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Monitoring UK hospital building type performance

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Monitoring UK Hospital Building Type Performance

by

Louis-James Fifield

December 2016

A Doctoral Thesis Submitted for Degree of Doctor of Philosophy

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Abstract

The British National Health Service (NHS) is one of the largest public services in the world and consequentially in 2004 it produced 25% of the total public sector carbon emissions for England. To meet national carbon targets the NHS must reduce its emissions; 26% by 2020, 64% by 2030, 80% by 2050 and is therefore interested in the development of strategies for reducing carbon dioxide emissions from buildings. The NHS building stock consists of a range of building archetypes constructed over the past 100 years. The energy used for heating and cooling hospital premises is the source of 22% of all NHS carbon emissions. The individual buildings are distributed across hospital sites that often have centralised energy plants, which make it difficult to monitor energy consumption on an individual building level.

This thesis develops a method for monitoring the energy consumption of individual hospital buildings. The method was implemented on three case study buildings at Bradford Royal infirmary (BRI); a 1920s Nightingale, a nucleus and a modern modular building. Lessons were gathered from these studies to advance the knowledge on monitoring in UK hospitals. One of the key findings was that empirical models based on measured data are useful for estimating individual buildings annual heating energy consumption.

The results show that the mechanically ventilated nucleus building had the highest energy consumption (808.7kWh/m^2), followed by the naturally ventilated Nightingale building (420.7kWh/m^2) and then the mixed-mode modular building (289.0kWh/m^2). The internal environment was optimal in the nucleus building, but the Nightingale and modular buildings underperformed, with the modular overheating in summer and both buildings failing to meet air quality recommendations. Taking energy consumption and summer thermal resilience into consideration the Nightingale building had the best performance, demonstrating the longevity of the traditional design.

The work identified a number of useful hospital design features; well-insulated heavyweight building fabric, well-controlled space heating, use of heat recovery ventilation and installation of localised monitoring equipment. Further useful research into this area could involve: using dynamic thermal simulation to test recommended building design features, investigating the monitoring method on a wider sample of sites and investigating air quality monitoring in hospitals.

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Nomenclature

Main symbols

C_p	Specific heat capacity of transfer medium (J/kg K)
q_a	Volume flow rate of air (m^3/s)
Q_{AH}	Gas used for heating air in building (W)
Q_{LTHW}	Predicted LTHW heating for the building (W/m^2)
Q_{SH}	Minutely space heating used for building (W)
q_w	Volume flow rate of water (m^3/s)
T_{ai}	Air supply temperature (°C)
T_{ao}	Ambient air temperature (°C)
T_{ar}	Average floor area weighted air temperature (°C)
T_r	Return pipe temperature (°C)
T_s	Supply pipe temperature (°C)
μ	Seasonal efficiency
ρ	Density (kg/ m^3)
M	Total heat loss coefficient
A_T	Total area of monitored spaces in ward (m^2)
Q_E	Total annual electricity consumption for space (kWh/yr)
$\dot{V}_a$	Air Flow rate (m^3/s)

Acronyms and Abbreviations

ach^{-1}	Air changes per hour
ADB	Activity Database
AHU	Air handling unit
ASHRAE	American Society of Heating and Air-Conditioning Engineers
BADC	The British Atmospheric Data Centre
BE	Back Entrance
BMS	Building Management System
BRI	Bradford Royal Infirmary
BSEN 15251	British standards - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality , thermal environment , lighting and acoustics

CD	Corridor
CHP	Combined Heat and Power
CIBSE	Chartered Institute of Building Service Engineers
DEC	Display Energy Certificate
DECC	Department of Energy and Climate Change
DeDeRHECC	Design and Delivery of Robust Hospital Environment in a Changing Climate
DHW	Domestic hot water
DSY	Design Summer Year
ERIC	Estates Return Information Collection
FE	Front Entrance
HTM-03-01	Health Technical Memorandum 03-01: Specialised ventilation for healthcare premises
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor air quality
KTOE	Kiloton Oil Equivalent
kWh	Kilo-Watt Hours
LTHW	Low temperature hot water
MB	Multi-bed Space
NHS	National health service
NS	Nursing Station
PPM	Parts per million
SB	Single Bed Space
SRI	Solar Radiation Intensity
TRY	Typical Reference Year
VAV	Variable air volume

1 Introduction

1.1 Background

Climate change is a well-established phenomenon posing an increasing threat to the world we live in (Stern, 2006). Its main effects are a slowly rising global temperature which has the detrimental impact of raising sea levels *(ibid)*. In addition, the frequency and intensity of heat waves is increasing (Department of Health, 2010) having the effect of destroying the worlds ability to produce and harvest crops thus threatening the financial and food security of nations (Stern, 2006).

The rising temperatures are caused by greenhouse gases, the most prevalent being carbon dioxide which is closely linked to human activity (DTI, 2007). In recent years leading countries have come together to solve this problem, an example of this is the Kyoto Protocol where many industrial countries agreed to make reductions in the amount of greenhouse gases they were emitting *(ibid)*. The UK itself set an ambitious target to reduce carbon emissions 80% by 2050 compared to 1990 levels (Parliament of the United Kingdom, 2008).

The NHS is one of the largest services in the world, every day its 1.3 million staff serves just fewer than 1 million patients (NHS SDU, 2009). As a consequence of the NHS's activity, in 2004 it produced a total of 18MtCO_2, which is 25% of the total public sector emissions and 3.2% of the total emissions for England *(ibid)*. The NHS need to meet the national carbon targets and have set a pathway where there must be a carbon reduction of 10% by 2015, 26% by 2020, 64% by 2030 and 80% by 2050 *(ibid)*.

Out of the total energy consumed in the UK, 44% comes from buildings, with 14% and 30% coming from the service and domestic sector respectively (DTI, 2002). Within the NHS, 22% of the carbon emissions are emitted from buildings and within buildings at least 77% can be attributed to acute hospital sites (Hospital Estates and Facilities Statistics, 2011). Therefore reducing the energy consumption in hospital buildings is a high priority for the NHS to be able to fulfil their carbon targets. The NHS have a number of ways in which they are attempting to achieve this, one of them is that:

> *"A Low Carbon Design Taskforce of public and private sector expertise should be established to develop a blueprint for the optimum low carbon healthcare building, accompanied by best practice guidance."* (NHS SDU, 2009)

Climate change poses two major challenges for building designers, the first is mitigation and the second is adaption. As climate change becomes more pronounced adapting buildings to its effects is becoming an increasingly important consideration. Although carbon emissions and energy consumption are significant to the NHS, the primary aim of hospital building designers is to provide an environment that is suitable for patients. In the next 50 years, the temperature is likely to increase by 2-3˚C (Stern, 2006), which will have a profound impact on the amount of overheating which takes place within buildings and the frequency and intensity of heat waves. In the summers of 2003 and 2009, there were heat waves which resulted in an increase in the death rate by 16% and 4% respectively. The majority of the people in this group were over 75 years old (Department of Health, 2010) the demographic which are the most regular users of hospitals. The growth in the frequency of overheating in buildings will also impact the quantity of energy being consumed for heating and cooling. Studies undertaken to look into the effects of rising temperatures have concluded that that cooling loads will increase while the heating will decrease (Frank, 2005). It is therefore essential to take this into consideration when developing a blueprint for the optimal hospital building.

As well as the design of new low carbon hospital buildings, the NHS has an extensive existing building stock whose energy consumption needs to be addressed (NHS SDU, 2009). One of the key methods for doing this is benchmarking, monitoring and targeting where buildings energy consumption is monitored and compared to the national benchmark which enables energy managers to identify where improvements in energy can be made *(ibid)*. The NHS realise their need for research and innovation in this area and are looking for ways to create a national standardised methodology to monitor, benchmark and target carbon emissions for the different levels within the organisation. Their leading document on carbon emissions states:

> *"further information is required to establish metrics which will allow each NHS organisation to benchmark their actions and set themselves targets for reduction ... Research is required to ensure organisations are able to measure their carbon impact efficiently and consistently. Establishing*

national standards for this information will create consistent recording of carbon footprints and ensure all organisations contribute to carbon reduction." (NHS SDU, 2009)

International hospital building services and their related energy consumption vary highly depending on the local climate and socio-economic area the hospital is located. Countries with diverse climates are often primarily mechanically ventilated and hence consume high levels of energy, i.e. US hospitals generally use over two times the amount of British hospitals (Hatten et al., 2011; Sheppy et al., 2014). In contrast, Indian hospitals energy consumption is closely related to its funding source, i.e. whether it is privatised or Government run (Kapoor & Kumar, 2011). Therefore, to narrow the scope of this thesis, the study will focus chiefly on hospital buildings within the UK, with the literature review touching on international hospitals to provide a wider context for the work.

The main NHS challenge regarding the conventional benchmarking and monitoring methods surrounds the way their stock is constructed. Each NHS hospital trust site contains a wide range of buildings built over a period of up to 100 years. These buildings are designed after different hospital archetypes and hence have energy demands that vary according to the internal and external design, occupancy and departmental use within the individual buildings. The first problem arises because it is the general arrangement for the buildings to have their heating provided by a central plant which makes it difficult to monitor the energy consumption of the buildings and departments individually.

The second challenge is that the difference in energy demand from building to building means that the standard national benchmark may not be suitable for each individual building. An example of this can be seen in two recently published papers by Lomas et al. where a pre 1940s Nightingale ward (Lomas & Renganathan, 2012) and a 1960s tower hospital building (Short, Lomas, Giridharan, & Fair, 2012) were simulated. The models predicted that the annual energy demand for 2010 was 25GJ/m^3 and 101GJ/m^3 for the Nightingale ward and 1960s tower respectively. These results show large disparity and differ greatly from the benchmark which is 55-65GJ/100m^3. Although studies have modelled aspects of hospital building energy consumption, it is well regarded that there is often a gap between modelled and monitored energy building performance (Burman et al., 2012). Due to reasons stated in the previous

paragraph there is little documentation of research conducted monitoring the energy consumption of individual types of hospital buildings in the NHS.

1.2 Research questions

The research needs in this area will be addressed in the following questions:

1. What is the monitored energy consumption of the individual hospital building types in the UK?
2. How can the existing monitoring and benchmarking methods in the NHS be improved?
3. What is the relationship between internal environmental conditions and energy consumption for the individual building types?
4. Which principles from existing hospital building design can be carried forward into the design of new low carbon hospital buildings?

1.3 Aim and objectives

The aim of this work is to develop a monitoring method to quantify the energy and internal environmental performance of existing hospital building types to learn lessons which can be applied to the design and retrofit of low carbon, climate change resilient hospitals of the future. This was achieved through the following objectives.

1. Review the literature surrounding the internal environmental conditions and energy consumption of hospital buildings, investigating monitoring practices and energy reduction methods applicable for hospital buildings.
2. Use findings from literature to develop a method for monitoring the various aspects of hospital buildings energy consumption.
3. Survey hospital case-study sites, collecting existing secondary data on their construction, services, operational use and energy consumption to create a clear picture on their design and function.
4. Choose suitable case-study buildings representing the spectrum of hospital building types in the UK to monitor their energy consumption and internal environmental conditions including heating, ventilation, electrical demand, summer and winter thermal comfort, air quality and window opening patterns.
5. Compile, clean and analyse the collected data to quantify the internal environmental conditions and yearly energy consumption for each hospital building type.

6. Make recommendations on best practice for the monitoring of individual hospital buildings and the design of low carbon hospital buildings.

1.4 Thesis structure

Chapter 2. Literature Review: Reviews the literature and current knowledge in the broad field of hospital energy demand, looking at the development of energy usage within hospital buildings. It compiles findings from objective 1 and identifies the methods used in reducing energy consumption in hospitals.

Chapter 3. Methodology: Takes the lessons learnt from literature review to specify the approach used in this study presenting the methodology which was implemented to monitor the internal environmental conditions and energy end-uses.

Chapter 4. Hospital Case-Study Sites: Describes the hospital sites that were studied, to learn about the different hospital sites in the NHS and their building type make up. It was not possible to monitor the energy consumption in all of the buildings on every site. This chapter therefore specifies some of the limitations of the method and difficulties of applying it in certain situations.

Chapters 5-7. Nightingale, nucleus and modular case-studies: Presents the case-study buildings that were investigated in Bradford Royal Infirmary; describing their construction, building services equipment and usage. The chapters also expands on the methodology presented in chapter 3 to detail how monitoring was carried out in each the particular building, in addition to presenting the analysis and discussion of their respective results.

Chapter 8. Comparison and Discussion of Case-studies: Compares the results from chapters 5-7 discussing how the individual building designs impact their energy consumption and internal environmental performance. The impacts of some simple energy reduction measures on the buildings heating consumption are estimated and recommendations for the design and monitoring of hospitals are made.

Chapter 9. Conclusions: Presents the summary of the work gathered together in the thesis looking at its contribution to knowledge in the field of hospital energy demand reduction and while also providing recommendations for areas of further research.

2 Literature Review

This chapter reviews the academic research and guidance documents relevant to monitoring the energy consumption and internal environmental performance of hospital buildings in the UK. Section 1 provides the history and background of energy consumption in UK hospital buildings, describing its building services, energy use and future priorities. Section 2 delves into the specifics of the UK hospital stock, reviewing how it can be disaggregated and what factors influence its energy consumption. Hospital energy management is discussed in section 3, especially focusing on monitoring and benchmarking. In the fourth section the methods that have been successfully used to lower the energy consumption in hospitals are reviewed. The final section discusses hospital thermal resilience and the chapter closes with a summary of the literature appraised, as well as recommendations for areas of further research in the field.

2.1 Context

2.1.1 History

In the 19th century, healthcare was very much an activity that took place at home and if an individual was sick a nurse or family member would care for them. Small hospitals were built towards the end of the 19th Century and from that time until 1948, hospitals were owned by private charitable organisations. On 5th July 1948, the government, under the direction of Nye Bevan passed the National Health Service Act, which marked the birth of the NHS. This act was the result of legislation created in 1946 by the Labour government based on the Beverage report which identified five wants which civilisation needed to address; “want, disease, ignorance, squalor and idleness”(Darzi, 2008).

The centre of Nye Bevan’s plans was the “District General Hospital”. A committee came together to plan this type of building in 1960 and they came up with a design which served populations of 200,000-300,000 people, each hospital having 1000-2000 beds. The main area of the hospital was split into three sections: the nursing, clinical and support zones. The nursing zone is the area where patients stay and are cared for. The clinical zone is where diagnostic and treatment takes place and the support zone holds the kitchen cafeteria, laundry boiler house, staff changing stores etc. The other areas which make up general district hospitals include training facilities for staff,

university students and medical researchers, and offices whereby the administrative processes can take place (James & Tatton-Brown, 1986).

In 1973, there was the first of two energy crises' which took place in the '70s. In response the government began to emphasise the need to be as efficient as possible with energy. Prior to this, little focus went into building energy consumption and hospital buildings were very energy intensive. The first initiative undertaken by the Department of Health and Social Security (DHSS) was the nucleus project, which had the aim of designing a building which was simple to construct while having reduced energy consumption. It utilised natural ventilation, day lighting and also included thermal insulation which reduced the heating consumption from 35% of load for a district hospital to 7% of the energy load for the nucleus building. The buildings which were designed and built after 1973, used 10-25% less energy compared to those built before the 60s (Adderley et al., 1987).

In 1978, there was an impetus to have still further improvements. A second team was set up and modelling was used to see if the 300 bed nucleus building could be further enhanced. By looking at each end-use system, it was found that, compared to the standard nucleus building design, an additional 30-35% savings in energy consumption were possible (Adderley et al., 1987). Their findings were published under the title "DHSS low energy hospital study report", and were given to the hospital authorities in 1983 (NHS Estates, 1994a). The report claimed that the reduction was made possible through energy conservation methods, i.e. improving the air tightness, thermal insulation, glazing ratios, air treatment systems and catering equipment. Once this step was completed heat reclaim was implemented which further reduced the energy needed for heating.

In 1981 Isle of Wight's St Mary's hospital was commissioned as a case study to actually test the design presented in the DHSS report. Over a three year period the DHSS published yearly reports on the energy performance of St Mary's hospital. In the first year savings from the special design were 35% when compared to the benchmark for a regular nucleus building and another hospital of a similar size (NHS Estates, 1994a).

After the first DHSS report and the St Mary's performance assessment, further improvements were desired and a third programme of research was undertaken. In 1983 proposals were put forward for the Wansbeck Hospital in Ashington

Northumberland and the following year the draft proposals stated that there was a possibility to produce savings of over 68% over the original nucleus hospital. This building was intended to be the new basis, or standard for hospital buildings in the 1990s. The first Wansbeck report pointed out that a reduction of 67% above the nucleus building was indeed possible, therefore for the Wansbeck hospital, a target of 60% reduction compared to the nucleus benchmark was set (NHS Estates, 1995b).

Wansbeck hospital was monitored for three years, from 1993-1996. In theory savings of 60% were desired, but when tested, there were savings of 34.5% compared to a standard nucleus hospital (NHS Estates, 1995b). In the second year, Wansbeck used 44% less fuel than the nucleus hospital benchmark, resulting from savings in air heating and hot water usage, through management and good housekeeping (NHS Estates, 1996). In the third year, there was no energy manager and this resulted in a reduction of the amount of energy saved, from 44% to 37%. Although there was an increase in energy usage, the increase in the cost of the energy was less than the cost of the energy manager. It was also found that the way the systems worked together affected the amount of energy saved, hence magnifying the need for optimisation.

2.1.2 Current UK Hospital Energy Consumption

In a recent study (Godoy-shimizu, et al. 2011), Display Energy Certificates (DEC) were used to analyse and compare the energy consumption of buildings within the non-domestic sector. The results (Figure 2.1) demonstrate that, although the number of hospital and emergency services buildings is low in comparison to the likes of school buildings, they have the largest carbon emissions, almost doubling that for schools.

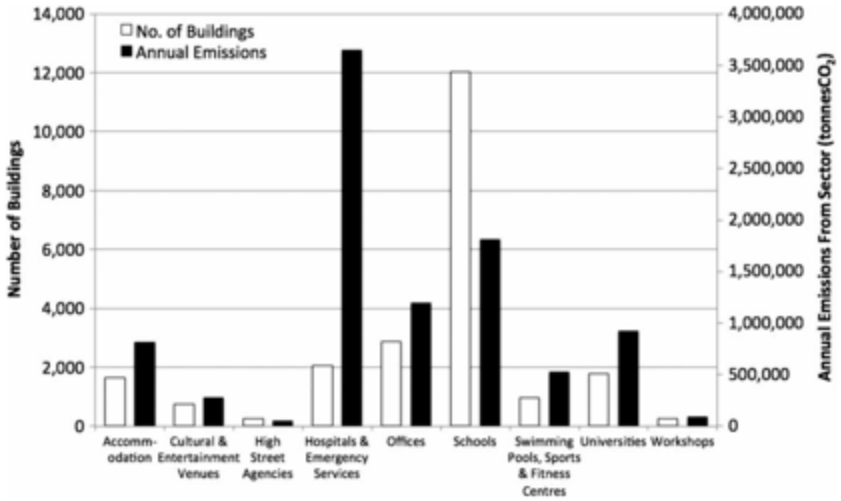


Figure 2.1 - Annual CO_2 emissions by sector (Godoy-shimizu et al., 2011)

Benchmarks give a good indication of the general energy consumption for different types of buildings. CIBSE Technical Memorandum 48 includes individual benchmarks for 29 different categories of non-domestic building (CIBSE, 2008). When comparing the categories in the CIBSE benchmarking guidance, it can be seen that hospitals are the 7th highest produces of carbon emissions and the 4th largest consumers of energy. In July 2013, the Department of Energy and Climate Change (DECC) produced a series of reports discussing energy consumption within the UK. When looking at energy consumption attributed to buildings, the domestic sector was responsible for consuming 43,153ktoe, the service sector was responsible for 19,027ktoe and healthcare, which is part of the service sector, was responsible for 1,700ktoe or 9% of the energy consumed in the UK service sector (Department of Energy & Climate Change, 2013).

2.1.3 Hospital End-use Energy Consumption

Figure 2.1 shows that hospitals have very large energy intensity, i.e. they use a lot of energy per unit floor area. One reason for this is that hospitals have a comparatively large air and space heating load (43%) to support their services which are provided 24 hours a day 365 days each year (Congradac et al., 2012). Figure 2.2 shows that compared to all the different buildings in the service sector, hospitals consume the largest part of their energy for heating. The next highest energy consuming area used in healthcare buildings is hot water, which is followed by lighting, catering, other and then computing. It is interesting that the results from the DECC report shows that healthcare buildings presently do not utilise mechanical cooling.

