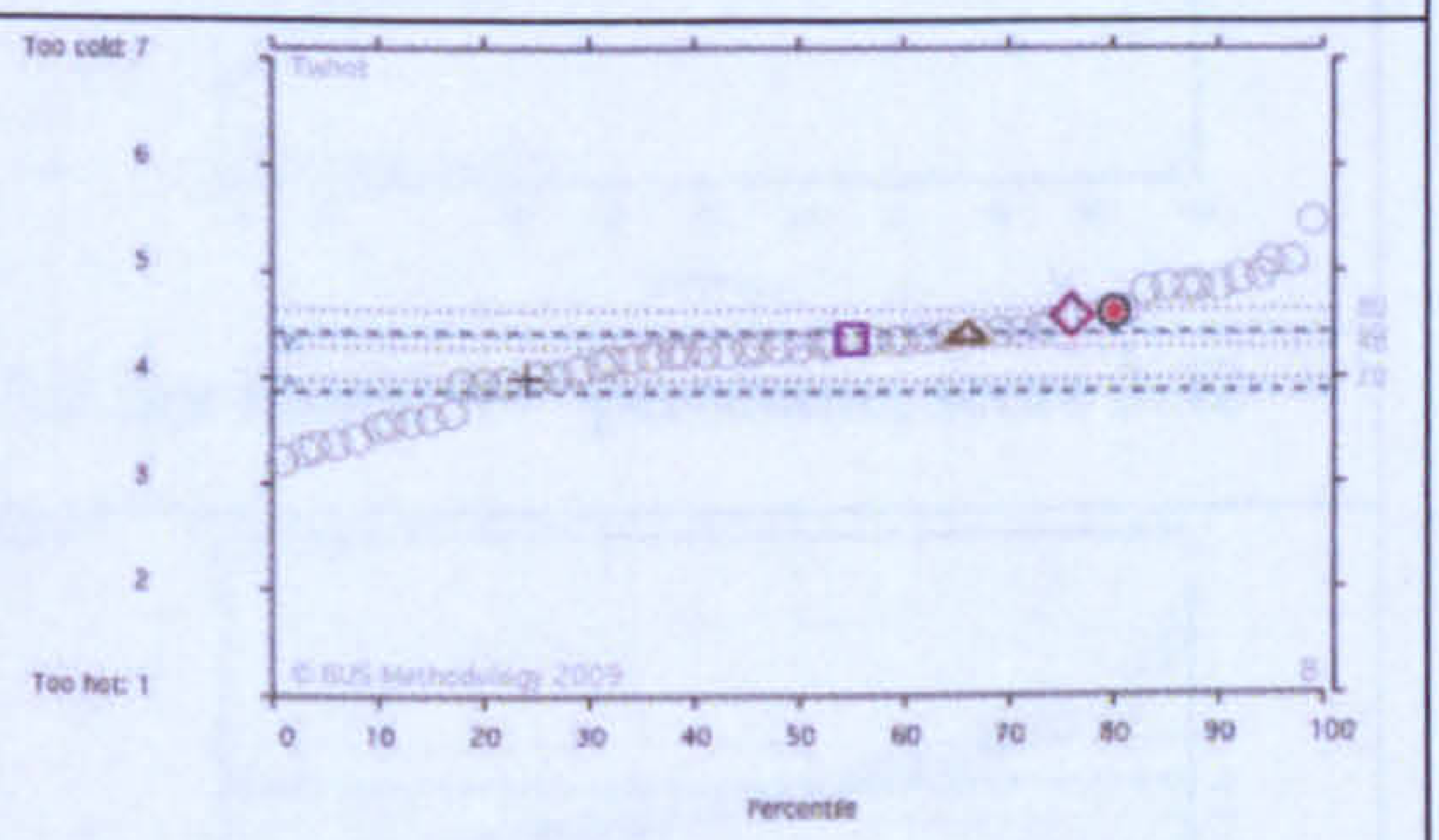
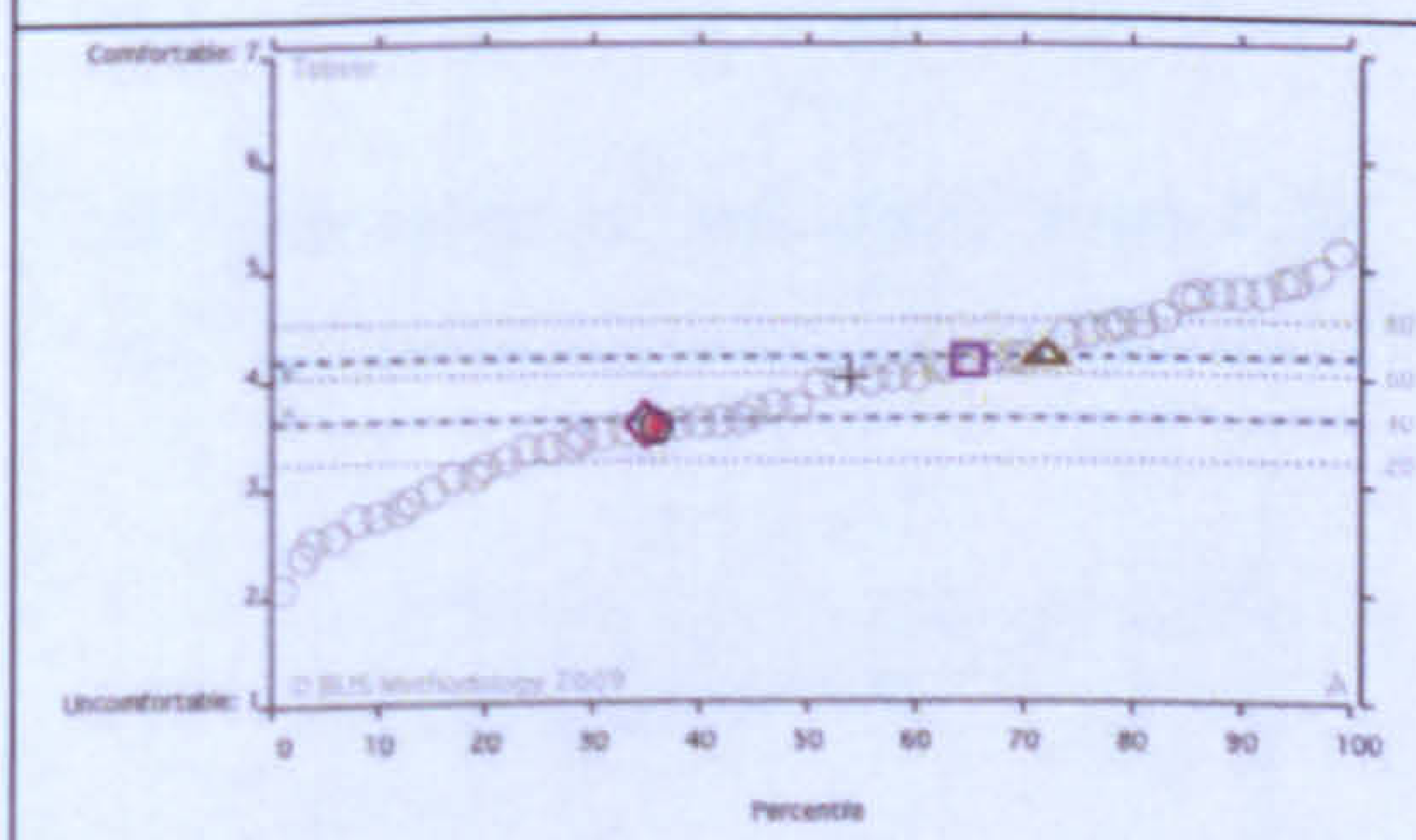
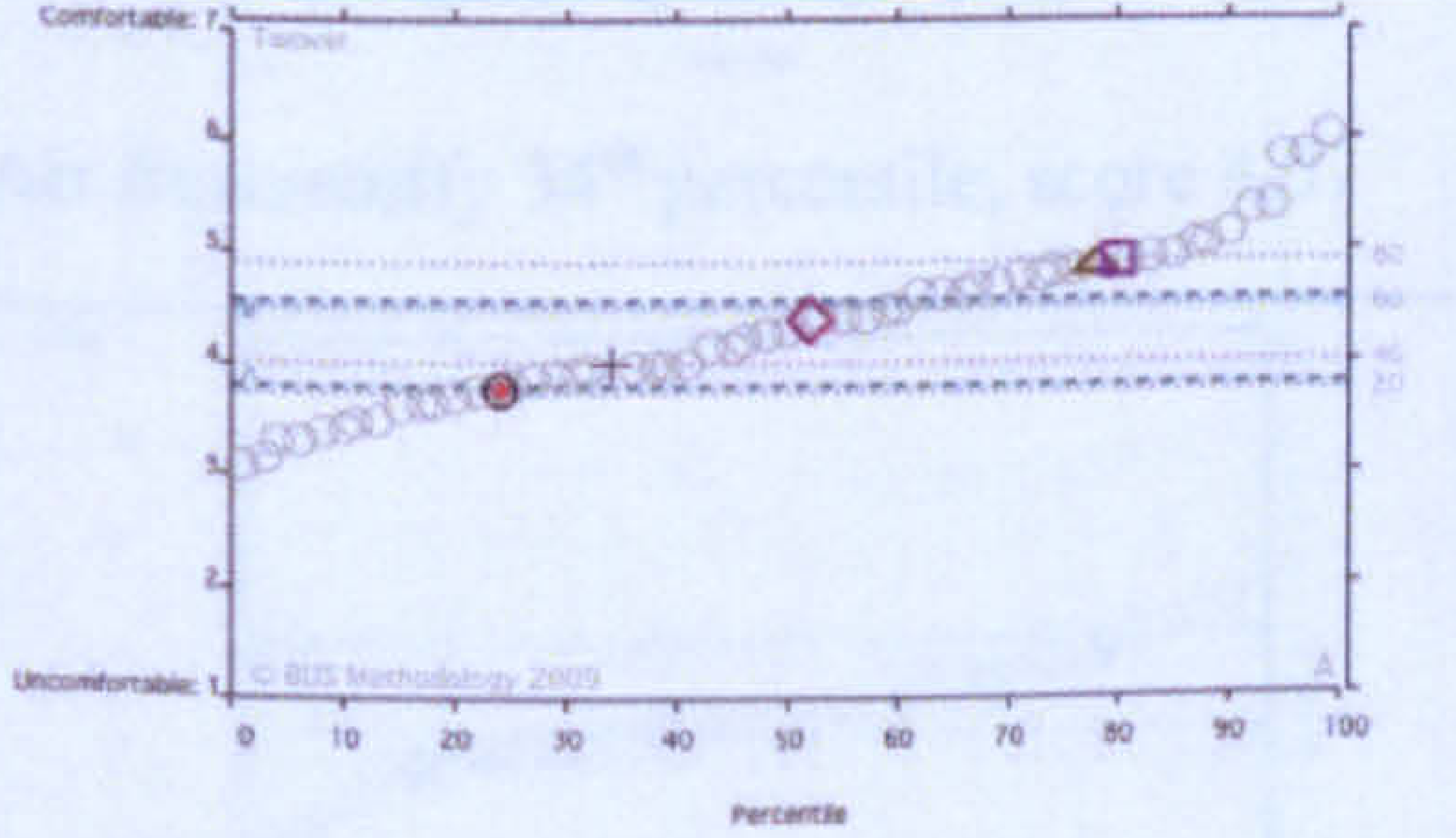
Table A-8: Fans, pumps and controls related costs (£)

	Occupancy										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
As built, as managed	20428	20569	20240	20295	20008	19960	20061	20056	20104	20003	19766
As built, inherited management	8186	8427	8829	9035	9133	9430	9918	10006	10186	10192	9788
As built, good management	129	1012	2156	3083	4018	4805	5900	6831	7985	8723	9788

Appendix B

Appendix B presents the graph for the results of individual aspects of the survey. In Figures B-1 to B-7 follow the overall result for the building is represented by the shaded circle, and the diamond, triangle and square superimposed on the figure represent results from other surveys done on UK 'green' office buildings. A red shaded circle represents an aspect that performed considerably worse than the BUS benchmark score, an amber shaded circle represents an aspect that performed similar to the BUS benchmark score and a green shaded circle represents an aspect that performed significantly better than the BUS benchmark score.

The graphs have either an 'A', 'B' or 'C' noted in the bottom right hand corner. This refers to the graph type. Type 'A' have the best buildings in the top right hand side of the chart, type 'B' have the best buildings in the middle and type 'C' charts have the best building with results towards the bottom left hand side of the graph.

Summer	**Winter**
 Temperature summer (hot/cold): 81st percentile, score 3.77	 Temperature in winter (hot/cold): 81st percentile, score 4.65
 Overall temperature in summer: 36th percentile, score 3.59	 Overall temperature in winter: 24th percentile, score 3.79