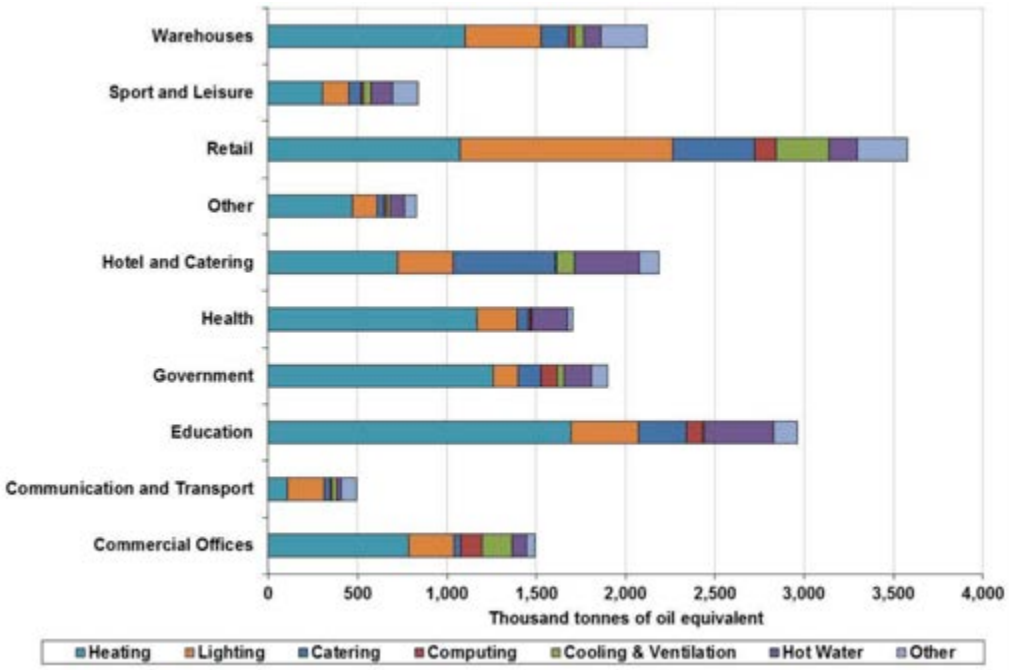


Figure 2.2 – Figure demonstrating the service sector energy consumption by end use and sub-sector, UK (2012) (Department of Energy & Climate Change, 2013)

The end-use distribution reported by DECC (2013) is further supported by Figure 2.3 from a document called "making energy work in healthcare" (Department of Health, 2006a). It shows that the energy use in hospitals is split into air heating, space heating, fans, hot water, catering, lighting, small power, refrigeration, sterilisation and humidification.

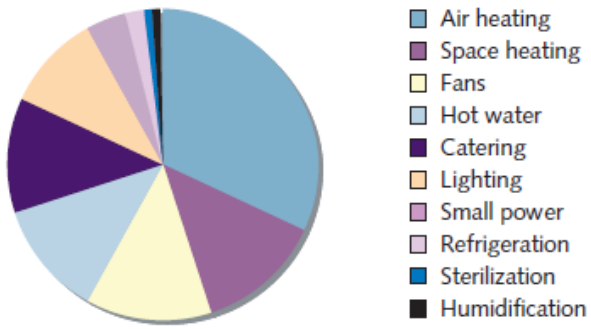


Figure 2.3 - Energy consumption in a typical hospital by end use (Department of Health, 2006a).

2.1.4 The future

One of the most influential reviews undertaken on the NHS has been, "High Quality Care for All" (Darzi, 2008). This review of the NHS highlighted some interesting points for the future direction of the NHS. Although it does not directly address the energy

consumption of the building stock, it does provide a framework for the future of the NHS that has implications for the energy consumption of the buildings.

It is the NHS's aim that *all* buildings are low carbon (NHS SDU, 2009), however this poses a problem. As Lord Darzi highlights, although the NHS has universally high standards, it does not aim to be uniform. The organisation is split into individual Trusts with the power to make distinct decisions suited to their population. This leads to NHS Trust's with a wide variety of buildings with different uses, and consequently different energy consumption. This creates a challenge to the implementation of energy efficient measures across the stock.

The report notes that the care of the UK's aging population is becoming an increasing financial burden for the NHS. The growing rate of admission to hospitals points to the need for the NHS to expand the size of their building stock to meet the larger demand for beds. One approach to increasing the number of beds on a hospital site can be found in Bradford Royal Infirmary, where modular buildings were added to provide more space for patients (Hinitt, 2008). In general, an increase in the floor area of the NHS building stock would increase the energy consumption. This has been demonstrated between 1999/2000 and 2004/2005 where a 14.1% increase in the size of England's estate resulted in a 7% increase in its total energy consumption (Department of Health, 2006b).

The function of hospitals will also change considerably. It is planned that care for specific diseases will be moved into specialist centres of excellence, where there will be the expert knowledge and specialist equipment in order to provide the highest quality care for each patient. Britain is moving toward relying more upon its knowledge economy to drive its finances, this and the demand for innovation within healthcare will mean that hospitals will be connected with more universities for the purpose of training and advancing research in the medical field. The move to specialist and educational hospitals with research centres will tend to increase the electricity demand of hospital buildings, due to the additional specialised equipment that will be fitted in the hospitals. This inference is supported by the NHS statistics which indicates that although fossil fuel consumption has decreased since 1999, electricity consumption has increased over the past years (Department of Health, 2006b).

Since the publication of the Darzi report, Britain has undergone severe economic changes. Despite this recession, the NHS report to have been successful in providing

a high quality service for its growing population, reducing, waiting times, increasing chance of recovery from debilitating diseases and gaining positive feedback in public surveys (NHS, 2014). The general challenges the NHS faced during the Darzi study are similar to those today, mainly increasing patient admission and an ageing population. However, a significant difference is that with the growth of mobile apps and the internet of things, programmes are being innovated which enable patients to manage their own care at home, reducing the need for admission to hospitals (NHS England, 2015).

The original NHS carbon reduction strategy, “saving carbon improving health” stated that the NHS aimed to reduce their carbon emissions 10% by 2015 compared to 2007 levels (NHS SDU, 2009). In 2015, the NHS met this goal by reducing their emissions 11% compared to 2007 (NHS SDU, 2016a) as well as reducing their carbon emissions 12% compared to 1990 levels (NHS SDU, 2016b) despite activity levels within the organisation increasing by 18%.

As predicted by Darzi, the NHS continues to become more specialised (NHS, 2014), and therefore electrical consumption has continued to rise, which is a concern as electrical consumption accounts for double the emissions as other fuel sources (Department of Health & Carbon Trust, 2015). Although the NHS have met their carbon reduction targets, the savings in building energy were small (4% reduction) with the majority coming from reduced spending on procurement (16% reduction) and pharmaceuticals (38% reduction) (NHS SDU, 2016a).

The NHS’s next target is 2020 where they need to reduce their emissions by 34% compared to 1990 levels. The current projections take into consideration expected government and international policy decarbonising energy and procurement pathways. Yet there are still interventions which the NHS must implement if they are to meet their goals (NHS SDU, 2016b). The literature states that refurbishing all NHS buildings using low carbon technology will reduce building energy consumption by 25% and replacing all NHS buildings with a super efficient stock will save another 25%, contributing up to 12% of the 2020 34% reduction in emissions goal (Department of Health & Carbon Trust, 2015; NHS SDU, 2010). Replacing the entire NHS stock is a huge task, and it is unlikely this will happen in the near future, nevertheless, to increase the efficiency of existing stock, the guidance has been updated in the latest health technical memorandum, EnCO_2de – Making energy work in healthcare (Department of Health & Carbon Trust, 2015). This guidance differs from the older

version as it has a special emphasis on the mitigation and adaptation of hospital buildings to climate change.

2.2 Hospital Building Performance

This part of the review identifies the various factors that influence the use of energy in hospitals. The literature indicates that the factors influencing building energy consumption can be split into three areas; buildings, services and occupants, which studies show have an equal influence on energy consumption in buildings (Baker & Steemers, 1996; Butala & Novak, 1999).

2.2.1 Building Design

The form of a building has a great impact on the amount of energy it consumes and can generally be categorised into two areas: firstly building design parameters and secondly engineering parameters. Building design parameters include, plan, section, facade design, orientation, position on site in relation to other buildings, and the organisation of functions in buildings. These parameters are important during the early stages of the architectural design process, as they are difficult to change once the building has been constructed. Furthermore from an energy perspective they influence the possibility of passive building design in terms of lighting, heating, cooling and natural ventilation. An example of an engineering parameter is the U-value of the walls, which has a great impact on the thermal properties of the building. New hospital building fabrics are to be built according to the standards set forth in the building regulations (HMGovernment, 2010)(Table 2.1). Over time the quality of the building fabric in hospitals have improved, with emphasis on lower U-values and less infiltration to reduce heat loss.

Area	*Limiting fabric parameters*
Roof	0.25 (W/m^2K)
Walls	0.35 (W/m^2K)
Ground	0.25 (W/m^2K)
Windows	2.2 (W/m^2K)
Permeability	10.0 ($m^3/h.m^2$)

Table 2.1 – Current building fabric regulations for non-domestic buildings (HMGovernment, 2010)

Section 2.1.1 identified a rich history of over 100 years of hospital building design. As can be expected, the energy consumption will vary with the various hospital design characteristics. A study undertaken in Greece identified that the energy consumption varies significantly between the category and function of building (Santamouris, et al.

1994). This section will take a closer look into the different design characteristics and consequential energy consumption of the various hospital archetypes in the NHS.

Nightingale/Pavilion Buildings

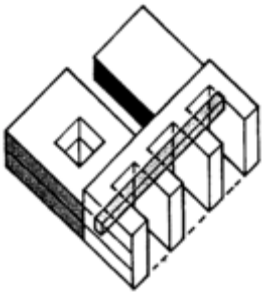


Figure 2.4 - Nightingale building form (James & Tatton-Brown, 1986)

Nightingale/Pavilion hospital buildings date back to the middle of the 19th century. They contained Nightingale ward layouts and were the main form of hospital building prior to 1948. The buildings utilise the spine and pavilion building design, which typically had north/south pavilions, which enabled the spaces building to be benefited from cross flow wind ventilation. Pavilion buildings can hold a number of different ward layouts, but the original Nightingale layout (Figure 2.5) consisted of having beds on either side of the ward in between operable windows providing varying levels of ventilation to the space. In addition to the windows, the original buildings utilised low level vents placed behind radiators to provide additional airflow (Lomas & Giridharan, 2012a) as well as high ceilings. A recent study found Nightingale wards can achieve ventilation rates of up to 30ach^{-1} (Gilkeson et al., 2011). These types of buildings are one of the primary naturally ventilated hospital building types in the UK. As such, additional literature has been reviewed on Nightingale buildings in section 2.4.2.

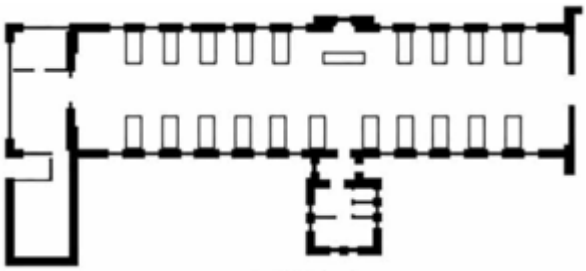


Figure 2.5 - Original Nightingale Ward layout (Short et al., 2014)

In regards to energy consumption, a study undertaken on a Nightingale building in Bradford found that this type of building had a modelled energy consumption of 25GJ/100m^3 (Lomas & Renganathan, 2012). This low consumption is a result of not needing mechanical ventilation due to the cross ventilation provided by the pavilions.

Deep Plan Buildings

Figure 2.6 - Example of deep plan hospital (Bing maps 2012)

Deep plan hospitals are characterised by high energy consumptions due to the need to rely wholly on electrical lighting and mechanical ventilation to supply the environmental comfort for occupants in the extensive area away from perimeter (Baker & Steemers, n.d.). Consequently this design has been stated as one of the key barriers to low-energy strategies being implemented in hospitals, (Department of Health, 2006b). This challenge has been acknowledged and addressed in a detailed study where the authors developed a natural ventilation cooling system which enabled deep plan buildings to have an energy consumption as low as 38 GJ/100m^3 [i] (Short & Al-maiyah, 2009).

1960's Towers

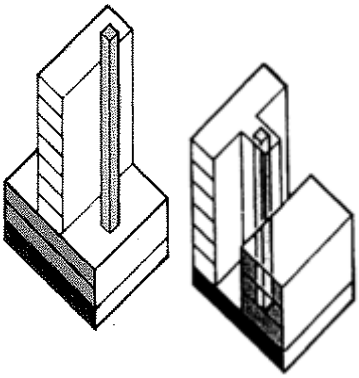


Figure 2.7 - Two arrangements of tower hospital buildings (James & Tatton-Brown, 1986)

Tower block hospitals were built in the 1960's to meet the NHS's aspiration to build district general hospitals to a capacity of between 1000-2000 beds as well as services including teaching, psychiatry, geriatrics and chronic sickness. The challenge of the multiplicity of services was solved by constructing upwards; placing nursing and patient care in the tower, clinical areas close to ground level and the support zone in the basement. In the 1960's mechanical ventilation was widely used in hospital design

[i] Energy demand in hospitals is often normalised by volume, to give units in GJ/100m^3.

due to the perceived benefits in reducing nosocomial infections (James & Tatton-Brown, 1986). Hence much of these buildings were fitted with air handling units providing mechanical ventilation. According to a recent study there are 50 tower block hospitals with at least seven storeys in the UK (Short et al., 2012).

The energy consumption of a ward of this building type was modelled in a recent study. The results indicated that it used 101GJ/100m^3, 46% to heat the fresh air, 38% for heated ceiling panels and 14% to drive the mechanical ventilation fans (Short et al., 2012).

Closed and Open Court

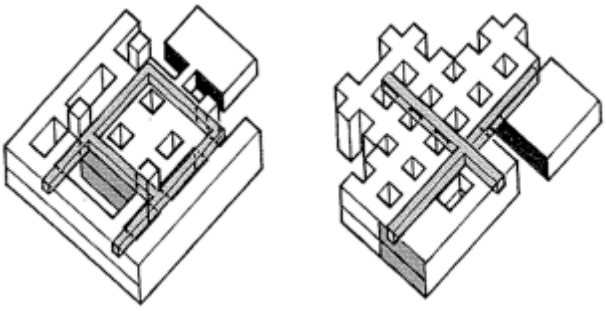


Figure 2.8 - Left closed court, 'best buy' design, Right open court nucleus (James & Tatton-Brown, 1986)

At present there are just over 100 closed and open court constructions in the UK. These types of hospital building are also known as nucleus buildings and were a method of designing hospitals popular in the UK from the late 1970's through to the early 1990's (Giridharan et al., 2013). The nucleus building was developed from the Best Buy and Harness projects, which aimed to standardise hospital building design on a national scale (James & Tatton-Brown, 1986). The crucifix/courtyard design's intention was to encourage natural ventilation and lighting from the courtyards. In addition to being naturally ventilated, the buildings utilised air handling units to create an overall mixed-mode ventilation strategy (NHS Estates, 1995b)

In the 1990's the NHS undertook a study into the sustainability of St Mary's; a new nucleus hospital that was fitted with energy saving features (see section 2.1.1). One of the highlights of the study was the finding that the new building was using 407kWh/m^2

(54GJ/100m^3) compared to 720kWh/m^2 (96GJ/100m^3)[i] which was the standard energy consumption for a nucleus building (NHS Estates, 1995a).

Modular Buildings

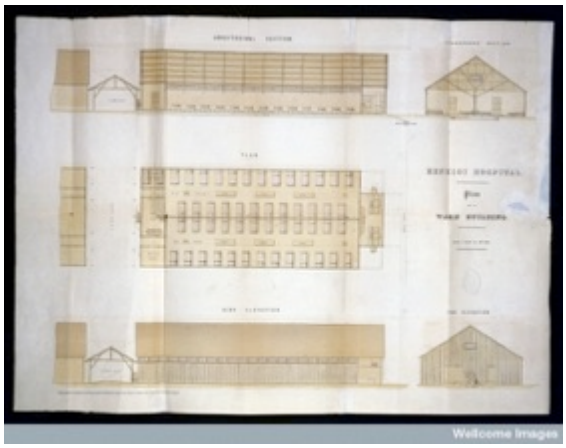


Figure 2.9 – Plans for the original Modular wards used in the Crimean war (Images.welcome.ac.uk)

The modular hospital building type is a prefabricated construction which is used for the function of a hospital. Generally they are multifunctional and the space can be adapted to fulfil the roles of a traditionally constructed hospital: from operating theatres and ward care to diagnostics and clinical assessment (Yorkon, 2010). The first modular hospital building was at Renkioi in Turkey, which was designed by Kingdom Brunel to provide an improved hospital environment for Florence Nightingale and her patients in the 1855 Crimean war (Brunel, 1855). The largest modular hospital in Europe can be found at Bradford Royal Infirmary (BRI) (Hinitt, 2008; Yorkon, 2010). This was constructed in 2004 and since then there has been even more demand for accommodation at BRI. The construction options available to the BRI facilities team were a modular or a three-floor extension building. The modular building was slightly more expensive but it offered the advantage of being completed in just six months compared to 18 months for the traditional construction technique (Hinitt, 2008).

One of the reasons modular building construction is much quicker than traditionally designed buildings is that the two important stages in the construction processes takes place at the same time. While the ground and foundations are being prepared on site, the different modules are being constructed in a factory. So by the time the foundations are ready, the modules are ready to be transported to the site for

[i] For the estimated conversion between kWh/m^2 and GJ/100m^3 it has been assumed that the floor to ceiling height is 2.7m; this is a general figure measured when visiting hospitals, it has been used for the conversion in every other chapter.

assembly. Another advantage, which adds to reduced construction time, is the high quality standard of the modules. In the factory the construction of the modules begins from the steel frames all the way through to the complex mechanical, electrical and medical gas systems. These aspects of the building are checked and tested during the construction and finally verified before being shipped to site. In addition to this, clients are encouraged to visit the factory to view their product before it is finished to assure the building is meeting their specifications. All of this saves the time which would otherwise be spent checking and testing the building once it has been constructed on site. Furthermore, the high quality of construction ensures that the buildings are more air tight than traditional buildings. When transported to site, the modules are erected into position using cranes, this means that these buildings can be fitted into the most restricted of spaces. The erection of the modules usually takes a few days and is normally scheduled for weekends to avoid disruption to other services. Other than these times, the construction is less disruptive than the traditional methods as due to fewer workers, there is less congestion in car parking and traffic. There is also a lot less noise and dust pollution during the construction process. Finally, because of reduced construction activity on site there are higher levels of health and safety for patients, staff and visitors (ModuleCO, 2013).

Modular buildings generally come fitted with high levels of insulation, which helps improve energy efficiency (Rogan et al., 2000). There has however been very little published research on modular hospital building energy consumption, let alone anything stating the quantitative performance of this type of building.

When assessing the energy performance for each of these building types, some of the studies have energy performance data from modelled studies. However, it seems to be the case that with the exception of St Mary's nucleus building, there is a lack of research identifying the energy consumption of each of these buildings types from measured data.

2.2.2 Occupancy

The UK NHS building stock can be broken down at three different levels. The organisational level which covers the different types of NHS Trusts, i.e. Acute – large, Acute – teaching, Primary care, ambulance etc. (HSCIC, 2013). The site level, in which the typical hospital site consists of a multiplicity of buildings each of differing age,

use, construction and layout (Adderley, 1989). Then the hospital building level, which includes the different spaces inside a typical hospital building.

The NHS uses a software tool called the activity database (ADB) for briefing and designing their healthcare environments. It includes information on, activities, personnel, recommended size, engineering requirements (i.e. thermal comfort), schedule of equipment, and graphical room layout (Department of Health, 2012). In a recent study the ADB was used to define the categories of spaces within hospitals (Short & Al-maiyah, 2009). The paper mentioned that a typical hospital will have between five and ten room types, but it chose to focus on six. These six were, Waiting area, Patient single bedroom, Examination room, Treatment room, Imaging room and Operating Theatre. Another source, Hospitals - Design and Development (James & Tatton-Brown, 1986) specifies five areas into which the hospital can be divided.

1. Nursing Area – patients stay and are looked after, in temperate climates the spaces are often naturally ventilated.
2. Clinical – diagnostic and treatment facilities, often artificially ventilated and associated with technical equipment required for procedures on patients.
3. Support Zone – kitchens, cafeteria, laundry boiler house, staff changing, stores, workshops and other industrial plants.
4. Offices – these are similar to general office buildings.
5. Teaching Facilities – these include lecture theatres and research facilities.

The ADB seems to focus more on the areas of the hospitals that patients come directly in contact with, i.e. the nursing and clinical areas spoken of by James & Tatton-Brown. In fact nursing areas, clinical and operational theatres are the areas which are most specific to hospital buildings, the others are found in other non-domestic buildings and there is an abundance of research on low carbon offices and schools. Wards are the centre of the hospital, canteens are there to provide food for people visiting or working on wards, most people who go into operating theatres end up in wards and the offices are essentially there to support the work which takes place on wards. Nevertheless, the weight of research conducted on hospital buildings is in the sphere of operating theatres, this fact is demonstrated, especially in the field of ventilation (Beggs et al., 2008).

It has been stated that “Wards are particularly worthy of study because they occupy a substantial fraction of the floor area of hospitals and thus there is great potential for replication of a low-energy and resilient design solution,” (Lomas & Ji, 2009). This

paper and Short & Al-maiyah, 2009, have paved the way for a number of other papers which have since been published on the impact building design has on hospital ward energy consumption and internal environmental conditions (Adamu et al., 2012; Lomas & Giridharan, 2012a, 2012b; Short et al., 2012). These studies will be discussed in detail further on in this review.

There are a number of different ward designs, each having their particular strengths and weakness from the occupant perspective. Three of these wards were described in a study, linking UK ward design to occupant satisfaction (Hurst, 2008). The first, Bay wards have been adopted in the past quarter century in the UK and are characterised by a central nurses station and peripheral rooms housing a small number of beds. The second, Nightingale wards, are the traditional design and the primary choice up until the 1950's. They have large rooms where beds are placed along the edge and a centrally placed nursing station. Thirdly, Hub and Spoke designed wards have the nurses station centralised and surrounded by ward spaces. In these wards, the equipment is usually stationed in the nurses station which can lead to heat gains and hence the need for cooling. This pattern of overheating in nurse stations has been identified in various building types i.e. nucleus (Giridharan et al., 2013a) and tower (Lomas & Giridharan, 2012b).

There is a general emphasis to move from multi-bed wards to single bed rooms (Darzi, 2008). New wards are expected to include half of its beds as single rooms with the purpose of improving infection control, privacy and the overall quality of hospital stay. Most UK hospitals buildings have at least one single room for isolation however a study suggested that patients preferred multiple occupancy rooms. In 1982 it was found only 11% of people wanted to stay in single rooms due to missing the company offered in multi-bed spaces. However, it was also found that those who did stay in single occupancy rooms were more satisfied at the end of their stay than those in bay wards (Hurst, 2008).

A handful of studies have been conducted on isolation rooms with the weight of them focusing on their ventilation systems. What is particular about isolation rooms is their need to be negatively pressurised for infectious patients and positively pressurised for patients who are immune compromised (CDC, 2003). Negatively pressurised Isolation rooms are fitted with ventilation systems which extract air and provide the pressure differential between the isolated space and the surrounding rooms and corridors. This pressure differential and the air tightness of the space only allows air to leak inwards

preventing outward escape of airborne contamination (Tung et al., 2009). Cheong and Phua conducted an investigation into the most effective strategy for removing pollutants from isolation rooms. They used computational fluid dynamics (CFD) to model isolation rooms varying the positions of the supply and extract ducts. The results demonstrated, that the most effective method was to have clean supply air flow from the cleanest zone (near the health carer) into the contaminated zone (patient) with the extract grill located at low level near to infectious source (Cheong & Phua, 2006).

Operating theatres need to have very specific indoor environmental conditions (Balaras et al., 2007). As a consequence, many papers have been published documenting research on their particular indoor environmental needs, which have been reviewed in detail in a literature review on hospital thermal comfort (Khodakarami & Nasrollahi, 2012). In hospitals, priority is given to the internal environment of the patient over energy efficiency (Saidur et al., 2010) and there is the "*viewpoint that patients should have maximum comfort at all the necessary conditions* " (Congradac et al., 2012).

2.2.3 Services and Internal Environmental Criteria

Ensuring the patient environment is optimal for recovery is the most important aspect of hospital building services. In order to achieve suitable conditions, thermal comfort, air quality and lighting levels need to be closely controlled. This section of the literature review assesses the different design criteria that are available for the hospital internal environment.

Thermal Comfort

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" (Fanger, 1970). It is the job of hospital designers to use heating ventilation and air conditioning combined with natural systems to create spaces wherewith the highest possible percentage of its occupants experience thermal comfort. There are two main approaches for specifying thermal comfort, the Fanger (static) method and the adaptive method (Nicol, 2002).

The widely used static method originated with the work of Fanger, one of the pioneering researchers in the field of thermal comfort who developed an equation to model a thermally comfortable environment. The equation was based upon the

principle that there are three basic conditions which must be fulfilled for thermal comfort to be achieved. The first condition is that there must be a heat balance between the person and their surrounding environment with this heat balance being split between the personal variables of; activity level and the thermal resistance of clothing and the environmental variables of; air temperature, mean radiant temperature, relative velocity and humidity (Fanger, 1970). The second and third conditions to be fulfilled involved the mechanisms whereby the human body can naturally adapt to find comfort in various thermal conditions. The thermo-regulatory system can maintain the appropriate deep-body temperature in a wide range of combinations of activity level and environmental variables (CIBSE, 2006b), generally this is done through sweating and raising skin temperature which are both a products of physical activity (Fanger, 1970).

Index Value	*Thermal Sensation*
+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

Table 2.2 – Predicted mean vote thermal sensation scale (CIBSE, 2006b).

The equation developed was based on laboratory studies testing how individuals rated a particular thermal environment, relating their experience of thermal comfort on a thermal sensation scale (Table 2.2). The results of the test led to the relation of the thermal equation to the thermal sensation scale enabling one to identify how the variables could be manipulated to create the optimal thermal environment. The rating system is known as the predicted mean vote (PMV), a grade of the perceived levels of comfort of a large group in the environment. As humans differ in their physical response to temperatures, there were slight variations in the perceptions of the environment, meaning that at any point in time, there would always be persons who were dissatisfied with the environment, this led to a rating called the predicted persons dissatisfied PPD (Figure 2.10) (CIBSE, 2006b).

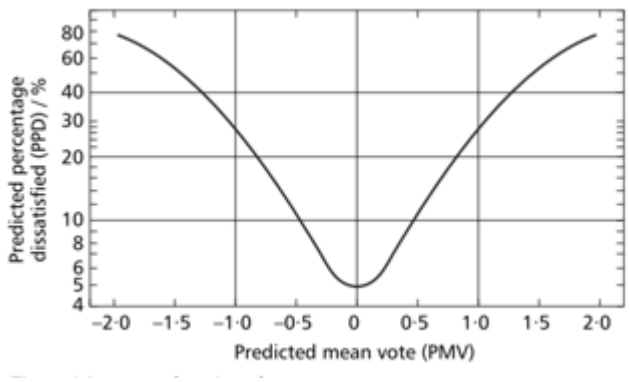


Figure 2.10 - PPD as a function of PMV (CIBSE, 2006b).

A study (Lomas & Ji, 2009) investigating natural ventilation in hospital buildings looked at the different thermal comfort criteria applicable in a healthcare setting. The authors stated that defining suitable overheating criteria was more complicated than expected. The paper pointed out that static thermal comfort criteria for hospitals could be found in CIBSE Guide A (CIBSE, 2006b) and Heating and Ventilation Systems Health Technical Memorandum 03-01 (HTM-03-01) (Department of Health, 2007a). In these sources the Fanger model was used to set specific temperature boundaries to indicate what temperatures are acceptable for the particular indoor environment (Table 2.3). These temperature criteria correspond to a mean predicted vote falling within ±0.25 of neutral on the thermal sensation scale (Table 2.2), taking into consideration the people have the regular activity and clothing level for the particular space (CIBSE, 2006b).

Source	*Hospital Area*	*Winter Operative Range Temp (˚C)*	*Summer Operative Range Temp (˚C) (AC buildings)*
CIBSE Guide A	Bed heads/wards	22-24	23-25
	Circulation spaces	19-24	21-25
	Consulting/treatment	22-24	23-25
	Nurses station	19-22	21-23
	Operating theatres	17-19	17-19
HTM-03-01	General Wards, Single Room, Infectious Disease Isolation room;	18-28	18-28
	Critical Area, Birthing Room, SCBU, Operating Room,	18-25	18-25

Table 2.3 – Fanger temperature criteria for hospital buildings (Department of Health, 2007a)

The criteria given in Table 2.3 is in the form of operative temperature, an important metric which combines air temperature with the mean radiant temperature of a room for the assessment of thermal comfort. The mean radiant temperature, is defined as the uniform temperature of a black enclosure (imaginary room), which would result in the same heat exchange by radiation as the actual non-uniform enclosure under study. The mean radiant temperature can be calculated from measured values of the temperature of the surrounding walls and surfaces and their position with respect to the person. Cold walls have the impact of reducing the operative temperature due to their effect of reducing the mean radiant temperature of the room (Atmaca et al., 2007). It is important to consider radiant temperature in thermal comfort as radiant heat exchange takes place between the human body and its surroundings, just as between any two physical objects (Fanger, 1970). Thus cold walls may cause a person to feel thermal discomfort even though the air temperature is at acceptable levels (Atmaca et al., 2007). The asymmetry of radiant temperatures also plays a role in thermal comfort (Fanger, 1970). An unequally warm or cool surface can create an unbalanced distribution of heat over ones body that can lead to feelings of discomfort.

Thermal models are often used alongside the overheating criteria to assess the risk of overheating. They generate thermal performance using specific weather data, of which there is generally two types; the Design Summer Year (DSY) which represents a very hot year, taken as the third hottest summer in the past 20 years and the Typical Reference Year (TRY) which is composed of the most average months from the 20 or so past years of data (Levermore & Parkinson, 2006). The overheating criterion HTM-03-01 (Table 2.4) does not actually state the weather data to be used when assessing the thermal performance of a space using thermal simulation, CIBSE on the other hand specifies that it be used with the design summer year.

The thermal comfort connected to summer overheating of hospital wards has been discussed. As well as summer thermal comfort criteria, Table 2.3 shows the winter operative temperatures. The NHS document HTM-03-01 gives a rather broad recommendation of 18-28°C. Lowering the set-point temperature in residential and commercial buildings during the winter months has the impact of reducing the total energy consumption of the building (Hirst, 1982; Moon & Han, 2011; Vine, 1986). Therefore using the HTM-03-01 range, an energy manager would set the set-point temperatures to 18°C. However it is not clear whether this temperature is suitable for facilitating the recovery of hospital patients, as the guidance states no research on which the temperature choices are based. CIBSE Environmental Design (Guide A)

recommends that for wards, the temperature be between 22 and 24°C. These numbers have been based on the fact that patients have a low metabolic equivalent rating of 0.9(MET). This is the same level rated for bedrooms indicating a low level of physical activity.

Source	*Space*	*Summer Peak Temp (˚C)*	*Overheating Criterion*	*Thermal Modelling weather file*
CIBSE Guide A	Offices, Dwellings, Schools	28˚C	1% annual occupied hours over 28˚C operative temperature	DSY
	Dwellings – Bedrooms, (Night time criterion)	26˚C	1% annual occupied hours over 26˚C operative temperature	DSY
HTM-03-01	Patient areas	28˚C	Do not exceed 28˚C for 50hours in year	-
CIBSE TM36	Office, Dwellings	25˚C	5% annual occupied hours over 25˚C operative temperature	

Table 2.4 – Overheating criteria, Non Air conditioned buildings, [DSY = design summer year] (CIBSE, 2006b; Department of Health, 2007a)

The static/Fanger model is based on the science of people responding to their external environment through physics and physiological heat transfer. In contrast, adaptive thermal comfort design criteria work by varying the acceptable indoor air temperature according to the moving average of the outdoor air temp (Holmes & Hacker, 2007). Unlike the static model, this emphasises that people can adapt to the temperatures in a building, taking into consideration their particular circumstances, i.e. if they are wearing warm clothing or if there is a cool drinks machine in the workspace. The literature is clear that the adaptive approach is more successful with low carbon design, especially natural ventilation, as the internal temperature varies according to the outside temperature to a greater extent when a building is naturally ventilated. The thermal comfort criterion chosen when designing a building can determine how much energy can be saved. This approach is well documented and many authors agree on this point, (Holmes & Hacker, 2007; Moujalled et al., 2008; Nicol & Humphreys, 2009).

A further study by Lomas and Giridharan, (2012) investigated the impact of overheating in UK hospital wards. The authors identified the static criteria discussed above, as well as adaptive criteria which were sourced from CIBSE guide A, ASHRAE 55 standard and British standard BS EN 15251. The running mean of ambient temperature is used for the CIBSE and BS EN 15251 standards and reflects the daily mean temperatures of the previous days, with the most recent having the greatest influence on the mean, the day before having less influence, etc (British Standard,

2007). The running mean temperature is used as occupants tend to adapt to the temperature of the past few days.

The boundaries for the ASHRAE criterion are lower than the CIBSE and BS EN 15251 Cat I which are similar, with the exception that the CIBSE criterion only goes up to a running mean temperature of 25˚C (Figure 2.11). In general, Lomas and Giridharan found that BS EN 15251 had advantages when assessing the indoor temperatures of free-running buildings, i.e. being able to accommodate monitored and predicted performance, being functional up to 30˚C (running mean) and having specific category boundaries applicable for the various parts of the hospital (Lomas & Giridharan, 2012b).

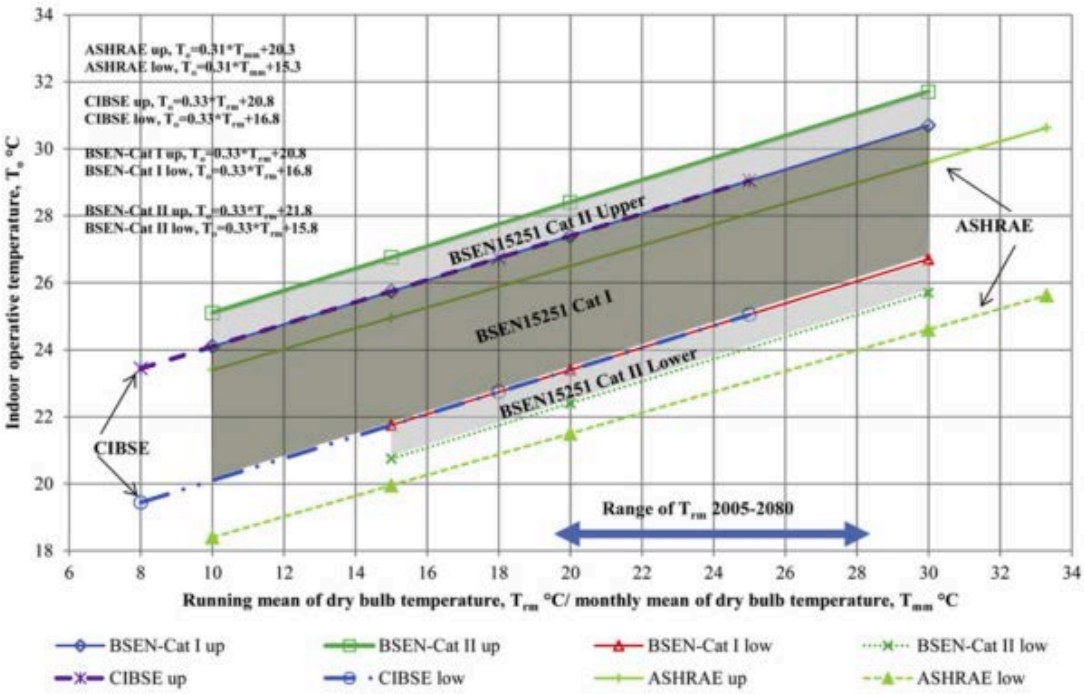


Figure 2.11 - Comparison of adaptive thermal comfort standards: equations, envelopes, boundaries and limits of applicability (Lomas & Giridharan, 2012b)

A well-rounded review on the literature relevant to thermal comfort in hospitals was carried out by Khodakarami and Nasrollahi. After reviewing the literature they concluded that further research needed to be conducted to identify the comfort requirements for different groups of people who must stay in a single room. Furthermore, they recognised that there were no publications on the relationship between thermal comfort conditions, the healing of patients, and levels of staff productivity in hospitals (Khodakarami & Nasrollahi, 2012).

Ventilation

Ventilation, the process of supplying air to, or removing air from a space for the purpose of controlling air contaminant levels, humidity or temperature within a space (ASHRAE, 2001) is another variable highly influential on the energy consumption of hospitals. It can be provided through mechanical means using fans or through the use of natural wind or buoyancy forces (CIBSE, 2005b). Ventilation is required to meet the UK's building regulations, and in hospitals it is specifically used for keeping the air at a level which is deemed fresh by the majority of occupants, maintaining thermal comfort, removing gases (labs, operating theatres), reducing transmission of infection and the control of humidity (Department of Health, 2007b).

In general, non-domestic building's (e.g. schools, offices etc.) ventilation systems need to be designed to reduce or eliminate the occurrence of building occupants suffering from symptoms of sick building syndrome (SBS). SBS symptoms vary from; eye nose and throat irritation, dry mucous membranes and skin, mental fatigue, headaches, higher frequency of airway infections, coughs, wheezing, nausea and more (Seppänen et al., 1999). Hospital ventilation systems also need to be designed to reduce these symptoms, however, in contrast to general non-domestic buildings, hospitals are highly sensitive areas holding people with varying levels of illness making it a place where disease can easily spread, therefore one of the main drivers for ventilation in hospitals is infection control. In the past there has been some debate into the extent to which diseases are transferred through the air (Beggs, 2003) nonetheless the general consensus is that infectious disease can be transferred through aerial dissemination (Li et al., 2007).

When infected patients, shout, cough, laugh and even speak, droplets carrying infectious agents are released into the environment. These particles come in different sizes, which have various implications on infection control. Large particles, also known as droplets, tend to settle within a close radius (1m) of the patient (ASHRAE, 2014) whereas small particles are liberated into the air and easily evaporated into droplet nuclei which can stay in the air for an indefinite amount of time enabling them be transported long distances (Beggs, 2003).

A review on aerial dissemination of pathogens within hospital wards has shown that in these spaces pathogenic organisms are frequently liberated into the air in relatively large quantities (Beggs et al., 2008). Therefore, an important part of the design of

hospitals is to make these spaces safe from cross infection through the transport of airborne pathogens. Diseases which can be transferred through this medium include; Tuberculosis (Menzies et al., 2000), measles (Bloch et al., 1985), chickenpox (Gustafson et al., 1982) and smallpox (Wehrle et al., 1970).

Airflow rates play a key role in reducing the infection risk through dilution, removal of contaminated air, and provision of pressure differentials (ASHRAE, 2014). Riley derived an equation which links the risk of infection to ventilation (Riley et al.,1978). When the variables are put into the equation, a graph (Figure 2.12) is produced which shows that as ventilation rate increases, the rate of infection decreases (Qian et al., 2010). The world health organisation also found similar results as well as the fact that rates of infection reduce the further you move away from the source due to the dilution of air (WHO, 2009).

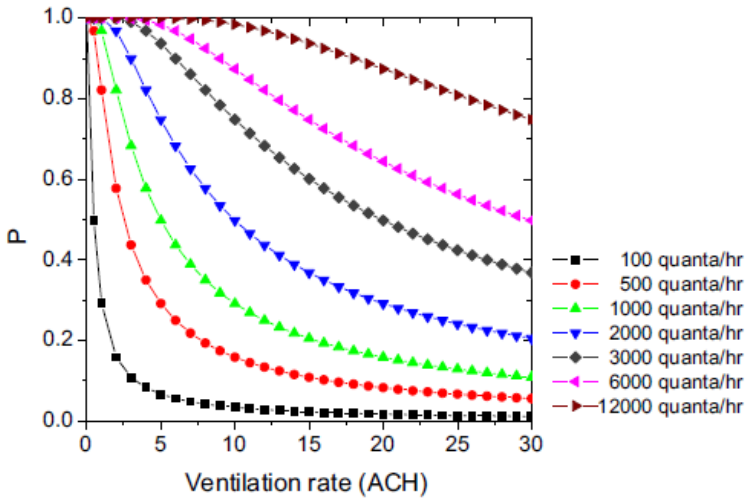


Figure 2.12 - The relationship between infection risk, ventilation rate and the quanta[i] generation. The unit of quanta generation is quanta per hour (Qian et al., 2010).

The caveat to high ventilation rates is that they naturally lead to increased energy consumption for fans, heating and perhaps cooling, due to the larger volume of air needing to be supplied and conditioned. A recent study stated that unless a highly efficient air handling system is used, the accepted HTM-03-01 standard for ventilation may be incompatible with the main energy targets (see section 2.3.1) for hospitals (Short et al., 2012). With the desired move to a low carbon economy, the question is often raised are such high ventilation rates necessary?

[i] A quantum (plural: quanta) of infection is the dose which is necessary to cause infection to a new susceptible and may be one or more airborne particles (Qian et al., 2010).