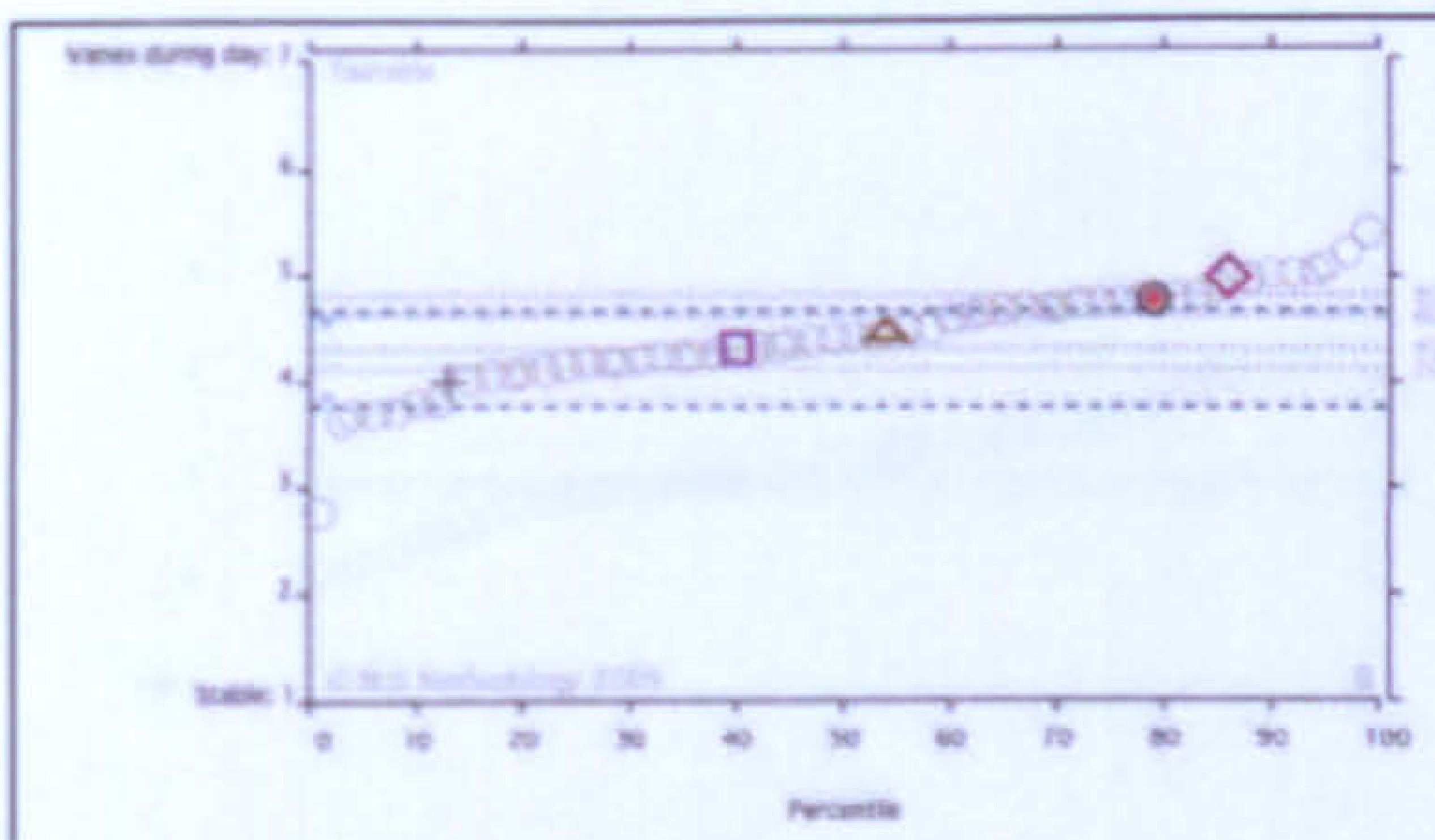
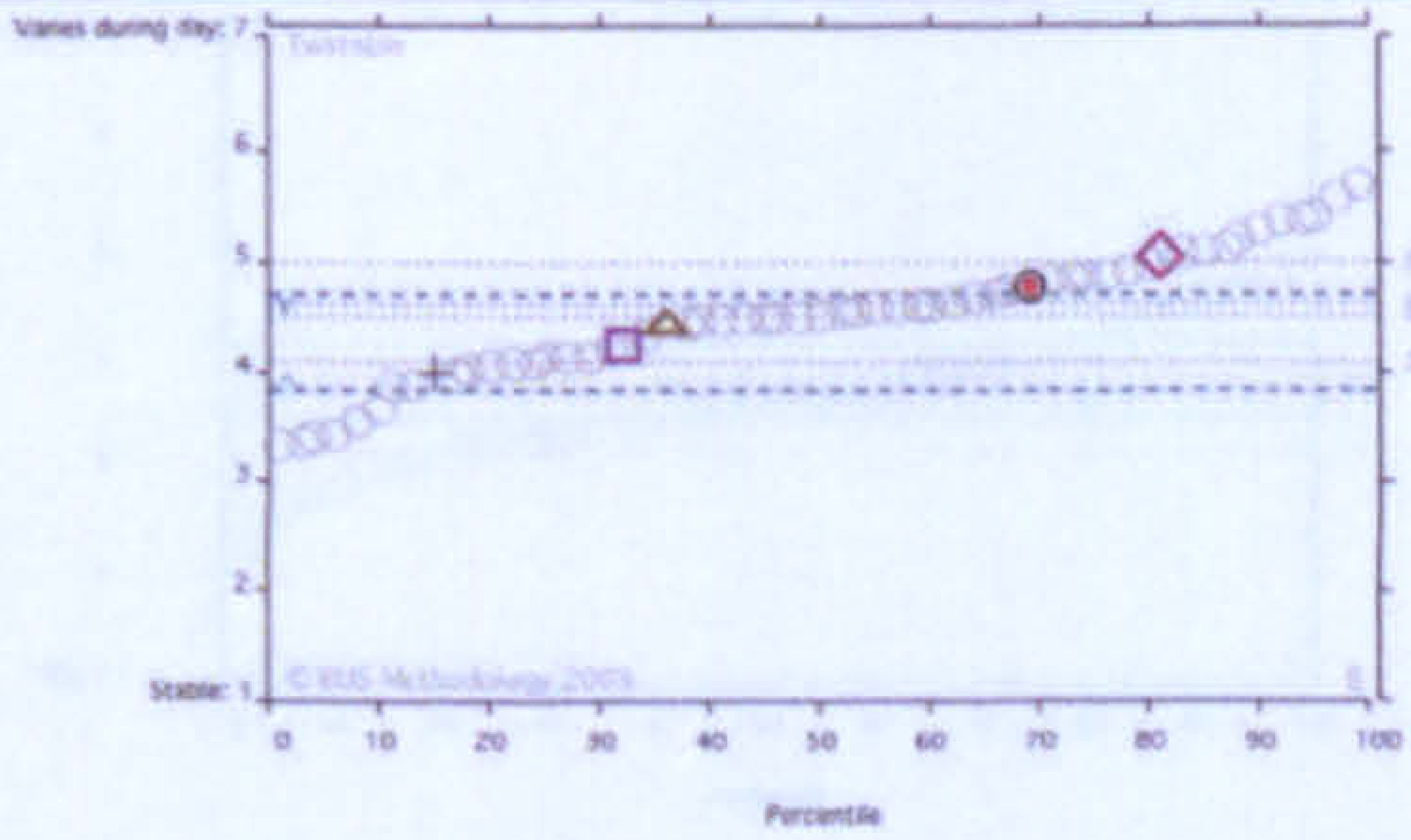
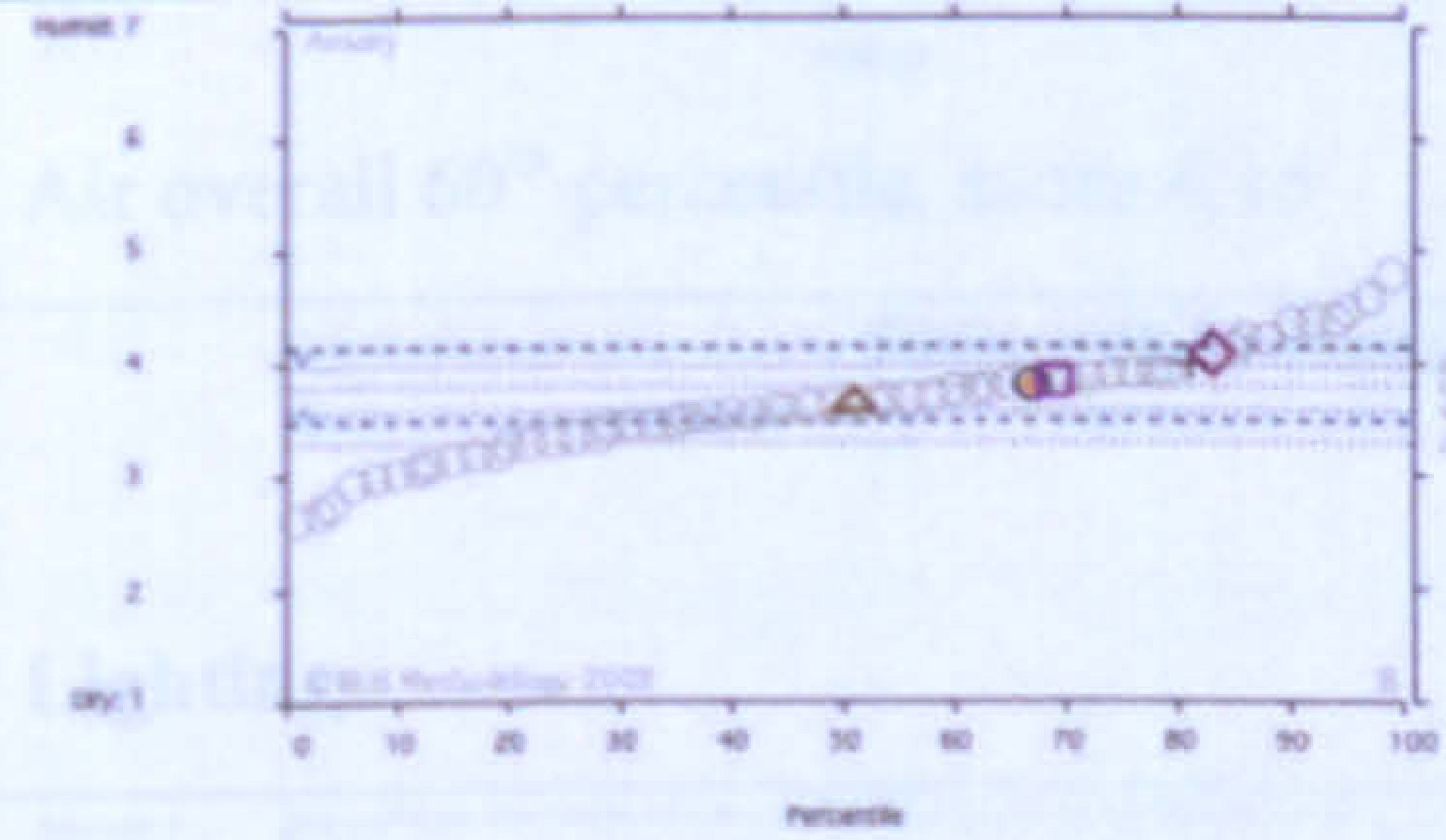
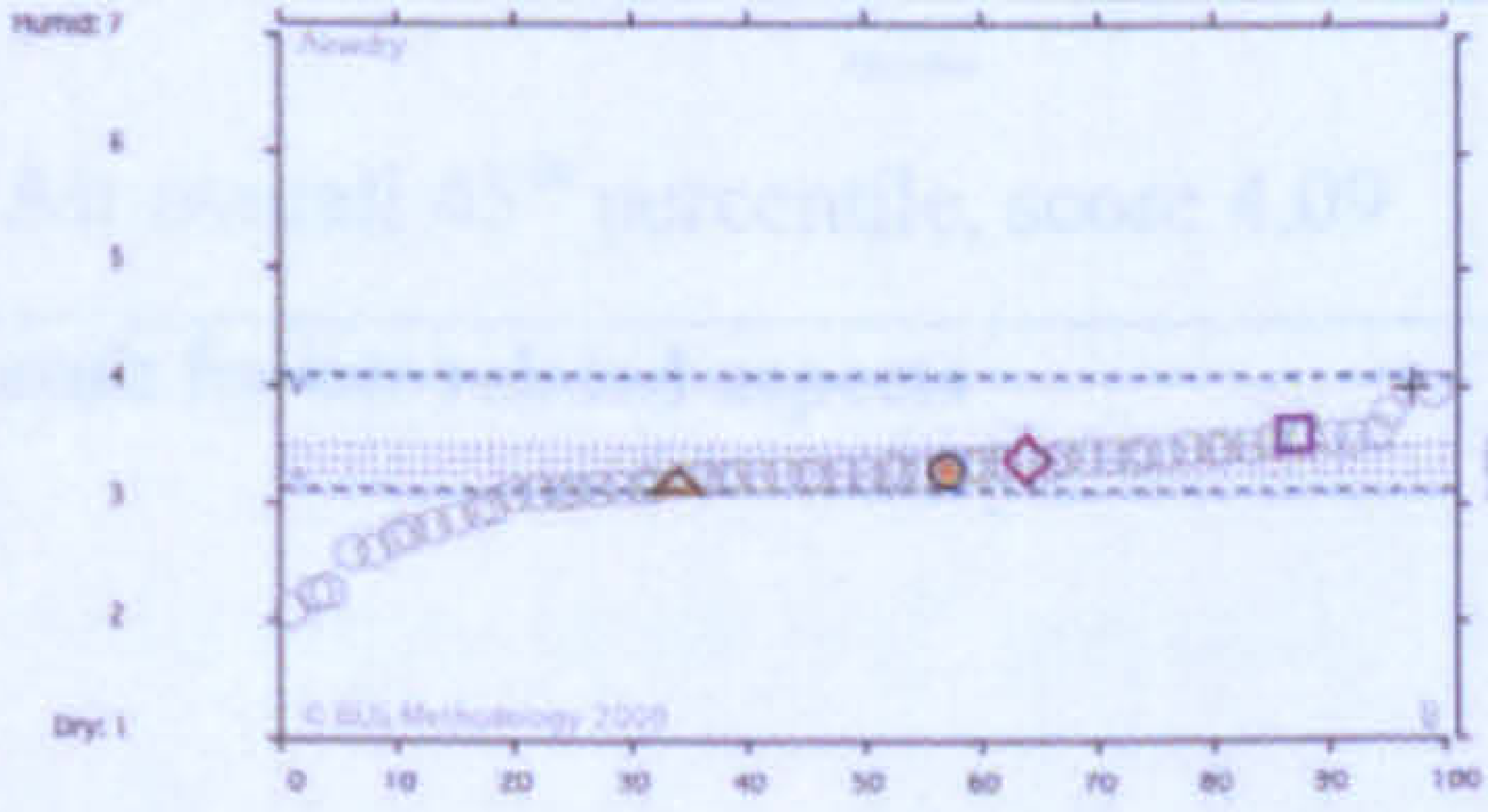
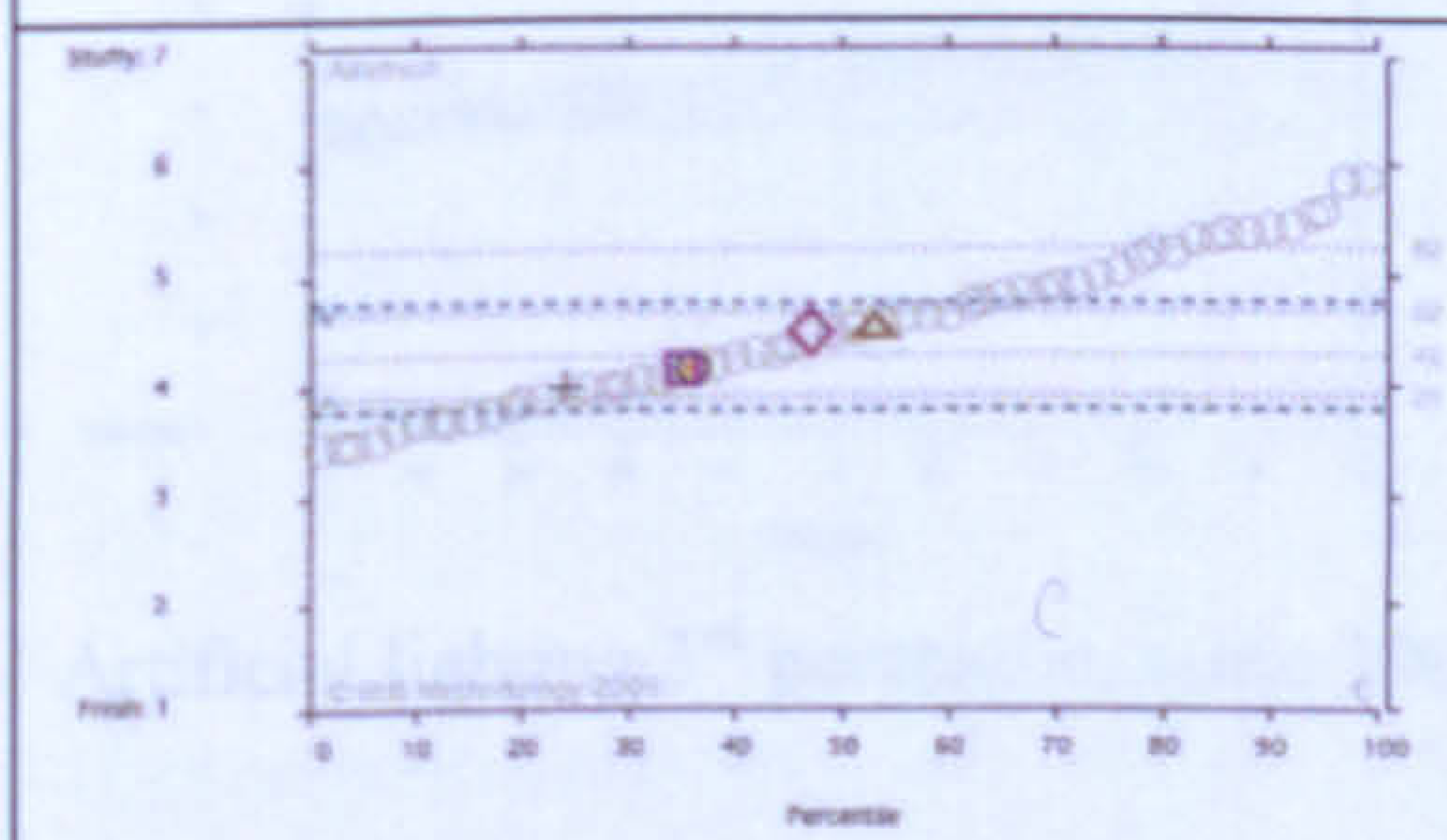
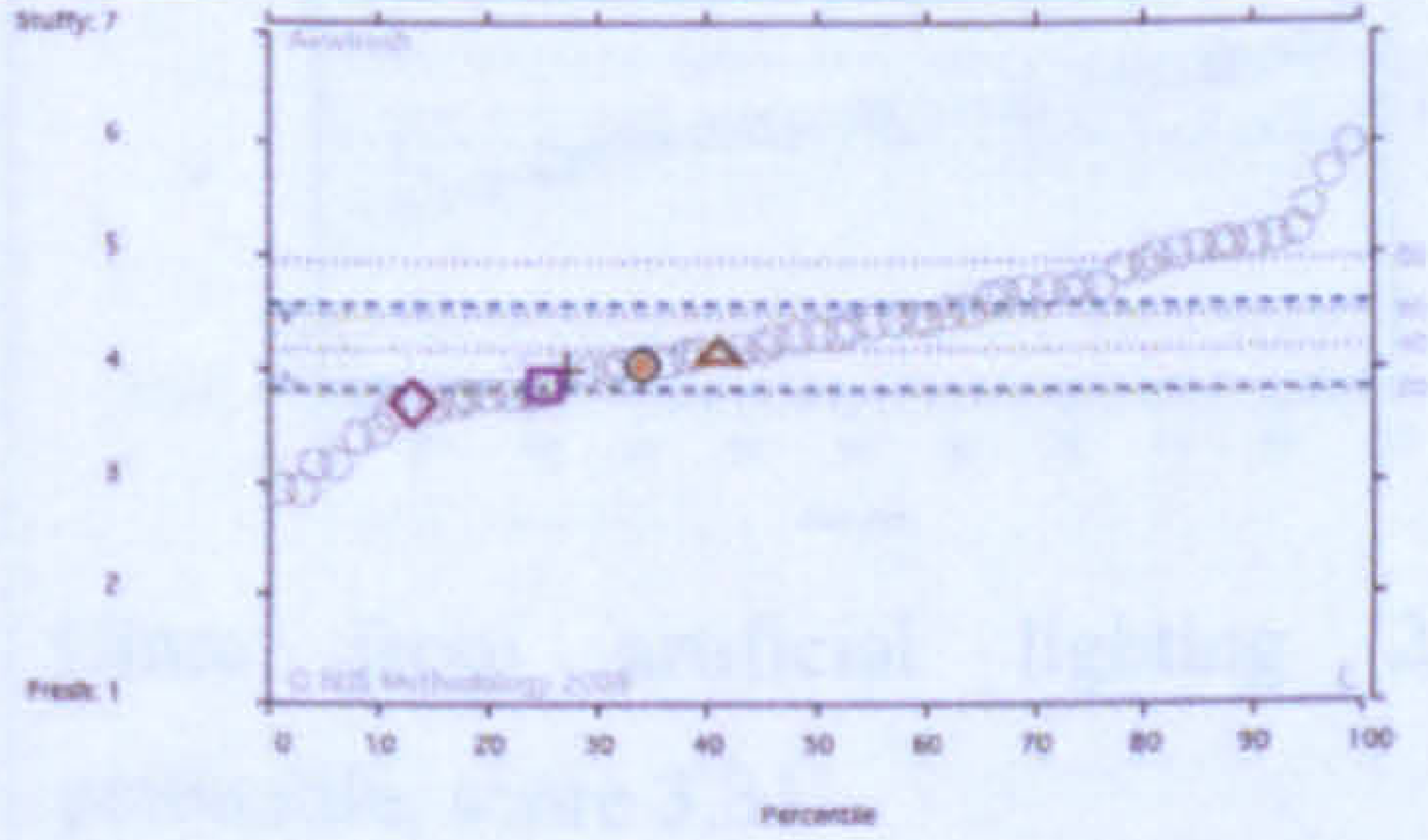