A cohort of researchers carried out literature reviews to identify the impact air flow rates have on reducing infection risk (Li et al., 2007; WHO, 2009). It was identified that as ventilation was reduced, the rate of infection risk increased. Much of the literature reviewed was unable to measure both ventilation rate and infection risk, however, one study investigated hospital ventilation and the risk of tuberculosis infection on health care workers. They measured tuberculin on the skin of participants to identify risk of infection and they measured the rate of ventilation to patient care areas by using the tracer gas technique. The results showed that high risk was associated with general or non-isolation patient rooms with levels of ventilation below $2ach^{-1}$ (Menzies et al., 2000).

A recent paper published (Li et al., 2015) investigated low energy ventilation systems in hospitals. It found that there were a number of useful methods through which energy consumption could be reduced while possibly maintaining low infection transmission rates. Some of these included, natural ventilation, ultraviolet air disinfection (UVGI), and personalised ventilation. Natural and personalised ventilation is discussed in section 2.4.2, UVGI is a method of using ultraviolet light to clean the air, which can be applied inside ventilation air handling units or in wards themselves (ASHRAE, 2014). The paper did mention that the uncertainty of transmission route for respiratory pathogens provides difficulties in choosing the most effective engineering control strategy (Li et al., 2015) and that further multidisciplinary studies are necessary to truly identify if some of these methods work in a clinical setting.

As well as looking at ventilation rates, researchers (Li et al., 2007; WHO, 2009) also looked at the effect of airflow patterns, which is the movement of air within a building due to natural and fan forces, on infection control. Five conclusive studies were identified that demonstrated the link between airflow patterns and the spread of disease. All outbreaks in studies occurred in healthcare environments suggesting the importance of air movement patterns in healthcare buildings. It was concluded that there was strong evidence to demonstrate the association between air movement and spread of infectious disease. In all five studies, it was found that individuals at considerable distance from the disease source were infected via the airborne transmission route. The studies showed that the spread was directly related to building design. Placement of heaters, positively pressurised ward spaces and inoperative return air outlets all contributed to the spread of air-borne disease (Li et al., 2007).

One of the most effective ways to control infection risk is the use of isolation rooms that use pressure differentials to control the direction of the flow of air. Positive pressure rooms protect susceptible individuals from infection, and negative pressure rooms prevent infected patients from transmitting their disease to other occupants (The Stationery Office, 2005). In the past, these spaces were designed with the ability to change the pressure from negative to positive, this practice has been out dated due to the risk of the system not being controlled correctly and infectious particles being transferred in the wrong direction (The Stationery Office, 2005). As well as negatively pressurising isolation rooms, another design practice often used in the UK is positively pressurising corridors to stop the transfer of airborne pathogens into these spaces. Evidence for the usefulness of this method is found in a study undertaken by Tang et al. in which a patient infected with smallpox, placed in a negatively pressurised isolation room, infected a nurse who passed medication through door (without entering the room). This demonstrates that even though the room was negatively pressurised, the virus was still able to escape into corridor area thus the authors recommended that as well as negatively pressurising isolation rooms, the surrounding areas within the building should also be positively pressurised (Tang et al., 2005).

There are differing approaches to ventilation in the UK and US. Beggs 2008 describes how UK hospitals generally have multi-bed rooms whereas US have single or double bed rooms. In the UK it is common practice to naturally ventilate hospital wards (CIBSE, 2005b) compared to the US whose standard practice it to use air-conditioning as they often cannot naturally ventilate for large portions of the year. Due to the prevalent use of air-conditioning, recirculation of indoor air through high quality filters is used as a key part of the ventilation systems energy saving strategy. The use of filtration has been named as the most important factor in infection control in US hospitals. High efficiency particulate arresting (HEPA) filters are the most commonly used due to their quoted 99.97% efficiency rating (CDC, 2003).

Ventilation, especially air-conditioning, not only impacts air quality but also thermal comfort and humidity levels. In general, the literature shows that the effect of temperature and humidity on pathogens is unknown (Li et al., 2015). Nevertheless, a few studies seem to indicate that higher humidity levels reduce the rate of infection (Schulman & Kilbourne, 1962). For example, the smallpox vaccinia virus can survive for long periods when relative humidity is low. In a study, it was found that when the building was heated, strong air currents were produced which disseminated virus

particles through the building and that low relative humidity favoured their survival (Wehrle et al., 1970).

Area	*Type of ventilation*	*HTM-03-01 (ach^{-1})*	*AIA (ach^{-1})*
General Ward	S/N	6	6 or 4[i]
Single Room	S/E/N	6	6 or 4
Critical care	S	10	-
Infectious disease isolation	E	10	12
Birthing Room	S & E	15	15
Operating Theatre	S	25	15

[i] *Ventilation rate for general wards or single rooms can be reduced to $4ach^{-1}$ when supplemental heating and/or cooling systems are used.*

Table 2.5 - Ventilation rates from two main sources of hospital ventilation guidance, (S=supply, E=extract, N=natural ventilation)

The building regulations Part F – 2010, point out that the guidance to be followed in the design of hospital ventilation systems is HTM-03-01: Specialised Ventilation for healthcare premises (Department of Health, 2007a). Another source of guidance for hospital ventilation rates is the American Institute of Architects (AIA) – Guidelines for Design and Construction of Healthcare Facilities (AIA, 2001). This guidance has been included in Guidelines for Environmental Infection Control in Health-care Facilities (CDC, 2003). The HTM-03-01 guidelines are specified for the UK and the AIA guidelines for the US. The recommended hospital ventilation rates from these two sources are very similar with the main difference being that the recommended $6ach^{-1}$ for the US includes some re-circulated air whereas the UK requires full fresh air. Table 2.5 shows how a ventilation criterion varies according to room type whereas Table 2.6 demonstrates the different criteria available for hospital wards. It illustrates that the literature provides guidance for determining the air quality of a space in three main units, air changes per hour (ach^{-1}), litres per second per person (l/s/p) and CO_2 parts per million (CO_2 ppm). In terms of air changes per hour, the weight of the guidance suggests $6ach^{-1}$ is a reasonable figure.

Source	*Room density*	*Ach^{-1}*	*L/s/p*	*CO_2 above ambient levels (ppm)*	*Reference*
CIBSE/Building Regs	-	-	10	-	(CIBSE, 2006b; HMGovernment, 2010)
HTM-03-01	-	6 [i]	10 (odour dilution)	-	(Department of Health, 2007a)
BS EN 15251/13779	-	-	High >15 Medium = 10-15 Moderate = 6-10	<350 500 800	(British Standard, 2007; Technical Committee CEN/TC 156, 2006)
ASHRAE/ANSI	10 p/100m^3	-	13	700	(ASHRAE, 2001)
AIA guidelines	-	6 [ii]	-	-	(AIA, 2001)

[i] *no recirculated air*
[ii] *including recirculated air*

Table 2.6 – Comparison between IAQ criteria guidance for hospital ward spaces

When comparing the guidance for minimum ventilation rates in hospital wards to those recommended for other building types, it is apparent that they are very similar. The CIBSE guidance recommends that hospitals wards and other buildings i.e. school rooms, lecture theatres, offices, with the exception of kitchens and bathrooms are provided with 10l/s/p (CIBSE, 2006b). This suggests that special consideration is not being given to infection control. HTM-03-01, the British regulation standard for ventilation, also suggests 10l/s/p but recommends that isolation rooms with filtration are used to increase infection control for infected patients (Department of Health, 2007a). The final guidance applicable for UK buildings is BS EN 15251, this standard provides recommendations in three categories. The first is Cat I “high level of expectation”, which corresponds to a 15% of persons dissatisfied and is recommended for spaces occupied by fragile and sensitive people, the second is Cat II a “normal level of expectation”, and the third is Cat III an “acceptable” level, which corresponds to new and existing buildings respectively (British Standard, 2007). The guidance states that the ventilation rates and CO_2 levels are based upon removing bio effluents produced by occupants and pollution from the building and systems. Although Cat I may seem well suited for hospital patients due to the fact that patients are generally fragile and sensitive, it is clear that, like the other standards, infection control has not unduly influenced the recommended ventilation rates, and therefore there remains a degree of uncertainty in regards to applying the criterion in a hospital setting.

As CO_2 levels and ach^{-1} have been used as an indicator of IAQ, it is important to understand more about the relationship between CO_2 levels, air flow rates and indoor air quality in hospitals. There are a number of methods for measuring the flow rate of ambient air coming into a building, the most common of these being measuring the decay rate of a tracer gas over time, which if undertaken correctly can produce less than 10% error (Guo & Lewis, 2007). Sulphur hexafluoride (SF6) was widely used as it satisfies all the requirements of a good tracer gas (Cheong & Phua, 2006) but climate change and health and safety concerns now argue against SF6 as a tracer. The downside of tracer gas techniques is that they are complex, expensive (Nabinger et al., 1994) and generally require rooms to be vacated by occupants (Persily, 1997), which is usually not possible in a hospital setting.

Another method that can be used to estimate the ventilation rates of a space is equilibrium analysis, which is based upon the mass balance of CO_2 inside and outside of a space (Nabinger et al., 1994). If one knows the number of people in a space and can measure the CO_2 levels inside and outside of the space, one can use the formula (Equation 3.6) to estimate the outdoor airflow into a space (Lu et al., 2010).

The method is useful, but limited in its accuracy as there are many conditions that need to be fulfilled in order to enable accurate predictions (Persily, 1997).

1. The CO_2 concentration must be uniform throughout the space.
2. There must be no airflow from another zone to the space i.e. the space must be isolated from other spaces except outside.
3. The CO_2 generation rate must be constant and known.
4. There must be constant outdoor CO_2 levels.
5. The ventilation from outdoors must be constant, i.e. mechanical ventilation should not be adjusted and outdoor weather conditions should be stable.

In addition to these conditions it is also essential that indoor CO_2 concentrations are at equilibrium, which means that the outdoor CO_2 levels, air flow rate and indoor CO_2 generation rate are constant for a long enough period of time that the indoor concentration stabilises to a constant value. (Persily, 1997).

The time it takes to reach equilibrium is dependent upon the rate of ventilation for the space. The lower the air change rate, the longer it takes for the space to reach equilibrium (Nabinger et al., 1994). When air change rates are 0.25 ach^{-1} or lower, it can take longer than 12 hours to reach equilibrium. Furthermore, the time demonstrated in Figure 2.13, is based on constant CO_2 generation levels, which is

difficult to achieve in a realistic environment as occupants are always entering and leaving rooms (Nabinger et al., 1994). This suggests that in a practical setting it may take longer to reach equilibrium, or equilibrium may never be reached at all.

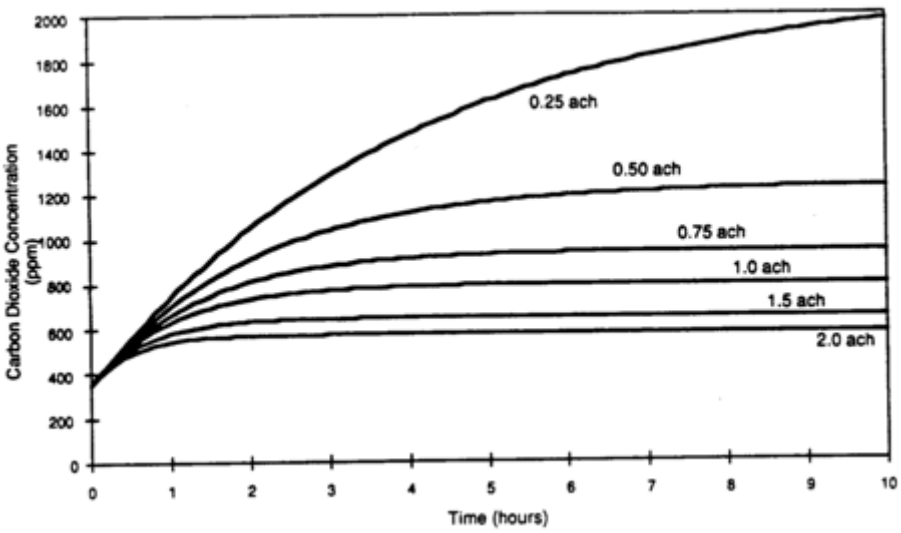


Figure 2.13 – Carbon Dioxide build-up as a function of air change rate (Generation rate =5.3x10^{-6} m^3/s; Outdoor concentrations = 350ppm; Volume per person based on ceiling height of 3m; Occupant density of 7 people/100m^2) (Nabinger et al., 1994)

Due to the CO_2 generation levels not being constant long enough for equilibrium level CO_2 concentrations to be established, lower measured CO_2 concentration levels are generally used in the estimation (Nabinger et al., 1994), which will result in calculating higher ventilation rates. This being acknowledged, one practical way of using this method is for determining an upper bound on the ventilation rate, confirming the inadequacy of a ventilation system, but not necessarily its adequacy (Persily, 1997).

CO_2 may be able to give rough indications of the air change rate in a space, however, it is important to identify the extent to which CO_2 levels are a true indicator of IAQ in hospitals. In general, buildings studies have correlated CO_2 levels with increasing symptoms of sick building syndrome. Reducing the difference between indoor and outdoor CO_2 levels had a drastic effect on reducing the prevalence of the symptoms of dry eyes, sore throat, sneezing and wheezing (Erdmann & Apte, 2004) and in a review of 21 studies primarily to do with offices, at least half of the literature suggested that the risk of sick building syndrome symptoms continued to decrease significantly with decreasing carbon dioxide concentrations below 800ppm (Seppänen et al., 1999). Despite these studies, the literature reveals a degree of uncertainty between the relationship of CO_2 and SBS, with studies suggesting no significant relationship between CO_2 levels stating that increases in SBS may be to do with factors other than

CO_2 levels i.e. contaminants not derived from humans; such as those from materials used in the buildings construction, carpets, wall paint etc. (Persily, 1996 & 1997).

In an attempt to reduce this uncertainty, researchers have isolated CO_2, testing the gas on people in a controlled environment. A study conducted in Hungary, tested 10 peoples' mental performance and comfort while varying the CO_2 levels in a test chamber. The results showed that occupants deemed the air unpleasant and became more exhausted when CO_2 concentrations were close to 3000ppm. Furthermore, occupants performed worse on mental tasks at 3000ppm compared to 600ppm and it was identified that cognitive function required more effort when CO_2 levels were higher (Kajtár & Herczeg, 2012). A second study built upon Kajtár's work by assessing the direct effects of exposing 22 participants to CO_2 levels of 600ppm, 1000ppm and 2500ppm in an office like chamber. The results identified that moderate reductions in decision making ability were recorded when CO_2 levels rose from 600ppm to 1000ppm and large and significant reductions in decision performance occurred when CO_2 levels increased from 1000ppm to 2500ppm (Satish et al., 2012; Fisk et al., 2013).

As well as the effects of increasing CO_2 levels on cognitive function, it seems to be established that increasing CO_2 levels impact the occupant's perception of the indoor environment. CO_2 levels in a space are directly related to occupant density and their activity levels, the levels of bio effluents emitted from an individual are also closely related to these variables; hence, as the CO_2 levels rise in a space so also the amount of bio effluents and thus odour levels (Persily, 1996; Technical Committee CEN/TC 156, 2006). The ASHRAE guidance suggests that indoor CO_2 levels below 700ppm above ambient are considered as fresh (ASHRAE, 2001).

It has been identified that CO_2 levels can be used to indicate the perceived 'freshness' of the air in a space; it is also essential to ascertain whether it can be used as an indicator of infection risk. Using the Wells-Riley equation, and the relation of CO_2 levels to ventilation, Rudnick & Milton developed an equation which can be used to estimate the risk of airborne infection. The work was based on the principle that exhaled breath is one of the vehicles for infectious particles and contains 40,000ppm of CO_2 compared to around 400ppm for outdoor air, therefore CO_2 can be used as a an indicator for exhaled breath, which enables the risk of infection to be calculated without measurement or estimation of air flow rates (Rudnick & Milton, 2003).

A research paper published in 2008 contained a section discussing evidence for aerial dissemination of infection. It stated there were two main forms for transport of airborne pathogens, coughing and skin squama being moved by bed making (Beggs et al., 2008). The transport via bed making is not directly related to the number of occupants in a space, so CO_2 levels may not be a good indicator for airborne pathogens from this source. However, the pathogens emitted from coughing are directly linked to number of people in a space, hence CO_2 may indicate the amount linked to this source. It needs to be noted that on occasions where there are no patients in a hospital space and therefore the CO_2 levels are low, the beds may have just been made transporting pathogens into the air. Following this reasoning, it can be ascertained that CO_2 levels may not be the best indicator of assessing the suitability of the air in a hospital environment where one of the primary requirements is reducing the risk of infection transfer.

In closing this topic, it is important to remark that overall, there seems to be a lack of research into the area of using CO_2 as an indicator for air quality levels in hospitals, this would be an area where further research could be beneficial.

Lighting

Hospitals have two main purposes for lighting, one to provide sufficient lighting for the various tasks taking place and secondly, to create an environment which is visually acceptable and emotionally healthful and will improve patients' rate of recovery (CIBSE, n.d.). Artificial lighting contributes to the hospitals electrical demand as well as impacting the heating and cooling loads due to the thermal gains. This can have the effect of reducing the heating load in winter, however, it can also increase the risk of overheating in the summer. The Society of Light and Lighting (SLL) has produced a comprehensive guide for the specific lighting needs of hospitals. This establishes that the lighting needed for general nursing care is 300lux increasing up to 1000lux when provided by localised lighting for examination and treatment. In the evenings there is a conflict of interests between the patients desiring darkness for sleep and the nurses requiring light to observe the patients. Hence, at night, the wards have a target of 20lux and nurses stations can vary between 30lux and 200lux. Hospital corridors are lit to 200lux during the day and 50lux during the night.

The guide also points out that there is a specific need for daylight, as this can reduce depression, improve rest and aid patients recovery. It recommends that for hospitals, a

daylight factor of between 2-5% should be aimed at with a uniformity value of between 30 and 50% (SLL & CIBSE, 2008). A study on low energy hospitals had a focus on lighting, it recognised the impact of thermal gains on increasing the need for cooling in summer and also identified the importance of the uniformity ratio. It found that the lighting level was 11,000lux next to glazing and 1200lux at the back of a four- bed ward. This contrast caused the perception of gloominess which encouraged occupants to almost always use artificial lighting (Short et al., 2010).

2.3 Hospital Energy Management

A number of guidance documents have been published on low carbon hospitals. Health Technical Memorandum – EnCO_2de 'Making Energy Work in Healthcare,' sets down guidance on how NHS hospital trusts can go about reducing their energy and carbon emissions (Department of Health, 2006a). A guide widely quoted in European literature on hospital energy consumption was produced by the Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (Technologies Centre for the Analysis and Dissemination of Demonstrated Energy (CADDET), 1997). In the US, researchers at the Lawrence Berkeley National Laboratory conducted research, and published guidance on providing "a roadmap to improved energy efficiency" (Singer & Tschudi, 2009). In addition to these, CIBSE Guide F and a number of research papers provide direct guidance on the reduction of energy consumption in hospitals (CIBSE, 2012; Khalil, 2010; Kolokotsa et al., 2012). The general theme running through them is that energy demand should be first reduced and then this low demand should be provided by renewable and low carbon sources of energy.

One of the first steps in the process of lowering the energy consumption of buildings is quality energy management. With the fundamental practical aspects of this process being energy monitoring, audits, analysis and benchmarking. These allow energy managers to identify how well the building is performing and accordingly make adjustments.

2.3.1 Benchmarking

"Benchmarking is an assessment approach in which energy-related metrics measured or estimated at one facility are compared to those from other facilities and/or specific performance targets" (Singer et al., 2009. pg 1). The main non-domestic building energy assessment method used in the UK is the display energy certification system

(DEC). DECs are legally required in all public authority buildings[i] over 1000m^2, with the purpose of providing transparent information about building energy performance and to motivate improvements (CIBSE, 2009). The fundamental part of the energy assessment is the buildings operational rating. This is a ratio of the building's annual carbon emissions calculated from metered energy data and a benchmark value for a building of the same category. The benchmarks are taken from one of 29 categories of buildings in CIBSE TM46: Benchmarking guidance (CIBSE, 2008).

Benchmarks are based on the average performance of buildings in the same category and hence can be quite general (CIBSE, 2004). CIBSE Guide F recommends that a best practice benchmark be used as an upper limit to design, mentioning that benchmarks will change as better data is gathered and building design improves. The CIBSE TM 46 benchmarks (Table 2.7) were derived from the benchmarks in CIBSE Guide F chapter 20. Looking into the CIBSE Guide F, it is clear that benchmarks originate from the Energy Consumption in Hospitals guidelines which were produced in 1996 (BRESCU, 1996). Recognising that the benchmarks may be out of date, CIBSE conducted a study in 2009 where the benchmarks for hospitals and other non-domestic buildings were reviewed. The DEC's for 1,117 hospitals throughout the UK were investigated and it was found that that the TM 46 benchmarks were a good fit for the stock of hospitals (Bruhns et al., 2011). Another source of benchmarks for hospital buildings, the "Estates Code" have been derived by the NHS estates department (DH Estates and Facilities Division, 2009). Rather than being in the format of kWh/m^2/yr normalising the data to floor area these benchmarks are in the units GJ/100m^3 with the energy consumption normalised by volume. There are three main categories, category A represents new buildings, category B represents the standard for existing buildings and then above category C represent a performance which is unacceptably high (Table 2.8). The literature states that very few hospitals fall into category A, with the most efficient hospital on record showing consumptions of 54GJ/100m^3 (Short & Al-maiyah, 2009). Category B, represents the current standard for existing buildings with the CIBSE benchmark falling into this category.

[i] Or buildings accessed by institutions providing public services to a large number of persons (CIBSE, 2009)

	$kgCO_2$	*kWh/m^2*	*$GJ/100m^3$ (h=2.7m)*	*$GJ/100m^3$ (h=3.6)*
Electricity typical benchmark	49.5	90	12	9
Fossil-thermal typical benchmark	79.8	420	56	42
Total	129.3	510	68	53

Table 2.7 - CIBSE TM 46 Benchmarks, (converted into $GJ/100m^3$ assuming ceiling height is 2.7m and 3.6m) [2008]

Category	*$GJ/100m^3$*	*kWh/m^2*
A - New Build	35–55	262.5 - 412.5
B - Existing	55–65	412.5 - 487.5
C - Unacceptable	>65	> 487.5

Table 2.8 – 'Estate code' Energy consumption benchmarks (converted into kWh/m^2 assuming ceiling height is 2.7m) (DH Estates and Facilities Division, 2009)

The benchmarks heretofore mentioned are useful for comparing hospital buildings and entire sites to each other. The literature identifies that this is good, but states that practice should not stop here, but continue to benchmark performance to as small a resolution as possible. This may mean benchmarking down to electrical end-users, individual buildings on campus or benchmarking departmental energy use, which allows hospital energy managers to pin point exactly where savings can be made (Singer et al., 2009). After analysing the energy consumption of a number of natural ventilation strategies in their paper, Lomas and Ji (2009) questioned the blanket use of a target for all spaces in a hospital complex as the spaces are very different. However to achieve this they did mention that this approach would require improved monitoring.

2.3.2 Monitoring

Benchmarking is only possible once the energy consumption of a building, or particular sub-section of a building has been quantified, this process of can be achieved accurately through energy audits and monitoring. The literature suggests that energy auditing is one of the most useful tools for increasing the energy efficiency in European countries (Butala & Novak, 1999).

'You can't manage what you can't measure' (DOH, 2006. pg 12)

The literature demonstrated that a number of studies involved monitoring hospital energy consumption. In 1982 a study auditing 48 hospitals in the US found that the average annual energy use was $480kBtu/ft^2$ ($1500kWh/m^2$) with the range 240-$840kBtU/ft^2$ ($750\text{-}2639kWh/m^2$) 50-175% of the mean. It was identified that through the implementation of energy efficiency recommendations, the energy consumption would

be reduced 20%; 66% of the energy saving from fuels and 33% from electricity (Hirst, 1982).

In the 90's, two sets of studies were undertaken by the Department of Health where the energy consumption of hospitals were monitored for three years before and after changes were made to its energy consuming services. The first of these, St Mary's appraisal 1, used a monitoring system independent of the hospital's building management system (BMS). It used electro-magnetic water flow meters and water temperature sensors to monitor heat flow, 3-phase kWh meters for electrical energy, wall mounted temperature sensors and fuel flow sensors for gas and oil. In total 283 sensors were installed for the project (NHS Estates, 1994a).

The St Mary's study represents a detailed energy monitoring strategy; there are however other 'lighter' approaches to monitoring and auditing hospital buildings. An example of this is a study conducted by Santamouris et al in Hellas Greece. Questionnaires were given to occupants and investigators were commissioned to fill in reports on 24 hospitals. This standardised report collected information about the building envelope, heating and cooling system, information about electrical equipment and the energy consumption of building. It was found that, the annual average energy consumption for hospitals was 407kWh/m^2 (Santamouris et al., 1994).

In a more recent study, the energy consumption of a US hospital was monitored to find out how much was used at end-use. In the past the energy consumption of hospitals had been modelled, but there was still a lack of understanding of end-use energy consumption, so monitoring was undertaken to provide more insight. It was found that the total energy consumption of the hospital was 214 kBtu/ft^2 (674.63kWh/m^2/yr). The focus of the monitoring was on the electricity consumption, which was monitored by metering the load for a month between January and February 2011 and then using the utility bills to extrapolate results for the year. This data was then used to calibrate an energy model (Hatten et al., 2011).

Earlier on in the literature review, in the section discussing hospital building design, a number of energy consumptions were stated for different hospital buildings generally found in the UK. It is interesting to observe the difference between the general energy consumptions within the UK and those internationally. The Greek energy consumption of 407kWh/m^2 is similar to that found in the UK, falling in the higher end of the estates code new build category. It is likely that this performance is related to the warmer

Greek climate that would require less heating during the winter season. In addition to this, although the climate in Greece is warmer than the UK, the survey showed that the buildings were cooled primarily through naturally means, with only 0.8% being used for cooling. In contrast, in the USA, hospitals tend to be heated and cooled primarily through the means of mechanical ventilation. In US hospital benchmarking study, Massachusetts General Hospital Gray Building and State University of New York Upstate Medical University East Wing consumed 1284kWh/m^2/yr (407 kBtu/ft^2·yr) and 615kWh/m^2/yr respectively (Sheppy et al., 2014). Both of these buildings and the case reviewed earlier (Hatten et al., 2011) (674.63kWh/m^2/yr), show unacceptable energy uses compared to UK hospitals benchmarks and demonstrate energy consumption similar to the mechanically ventilated tower building in Cambridge Addenbrooke's hospital (Short et al., 2012).

The literature seems to suggest that the energy consumption of hospitals across the globe depend on the particular local climate and economic capabilities of the vicinity. In India, private hospitals had an average energy consumption of 746kWh/m^2/yr and government funded ones had an average energy consumption of 90kWh/m^2/yr. The energy mix was heavily electric, with an average of 91% and 9% for electric and fossil fuel use respectively. Furthermore, India is a very large country with varied climatic conditions, thus the energy consumption of the hospitals was heavily impacted by whether the region was hot and dry, warm and humid or composite (Kapoor & Kumar, 2011). Brazil, another warm country compared to the UK had a high percentage of electrical use, averaging around the 70% mark for the different categories of hospitals, with a large proportion of this being attributed to air conditioning (Szklo & Soares, 2004). In a single Malaysian hospital case study it was found that a hospital consumed 234kWh/m^2/yr, which was high compared to other buildings in Malaysia, but low compared to British. The study stated that this building was actually mechanically ventilated with additional ceiling fans. Nevertheless, it mentions that patient admission varied and had an impact on the energy consumption (Saidur et al., 2010), which could help to explain why it was so low compared to British mechanically ventilated buildings. Finally a study conducted in Tianjin China, studied 22 hospitals in the city, found that they had an average energy consumption of 380kWh/m^2/yr and an energy mix, of 42% heating, followed by 7% cooling, 5% medical equipment, and 3.63% lighting (Jiang et al., 2012). Tianjin has a similar climate to the UK (Climate-Data, 2016), and therefore demonstrates similar energy needs to the hospitals in the UK.

Although there are examples demonstrating the measured or predicted energy consumption of hospital buildings, overall there is limited monitored data at the individual building level. The literature review from a paper studying dynamic energy performance in an Italian hospital identified that there was a lack of data in the literature regarding measured and estimated energy consumption in hospital buildings (Buonomano et al., 2014). It stated that only a small number of attempts were made to identify a building's consumption and these were generally models, which often were not a true reflection of the building's actual consumption.

The previous section mentioned that buildings should be benchmarked to end-use, which identifies the necessity of sub-metering at various levels of the buildings energy infrastructure. This is generally a practice recommended for large campuses, whether hospitals, colleges or universities (US EPA, 2002). The guidance specifies that metering should be considered at the early stages of building design (Department of Health, 2006a), or when the building is undergoing refurbishment (CADDET, 1997).

Although current practice recommends that sub-meters should be installed in the construction of buildings, much of the hospital stock worldwide was built before this guidance was common practice. Therefore, sub-metering energy consumption in these buildings can present a number of challenges. Singer et al highlights, that *"For multi-building campuses, energy can and should be resolved specifically for the hospital building…this is difficult for electrical, but yet even more difficult for heating and ventilation"* (Singer et al., 2009. pg 2).

In their report, Singer et al presents a method for determining the heating and cooling metrics with short duration monitoring, i.e. the energy consumption could be monitored on existing hospital buildings with temporary meters. At time of writing, their method was in the developmental stages and therefore was not fully presented in their report. Nevertheless, the report provides a good enough outline of the method to warrant further investigation. For the monitoring of the thermal loads, it recommends that the outdoor air temperature is tracked and that cooling and heating demand is monitored under various seasonal weather conditions using well calibrated equipment, to identify daily and hourly energy consumptions. The energy consumption is then regressed against the outdoor temperature, and the relationship combined with the hourly annual outdoor air temperature profile to estimate the annual cooling and heating demand (Singer et al., 2009).

CIBSE Guide F provides a similar method, where the energy consumption of a site is plotted against the daily degree-days[i] to form a simple linear regression relationship known as a performance line (Figure 2.14). This method is useful for calculating the site base load, but less so for identifying the energy consumption of a section of a building (CIBSE, 2012).

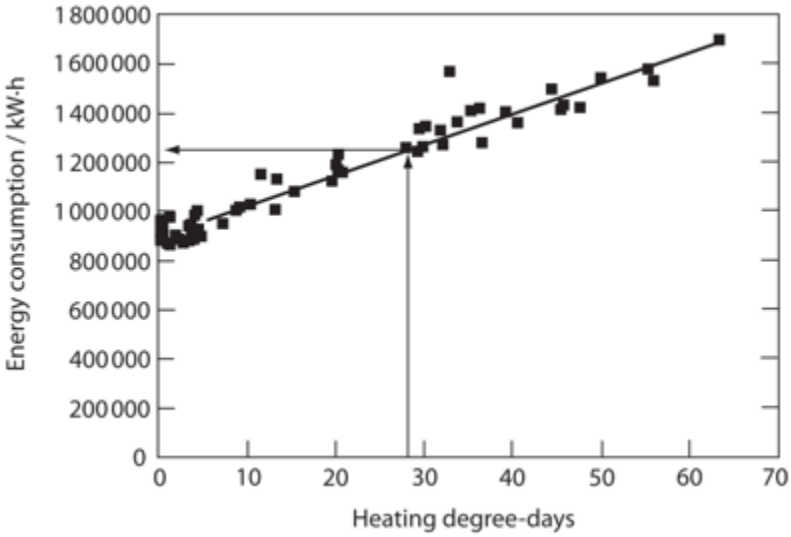


Figure 2.14 - CIBSE Guide F Energy performance line - Energy consumption versus degree-days showing base load (CIBSE, 2012)

Another CIBSE Guide which touches on a regression type building monitoring method is CIBSE TM 41; Degree-day: theory and application (CIBSE, 2006a). In the energy management section it discusses performance lines, but also adds energy signatures which are also a form of linear regression analysis. The difference being that energy signatures represent the relationship between daily heating energy consumption and mean daily external temperature, so they can be used to find the base temperature of the building (Figure 2.15).

[i] Degree-days are a metric used to indicate the amount of heating and cooling is needed for a building. The daily number of degree-days is the sum of the difference between the base temperature and outdoor air temperature for each hour in the day (where this value is larger than 0) divided by 24. The base temperature for hospitals is usually 18.5˚C (CIBSE, 2006a).

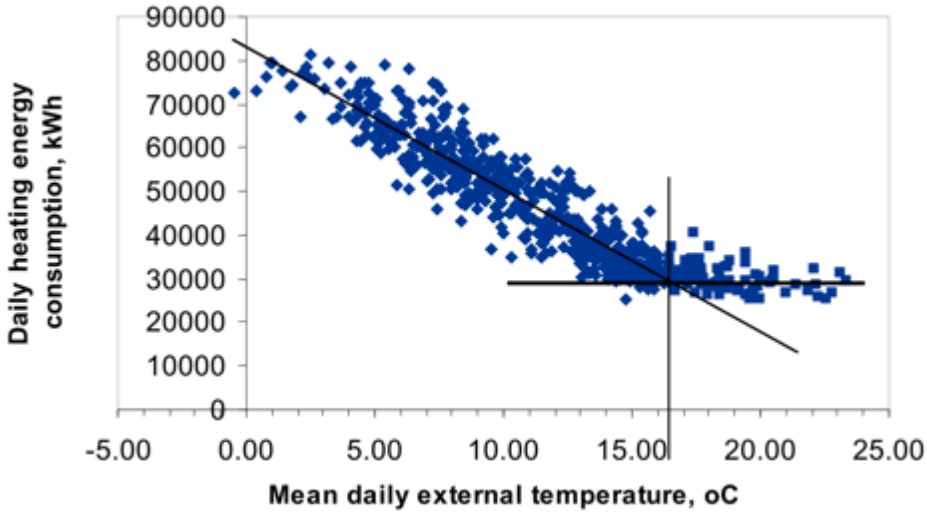


Figure 2.15 - Example of energy signature from CIBSE TM41 – point of inflection indicates the true base temperature of the building (CIBSE, 2006a)

The energy signature method closely resembles short term monitoring and forecasting. The key advantage of this method is that monitoring can take place in a building without installation of permanent sub-meters. The method was originally introduced in the mid-1980's, and discussed by Hammarsten in a research paper where the author remarks that yearly energy consumption can be predicted, but the building must have constant characteristic parameters for the duration of the year if estimates are not to be unbiased. It states that random errors can be decreased by increasing the number of observations, however, it does mention that when simple energy balance models are used there is a serious risk of bias errors which can render the interpretation of the model useless (Hammarsten, 1987). As the method is based on linear regression, the analysis produces the following formula:

$$\mathrm{Q} = \mathrm{M}(T_{ar} - T_{ao}) - \mathrm{X}$$

Where Q is the energy consumption, X is the energy consumption when the temperature difference $(T_{ar} - T_{ao})$ is 0, M is the total heat loss coefficient and T_{ar} and T_{ao} are the room and outdoor air temperatures (Hammarsten, 1987). In his critical analysis of energy signature models Hammarsten comments that one should use energy signature models for the estimation of building parameters with great caution, as there can be considerable errors.

Energy signature models have featured in a number of studies related to building energy consumption. In 1989, the energy signature method was used in assessing the heating demand of four UK hospital sites. In the study the author plotted the energy

used on the site for space heating against the local degree-day data, and overall it was found that the building with the largest amount of mechanical ventilation had the highest energy consumption (Adderley, 1989). In analysing the reliability of the site data, Adderley used 95% confidence intervals, which imply that there is a 1 in 20 chance that the true mean lay in the limits. In addition to this, the models were used to calculate the annual space heating consumption for each of the hospitals, the results were compared to the monitored results and it was found that the difference between the two were, 0.74%, 5.2%, 1.3% and 0.17%. This demonstrates that if used carefully, energy signature regression can be used to create accurate models that can predict the energy consumption of buildings.

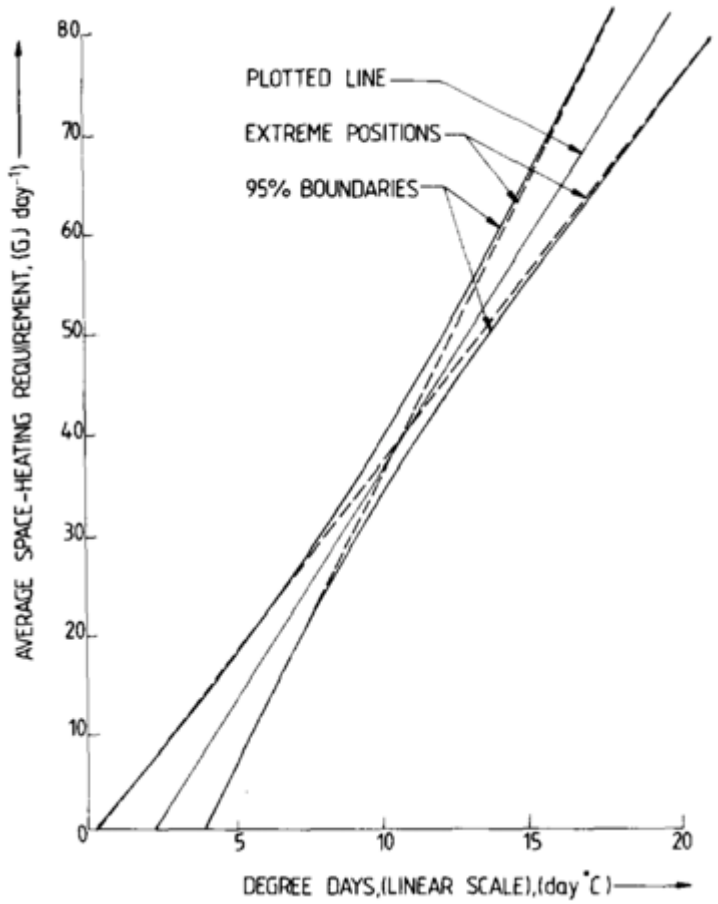


Figure 2.16 - A diagrammatic representation of the confidence limit boundaries (Adderley, 1989)

In 1992, Rabl and Rialhe conducted a study investigating the use of energy signature models of commercial buildings and found that they were reliable for applications where one needed to find the weather corrected annual energy consumption from measured data. However they identified that their use for the investigation of building parameters can be useful but caution is advised as they found that the relationship

between the energy signature parameters and the physical characteristics of a building can be treacherous especially for commercial buildings (Rabl & Rialhe, 1992).

A more recent study looked into how sensitive the total heat loss coefficient calculated by energy signatures was to different time periods and gained energy (Sjögren et al., 2009). When investigating the monthly data for nine multifamily buildings, they found that the total heat loss values calculated from the energy signature models were generally higher than the actual design heat loss values for the buildings with a range from 5-57% larger and an average of 20%.

Overall, the research conducted on linear regression energy signature models seems to suggest that with the correct assessment of confidence levels in the regression, energy signatures can be accurately used to forecast the energy consumption of buildings for the purposes of predicting savings from basic retrofit measures. It also shows that they can be used to calculate other building parameters such as the total heat loss coefficient, but that great precaution must be taken when doing this as the literature is agreed that there can be high levels of inaccuracies when adopting this approach.

When assessing the NHS carbon reduction strategy, it is apparent that the organisation wants to develop a framework for benchmarking and monitoring. One of their aims is,

> *"to establish metrics which will allow each NHS organisation to benchmark their actions and set themselves targets for reduction … Research is required to ensure organisations are able to measure their carbon impact efficiently and consistently. Establishing national standards for this information will create consistent recording of carbon footprints and ensure all organisations contribute to carbon reduction" (NHS SDU, 2009. pg 38).*

The NHS carbon reduction strategy and the Berkeley benchmarking framework were published in 2009. The Berkeley framework could contribute to the solution the NHS is seeking. A possible research opportunity is that the Berkeley limited duration monitoring accompanied by energy signature regression could be tested in the UK to see its applicability on this side of the Atlantic.

2.4 Low Energy Hospitals Methods

Benchmarking monitoring and modelling are pathways to identify how hospital energy use can be reduced. However it is not until physical changes are made to the building's operation or the design that energy can be saved.

In the NHS's carbon strategy they state,

> *"A Low Carbon Design Taskforce of public and private sector expertise should be established to develop a blueprint for the optimum low carbon healthcare building, accompanied by best practice guidance" (NHS SDU, 2009. pg 54).*

In 2012, a literature review was published discussing the various energy conservation techniques for hospital buildings. It concluded that the first action to reduce energy in hospitals is to utilise simple low cost measures such as changing time switches and switching off equipment when not in use where up to 10% of primary energy can be saved without high expenditure on new equipment. These changes as well as encouraging energy efficient behaviour by occupants and removing any inefficiencies in the services, through maintaining fans, cleaning filters, etc. will be a direct response to identifying the areas with highest energy usage through monitoring and benchmarking. The review also found that energy is lost because systems are not maintained, therefore one of its findings were that medium investment and improved operation and maintenance practices can provide instant and durable energy savings (Kolokotsa et al., 2012). Similar conclusions were also drawn in a study where up to 20% of a building's energy was saved due to small adjustments in it's operation (Santamouris et al., 1994).

Once the building is operating as efficiently as possible, other low carbon measures can be considered. EnCO_2de points out that energy conservation methods tend to be more difficult to install due to the need for retrofit and capital investment (Department of Health, 2006a). In a study conducted in an Italian hospital some of the more advanced measures including whole envelope insulation, advanced HVAC control, efficient heat recovery and renewable energy technologies were not even considered due to them being too costly for the hospital's budget. Furthermore, another barrier to these methods were that they would require an unacceptably prolonged interruption to hospital services (Buonomano et al., 2014). Hospital spaces need to operate 24 hours

a day, 365 days a year, closing down wards for refurbishment can cause disruption to hospital organisational logistics and services (Singer & Tschudi, 2009). The literature therefore suggests that it is optimal to introduce energy conservation measures during the design stage or at a time when the ward is already closed due to a retrofit or regular maintenance (CADDET, 1997).