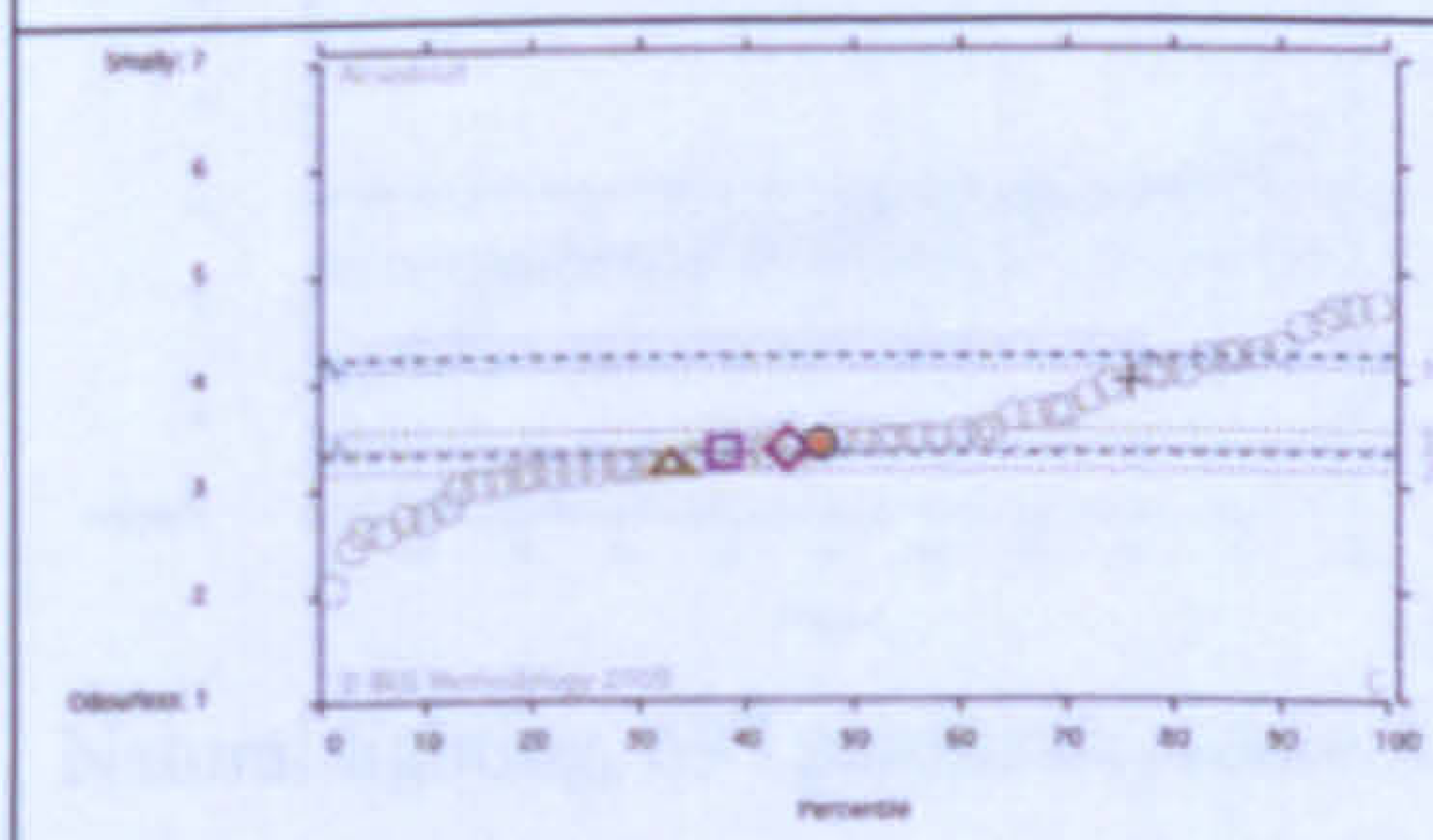
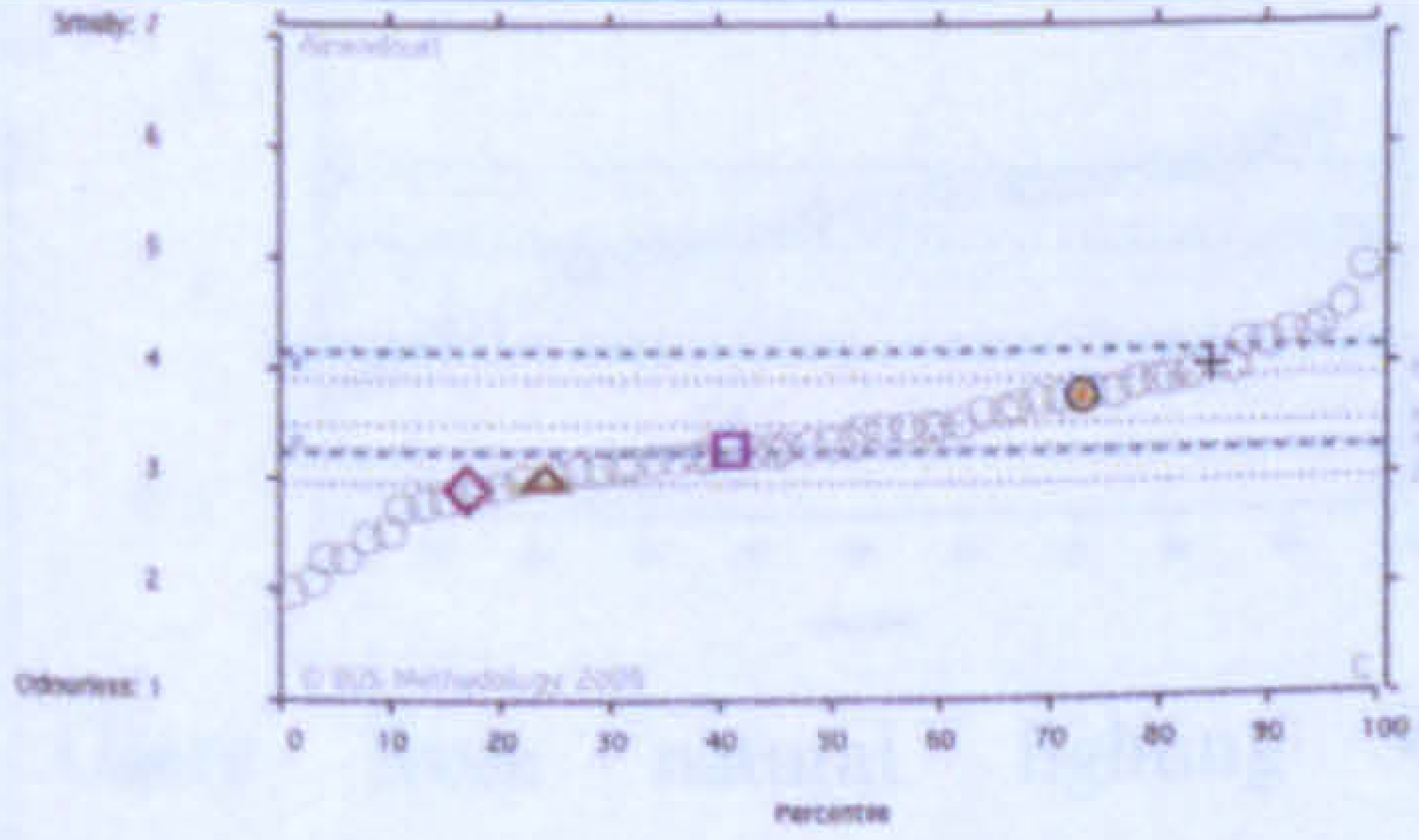
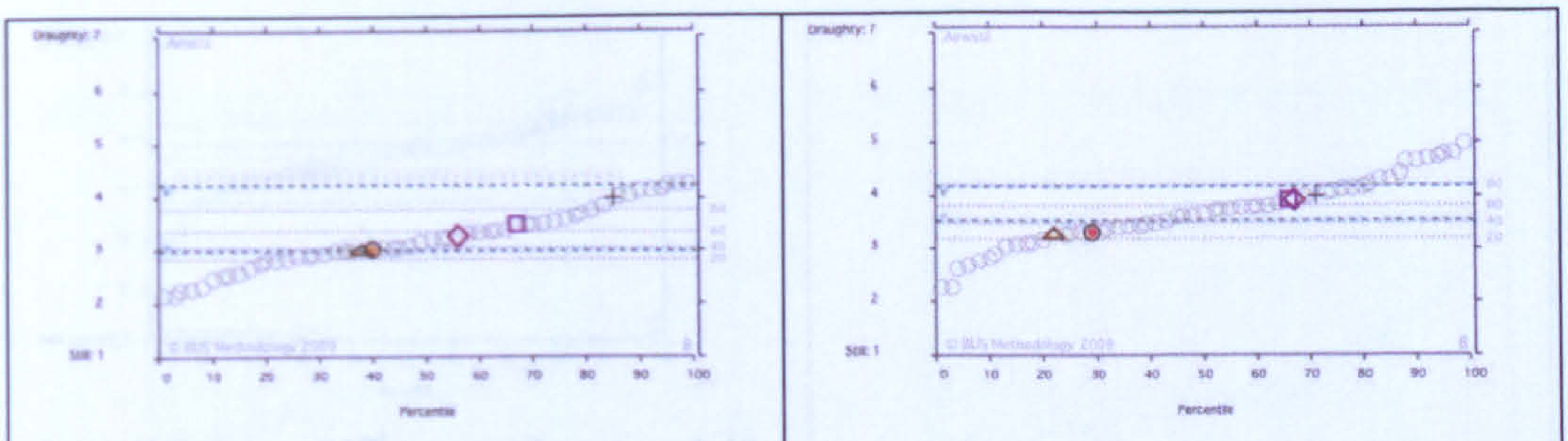
 Temperature stability in summer: 79th percentile, score 4.80	 Temperature stability in winter: 69th percentile, score 4.80