This section of the literature review will now focus on the research that has taken place into these energy conservation measures as they apply to the field of hospital design. The research comfortably fits into the following three areas. Heating ventilation and air conditioning, passive building design and plant energy supply.

2.4.1 Heating, Ventilation and Air Conditioning

It is widely accepted that hospitals buildings are behind in implementing low carbon measures (Johnson, 2010; Short et al., 2010). However, as touched on in the section on the development of energy use in healthcare buildings, there have been small conscious steps to improve the situation from the time of the 1970's. Then, in the '90s, the Department of Health issued two studies which looked into producing a pattern for a low carbon hospital (NHS Estates, 1994a, 1995b). In terms of the variables discussed earlier, space heating and lighting were the areas in which the most significant changes were made. For space heating, better insulation was used for the building fabric, double-glazing was fitted and air tightness was increased to reduce infiltration to below 0.5ach^{-1}. Windows were fully closed in winter, mechanical ventilation was supplied to perimeter spaces at between 1 and 2ach^{-1}, all radiators were fitted with thermostatic valves for individual control and to stop overheating. For mechanical ventilation, a low velocity system with heat recovery replaced the dual duct high velocity system, meaning fan speeds were lower and the heating and cooling loads were reduced.

Replacing old motors with energy efficient ones and fitting variable speed drives have been found to reduce energy consumption. In a study taken in a Malaysian hospital, it was found that a hospital's energy intensity could be reduced by up to 1.64% and 32.88% through using energy efficient motors and variable speed drives respectively. Through this, the energy intensity was reduced from 234 to 157kWh/m^2. The study showed that the larger the percentage speed reduction within the variable speed drives, the more energy was saved and the shorter the pay-back period for the equipment (Saidur et al., 2010).

A study in an Italian hospital tested various combinations of energy saving measures in a building energy model, with the authors finding that the most efficient method was close control of the HVAC system. The original practice within the hospital was to allow the air handling unit (AHU) to work all day even when the room was not occupied. However, in the study, the building model's HVAC control system was programmed to turn off the ventilation when not in use. This simple measure saved more energy than the other options, which included insulating roofs, and updating the HVAC system by installing thermostatic valves (Buonomano et al., 2014). Kim & Augenbroe also concluded that reducing the time the ventilation system was operating could have a significant impact on lowering the energy consumption. They found that through the utilisation of variable air volume (VAV) ventilation systems this result can be achieved without limiting the safety needs of an isolation room (Kim & Augenbroe, 2013). Another study focusing on isolation rooms found that by adjusting the air flow rate and the pressure differential, one could improve the efficiency of contaminant removal. It found that a -15pa pressure differential, with a flow rate of either 12 of 24 ach^{-1} increased the ventilation efficiency, with -15pa/12 ach^{-1} being more effective than -8Pa/24 ach^{-1} (Tung et al., 2009). The paper, however did not mention energy consumption, nevertheless it can be assumed that by lowering the ventilation rate, while maintaining the pressure differential at -15Pa the energy consumption of the space can be reduced compared to having a low-pressure differential and high ventilation rate.

In warmer countries the energy consumption required for cooling can be very high. A technology that has been found to be useful is solar absorption cooling which was implemented in a hospital in Greece to meet its cooling load. It produced considerable energy savings and without funding had a payback period of 11.5 years (Tsoutsos et al., 2010). In Malaysia, where the climate is humid, ventilation heat recovery was used to lower the humidity of the air to ASHRAE standards improving the safety and quality of the air as well as lowering the energy consumption of the building. The study stated that the cost of the improvements to the HVAC system had a pay-back period of 1.6 years (Ahmadzadehtalatapeh & Yau, 2011).

Infection control limits the degree to which low energy technology can be used in a hospital setting. A recent paper reviewing the current knowledge on relationship between respiratory infection control and low energy design in hospitals (Li et al., 2015) identified that the transmission route of airborne pathogens produces complexities for

designing low energy systems. The study was able to identify from the current literature that natural and displacement ventilation, air disinfection, radiant ceiling heating and chilled panels may be useful in lowering the energy demand of hospitals. However, the work was limited in that the studies reviewed that identified these methods as useful did not investigate them in the context of infection control. The work found that there were no studies which considered both infection control and low energy technology for hospitals and suggests that a multidisciplinary approach was needed to conduct field studies on new technologies to develop evidence of their usefulness for infection control (Li et al., 2015) .

2.4.2 Passive Building Design

Natural ventilation is the process by which fresh air is supplied to a building using the forces of wind (wind effect) and temperature (stack effect) (CIBSE, 2006b). In a hospital setting wind is the driving force which is the most frequently used, as it is known to be able to provide ventilation rates which can meet design regulations (WHO, 2009). When wind strikes a building, it induces a positive pressure on the building's windward face and negative pressure on its leeward face. This pressure difference combined with the correctly sized vents, allows air to move through the building, ventilating it through the wind effect.

The main advantage of using natural ventilation in hospitals is that these high ventilation rates can be achieved while reducing the costs, maintenance and energy consumption, which are associated with mechanical ventilation systems. Despite these advantages, a serious challenge in naturally ventilating hospital spaces is that the main driving forces wind and temperature vary significantly depending on climatic conditions. This leads to wide fluctuations in the airflow rate, with low ventilation rates often being experienced when ambient conditions are unfavourable. Variability in climatic conditions, especially wind direction can also make it difficult in control airflow directions and pressure differentials, leading to air leaking into areas where it is not desired. Furthermore, filtration is almost impossible for natural ventilation, meaning that in certain conditions, airflow sources must remain closed. Many of these problems can be solved by supplementing the natural ventilation with mechanical ventilation when conditions are unable to be met through the wind or stack effect. Systems using both forms of ventilation are known as hybrid ventilation systems (WHO, 2009).

Section 2.1.3 showed that hospital HVAC systems can consume over 50% of an entire building's energy consumption. Hence, the reduction of energy used for ventilation can significantly reduce total hospital emissions.

The Department of Health's guidance on ventilation states:

> *"Natural ventilation is always the preferred solution for a space, provided that the quantity and quality of air required, and consistency of control to suit the requirements of the space, are achievable."* (Department of Health, 2007a)

Due to the important role natural ventilation plays in reducing building energy consumption there has been a wide range of studies investigating natural ventilation for the hospital settings. One of the most important aspects of hospital ventilation is reducing the airborne transmission of disease and in 2007 researchers began testing natural ventilation for infection control using field measured data (Escombe et al., 2007). The work studied 70 naturally ventilated spaces, in 8 hospitals in Peru. Flow rates were measured using the tracer gas method and infection risk was calculated using the Wells-Riley equation. The results were compared with those from mechanically ventilated isolation rooms, negatively pressurised with the recommended $12ach^{-1}$. What the results found were that opening windows and doors provided a median air change rate of $28ach^{-1}$, more than double the mechanical rate ($12ach^{-1}$). Furthermore, it was identified that pre-1950s buildings had higher rates of ventilation than modern buildings, $40ach^{-1}$ vs. $17ach^{-1}$. In terms of infection risk after a 24 hour period, 39%, 33% and 11% of susceptible individuals would be infected for mechanically, modern naturally and pre-1950s naturally ventilated buildings respectively. The difference between the old and newly naturally ventilated spaces was that the old buildings had higher ceilings that helped to increase airflow. Overall the study demonstrated that when respiratory isolation is not possible, opening windows and doors drastically reduces the chances of airborne contagion (Escombe et al., 2007).

In 2009, the world health organisation published guidelines on designing natural ventilation for infection control in health care (WHO, 2009). A multi-disciplinary team compiled the guidance based on their professional experience and a comprehensive review of the literature. The guidance went into great detail on natural ventilation in

hospitals, but the main recommendations were that 1, there should be adequate ventilation in all areas. 2, areas with high risk of infection should have minimum hourly average ventilation rate of 160l/s/patient with a minimum of 80l/s/patient and 3, 60l/s/patient should be provided for general wards. The guidance also recommends that it is essential design takes into account fluctuations in the ventilation rate and that when design criteria cannot be met solely through natural ventilation, hybrid ventilation should be considered. Finally, concerning airflow direction, it recommended that the spaces should have air flow which brings air from contaminated sources to areas where there is sufficient dilution (ideally outdoors) (WHO, 2009).

Natural ventilation for infection control was discussed in more detail by (Qian et al., 2010) where the researchers measured naturally ventilated hospital wards in Hong Kong. Similarly to the work undertaken by Escombe et al., 2007, it was identified that high ventilation rates (up to 69ach^{-1}) could be achieved when windows and doors were opened, however, the airflow direction was unstable, and there was a negligible pressure difference between the corridor and the room. To try and solve this problem, a fan was installed to negatively pressurise the room, nevertheless the results identified that it was effective only when all of the windows were closed.

During this same time period two leading research teams collaborated to publish two papers on natural ventilation in hospitals. One paper focused on the intricacies and architectural design of natural ventilation in hospitals (Short & Al-maiyah, 2009) while the other focused on modelling advanced natural ventilation strategies, assessing their performance in the present and future climates (Lomas & Ji, 2009). In the first study, the approach taken was to break the hospital building down into different room categories and then to apply natural ventilation techniques to each space. All of these low carbon measures were simulated together in a multi-zone building model, which predicted that the energy consumption would start at 38GJ/100m^3 in 2005 and decrease to 36.7GJ/100m^3 in 2080.

The study mentioned that the results were calibrated, thus indicating that significant savings could be achieved. However it also comments that the results are representative of a selection of rooms. Additionally, the paper states that “the NHS target is certainly ambitious” as results show that although many design strategies have been implemented, the results are still not below the most stringent benchmark (35GJ/100m^3). The paper goes onto state that the study should be seen as a scoping exercise for a larger project, and not guidance for hospital design pointing out the need

for more research in the field to establish confidence in naturally ventilating more sensitive clinical spaces (Short & Al-maiyah, 2009).

In the second paper, Lomas and Ji modelled methods of natural ventilation with the aim of lowering energy demand to provide resilience in hospital wards in a warming UK climate. The paper compares an advanced natural ventilation strategy with a mechanically ventilated system. It was found that the naturally ventilated building had an energy consumption of 30.08GJ/100m^3 and 11.78GJ/100m^3 when the flow rates were 40-50l/s and 10-20l/s respectively. In a warmer climate the reduced demand for heating decreased the naturally ventilated building's energy consumption to 21.58GJ/100m^3. An interesting point this paper highlighted was that as the energy demand was reduced through the implementation of natural ventilation, lighting began to take a larger share of the energy consumption. Hence natural lighting is an essential component in any natural ventilation strategy. What makes this more important is that, electricity is responsible for more carbon emissions than fossil fuels. In all of the natural ventilation scenarios, the lighting produced equal or more carbon emissions than the heating (Lomas & Ji, 2009).

Natural lighting was addressed, in a paper reporting a case study modelling the maternity wing at Northwick Park hospital in England. It was found that the south facing room was receiving more sunlight than was necessary and consequently contributed to overheating. It was found that advanced natural buoyancy driven ventilation that drew air through a plenum with cross venting, demonstrated a marked improvement in thermal comfort and energy performance. The paper continued to identify that a holistic approach to the refurbishment of the hospital, beginning with improving the airtightness of the building and removing solar gains through shading, was the optimal way to reduce it's energy consumption (Short et al., 2010).

Some of the most recent contributions to the field of advanced natural ventilation has come from Adamu who developed called natural personalised ventilation. In this approach, advanced natural buoyancy-driven ventilation is used to provide ventilation directly to where the occupant is stationed; in a hospital ward setting this would be directly above the bed. A study modelling a hospital ward, designed following the ADB specification, showed that this method could be usable for eight months of the year without extra heating (Adamu et al., 2011). This indicates that the energy consumption could be significantly low, however, the method was tested in a London climate and

hence needs to be assessed more closely to specify its energy and thermal performance in a real hospital building in different climate conditions.

A further study was undertaken using this method of ventilation at a ward in great Ormond Street hospital. Modelling was used to simulate four natural ventilation strategies and it was found that the methods produced a wide range of air flow rates into the space. In response, the author suggested that it would be helpful for there to be more comprehensive guidance on how buildings can be designed to actually achieve the given flow rates. The natural personalised ventilation approach, in this study, called ceiling-based natural ventilation (CBNV), was able to provide comfort while maintaining low energy performance, due to its mixing behaviour allowing the flow rates to be relatively low. In general the flow rate of air into the space is proportional to the heating energy consumption, hence the dual opening ventilation method, which provided high flow rates, had high energy consumption. The benefits of this method were the ease of installation in a refurbishment context and the comfort it provided during the summer months. The flow rate of the stack was arguably too high during the winter which in turn increased its energy demands. One of the problems with the CBNV was that it could not provide any air flow for 222h between July and august. This problem could be solved through the use of fans in the ducts. One limiting factor of this study however, was that it did not assess the energy consumption of the different methods to the NHS benchmarks in GJ/100m^3 (Adamu 2012).

A central theme in the research of naturally ventilated hospital buildings in the UK has been the traditional Nightingale hospital buildings/wards. One of the UK's original hospital types, these buildings were designed to be naturally ventilated from their conception. In recent years three key papers have been published on the ventilation capacity of these types of building.

The first paper published by Camargo-Valero, (2010) aimed to highlight the features of natural ventilation and pathogen transport mechanisms in a traditional open ward with and without an infection control strategy in place. Experiments took place in an abandoned Nightingale ward that was split into two sections, one partitioned and the other opened as originally designed. CO_2 was used as a tracer gas and its decay tracked with time to identify airflow rates that ranged from 2ach^{-1} to 30 ach^{-1}. In regards to ward arrangement, results showed that partitions reduced cross infection in a sideways direction. However, they posed an increased risk to healthcare workers and

visitors, as pathogens were concentrated in the bay where they were generated. (Camargo-Valero, 2010)

In 2013, Gilkeson et al., published a study which was a continuation from the work undertaken by Camargo-Valero, (2010). The same building was investigated, with additional measurements taken. The results showed that wind speeds of 1-4 m/s correlated with 13-27 ach^{-1}, giving an average of 3 to 7 ach^{-1}, which is comparable to the Department of Health's recommendation of 6 ach^{-1} (Department of Health, 2007a). In this study, additional scenarios where tested: when all windows closed, ventilation from leeward and windward directions, and using fans to supplement natural ventilation. Closing all windows resulted in reducing ventilation rate of typically around 4 to 5 ach^{-1} to an equivalent rate of 1 ach^{-1}, which was detrimental to infection control, readings showing up to a four-fold increase in tracer exposure across the whole ward. The addition of extract fans to each bay of the partitioned ward reduced infection risk compared to the case with no ventilation, and in the central release scenario yielded average exposure results only marginally higher than the cross-ventilation case. This suggests that using hybrid ventilation when windows are closed or wind speeds are low may offer a cost effective approach of reducing airborne transmission of infection year round (Gilkeson et al., 2013).

One of the most recent papers on Nightingale type buildings was published by Short et al in 2014. The paper reviewed the literature to date on Nightingale building performance, especially that to do with ventilation and summer thermal comfort. In this study, four adaptions to the original Nightingale ward design were evaluated for ventilation effectiveness, cost and practicality from a clinical stand point. The four arrangements designed to increase privacy and dignity in the current envelopes of the Nightingale ward buildings were; partitioned, Pullman, skewed island and external corridor (Figure 2.17).

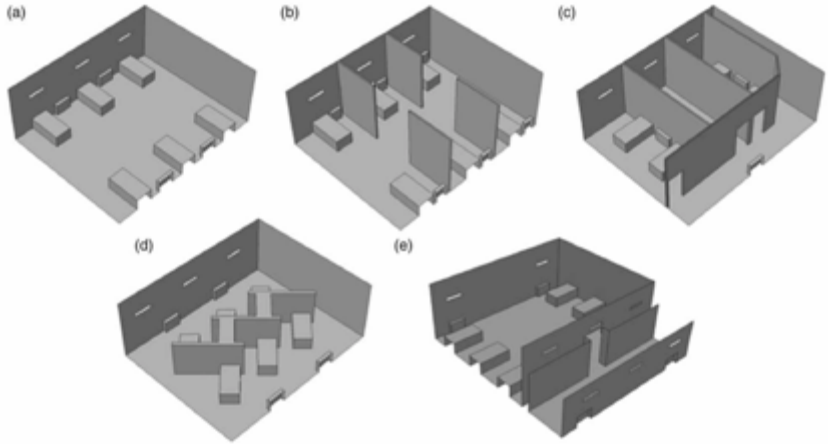


Figure 2.17 - The hospital ward layouts studied: (a) traditional, (b) partitioned, (c) Pullman, (d) skewed island and (e) external corridor configurations (Short et al., 2014).

Each of these arrangements was modelled using CFD to simulate their ventilation performance. The results for the new arrangements showed that cross-ventilation is still possible in all arrangements, but highlighted that it is important to ensure there are adequate ventilation openings to enable through flow of air. It was found that this was the most vital where there was a corridor at the side of the ward (c and e), as these walls had the effect of blocking airflows. In terms of costs, each of the refurbishments would be considerably cheaper than new build alternatives and quicker to deliver.

The ventilation strategy implemented in a hospital is key to reducing the energy consumption, but another equally important aspect is the buildings envelope. UK building regulations conservation of fuel and power in new non domestic buildings (HMGovernment, 2010) has set limiting fabric parameters (Table 2.9) which must be applied to all new build hospitals.

Building (w/m^2K)	*Part L2a*
Wall	0.25
Roof	0.35
Ground	0.25
Windows	2.2

Table 2.9 – Building regulations Part L2A: limiting fabric parameters (HMGovernment, 2010)

The effects of hospital building fabric have been investigated in a number of studies; one of these covered the actions for an energy retrofit of a hospital in Naples. The original building had a combination of high thermal mass and high thermal transmittances of both opaque and glazed components that resulted in poor performance in the heating season. The study also found that roof insulation only provided marginal savings and therefore the payback period was long and due to the

larger surface area, more effective on low buildings than tall buildings (Buonomano et al., 2014). Passive methods were used in a study in an Iranian hospital; thermal insulation, shading and thermal mass were added to the building envelope, the heating energy consumption was reduced to 9% of the original and the cooling was reduced to 73% of original (Khodakarami et al., 2009).

A recent study investigated the achievable energy savings and control of the internal environment from retrofitting the building envelope of a hospital in the Mediterranean. Thermal simulation software was used to model the hospital in a Mediterranean climate. The results demonstrated that higher levels of thermal insulation, solar shading and thermal mass all contributed to reduced fluctuations in indoor temperatures and improved the summer performance by providing comfortable indoor temperature during cooling periods. Overall the energy savings were 50%, 31% and 16% for thermal only, thermal ventilation and thermal/ventilation and humidity HVAC systems (Ascione et al., 2013).

2.4.3 Plant Energy Supply

Hospitals are highly energy intensive and the heating and cooling plant is a key part of the energy system. Up until this point in this chapter, little has been mentioned on hospital energy supply. However, from reviewing the research on lowering hospital energy consumption, it is clear that this is one of the areas where the most research has taken place. One of the fundamental ways for increasing the efficiency of a hospital plant is to use cogeneration which is also known as combined heat and power (CHP), an efficient method of providing both the thermal and electrical needs of a hospital in a single process (Alexis & Liakos, 2013). CHP systems are a tried and tested method of improving energy efficiency due to electrical power stations being at best, 40% efficient, meaning 60% of primary energy is wasted whilst cogeneration has much smaller losses, i.e. 15-20% (Renedo et al., 2006). The premium guidance for hospital energy consumption recommends that CHP will be a successful option for all medium to large hospitals (Department of Health, 2006a). A nationwide study conducted in Brazil found that the potential for CHP use in hospitals depended on the electrical load used in hospitals in the various parts of the country (Szklo & Soares, 2004). In 2006, four different alternatives to a regular boiler plant were investigated in a Spanish hospital, the options were a diesel or gas supplied CHP system, controlled for maximum electrical production or maximum time of use at full load. All alternatives were significantly more efficient that the standard gas boiler system. The authors concluded that a further benefit of using co-generation in hospitals is that they provide

a stable off-grid supply of electricity in the case of power cuts. Linked to this, they found that diesel powered units had the advantage of storing fuel which would provide a supply even when gas was not available. The paper also mentioned that tri-generation, adding cooling to the system could also improve the efficiency of the system allowing it to run for longer periods during the year (Renedo et al., 2006).

As highlighted earlier, in warmer climates cooling is a major consumer of energy, consequently, the combined production of electrical, heating and cooling energy is becoming an increasingly important technology (Ziher & Poredos, 2006). Tri-generation utilises the heat produced by a CHP systems to provide energy for adsorption heat pumps which supply cooling (Arcuri et al., 2007). In their study, Arcuri et al., investigated the optimal design of tri-generation in a hospital, their conclusions identified that when the tri-generation system is used to meet the cooling and heating loads of a hospital, heating demands can be managed more effectively and energy costs reduced (Arcuri et al., 2007).

Adsorption cooling technology is not restricted to cogeneration systems but can also be used in other applications. In 2010 Tsoutsos et al. conducted a study on improving the cooling supply to air conditioning systems in a Greek hospital. The study used TRNSYS to simulate solar thermal panels which were used to power an adsorption chiller, providing cooling energy for the air conditioning system. The system was rather expensive having a pay back period of 11.5 years, nevertheless, the authors found good savings in energy consumption and expect that this will be a technology that is increasingly used in the future (Tsoutsos et al., 2010).

Other than cogeneration there are many ways of providing heating and power for hospitals buildings. Fuel cell technology has been discussed in two papers authored by Bizzarri. In the first, a fuel cell was simulated in a typical hospital setting, the results showed that the electricity produced could meet the sites requirements for each month with the exception of the summer. The only drawback to this method was its current high cost which caused the pay back period to be longer than the expected life of the fuel cell. The author also suggests that a development of this system would be to use the recovered heat for absorption chilling to meet buildings' cooling needs (Bizzarri & Morini, 2004). In their second study on the subject, the authors compared the performance of three systems for producing energy: fuel cells, photovoltaics and solar thermal systems. Each of these technologies were tested in a system with an absorption chiller to utilise the recovered heat. It was found that each of the systems

produced considerable greenhouse gas reductions, however the solar thermal system worked the most effectively. Nevertheless, one finding which supported their first study was that the cost of the devices were a market barrier (Bizzarri & Morini, 2006).

The thermal storage capacity and thermal properties of the ground have been used to provide energy for hospitals. In Rotorua, New Zealand, a monitoring study was conducted on a hospital's geothermal system. Rotorua sits on top of a shallow geothermal reservoir and in the '70s the hospitals designers choose to make use of this natural resource. After over 30 years of use the system was still functioning well and was able to meet the heating needs of the entire site (Steins & Zarrouk, 2012). A study in Belgium identified that it is not necessary to be fortunate enough to have deep thermal reservoirs below your hospital, geothermal properties of the earth can be used in almost all locations to provide heating and cooling for a portion of the year. In Antwerp an aquifer thermal energy storage system was monitored for over 3 years. The system included two 65m deep wells 100m apart, one for heating and one for cooling. The system was able to meet 81% of the hospitals cooling needs and 22% of the total heating, and in terms of economic feasibility, it had a pay back period of 8.4 years (Vanhoudt et al., 2011).

2.5 Hospital Thermal Resilience

Up until this point of the literature review, the focus has been on reducing the energy consumption of buildings, with the purpose of reducing the overall climate impact of hospital buildings. Although great efforts have gone into reducing the carbon emissions in hospitals and other buildings, carbon emissions are still rising worldwide and the temperatures around the world are forecast to increase over time. In the most optimistic circumstances, the intergovernmental panel on climate change predict an increase of at least 1.8°C in the global average surface temperature by 2100 (Pachauri & Reisinger, 2007). Under the UK climate projections (UKCP09) best case scenario, the mean daily maximum temperatures are predicted to increase by a minimum of 1.4°C in the south of England by 2080 (Murphy et al., 2010). As the temperatures are increasing, it will require more effort to cool buildings. As a result, there are an increasing number of researchers investigating the adaptation of existing buildings to the effects of climate change (Albers et al., 2014; Gupta & Gregg, 2012). The reason why this is a key area for research in energy reduction in buildings is because air conditioning systems are often installed in buildings to reduce the temperature, which in turn adds to the energy consumption of the building (Guan, 2012).

As discussed in the thermal comfort section, hospitals are buildings with thermally sensitive internal environmental criteria; hence any increase in temperature can be detrimental to the health of patients. In 2010, the NHS published their “Heat wave Plan for England” where they described their strategy for providing suitable temperatures for hospital spaces during heat waves. Their plan included focusing on improving the design of hospitals to aid passive cooling and target vulnerable areas with air-conditioning and installing monitoring devices to track the room temperatures. They also mentioned that it is important to ensure buildings are well insulated with both loft and cavity insulation as this helps to reduce heat build up while reducing carbon emissions and improving energy efficiency (Department of Health, 2010).

In 2010 the Design and Delivery of Robust Hospital Environments in a Changing Climate (DeDeRHECC) project was established to address the NHS targets of adapting hospitals to the expected increase in the magnitude and frequency of heat waves (Lomas & Giridharan, 2012b). One of the project’s central aims was to develop a methodology for assessing the resilience to climate change of UK hospital buildings. The methodology had 5 steps: 1. Carry out building audit to obtain an understanding of all the essential features of the building; 2. Monitor the internal temperatures in targeted spaces; 3. Compare temperatures with relevant thermal comfort criteria; 4. Use dynamic thermal modelling to simulate the monitored building; 5. Use the thermal model to predict the internal temperatures in future climates with various retrofit measures (Lomas & Giridharan, 2012b).

The project published five core papers which are related to this section of the literature review. The first paper discussed in depth in section 2.2.3 built upon the work in the paper on natural ventilation in hospitals where Lomas and Ji identified criteria which could be used for assessing the resilience of hospitals to overheating (Lomas & Ji, 2009). It laid the foundation for the DeDeRHECC project, addressing the need for a clear definition of what comprises overheating in hospitals (Lomas & Giridharan, 2012b). Thermal modelling was used to investigate a 1960’s tower block building case study, it found that ceiling fans improved the building’s resilience to climate change while having a minimal impact on its energy consumption. The same building was revisited in another paper where further refurbishment measures were implemented. The simulation predicted that natural ventilation could reduce the energy demand from 100GJ/100m^3 to between 20-25GJ/100m^3. The problem with natural ventilation, was that the building would overheat in future years. It was therefore suggested that some

sort of mechanical ventilation would be needed to provide resilience for the future (Short et al., 2012). However, mechanical ventilation did not mean an extremely high energy consumption. With the use of passive house standard insulation and air tightness, the energy consumption was reduced to 46GJ/100m^3. This indicates that even with passive house standards, it is challenging to meet the NHS benchmark.

In a third paper, the energy efficiency and thermal resilience of Nightingale wards was investigated using thermal modelling (Lomas & Renganathan, 2012). The original building had an energy efficiency of 25GJ/100m^2, which is well below the target for refurbished and new buildings. The buildings insulation was reduced to 0.2 W/m^{2}K and 0.1 W/m^{2}K for walls and roof respectively. The primary purpose of the changes to the building was to improve its thermal resilience in the summer. The results showed that after the space was insulated, fitted with shading and a ceiling fan, annual energy consumption was more than halved to 10.68GJ/100m^3. This was possible while providing comfortable summer temperatures, the third option used ceiling radiant heating and cooling, which increased the energy load to 12.8GJ/100m^3. The cooling however did not provide an improvement in thermal performance over the fan, as the max internal temperature was 26.8°C with radiant cooling and 26.2°C with the fan.

The DeDeRHECC project's fourth paper, carried out analysis of the thermal environment within a nucleus hospital. The paper modelled the ward space and assessed the thermal condition in the building, but did not however discuss the energy consumption. The paper predicted that through the implementation of fans, the building could stay comfortable up until 2080 (Giridharan et al., 2013a).

The first four DeDeRHECC papers followed the 5-step approach, the most recent paper however, took a slightly different approach. Rather than focusing on one particular building type, this study used the DeDeRHECC data to create distributed lag models for nine spaces in five of the hospital buildings. The findings demonstrated that the heavy weight Nightingale building had a much lower diurnal swing than the lighter weight modular building. Solar radiation was the most influential factor on room temperature, with the diurnal swing increasing from winter to spring as the solar radiation intensity increased. However, in the cases where spaces were well shaded, there were no signs of increased temperatures. In addition to studying a variety of buildings, time series analysis was used to produce distributed lag models representing the thermal performance of each of the studied spaces. The Nightingale building performed the best, followed by the tower block buildings at Bradford and St

Albans and then the modular building at Bradford, which was dangerously hot with temperatures falling outside the Cat II boundary for 40% of the summer. East facing wards tended to heat up earlier in the day and therefore recorded more hours over threshold. The method produced accurate results, and the overall conclusion from the work was that the lightweight buildings like the modular were warmest, followed by concrete constructed tower blocks, with the masonry buildings being the coolest.

2.6 Summary

The UK has a rich history of hospital building construction showing considerable changes since the first buildings in the middle of the 19th century. UK hospitals are generally sites consisting of a range of buildings constructed over a long period of time. They operate 24 hours a day 365 days a year and consequently have a high annual fossil fuel and electrical energy consumption. The key energy users for hospitals are ventilation heating, space heating, fans, domestic hot water, catering, lighting and support equipment. The dynamics of hospitals are changing, moving away from solely providing patient care towards specialist care and research centres which impacts the balance of the energy load towards increasing electricity consumption.

The performance of hospitals can be related to three distinct factors; building form, services and occupancy. In the UK there are a number of reoccurring hospital archetypes, the Nightingale pavilion type building, prevalent before 1948, characterised by heavy masonry construction and natural cross ventilation. Deep plan and tower buildings which were the focus of design in the ‘50s and ‘60s and recognised by their need for mechanical ventilation and high energy consumption. Closed and open court buildings, which were constructed after the ‘70s energy crisis, with mixed mode ventilation in an attempt to produce a repeatable model of hospitals around the UK. In recent years, the pattern of construction has been hospitals with high levels of insulation, low infiltration rates and efficient heat recovery systems. Modular hospital buildings are a special example of this modern archetype, especially adapted to meeting NHS Trust needs through their rapid construction time.

The criterion used for designing a hospital building services system has a large impact on the amount of energy the system consumes. Thermal comfort criteria are generally split between winter and summer performance with a number of sources providing guidance on acceptable temperature. All sources state that the maximum allowable temperature in hospital wards should be 28°C, but ideally it should be around 24°C. It is deemed general practice that hospitals are heated to a slightly warmer temperature

than other non-domestic buildings due to the reduced activity levels of patients. Ventilation is an influential factor on the energy consumption because of the high levels of heated fresh air that is needed. Higher levels of ventilation mean a higher proportion of the energy is used for fans and air heating. The general consensus is that infectious disease can be transferred through aerial dissemination, therefore the prevention of infection transmission is the key driver for ventilation in hospitals. Higher ventilation rates may increase energy costs but they have the positive effect of reducing the risk of infection, the literature identified that a reduced risk of infection is associated with rates above $2ach^{-1}$. In addition to flow rates, airflow patterns impact the spread of disease, hence pressurised rooms can be a useful tool to control the direction of airflow in hospitals.

Hospitals can be divided into three levels: the site level, building level and occupant level; with the occupant spaces specific to hospitals subdivided into operating theatres, clinics and nursing wards. Operating theatres are very energy intensive due to a heavy use of HVAC systems, consequently a large amount of research has gone into improving the performance of these spaces. Nursing wards are the central feature in hospitals and it has been recognised that these wards are moving toward single bed occupancy for the purpose of increasing privacy and reducing the risk of infection.

In terms of energy management, there are well established site level benchmarks which are currently providing a challenging but realistic target for building designers and energy managers. One area that is under development is the monitoring and benchmarking of hospitals on a building and end-use level. The review identified that a method of assessing a building's performance was to use measurement and energy signature models to provide an accurate representation of a building's annual energy consumption to investigate the use of energy reduction measures.

There has been a wide variety of research undertaken in the field of low energy hospital design and the literature is agreed that the best way to save energy is to implement simple energy saving measures. These are recommended since the more advanced methods have a large capital investment and can cause disruption to hospital services. In this review, the more extensive measures were split into the categories of HVAC systems, passive measures and energy plant. As ventilation and heating are the greatest consumers of energy in hospitals, a number of studies have investigated methods of making the mechanical ventilation systems more efficient and studies on naturally ventilated hospitals have featured in a number of papers. Other

than this, the research has covered other passive measures effective in hospitals such as developing the thermal envelope and improving natural daylighting. Finally, in lowering the energy consumption, many studies have investigated different options for the energy production systems within hospitals. It is demonstrated that combined heat and power should be a fundamental part of a hospital site's main plant with the use of tri-generation as a useful method to increase the efficiency of cooling.

The literature reviewed demonstrates the resilience of hospital buildings to climate change varies widely between building types. It seems that the thermal envelope is the single factor in the building that has the largest impact on it's thermal performance, with lightweight buildings overheating more than heavyweight buildings. Slow moving fans installed on the ceilings of wards have been shown to be an effective retrofit measure for reducing high temperatures in wards. Solar gains have been shown to be the most influential factor on room temperature so different forms of shading are always useful for reducing the internal temperatures.

This literature review has demonstrated that there is a comprehensive base of research about the energy consumption and performance of hospital buildings in the UK. Saying this, however, there are gaps in knowledge, these include:

1. The connection between the recovery rate of patients and the internal environment, especially focusing on thermal comfort and ventilation.
2. The use of CO_2 levels as an indicator of infection transmission and indoor air quality in hospitals.
3. Building level and end-use benchmarks as well as actual monitored hospital energy consumption data for the different hospital archetypes.
4. Development and implementation of energy signature methods for determining hospital building level energy consumption.
5. Relationships between energy and thermal performance of buildings for different building types, determined by measurement rather than by modelling.

Some of these areas are out of the scope of this study but offer the opportunity for other projects to carry out further research. Areas 3 to 5 will be addressed in the forthcoming chapters.

3 Methodology

This chapter presents the method used to meet the aims of this study. The first section gives an overview of the method followed in the thesis. The second discusses how general information was gathered about the buildings monitored. The third details the equipment, their verification and how they were used to take measurements. The final section discusses how the raw measured data were processed, analysed and assessed according to the relevant performance criteria.

3.1 Overview

One of the research questions for this thesis is to identify the relationship between internal environmental conditions and energy consumption for the individual building types. To fulfil this, it was necessary to apply a quantitative approach to gather information about both the buildings' performance and design. This work was associated with the DeDeRHECC project (Lomas & Giridharan, 2012b), which provided access to four hospital sites around the UK: Bradford Royal Infirmary, Glenfield Hospital, Cambridge Addenbrooke's and St Albans City Hospital. These sites contained buildings representing a broad spectrum of hospital building types identified by the literature review. The first task was to identify which buildings and wards would be taken as case-studies.

The performance of the buildings were categorised into two key streams as identified by the literature review, energy consumption and internal environmental performance. The energy category was divided into low temperature hot water (LTHW) for space heating, air heating, domestic hot water (DHW) and ward and plant electricity consumption. The internal environment category was divided into summer and winter air temperatures and indoor air quality. Although access was granted to entire hospital sites, preliminary surveys and pilot studies identified difficulties in certain buildings which meant that all of the sub-units mentioned above were not able to be studied in all of the different buildings, on each of the different sites (discussed in chapter 4).

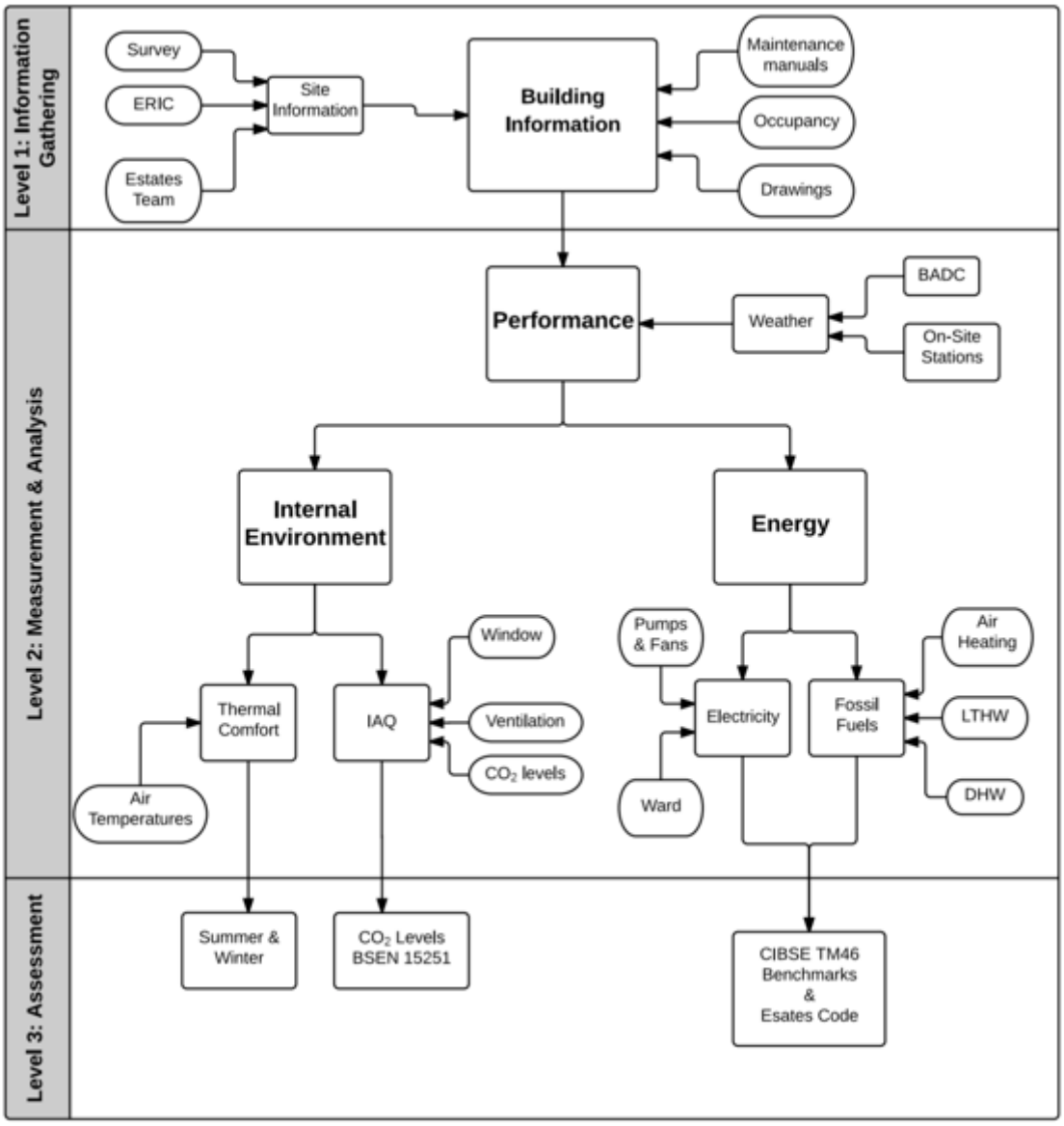
It was necessary to select buildings that would meet the aim and objectives of this study, but the key contributing factor that influenced the selection was accessibility. It was found that access to the areas and information needed to monitor the energy consumption of the buildings presented more restrictions than access to the ward areas to monitor the internal environment. Therefore, this study was limited to

monitoring the energy performance of three key case-study buildings: modular, Nightingale, and nucleus buildings all located at Bradford. This presented the opportunity to compare the performance of buildings built in the 1920s, 1980s and 2000s. The results for the performance of each of these case-studies are detailed individually in chapters 5-8.

Indoor air quality was monitored in the three case-study buildings, however the Bradford modular building was studied in the most depth with window opening being investigated and analysis undertaken on the AHU. This decision was made as the building was a unique case, and provided the opportunity to reveal insight into the performance of modern hospital design.

The monitoring of the three case-study buildings took place between February 2012 and July 2013. During this time visits were made to Bradford Royal Infirmary to monitor the performance of the buildings. The literature stated that the most difficult aspect to monitor within an individual building or section of a hospital was the heating (Singer et al., 2009), therefore this work spent a great deal of effort in this direction. The LTHW consumption, internal air temperatures, ventilation flow rates, CO_2 levels and electricity consumption were all monitored to quantify how the buildings were performing. Some of these measurements were taken through spot measurements and others needed devices to be installed for a longer period of time to record the data. Regular visits to the hospitals were undertaken to retrieve the data, which was then organised and analysed using relevant performance criteria.

The flow chart in Figure 3.1 illustrates the different steps in this method, as discussed in depth in this chapter. This chapter presents an overview of the main details in the methodology. Minor details varied according to the case-study building and these particulars are specified in the coming chapters.



The Estates return information collection (ERIC) is a database which holds all the estates data for the various NHS sites across the U.K.
The British Atmospheric Data Centre (BADC) records weather data for a wide variety of sites around the U.K.

Figure 3.1 - Flow chart giving overview of methodology

3.2 Building Information

3.2.1 Site Visits

Site visits were undertaken and information gathered to gain an in-depth understanding of the site. A valuable source of information was staff knowledge; the members of hospital estates and energy teams were generally well informed on the operation and design of the buildings. In addition, the nurses and doctors shared their experience of the wards IAQ performance and provided information on their occupancy patterns. No formal interviews were undertaken in this work but the

necessary information was gathered from the individuals on both the estates and patient care teams.