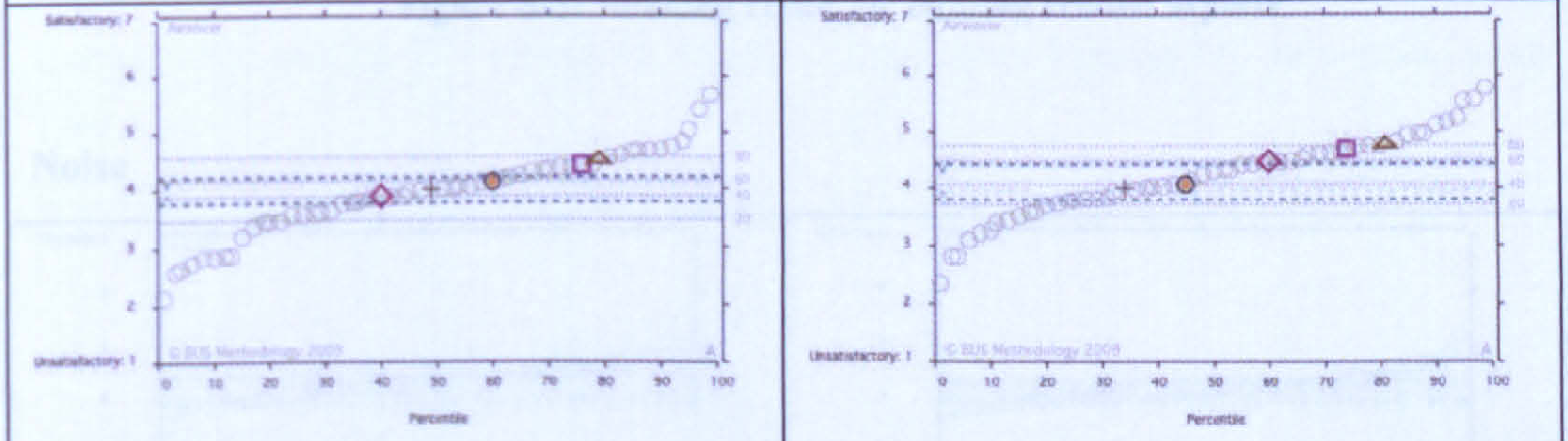
Figure B-1: Building result for temperature related aspects

Summer	Winter
 Air dry/humid 67th percentile, score 3.83	 Air dry/humid 57th percentile, score 3.32
 Air fresh/stuffy 36th percentile, score 4.20	 Air fresh/stuffy 34th percentile, score 4.07
 Air odourless/smelly 47th percentile, score 3.43	 Air odourless/smelly 73rd percentile, score 3.77



Air still/draughty 40th percentile, score 3.04

Air still/draughty 29th percentile, score 3.33

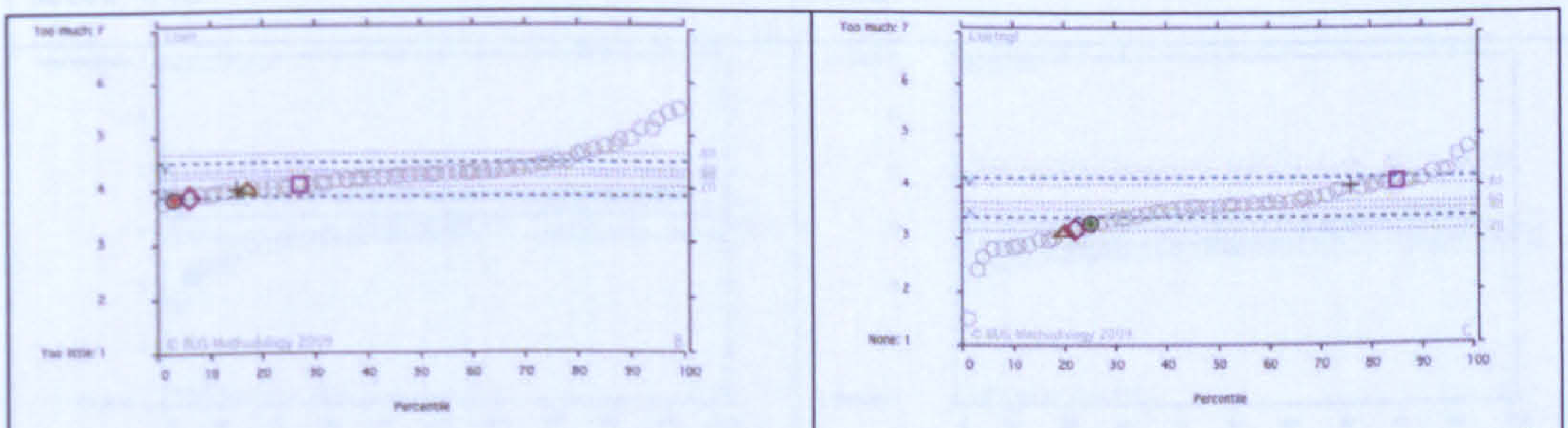


Air overall 60th percentile, score 4.15

Air overall 45th percentile, score 4.09

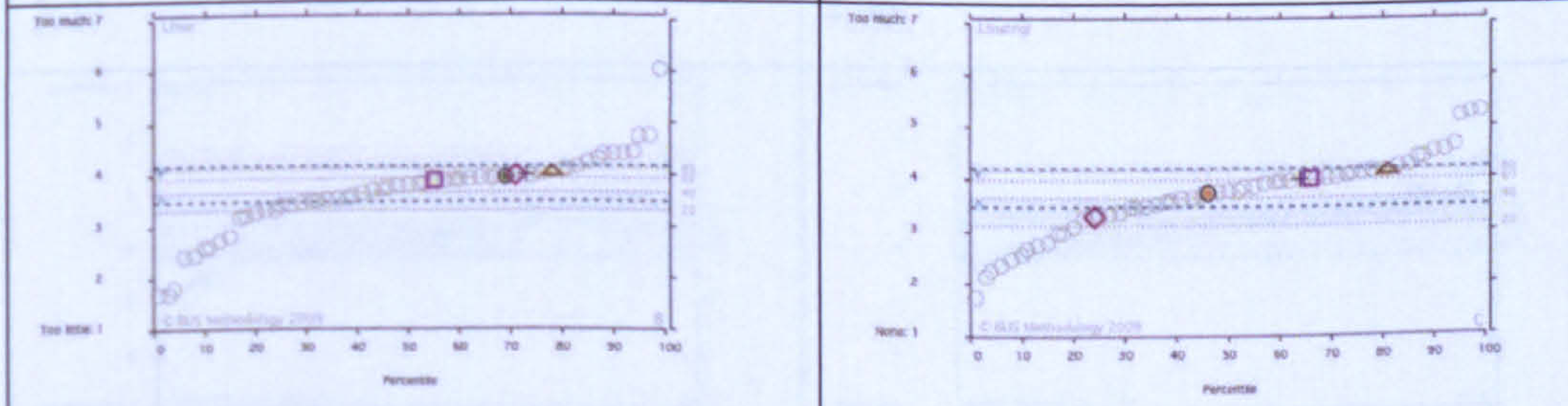
Figure B-2: Building result for air related aspects

Lighting



Artificial lighting 3rd percentile, score 3.85

Glare from artificial lighting 25th percentile, score 3.31



Natural lighting, 69th percentile, score 3.98

Glare from natural lighting 46th percentile, score 3.77

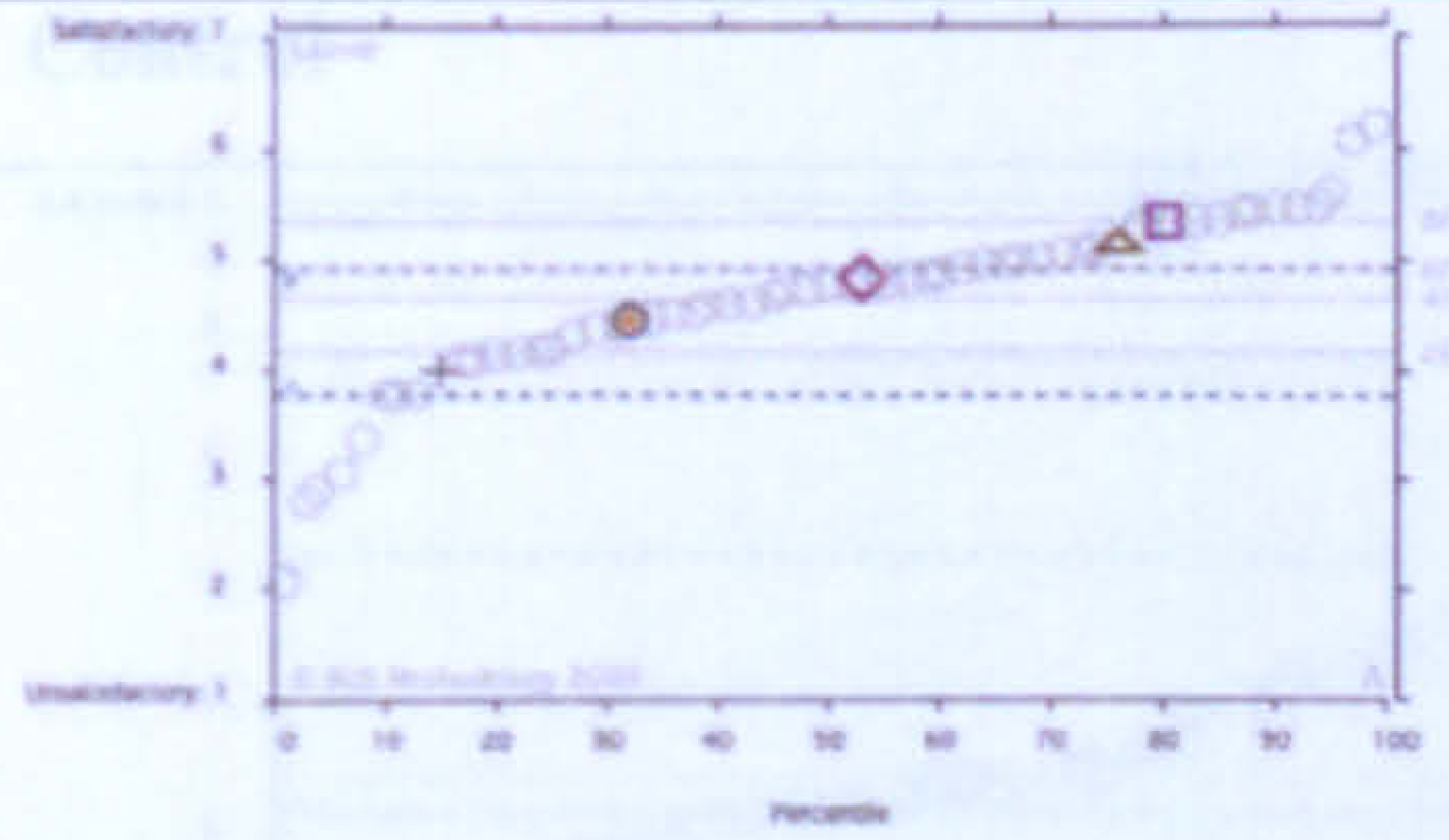
 Overall lighting, 32nd percentile, score 4.49	

Figure B-3: Building result for lighting related aspects

Noise

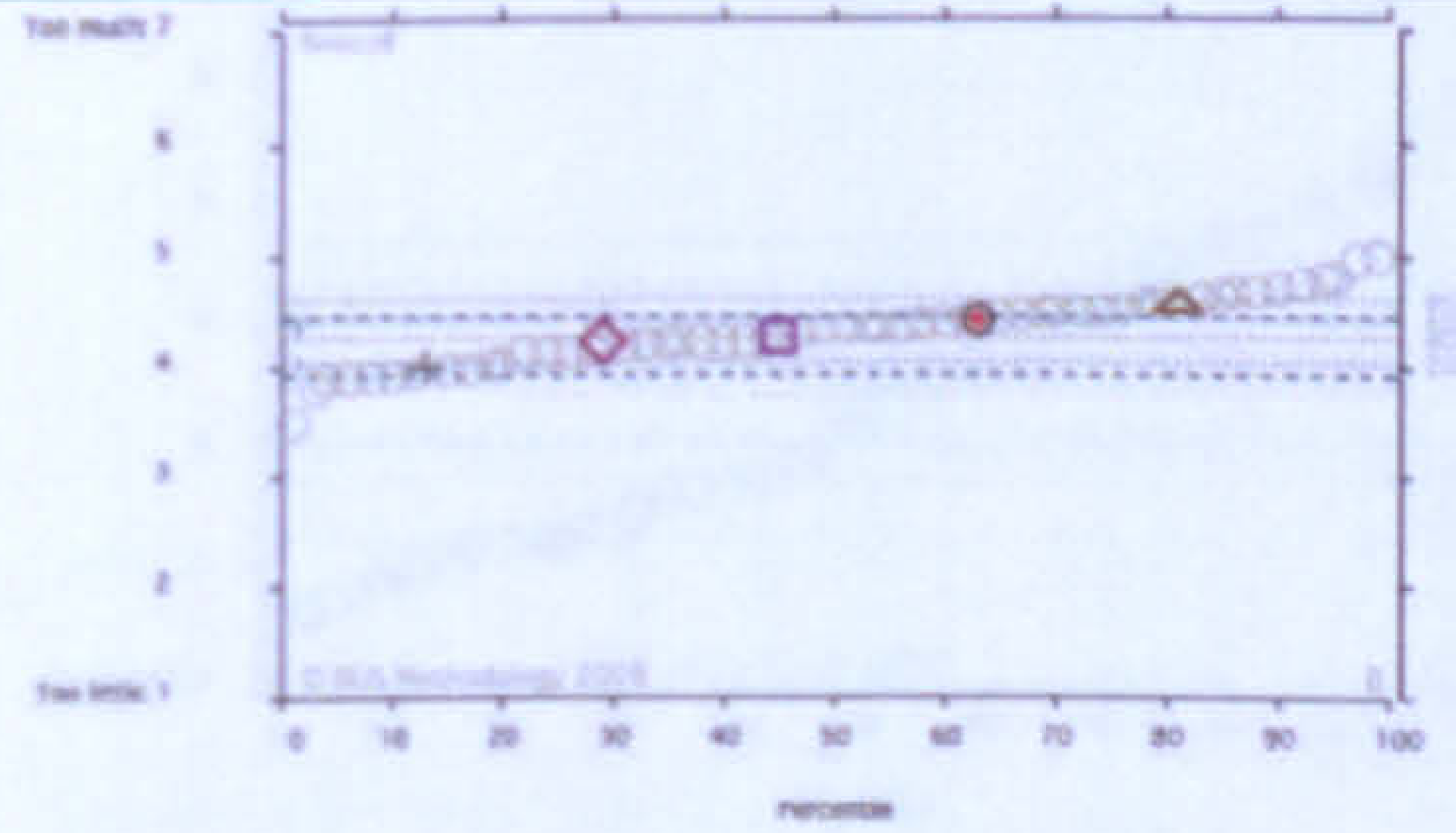
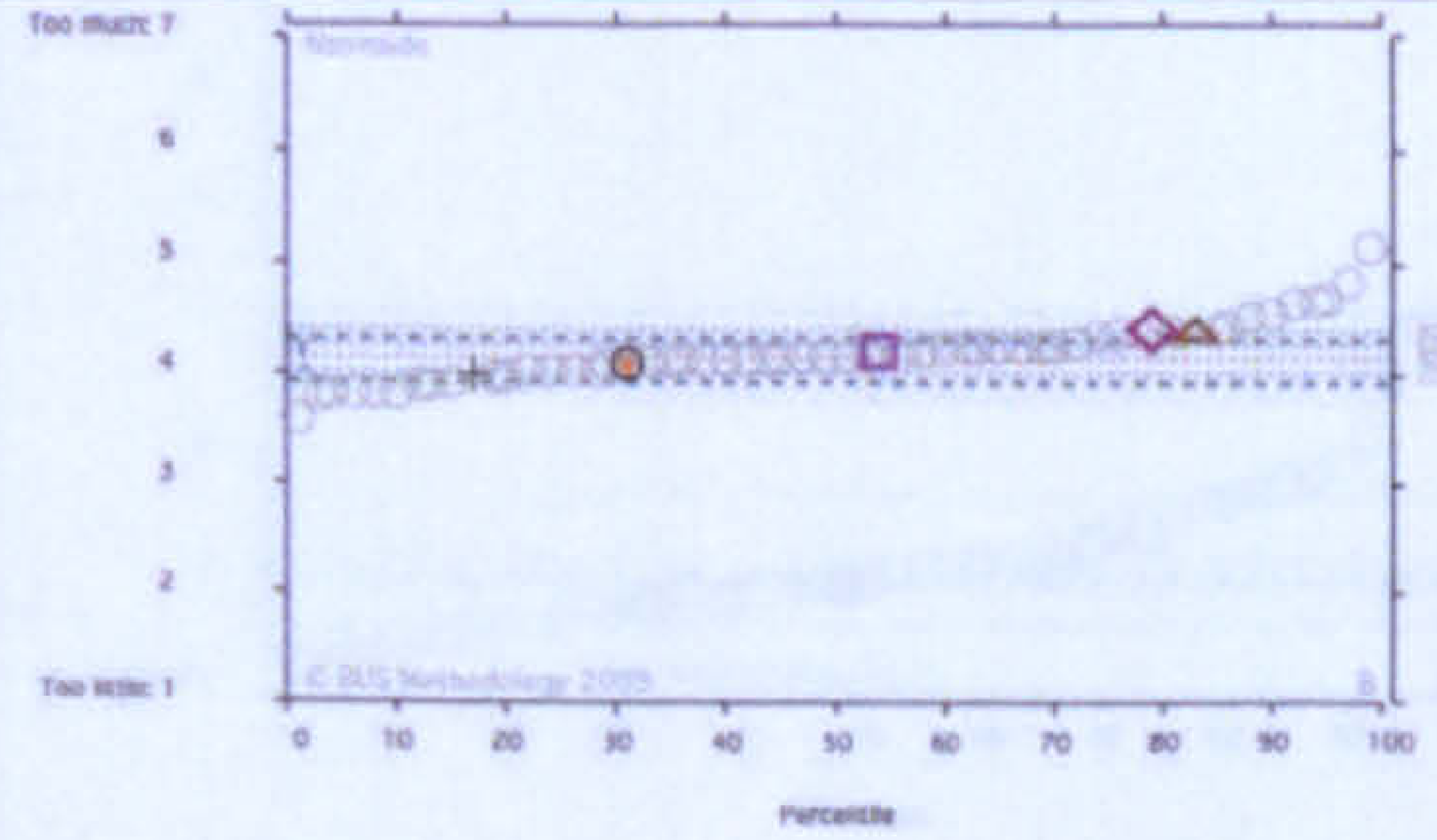
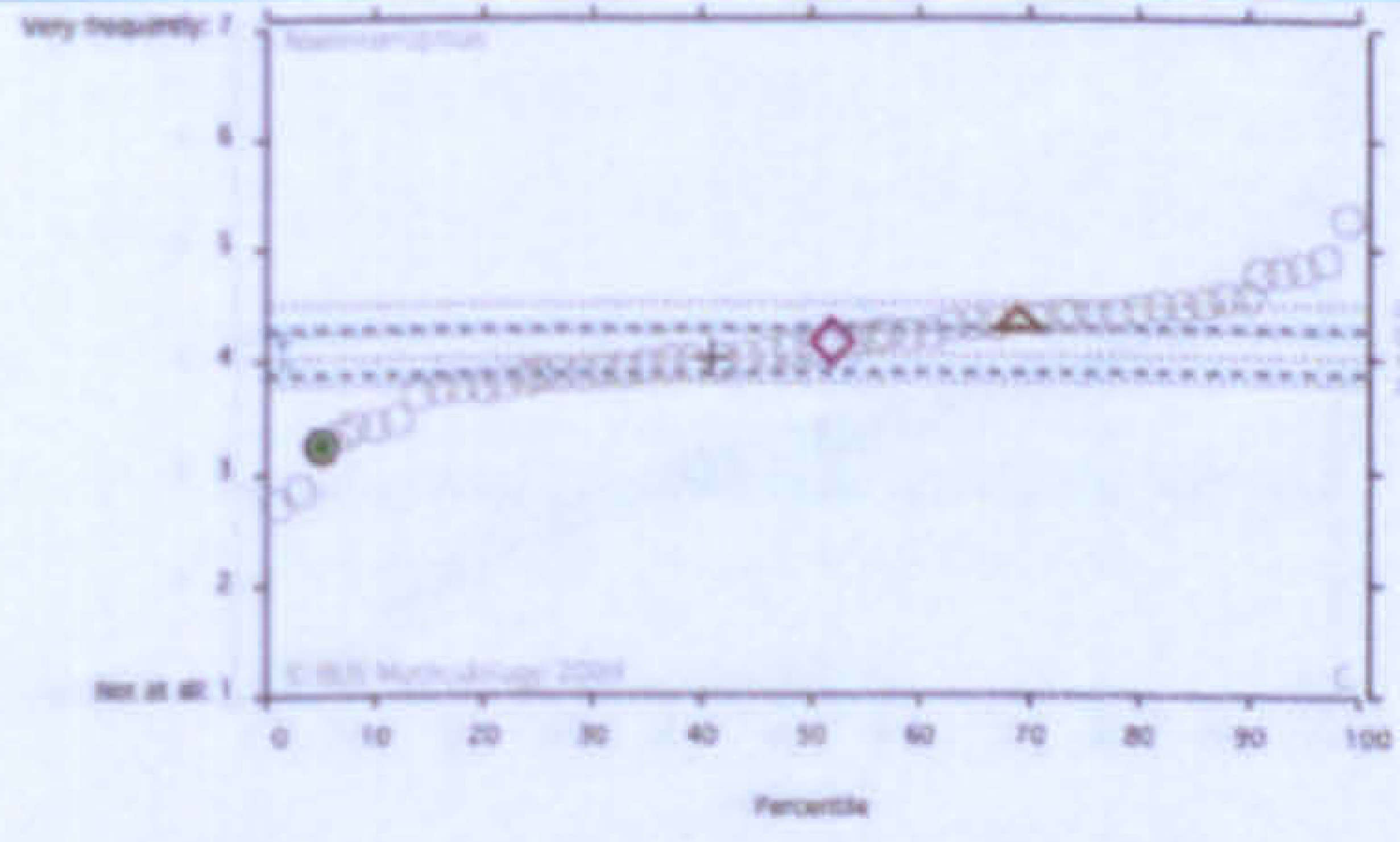
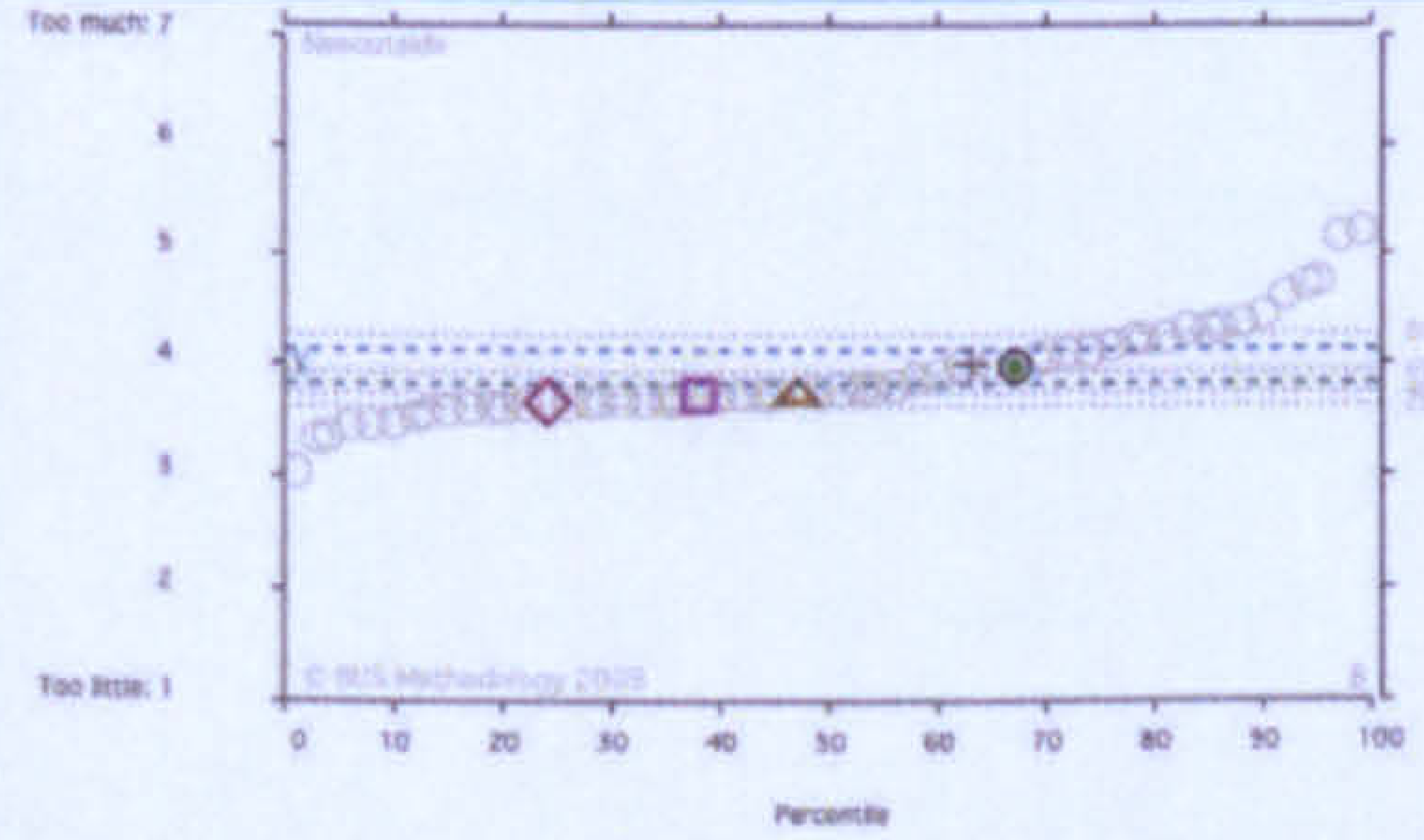
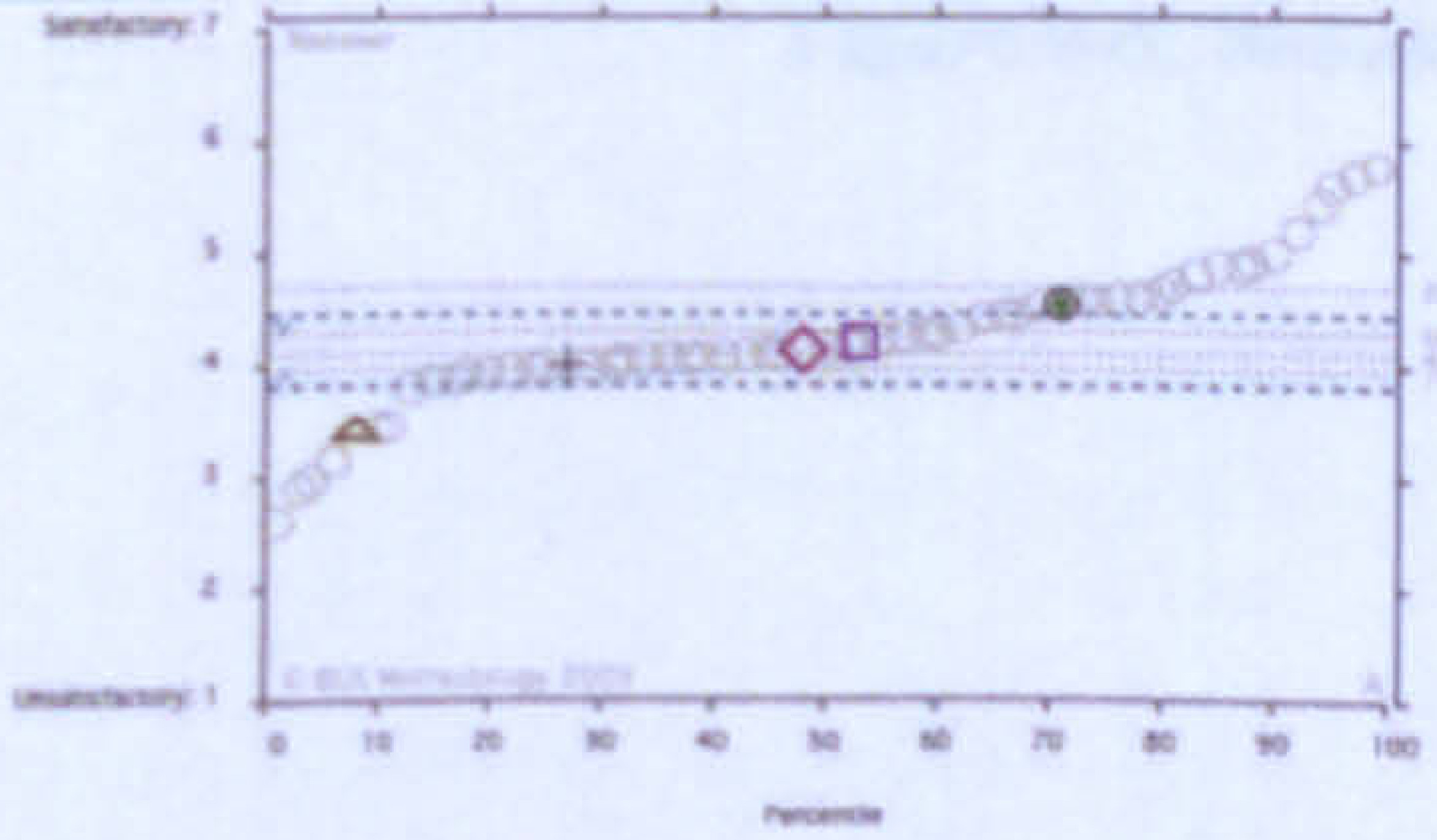
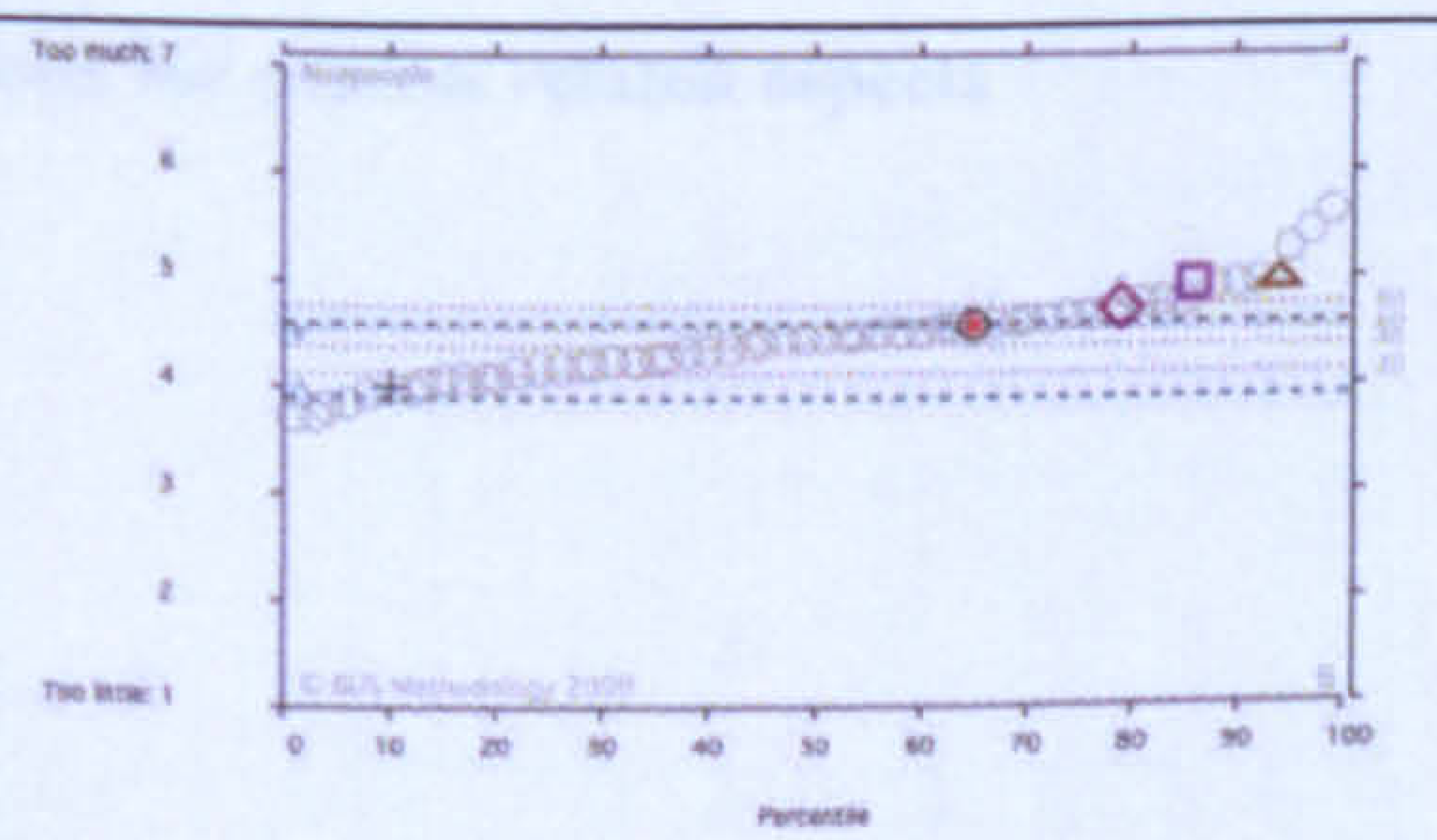
 Noise from colleagues 63rd percentile, score 4.45	 Noise from inside 31st percentile, score 4.12
 Unwanted interruptions 5thpercentile,score 3.27	 Noise from outside 67th percentile, score 4.00
 Overall noise 71st percentile, score 4.57	 Nose from other people 65th percentile, score 4.60

Figure B-4: Building results for noise related aspects

Control

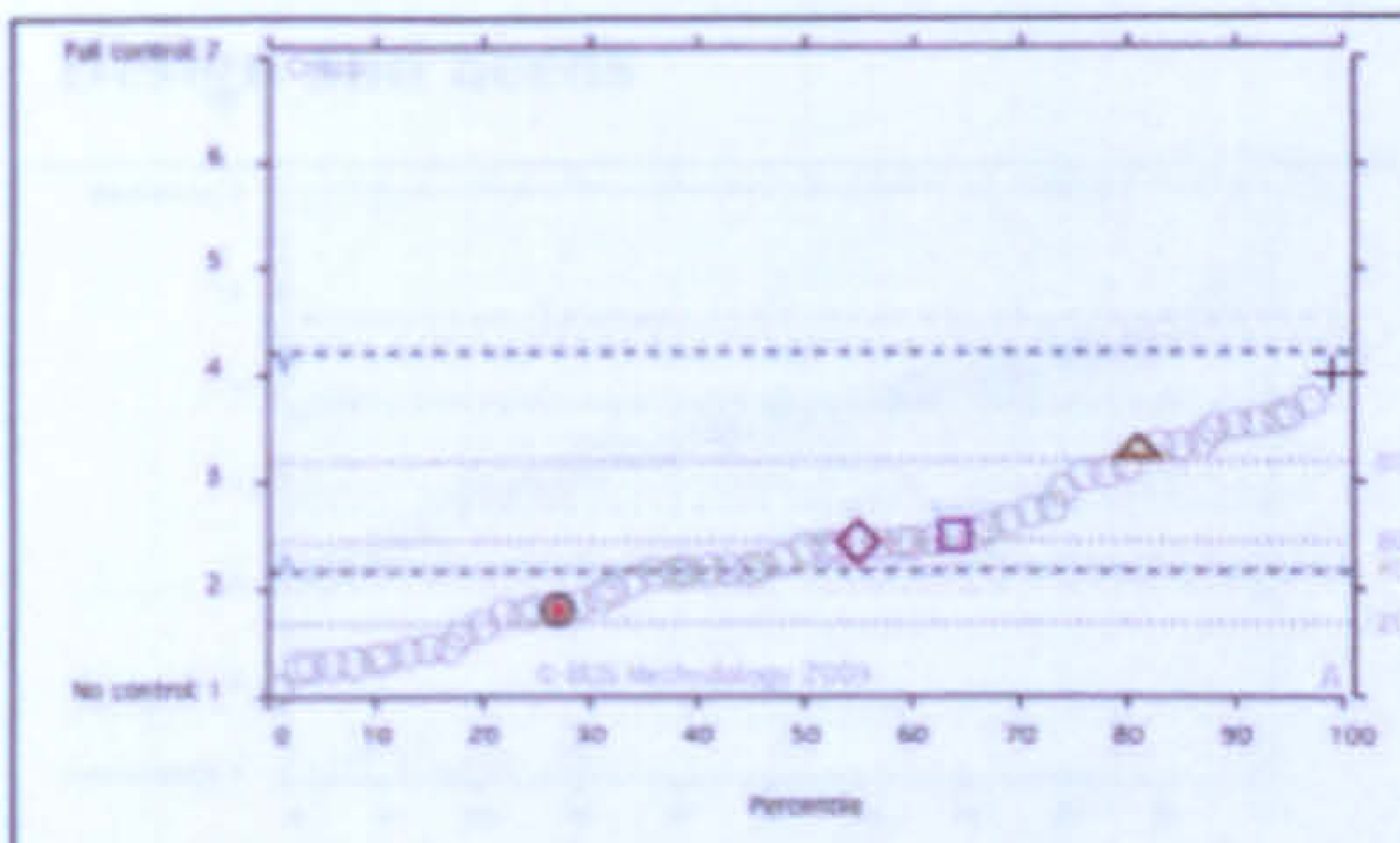
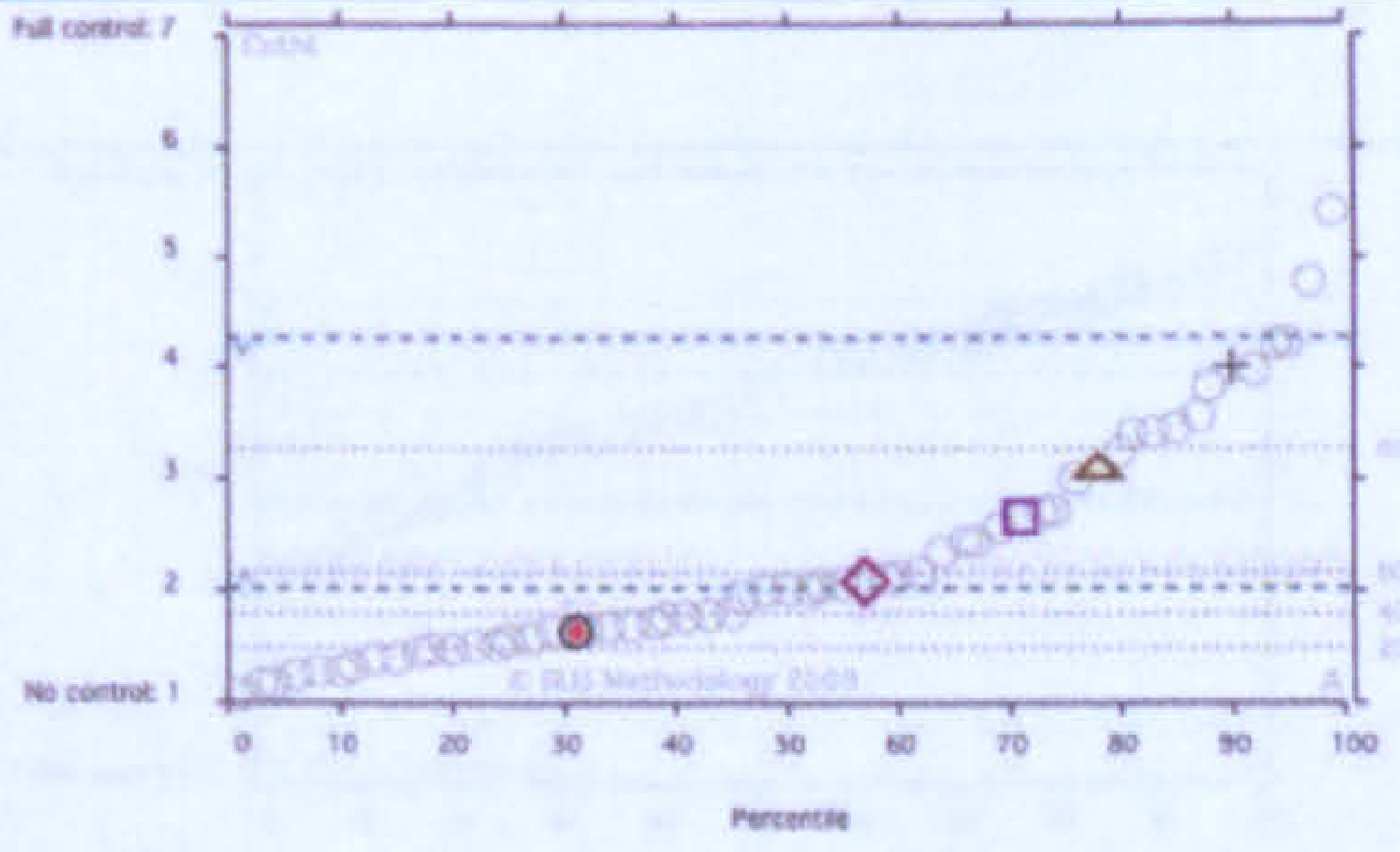
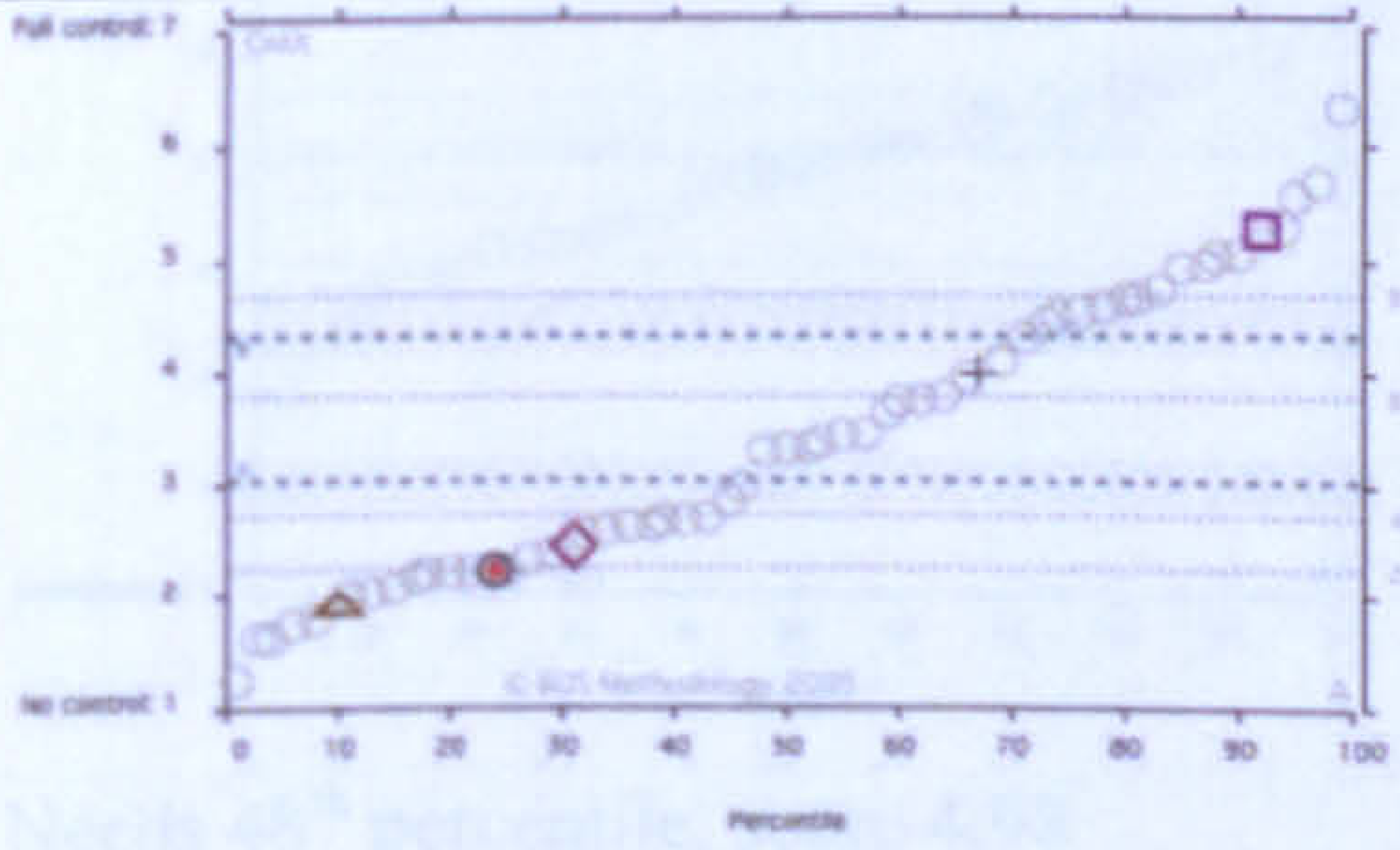
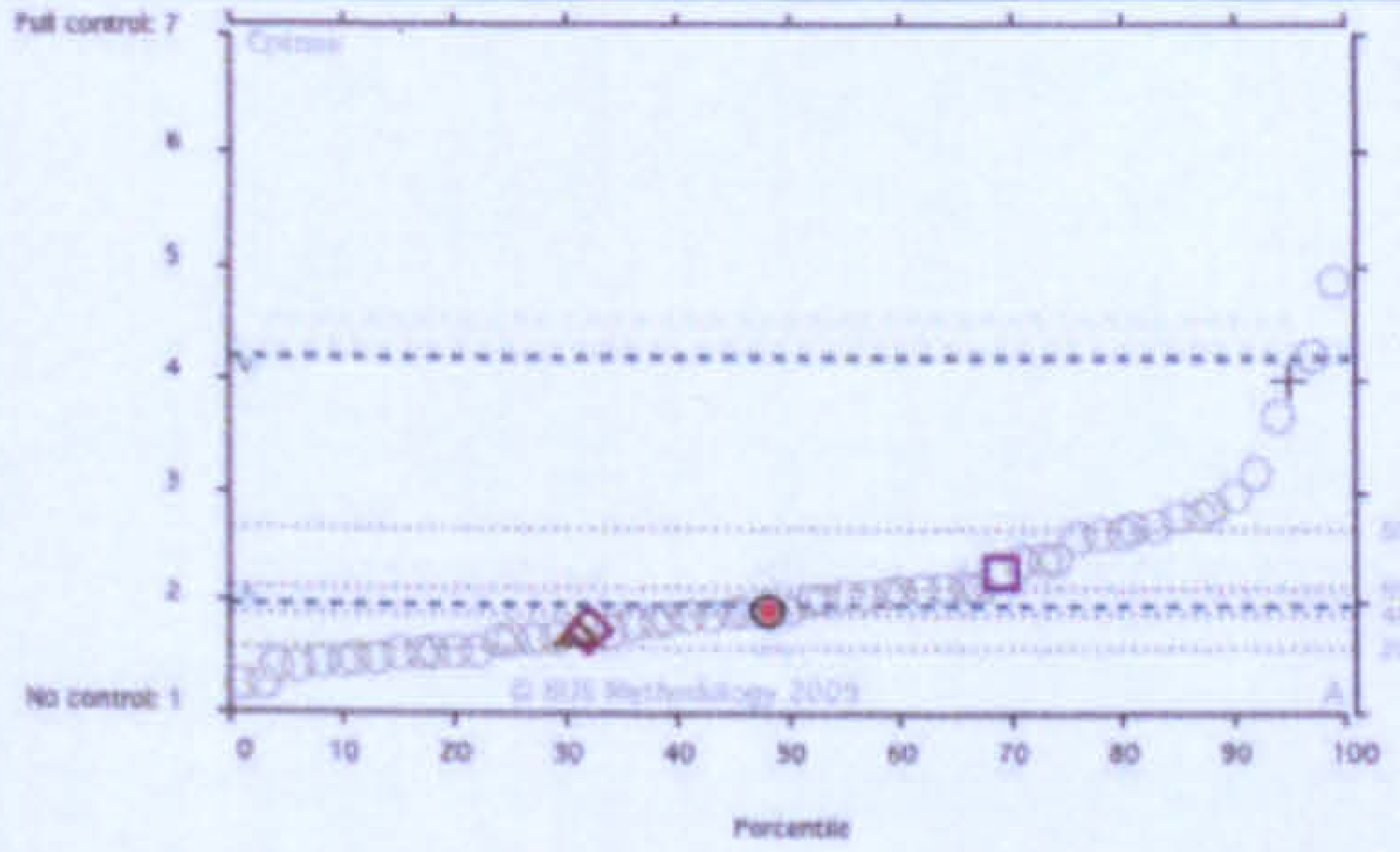
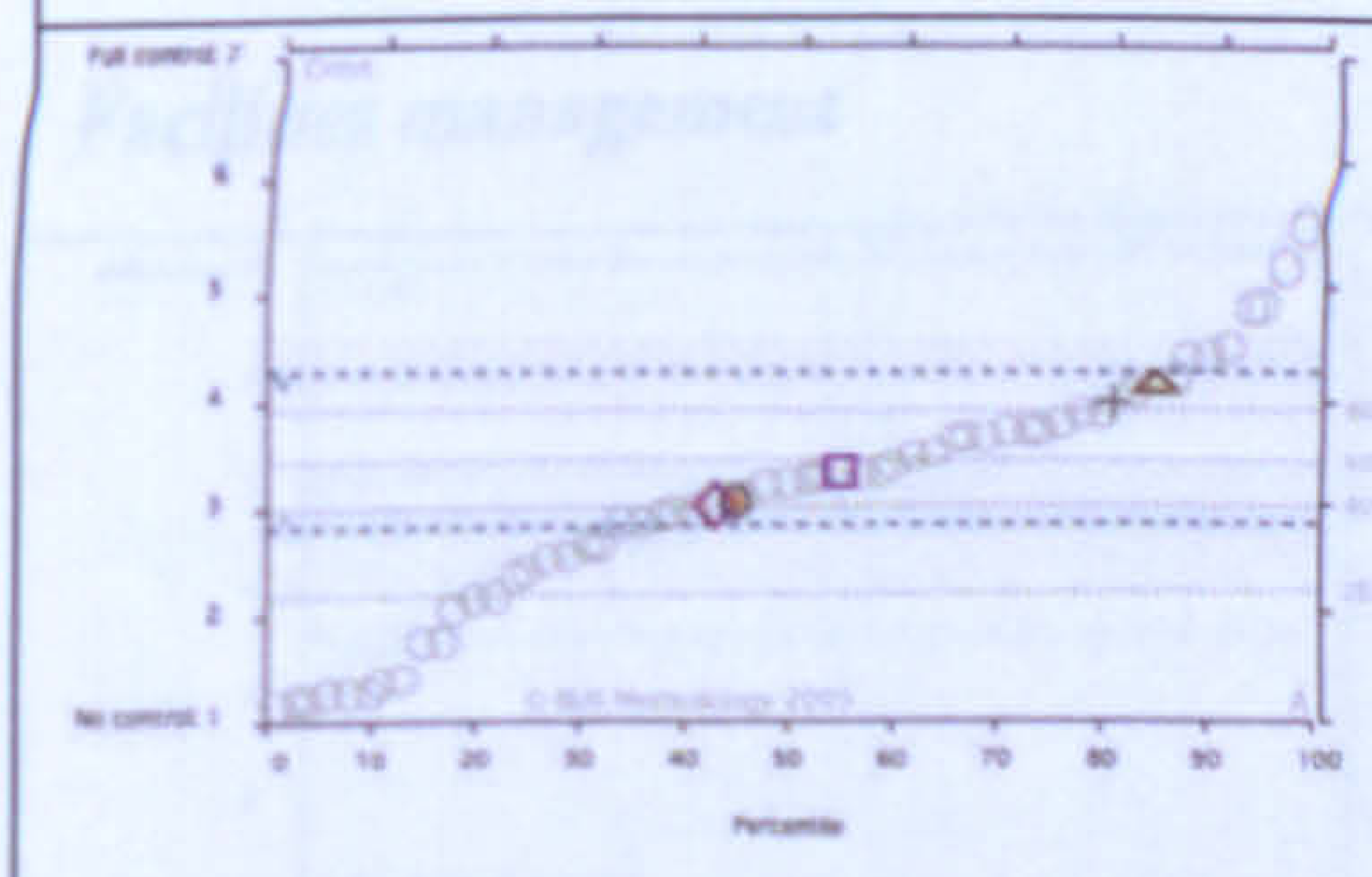
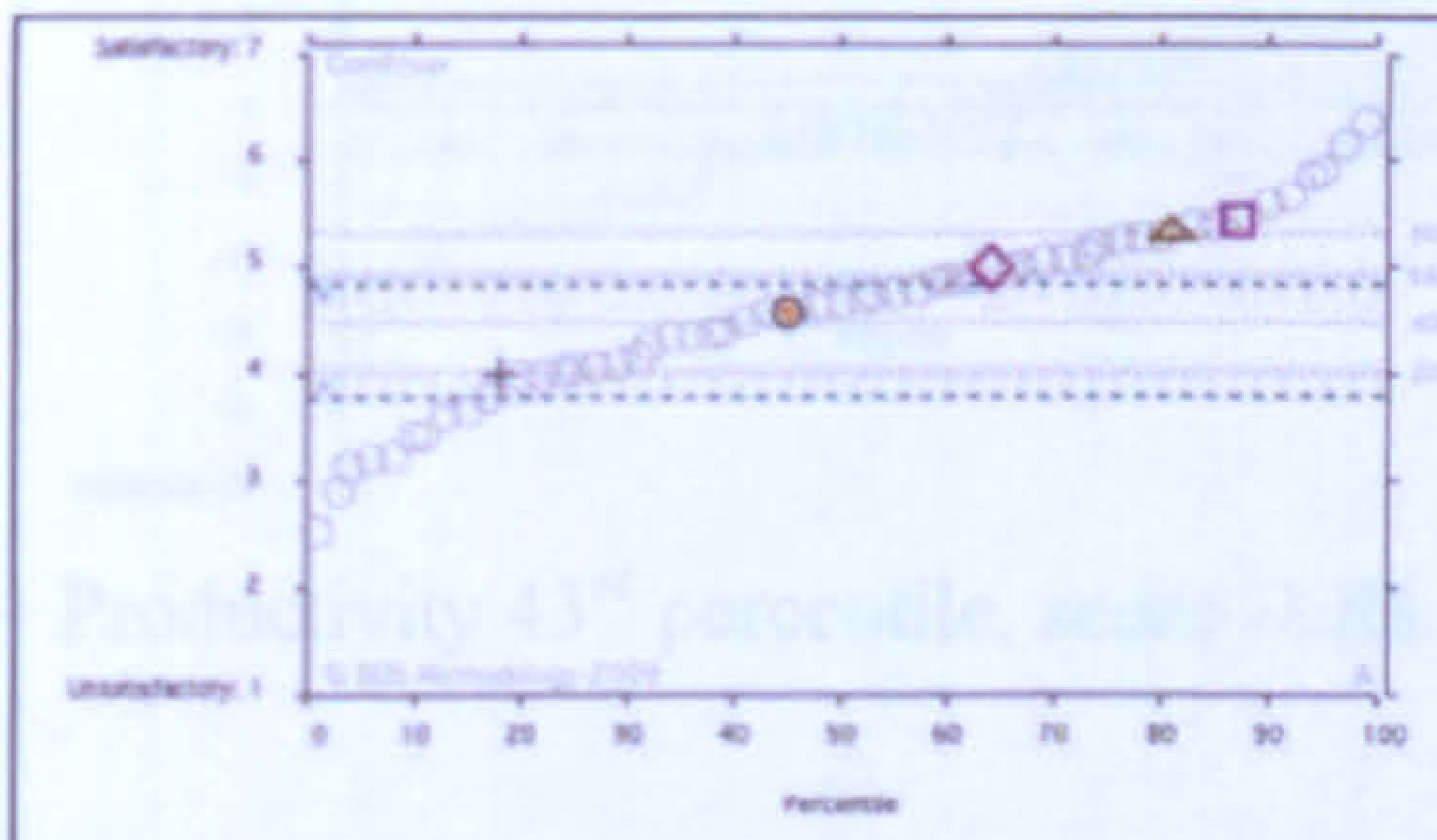
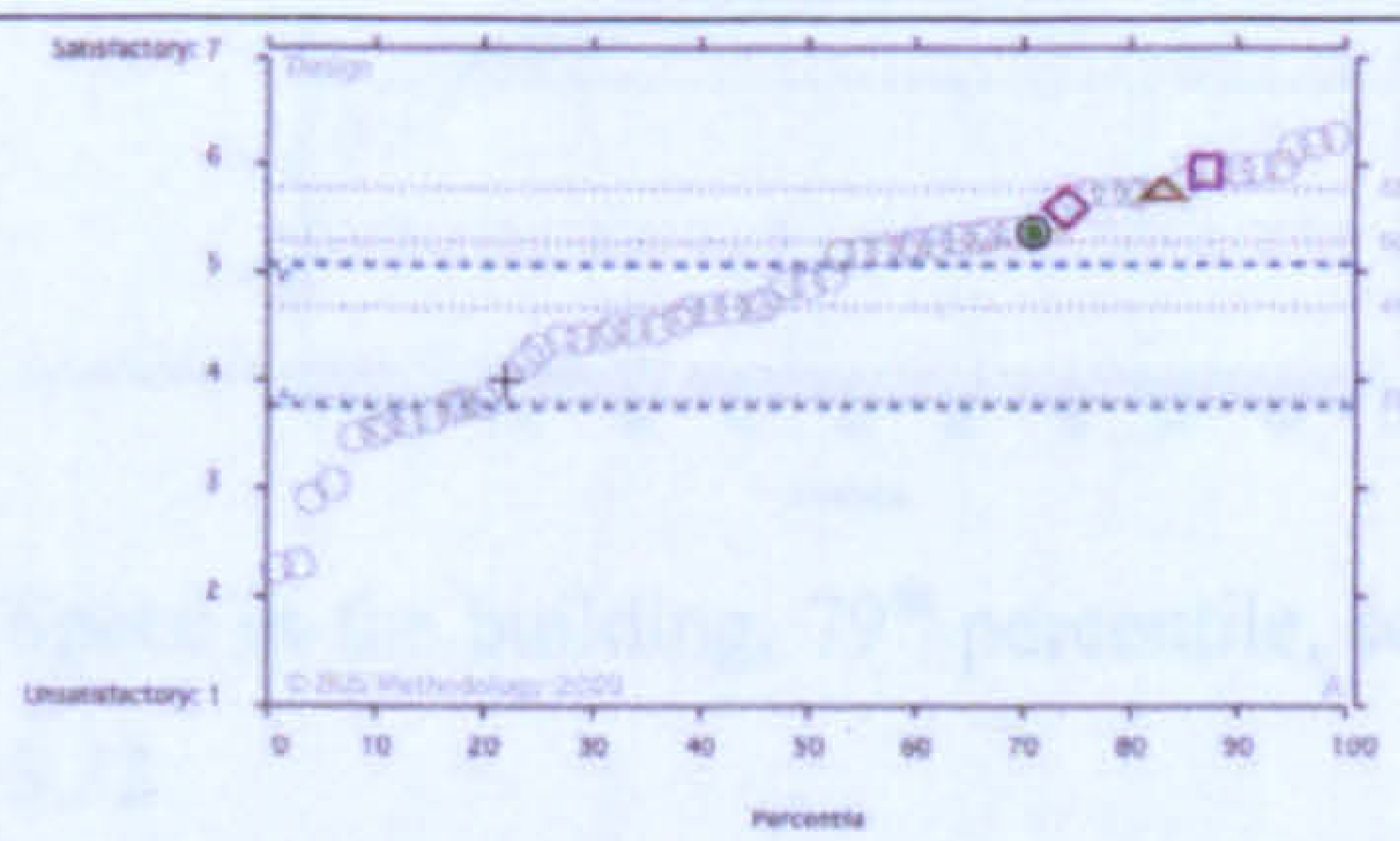
 Control over cooling 27th percentile, score 1.84	 Control over heating 31st percentile, score 1.67
 Control over lighting 24th percentile, score 2.25	 Control over noise 48th percentile, score 1.95
 Control over ventilation 45th percentile, score 3.07	

Figure B-5: Building results for control related aspects

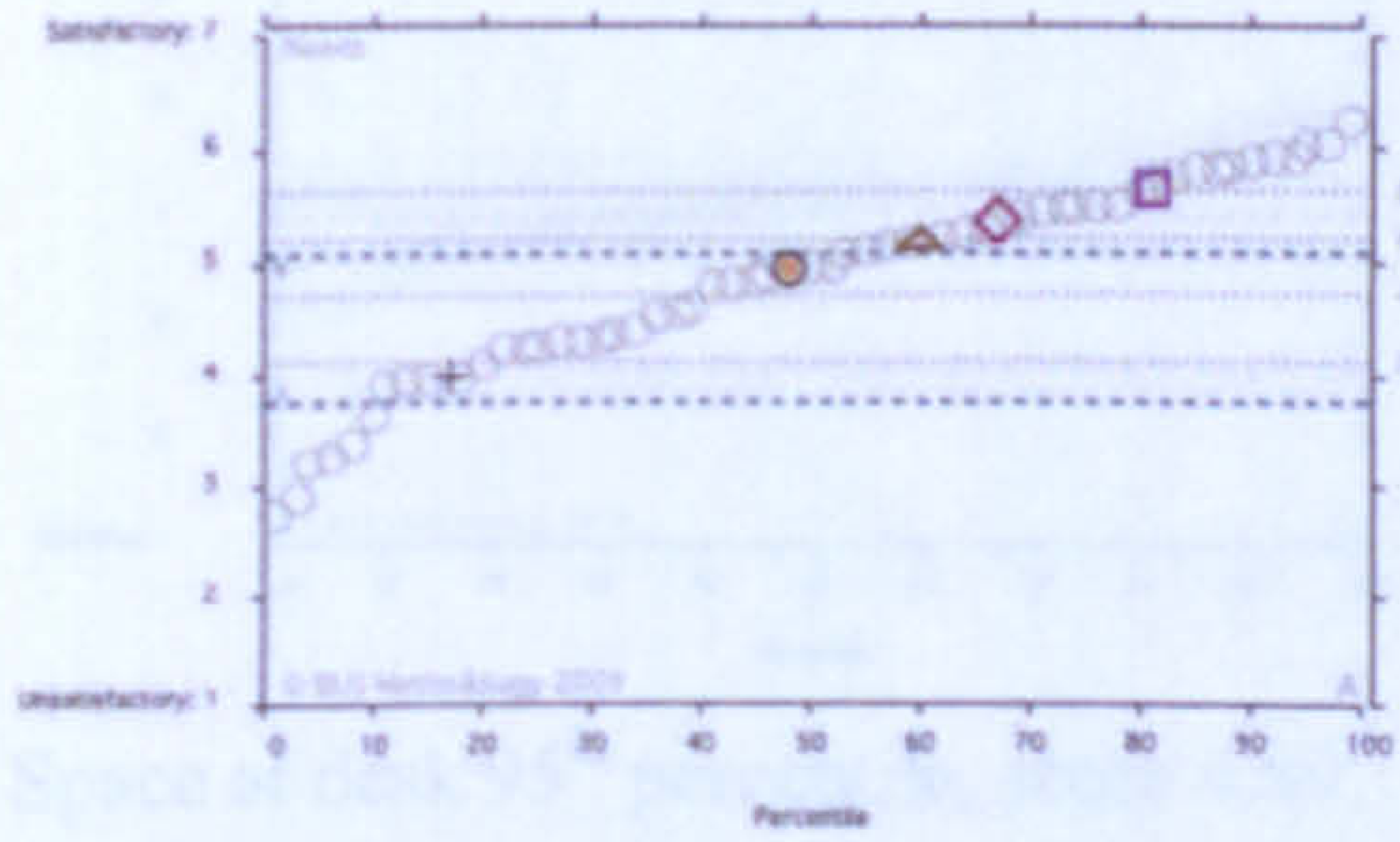
Design and needs



Comfover 45th percentile, score 4.60



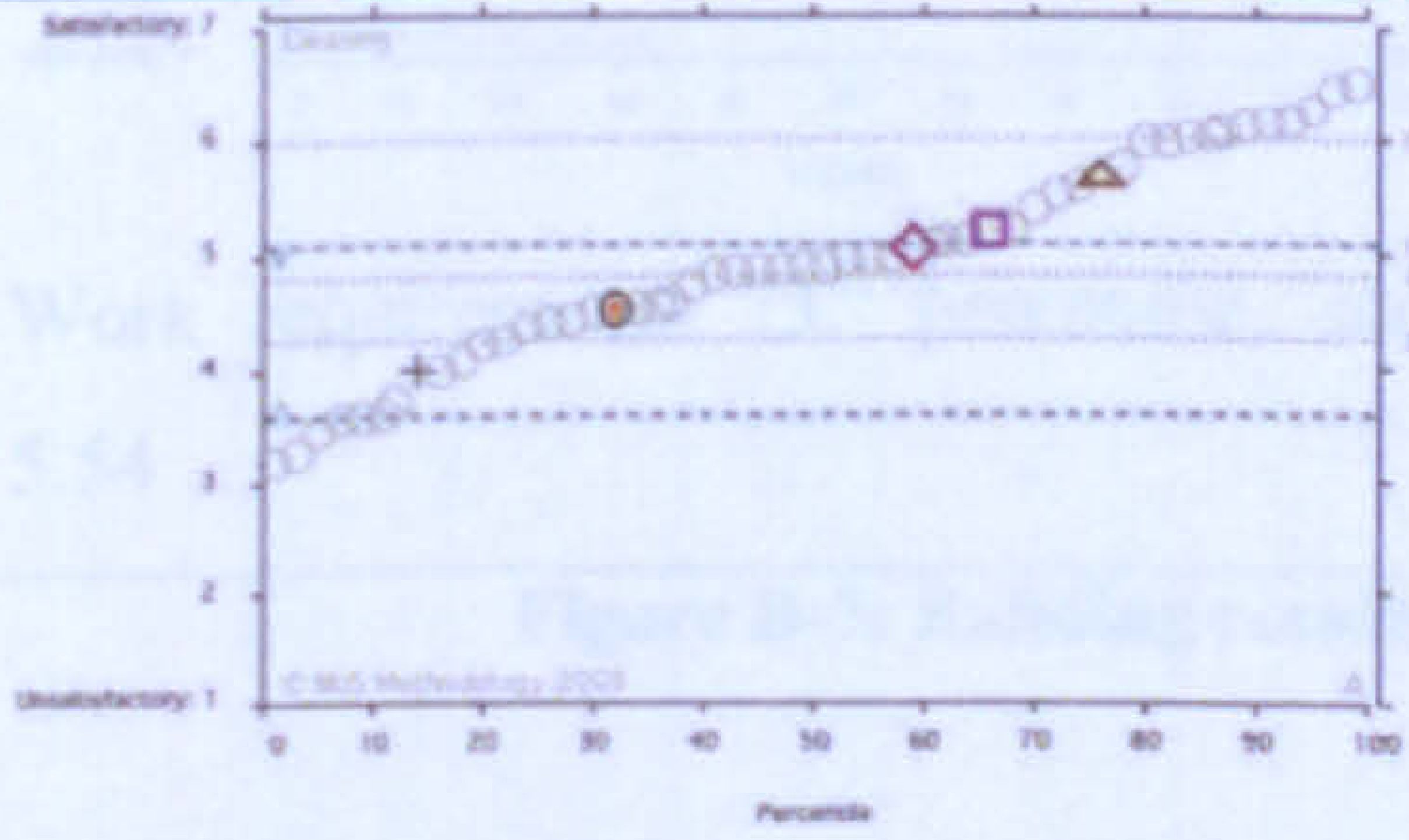
Design 71st percentile, score 5.39



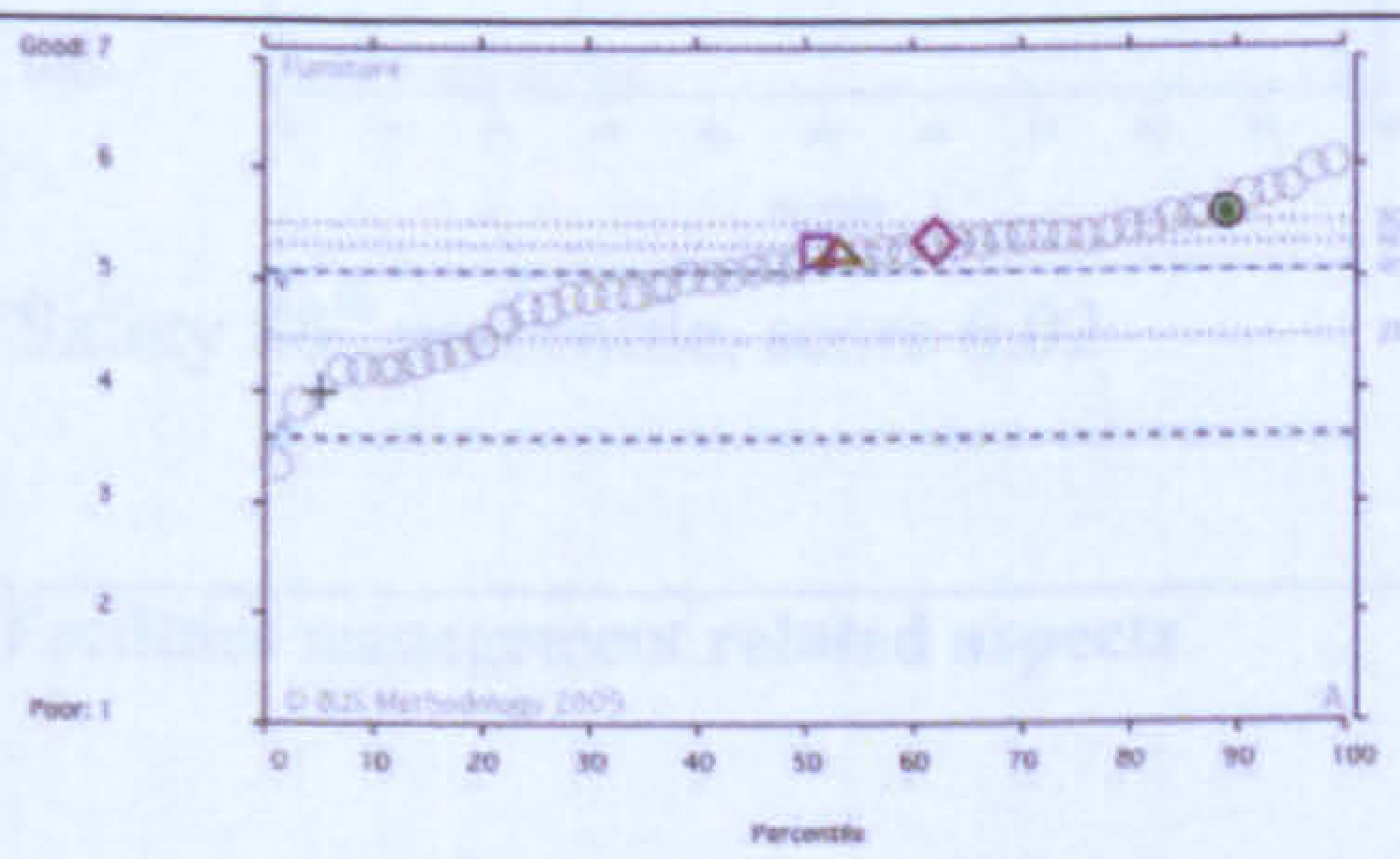
Needs 48th percentile, score 4.98

Figure B-6: Building results for design and needs related aspects

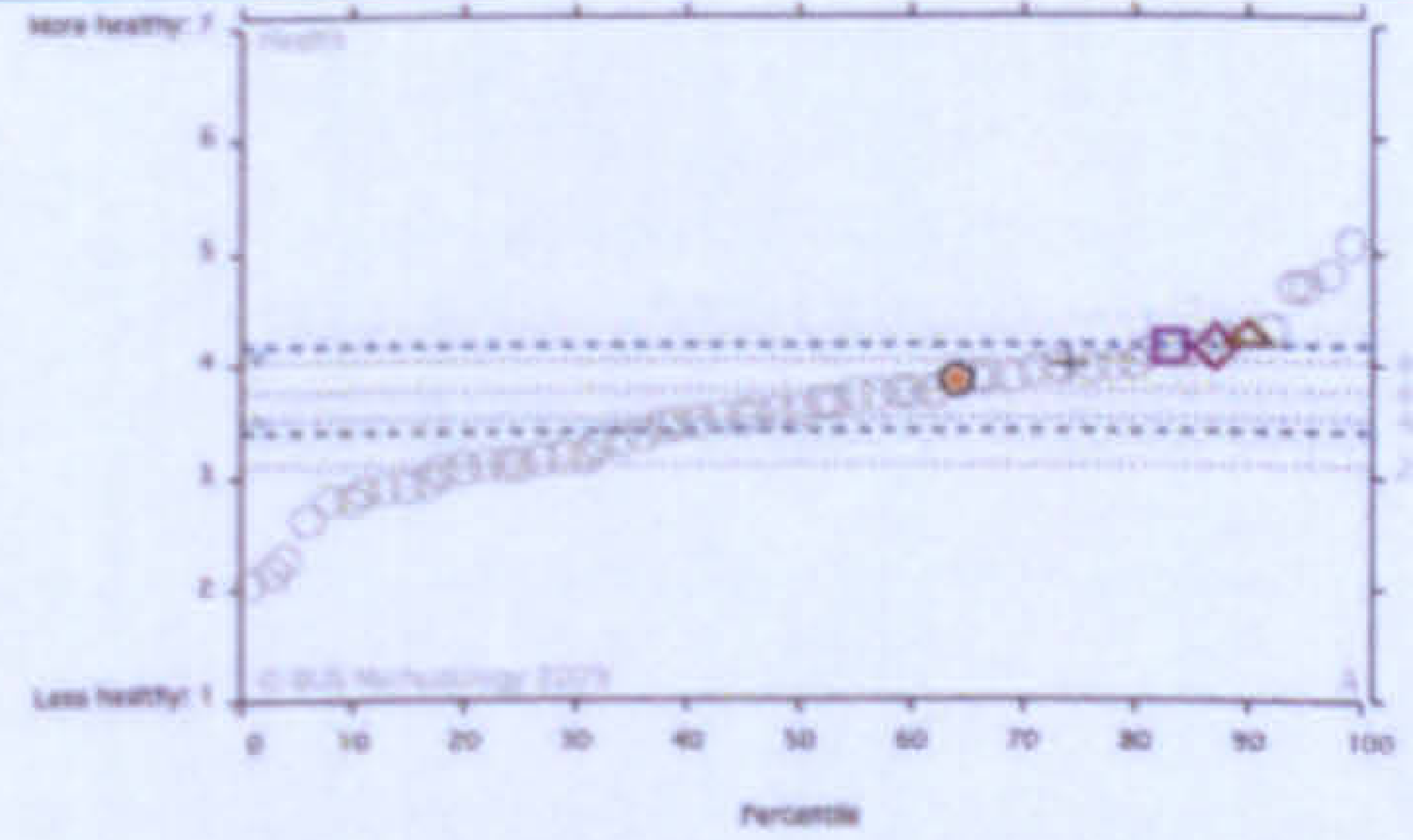
Facilities management



Cleaning 32nd percentile, score 4.56



Furniture 89th percentile, score 5.61



Health 64th percentile, score 3.88

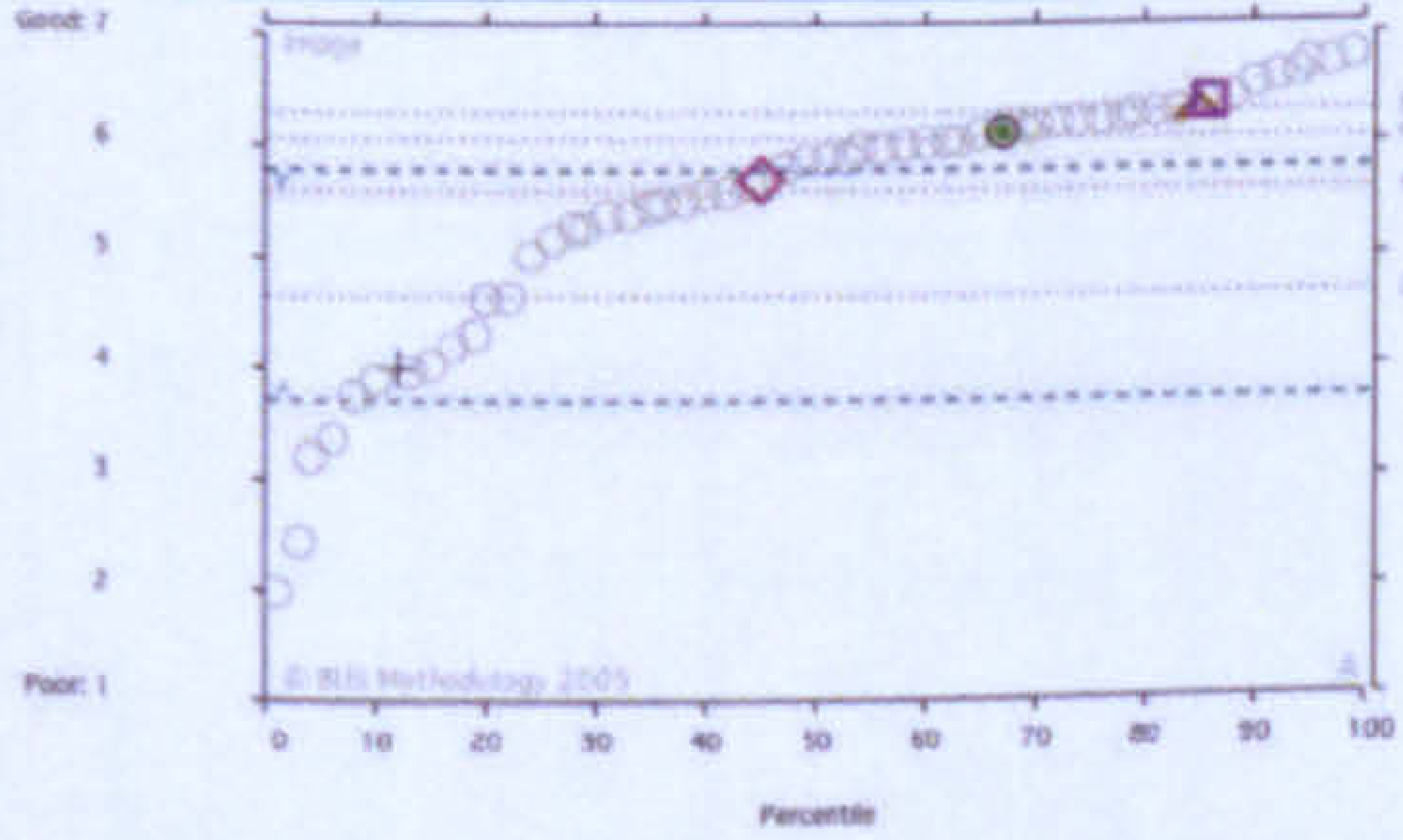
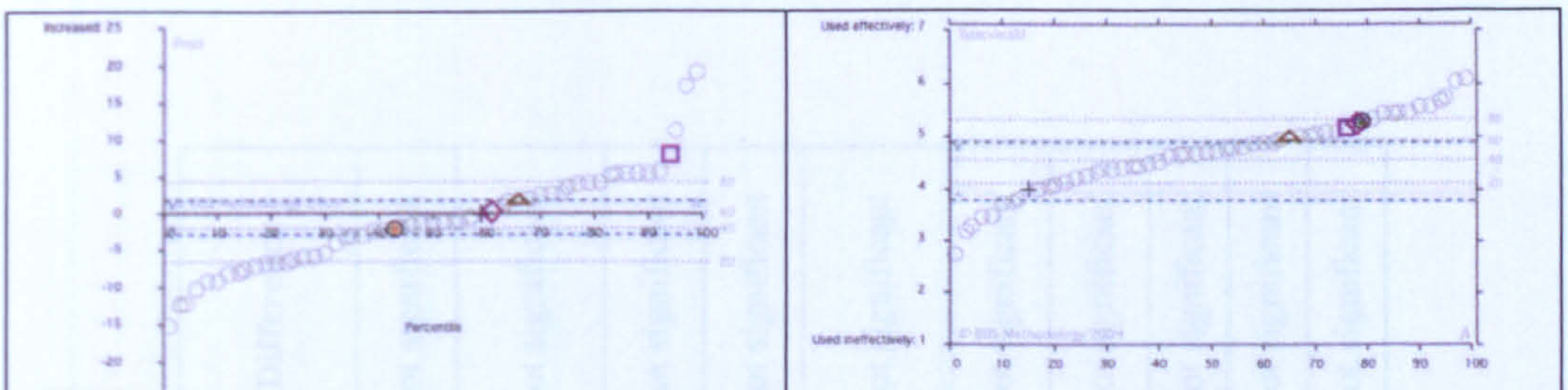
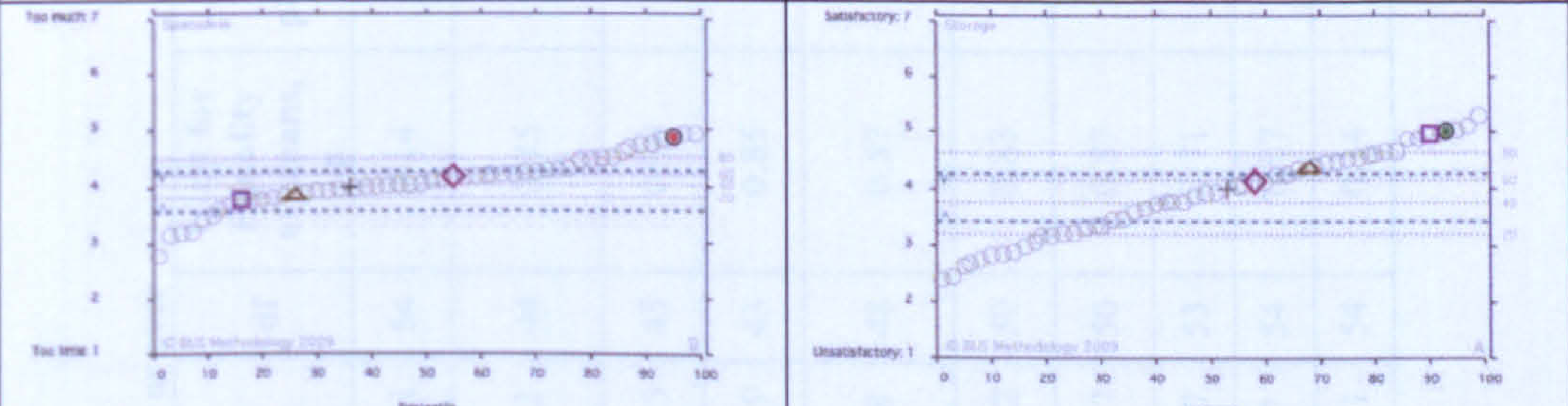


Image 67th percentile, score 6.14



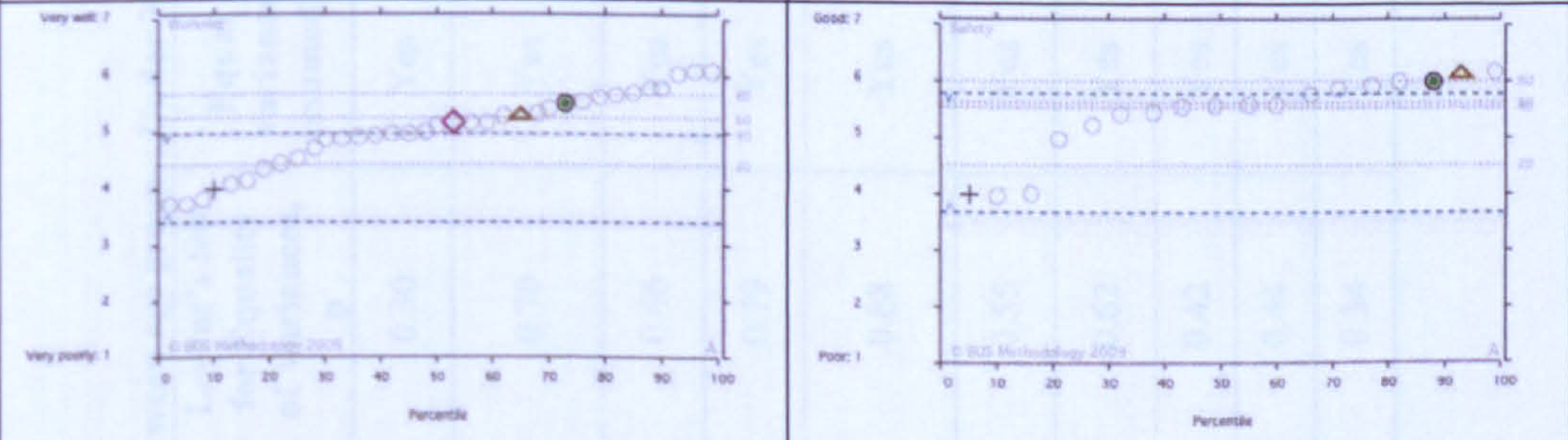
Productivity 43rd percentile, score -1.88

Space in the building, 79th percentile, score 5.32



Space at desk 95th percentile, score 4.89

Storage 93rd percentile, score 5.04



Work requirements 73rd percentile, score 5.54

Safety 88th percentile, score 6.02

Figure B-7: Building results for Facilities management **related aspects**

Appendix C

Table C-1: Difference between age groups: Under 30 vs. 30 or over

	Under 30 Mean	Under 30 SE	30 or over Mean	30 or over SE	Levene's test for Equality of Variances, p	Equal variance assumed?	t	df	t-test for Equality of means, p	Is p>0.05?	Difference
Building design overall	4.92	0.42	5.51	0.17	0.30	Yes	-1.51	54	0.14	Yes	Not significant
Temperature winter comfortable	3.92	0.51	3.74	0.28	0.70	Yes	0.32	44	0.75	Yes	Not significant
Temperature winter hot	4.62	0.40	4.68	0.25	0.66	Yes	-0.13	45	0.90	Yes	Not significant
Conditions winter overall	4.00	0.44	4.09	0.24	0.79	Yes	-0.19	43	0.85	Yes	Not significant
Temperature summer comfortable	3.82	0.48	3.51	0.25	0.88	Yes	0.58	48	0.57	Yes	Not significant
Temperature summer hot	3.69	0.36	3.79	0.24	0.55	Yes	-0.22	50	0.83	Yes	Not significant
Conditions summer overall	4.08	0.38	4.15	0.23	0.62	Yes	-0.17	50	0.87	Yes	Not significant
Noise overall	4.46	0.49	4.64	0.23	0.42	Yes	-0.37	53	0.71	Yes	Not significant
Lighting overall	4.62	0.47	4.51	0.31	0.44	Yes	0.17	54	0.87	Yes	Not significant
Overall comfort	4.00	0.37	4.74	0.24	0.34	Yes	-1.51	54	0.14	Yes	Not significant

Table C-2: Difference between wings: East wing vs. west wing

	East Mean	East SE	West Mean	West SE	Levene's test for Equality of Variances, p	Equal variance assumed?	t	df	t-test for Equality of means, p	Is p>0.05?	Difference
Building design overall	5.57	0.23	5.21	0.23	0.63	Yes	1.06	54	0.29	Yes	Not significant
Temperature winter comfortable	3.91	0.37	3.67	0.32	0.63	Yes	0.51	45	0.61	Yes	Not significant
Temperature winter hot	4.83	0.26	4.48	0.32	0.12	Yes	0.83	46	0.41	Yes	Not significant
Conditions winter overall	4.00	0.32	4.09	0.27	0.29	Yes	-0.21	43	0.83	Yes	Not significant
Temperature summer comfortable	3.27	0.31	3.75	0.29	0.66	Yes	-1.12	48	0.27	Yes	Not significant
Temperature summer hot	3.36	0.31	4.07	0.25	0.58	Yes	-1.76	50	0.08	Yes	Not significant
Conditions summer overall	3.64	0.27	4.47	0.26	0.44	Yes	-2.20	50	0.03	No	Significant
Noise overall	4.17	0.34	4.78	0.24	0.25	Yes	-1.50	53	0.14	Yes	Not significant
Lighting overall	4.78	0.33	4.21	0.37	0.07	Yes	1.09	54	0.28	Yes	Not significant
Overall comfort	4.74	0.32	4.45	0.28	0.74	Yes	0.66	54	0.51	Yes	Not significant

Table C-3: Difference between floors: Ground floor vs. 1st Floor

	Ground Floor Mean	Ground Floor SE	First Floor Mean	First Floor SE	Levene's test for Equality of Variances, p	Equal variance assumed?	t	df	t-test for Equality of means, p	Is p>0.05?	Difference
Building design overall	5.54	0.21	5.21	0.27	0.78	Yes	0.64	54	0.53	Yes	Not significant
Temperature winter comfortable	4.22	0.26	2.36	0.28	0.10	Yes	3.72	45	0.01	No	Significant
Temperature winter hot	4.32	0.23	5.73	0.33	0.14	Yes	-3.09	46	0.03	No	Significant
Conditions winter overall	4.29	0.24	3.27	0.30	0.20	Yes	2.26	43	0.03	No	Significant
Temperature summer comfortable	3.47	0.24	3.69	0.44	0.15	Yes	-0.47	48	0.64	Yes	Not significant
Temperature summer hot	3.33	0.21	4.75	0.35	0.58	Yes	-3.62	50	0.00	No	Significant
Conditions summer overall	4.11	0.23	4.13	0.35	0.85	Yes	-0.03	50	0.97	Yes	Not significant
Noise overall	4.47	0.27	4.63	0.28	0.06	Yes	-0.37	53	0.71	Yes	Not significant
Lighting overall	4.89	0.26	3.58	0.53	0.01	No	2.23	57	0.04	No	Significant
Overall comfort	4.76	0.24	4.21	0.40	0.24	Yes	1.24	54	0.22	Yes	Not significant

Table C-4: Difference between time in the building: Less than a year vs. More than a year

	Less than a year mean	Less than a year SE	More than a year Mean	More than a year SE	Levene's test for Equality of Variances, p	Equal variance assumed?	t	df	t-test for Equality of means, p	Is p>0.05?	Difference
Building design overall	5.708	0.229	5.152	0.222	0.684	Yes	1.71	55	0.093	Yes	Not significant
Temperature winter comfortable	4.000	0.414	3.688	0.296	0.508	Yes	0.60	45	0.549	Yes	Not significant
Temperature winter hot	4.600	0.349	4.667	0.260	0.653	Yes	-0.15	46	0.883	Yes	Not significant
Conditions winter overall	4.429	0.441	3.938	0.220	0.227	Yes	1.11	44	0.271	Yes	Not significant
Temperature summer comfortable	4.300	0.405	3.129	0.201	0.009	No	2.59	28	0.015	No	Significant
Temperature summer hot	4.250	0.315	3.485	0.243	0.551	Yes	1.93	51	0.059	Yes	Not significant
Conditions summer overall	4.850	0.372	3.727	0.181	0.043	No	2.72	28	0.011	No	Significant
Noise overall	5.208	0.255	4.094	0.274	0.274	Yes	2.88	54	0.006	No	Significant
Lighting overall	4.083	0.503	4.788	0.249	0.000	No	-1.26	34	0.218	Yes	Not significant
Overall comfort	5.083	0.351	4.242	0.238	0.487	Yes	2.06	55	0.045	No	Significant

Table C-5: Difference of sitting next to a window: Sitting next to a window vs. not sitting by a window

	Next to window mean	Next to window SE	Not next to window Mean	Not next to window SE	Levene's test for Equality of Variances, p	Equal variance assumed?	T	Df	t-test for Equality of means, p	Is p>0.05?	Difference
Building design overall	5.47	0.23	5.28	0.23	0.48	Yes	0.57	55	0.57	Yes	Not significant
Temperature winter comfortable	4.00	0.31	3.47	0.37	0.97	Yes	1.08	45	0.29	Yes	Not significant
Temperature winter hot	4.55	0.27	4.79	0.34	0.80	Yes	-0.56	46	0.58	Yes	Not significant
Conditions winter overall	4.25	0.24	3.83	0.36	0.42	Yes	1.00	44	0.32	Yes	Not significant
Temperature summer comfortable	3.62	0.28	3.55	0.34	0.88	Yes	0.17	49	0.86	Yes	Not significant
Temperature summer hot	3.52	0.25	4.14	0.30	0.68	Yes	-1.57	51	0.12	Yes	Not significant
Conditions summer overall	4.10	0.23	4.23	0.34	0.30	Yes	-0.33	51	0.74	Yes	Not significant
Noise overall	4.56	0.26	4.58	0.33	0.43	Yes	-0.05	54	0.96	Yes	Not significant
Lighting overall	4.91	0.33	3.96	0.39	0.90	Yes	1.86	55	0.07	Yes	Not significant
Overall comfort	4.66	0.29	4.52	0.31	0.33	Yes	0.32	55	0.75	Yes	Not significant

Appendix D

Table D-1: Feedback from the interviewing the occupants (interviews conducted on 16/07/10)

Occupant:	Groups of occupants from the same office- engineering, contracting, and infrastructure management services	Occupant 1- consultant	Occupant 2- building services engineer	Occupant 3
How long have you worked in the building?	9 months	1.5 years	2 months	1 year
Overall how would you describe your satisfaction and comfort levels within your office environment and the building? Have you experienced any form of discomfort? Is so what?	The group were not very happy with their office environment. They have reported the problems with the ventilation on many occasions. Their office is 18m^2, with only 1 window. (However POE identified that there is imbalance in terms of ventilation as there is no extract vents within their offices). The office often overheats. They keep the window open all the time (using a ruler, and golf club)	Overall the occupant is very happy. Temperature in his office is fine. When he uses the meeting rooms located on the west side of the building he finds that the plumbing / EVAC system can be very noisy. Smells from the toilets are very off putting.	The occupant found the major form of discomfort is the glare at his desk. He said that he occasionally feels quite cold. He is working alone in the office with 4 desks in and thinks this may be due to the lack of internal heat gains. His office is on the West wing (atrium side) but his office windows do not open onto the atrium, instead to the outdoors. He believes there is a problem with the partitioning as noise is a serious problem.	The occupant finds it often gets too hot in his office. He is positioned opposite the coffee pod- 2nd window down from the door to the ground floor east wing zone. He finds that the motion sensors in the office can be very annoying.
What do you like about this building? In your opinion what works well?	Atrium	Temperature.	Fresh airy, good image to clients. Vacuum flush toilets- he likes the fact they are low volume.	The occupant loves the atrium, feels it provides plenty of natural light. He likes the modern design, thinks that the layout is good. He feels that the buildings give off a good image to the client.
What don't you like about the building? How could it be improved?	Not enough ventilation- needs to be improved. They are often too hot. Smells from the toilets.	Partitioning, noise, smells from the toilets	Poor design. As a single occupant within his office, He commented on the annoyances associated with motion sensor lighting. He thinks that the lights should be positioned parallel to the windows not perpendicular.	Smells from the toilets.

Use of blinds: how often do you use the window blinds? Do you have any issues with privacy within your office?	No problems with privacy as they are on the first floor east wing overlooking the road. They keep the blinds in the up position all the time.	No problems with privacy as he is on the ground floor east side facing outwards. (opposite the plant room)	The occupant does use the blinds, but still a major problem with glare. His office is on the 1st floor so doesn't feel that there are any problems with privacy.	The occupant didn't feel that there was a privacy problem despite facing the coffee pod. He says that they often do close the blinds when no one is in the office and at the end of the day but they re-open them in the morning.
In the past if/when you have experienced discomfort, how have you alleviated it? Did you open the window, dress differently, just carry on as before?	Open the windows- ruler was used to open the windows past the safety level.	Open the windows.	He hasn't reported any problems; he has on occasion put a jumper on when he is feeling cold.	Open the windows. He has reported issues to management and feels there has been a good response to the problems reported.
If you had more freedom to do the things mention in the previous question would you be happier?	Yes, he would like more control.	Yes, he would like more control.	Yes	Yes, he would like more control.
Were there any barriers to acting in this way- such as noise, privacy issues with the windows opening onto the atrium?	No, wears short sleeved shirt when it gets too hot.	No issues		No
Did the building having green credentials influence on your decision to take space at Innovate/Icon?	Yes this did have a big influence. Travel links are also really good.	Yes this did have a big influence. It is conveniently positioned. Also with the nature of his business, positive environments are important. As this building is very light and fresh feeling he is happy to rent space. Also as the building is a serviced office this works well for Anthony. (he just pays a monthly bill to Icon)	Yes this did have an influence. As a building service company this was a big factor. Also compared to the serviced offices in the city centre, the price wasn't too bad at all.	Yes this did have an influence. Aesthetics were also good.
Travel: how do you currently travel to work? Have you considered alternative modes?	Drives	Drives it is convenient for him as he travels about a lot.	Car, however has considered cycling to work.	Drives

Any additional comments?	Car park – concerns over parking when the building's occupancy increases. One occupant commented on the fact that at the moment privacy is not a problem but when the area they are based in gets busier maybe this will become an issue. The same occupant also commented on the fact that the image of the building looks good for them as a contractor. The building gives off a good image and their clients always comment on how 'this must be an amazing office to work in'.	The occupant thinks green issues are very important and even created a website to help promote the building. Compared to old fashioned buildings he has worked in the past, this is definitely one of the better places he has worked	The occupant said it's probably the best place he has worked in. As a multi-tenanted serviced-office, the occupants pay a standard monthly rate- no incentive to switch computers off, reduce consumption, switch other appliances or electrical appliances off, car park space is included.	Biggest complaint is the smell from the toilets. It is better than the last place he worked in.

Appendix E

Table E-1: Feedback from the design team

Involvement in the project	**Sustainability advisor, environmental designer and building services engineer**	**BMS contracts engineer for the site**	**Termodeck Engineer: involvement included Temperature control using exposed mass of flooring**
Since completion and hand-over, have you had any further involvement in the building? If so, what was your involvement?	"We were called back the facilities management company that took over after the collapse of Innovate. We found that the BMS had been substantially altered from the design strategy and that the building was unable to function as designed. We also found that there were ongoing issues with the CHP. We made proposals to oversee the rectification of these problems to set the building back to work as designed, but since then we have received no response from the FM or Icon despite contacting them on numerous occasions."	"We have had a few return visits to look at issues, we have also been involved with the maintenance of the site but I have had no involvement with this."	"Two visits to discuss control issues. These were proposed by ourselves."
In their research Leaman and Bordass describe the success of an energy efficient office as one with a "virtuous" circle rather than a "vicious" circle. They suggest that a good brief, good design and good management is what is needed to aid the delivery of an energy efficient office. With this in mind, if applicable, please could you comment on the effectiveness of the project with regards to the following......			
Good brief?:	"Good"	"The design Idea was very good and how it should work was also quite innovative."	"Yes"
Communication between you and the client:	"Good"	"Our Client was the M&E contractor we had no involvement with the end client, we did have discussions with the consultant on how things should work which went well and brought up some good ideas."	"Little client contact"

Communication between you and the rest of the design team:	“Excellent”	“We had very minimal communication with the design team other than at the beginning to figure out how it would all tie together; the brief on how it should work is what we worked to.”	“Good”
Design phase:	“Good”		“Good”
Construction stage:	“Good”		“Good”
Hand-over/commissioning:	“ Moderate”	“The handover was minimal other than demonstrations to our client (M&E contractor) which we carried out, there were a few issues as we looked at how it would work and alterations were made on site as we tested things out. The strategy was very complex and took quite a while to work through on site with our client. I can’t comment on exact details as this was quite a while ago. “	“Controls commissioning conducted without us in a slightly secretive manner. Some changes were made without our agreement.”
Staff training:	“Poor”	“Staff training was minimal as none of the staff were technically minded, as an end user they found it fairly complex even though the user input needed to alter the system was fairly straightforward.”	“Could be better”
Management and running of the building:	“Disastrous”	“We haven’t had any real involvement with the management of the building, we did have the maintenance contract but I’m not sure we have that now”.	“Room for improvement. Centre staff have very limited knowledge of running such a building and the typical sort of contract they have with controls and maintenance companies, do not ensure that a building like this operates at its best.”

Were there any initial design aspirations that didn't become a reality? If so, what were they? Why were they omitted in the final design?	"There were a number of minor aspects of the design that changed due to cost or practicality, but all of the main aspirations made it through to the final building. The things that changed were: the window insulation / solar specification was reduced as the preferred window manufacturer was unable to supply glass to the original specification. The insulation to the walls was reduced marginally as to meet the original specification would have exceeded the largest polystyrene block size. We were unable to achieve the preferred level of recycled material in the concrete floor slabs as no-one was then manufacturing pre-cast floor planks with sufficient cement replacement due to the extended curing times. We ended up with standard light fittings rather than a bespoke beam system that was to have incorporated acoustic material and the fire alarm components etc."	"I didn't get involved at costing stage; M&E contractor would be able to answer this."	"No comment."
In your opinion how successful was the project?	"As a demonstration project Innovate was very successful, as signified by the number of awards. However as a working building it has been much less successful, primarily due to the procurement route, which separated the designers from the end users and the subsequent demise of Innovate which both have meant that the design team has not been involved in helping the users to settle in to the building and learning to use it properly."	"I think the ideas were really good, I still believe it could be more successful than it has been, there are items of plant which I don't believe have ever worked, i.e. the absorption chiller which should save them money. The night time cooling strategy I think could be improved by looking at temperature results and how well it is working."	"Successful for grabbing headlines. Unsuccessful when measured against energy running aspirations."
From your experience, how important are low energy buildings in the industry today? Are clients asking for low energy designs?	"Low energy buildings are becoming increasingly important, even vital, to achieving our national economic objectives. Clients in the private and public sectors are gradually waking up to this and the demand is growing."	"Yes all of our projects seem to be as energy efficient as possible with the use of natural ventilation rather than mechanical cooling. And I do think this is the way forward in times where we have global energy issues and green issues."	"Asking, yes; getting, no. Important, yes."
Has your involvement in the Innovate/Icon Business Centre Office project had any influence on projects you have worked on since or will do so in future projects? If so how?	"We are now much more wary of the procurement used for such buildings. The design and build approach puts far too much distance between the original designers and the building's occupiers. If we are now forced to take a design and build approach to low energy buildings we ensure that the client and the funders are fully aware of the risks of doing so."		"To some limited extent. Building do not always fill, so the design should accommodate this."

In your opinion, how important is the Post Occupancy Evaluation (POE) of buildings?	"Vital"	"Quite important to figure out the equipment and ideas is working as planned, we can't try new ideas without proper evaluation "	"Very. "
Who do you think should pay for POE? (e.g......the client, the designer, no one as they are not worthwhile?)	"Government. POE should be a requirement of all new buildings under the building regulations with the results lodged in a national database along with the energy performance rating and details of the design. This database must be free to search by building designers."		"I like the idea that an independent POE is done as a matter of course and that the building owner can pass the cost on to the Contractor."
Any additional comments you would like to make about the Innovate Office project.........	"This is a classic example of how important it is that the original designers retain an interest in the building beyond the completion date. We have tried on numerous occasions (as you will recall) to re-engage with the new owners but with no success. As we have not been able to maintain the dialogue a succession of people who don't understand the operating principles have tampered with the control of the building to try and make it work more like a conventional heating and air conditioning system. In doing so, they have set the systems and the building fabric in opposition to each other and so have lost control of the building. "		"Why are people like ourselves who would like to help, being held away?"

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