3.2.2 Estates Return Information Collection

One source which proved to be informative, was the Estates Return Information Collection (ERIC) which is the main database for NHS estates and facilities services. It contains hospital site information for all the NHS Trusts and private care trusts (PCTs) in the England since 1999/2000 with information being updated on a yearly basis with information (Table 3.1) covering the financial year (1st April to 31st March). It contains information regarding the energy usage of the site, including CHP, utility data, and renewable energy, furthermore it provides figures for the floor area and volume of the buildings on the site as well as the age of the buildings and number of beds they hold.

Categories	*Sub-categories*	*Usage in Project*
Organisational Profile	General acute, Multi-service, Short-term Non-acute, Long stay, Specialist, Community	Identify what type of hospital site it was (all sites taken from the General acute category)
Areas	Gross internal floor area (m^2), occupied floor area (m^2), heated volume (m^3), site footprint (m^2)	Normalise energy consumption for site
Function and Space	Occupied bed, single-bedrooms	Numbers of patients on site
Age Profile (%)	Pre 1948; 1948-1954; 1955-1964; 1965-1974; 1975-1984; 1985-1994; 1995-2004; 2005 to present	Identify the amount of each building type a site is comprised of
Combined Heat & Power	No. of units; total electricity and thermal output (kWh); total fossil input (kWh);	Identify site energy consumption and estimate plant efficiencies
Energy (kWh)	Electricity (renewable/utility), Gas, Oil, Coal, Steam consumed;	Identify site energy consumption

Table 3.1 - Summary of Estates return Collection Information outputs used in study

3.2.3 Maintenance Manuals

Other valuable sources of information were the maintenance manuals and building drawings. As the hospitals had teams dedicated to looking after their buildings, it was common that they had a store of drawings and manuals. These generally contained all, or at least some, of the specific details for the buildings HVAC systems, floor plans, piping locations and construction information.

3.2.4 Building Fabric

It was important to determine the building fabric properties as they have a significant impact on a building's ability to manage heat-loss, thus affecting the buildings energy consumption and thermal comfort. In order to calculate the U-values of each building, maintenance manuals were consulted to identify the buildings construction materials and their specific thicknesses (Bradford Estates, 2012). These values were then used with thermal conductivities (Clarke et al., 1990) and thermal resistances (BSI, 2007) to calculate the U-values. The construction materials and U-value calculations for each of the fully monitored buildings can be seen in the Appendix II.

Layer (Out-In)	*Name*	*Thickness (mm)*	*Thermal Conductivity (K)*	*Thermal Transmittance*	*Thermal Resistance (m^2K/W)*	
se	External Surface (Upwards)				0.04	
1	CR32 Steel Sheet	3	45		0.000	
2	Plywood	9	0.14		0.064	
3	Kingspan Thermaproof TR31	80		0.275	3.636	
4	Air (flowing Up)	35			0.160	
5	Plasterboard	15	0.17		0.088	
6	Isowool Insulation	185	0.04		4.625	
si	Internal Surface (Upwards)				0.1	U-value
Total					8.714	0.11

Table 3.2- Example of U-value calculation method

3.3 Monitoring

3.3.1 Weather

The local weather, especially the ambient air temperature is an influential external factor on building energy consumption and environment. Therefore weather stations were installed on each of the sites investigated to monitor the local weather patterns.

Figure 3.2 - Delta T WS-GP1 weather station

The equipment chosen to monitor the weather was the delta-T WS-GP1 weather station (Delta-T, 2015). This weather station monitored ambient air temperature, wind speed/direction, horizontal solar radiation and rainfall. Ambient air temperature was the main measurement needed for the methodology and the stations had an accuracy of ± 0.3°C. The weather stations were set to log the temperatures on an hourly basis and were installed with solar panels to enable them to be powered without the use of a battery. Data was saved to the memory of the stations and downloaded on visits to the sites.

To validate the ambient air temperature from the weather station and obtain data for periods prior to the installation of the WS-GP1 station, data was sourced from the British Atmospheric Data Centre (BADC) (National Centre for Atmospheric Science Natural Environment Research Council, 2015) for the closest stations to the site. Table 3.3 shows the BADC weather stations chosen and their distance from their respective sites. In addition, it also demonstrates the difference between the temperatures measured by the BADC and WS-GP1 weather stations.

	MET Station Name	*Distance & Direction from Hospital (miles)*	*Average Difference (Site – BADC) (°C)*	*Standard Deviation of Difference (°C)*	*Period of Comparison*
Bradford	Bingley	2.9 W	-0.03	0.74	1/1/12-31/12/12

Table 3.3 – Location of BADC stations used for supplementary data in study and comparison between the hourly air temperatures monitored by the WS-GP1 stations on site and BADC stations for specified time periods.

Figure 3.3 gives an example of why two sources of weather data were used. From January 1st to the end of October the BADC station and local WS-GP1 weather station show very similar recordings for the external temperature. However from late October, the weather station lost power and failed to take measurements. Using the two weather stations enabled the ambient temperature to be available when one source was missing data.

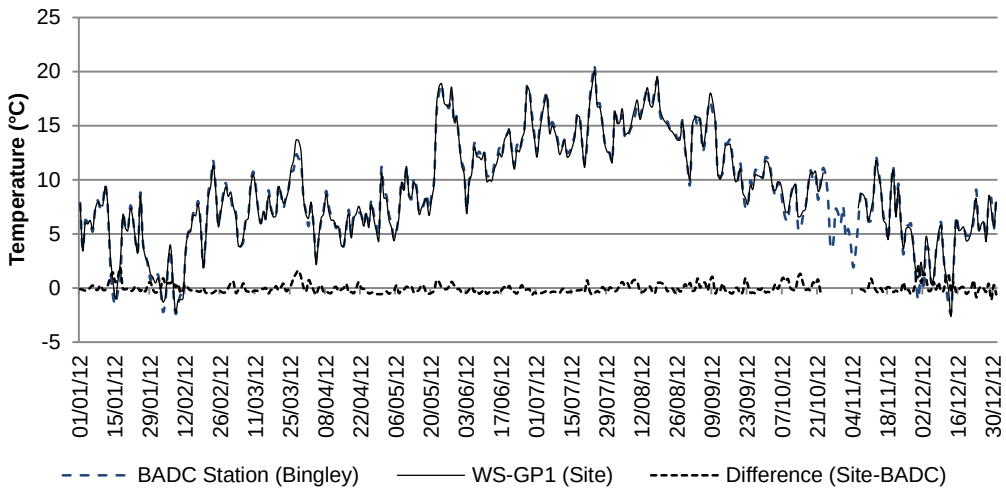


Figure 3.3 - Comparison between average daily temperature measured by the nearest BADC station and onsite WS-GP1 weather station installed at Bradford Royal Infirmary.

3.3.2 Air Temperatures

Hobo temperature sensors were placed on the wards to monitor the temperatures of the different spaces. The sensors used were the hobo U12 and pendant data loggers (Tempcon, 2015) (Figure 3.4) which had manufacturer's stated accuracies of ±0.35˚C and ±0.53˚C respectively. In order to check this accuracy, loggers were placed in a box and set to monitor the air temperature which ranged from 18.5°C to 21.5°C it was found that the error was less than ±0.3˚C for both U12 and pendant loggers.

Figure 3.4 - Indoor temperature sensors (Hobo U-12 [Left], Hobo Pendant [Right]) (Tempcon, 2015)

The sensors were placed in corridors, nurse stations, and a selection of single and multi-bed rooms to determine the temperature in these spaces (for the particular placement in each ward, view future chapters). They were strategically positioned at head height away from the influence of solar gains. One sensor was placed in each single bedroom and nurse station, however two sensors were placed in the multi-bed spaces and corridors to identify the variations in temperature in these larger spaces. The temperature logging devices were set up to log the spot values on the hour.

3.3.3 CO_2 Levels

CO_2 loggers were placed in multi-bed rooms in order to monitor the CO_2 levels in the winter months. The CO_2 sensors used were Telaire 7001i (Onset, 2015b), which manufacturers stated had an accuracy of ±1ppm. However when using two devices to carry out a walk around survey to measure a rooms CO_2 level there was a regular difference of about ±50ppm between the devices. These sensors were coupled with Hobo U12 data loggers in order to log the CO_2 levels on an hourly basis. The sensors needed to be plugged in so they were stationed close to a power supply at head height away from CO_2 sources. The length of time these loggers monitored the rooms CO_2 levels varied between 2 days and 2 months depending on the ward being monitored.

3.3.4 Window Opening

The window opening patterns in one building's multi-bed room was monitored. Hobo g accelerometers (Onset, 2015a) (Figure 3.5) were attached to each of the operable windows in the space and set to monitor angular displacement on an hourly basis for 6 months from August 2012 – February 2013. The loggers measured acceleration in the x/y/z axis in units of g-force with a range of ± 3g. These devices were set to measure the static acceleration of gravity making it possible to measure the degree of the tilt of the window.

Figure 3.5 - Hobo Pendant G, accelerometer (Onset, 2015a)

3.3.5 Heating Energy

The heating energy use was the main contributor to fossil fuel consumption in the individual hospital buildings. This heating was divided between three main sources, LTHW, air heating and DHW. In this work direct measurements were taken to estimate the LTHW and air heating loads whereas DHW was estimated using secondary information.

The method of quantifying the heat being transferred into a building through LTHW was to measure the flow rate and supply and return temperatures of the LTHW and

put the results into the heat transfer formula (Equation 3.7). In order to do this the LTHW pipes supplying the area were located from the site surveys, staff knowledge and site drawings.

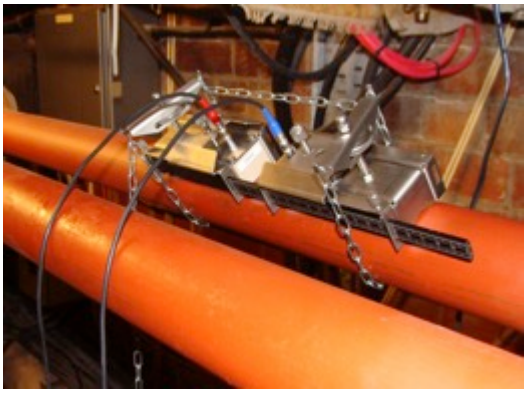


Figure 3.6 - Flow meter transducers connected to pipework

The equipment used to monitor the flow rate in this investigation was a non-intrusive ultrasonic flow meter. Another option available was a fixed position flow meter, this was not suitable for this project because it would be unfeasible to turn off the hospitals energy systems in order to fit the device. In addition, the project only lasted for a short period of time making a permanent flow meter installation costly.

Ultrasonic flow meters measure the velocity of a liquid or gas using the principle of ultrasound, they use ultrasonic transducers to measure the average velocity of a sound wave passing through the fluid. Ultrasonic flow measurement is affected by the temperature, density and viscosity of the flowing medium.

There are two main types of ultrasonic flow meters, firstly the transmission type, which can either be permanently fitted inside a system or a non-intrusive clamped on version and the second type is the Doppler shift flow meter. Ultrasonic transmission flow meters work by sending ultrasonic pulses through the flowing fluid. When the velocity of the fluid is zero, the transit time of an ultrasonic pulse is the same in both upstream and downstream directions. When there is flow, the upstream sonic pulse will travel at a slower rate than that of the downstream pulse (Figure 3.7). When flow rate increases, the transit time differential increases linearly. As the cross-sectional area of the pipe is already known, the product of the velocity (transit-time differential) and the pipe's internal cross-sectional area equates to a volumetric flow. It is widely accepted that transit-time flow measurement devices are more accurate than the clamp on Doppler equivalents (Cascetta, 1995).

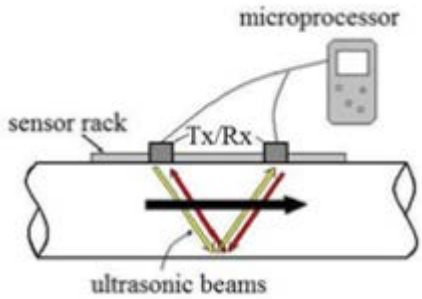


Figure 3.7 - Transit Time Ultra Sonic Flow meter (Bengtson, 2010)

The pipe diameters monitored in the work were between 20-100mm and the water in the pipes varied from 50-80˚C, therefore the instrumentation needed to be able to work with these ranges. Furthermore, the instrumentation was left to monitor the LTHW for a prolonged period of time, therefore it needed to be able to log the results to memory and transfer them to a PC for analysis.

The transmission ultrasonic flow meter chosen for this investigation was the Portaflow 330 (Micronics, 2015). The datasheet for the equipment stated that to produce accurate measurements (Table 3.4), there should be a straight length of pipe between 20 times the pipe diameter upstream of the device and 10 times the diameter downstream of the device (Micronics, 2012).

Scenario	*Accuracy (%)*	*Flow rate (m/s)*	*Pipe internal diameter (mm)*
1	(±)0.5-2	> 0.2	> 75
2	(±) 3	> 0.2	13-75
3	(±)6	< 0.2	-

Table 3.4 - Accuracy of Portaflow 330 Flow Meter (Micronics, 2012)

Figure 3.8 - Test rig set up to evaluate flow meter performance

In order to validate the accuracy of the flow meter and gain experience in its use, a testing rig was set up to emulate a hospital LTHW pipe. The results from the validation study showed that the average error between the value measured by the flow meter and the value measured in the experiment was, 3.11%. This is in line with the manufacturers stated error for scenario 2, ± 3% (Table 3.4). The small difference is likely due to error in the method of measuring the flow rate coming out of the pipe. In addition to this, the study identified that turbulence in the system would cause positive and negative spikes in the flow reading that would need to be filtered in the data analysis stage. For further information on the validation study, see Appendix I: Flow Meter Pilot Study.

The temperature of the LTHW supply and return pipes was monitored using Tinytag Talk 2 (Gemini data loggers, n.d.) temperature loggers fitted with thermistor probes. This device was chosen for the study as it had a small probe, which provided a direct contact with the pipe and was operational up to temperatures of 125˚C.

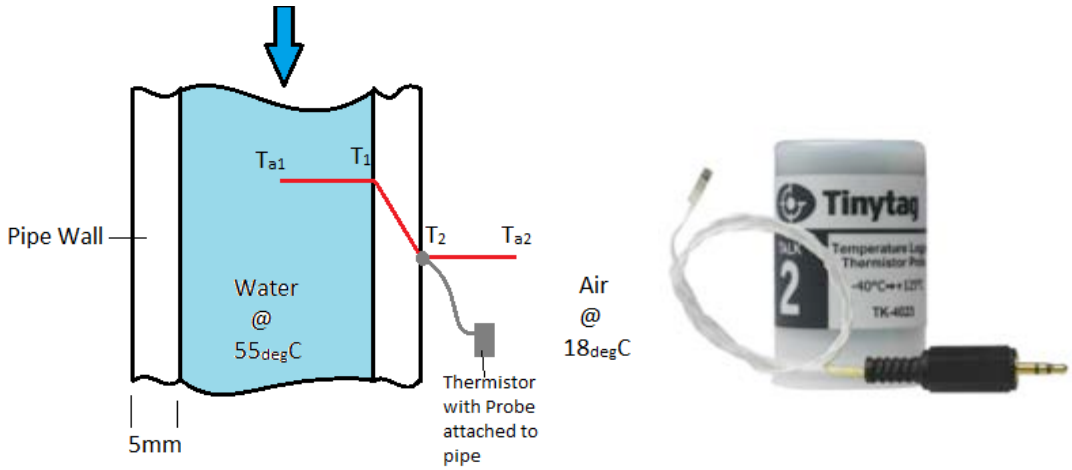


Figure 3.9 - Heat transfer between water and thermistor [Left]; Tiny Tag temperature logger with thermistor probe (Gemini data loggers, n.d.)[Right]

It was the aim to monitor the temperature of the water, however this was not actually possible as the pipe was closed. To get a close estimate of the water temperature the temperature of the surface of the pipe was measured. Heat transfer principles were used to calculate the difference between the actual temperature of the water and the temperature that would be measured on the surface of the pipe. It was calculated that when the fluid flow was 55°C (Figure 3.9) there would be a difference of 0.041°C between the actual water temperature and the surface temperature of the pipe (for further information see Appendix I).

The temperatures to be monitored for the hot water supply were between 50 and 70˚C. Therefore, according to the manufacturer the accuracy of the Tinytag Talk 2 sensors was 0.4˚C. When two Tinytag Talk 2 sensors were tested against each other, it was found that there was a maximum difference of ±0.3°C between their measurements while measuring an object at 23°C.

3.3.6 Monitoring Ventilation

A DPM hood balometer (DPM, n.d.) was used to assess the ventilation rates of the building (Figure 3.10), this piece of equipment had been calibrated within a month of the beginning of its use and had a stated accuracy of ± 3% of the measured value. Furthermore, when taking readings in one of the buildings at Bradford Royal Infirmary, it was found that the total flow rate measured by the DPM balometer was only 2.2% different from the design flow rates (Figure 3.10).

Grill	*Design (l/s)*	*Measured (l/s)*	*Difference*
1	80	87	8.8%
2	80	88	10.0%
3	28	22	-21.4%
4	80	80	0.0%
5	80	74	-7.5%
6	111	118	6.3%
Total	459	469	2.2%

Figure 3.10 - DPM balometer being used to measure the airflow rate out of a ventilation grill [Left] Difference between design and DPM balometer measured airflow rates from grills in the Bradford modular building Ward 30 corridor [Right]

3.3.7 Electrical Energy

Current transformers were used in monitoring the different aspects of the buildings electrical energy consumption. They were chosen as they allowed the current flowing through a circuit to be measured non-intrusively. This was important, as it was not possible to stop the usage of the electrical equipment to install permanent electricity metering devices. The instruments of choice were the SPC mini (SPC Loggers, 2013) and the onset CTV-A (Onset, 2013) current transformers (Figure 3.11). The SPC mini was mainly used for spot measurements as it had a visible screen on it, it had a range

of 0-500A, an uncertainty of ±1% and an ability to log at intervals of between 1 and 60 seconds. The onset transformers were used for long periods of data collection, had a range of between 0-20A (CTV-A) and 0-100A (CTV-C) and had an uncertainty of ±4.5% of full range, which gives a stated accuracy of ±0.9A (range A) and ±4.5A (range C). The device was not fitted with a logging function, so it used Hobo U12s to log the various currents.

Figure 3.11 - Electricity logging devices, (L-R: SPC Mini (SPC Loggers, 2013), CTV-A (Onset, 2013))

With the assistance of a hospital estates electrician, the current transformers were installed on site. The CTV devices were installed in the distribution boards of each ward for 15 days periods, logging readings at 1-minute intervals. The devices were moved from ward to ward and then into the plant rooms until all the required wards, pumps and fans had been monitored.

Some of the wards in the hospital had electricity meters in the distribution boards that provided the total electricity used over a period of time (they could not logger minutely data). To validate the accuracy of the measurements, the measured values were compared to the metered values (Figure 3.12). It was found that there was 1.1% difference between the value from the CTV's and the hospital monitoring equipment.

Figure 3.12 - Ward distribution board, (Hobo loggers and CTV current transformers [Left]) (ward monitoring device [Right])

3.3.8 Summary of Instrumentation

There were a number of different pieces of equipment used in monitoring in this project, a summary of them is given in table Table 3.5.

Measurement	*Device*	*Accuracy*
Fluid Flow Rate	Micronics Portaflow 330	±3%
Pipe Temperature	Tinytag TK-4023 Temperature logger with thermistor probe	-40 to 125˚C Resolution =0.05˚C or better Accuracy =±0.4˚C
Current	Onset CTV-C current transformers	±4.5% of scale
Current	Elcomponent SPC Mini	±1%
Weather	delta T WS-GP1	-
Air Temperature	Hobo U12	±0.35˚C
Air Temperature	Hobo Pendant	±0.53˚C
CO_2 Level	Telaire 7001i	±1ppm

Table 3.5 - Summary of Measurement Instrumentation

3.4 Data Analysis

This section of the chapter focuses on the analysis that enabled the monitored data to be used in assessing the performance of the buildings. The assessment was split between the winter heating and the summer period: December-February and May-September respectively.

3.4.1 Internal Environment

Thermal Comfort

Monitored ward air temperatures were analysed to assess the thermal comfort. The data were logged hourly, and the weighted average hourly temperature (T_{WA}) was calculated for each wards floor area(A_s) (Equation 3.1 and Equation 3.2).

$$T_{WA} = \frac{A_1}{A_T}T_1 + \frac{A_2}{A_T}T_2 + \cdots + \frac{A_n}{A_T}T_n$$

Equation 3.1

$$A_T = \sum_{s=1}^{n} A_s$$

Equation 3.2

Where:

T_{wa} = Weighted average hourly temperature (°C)

$T_{1...n}$ = temperature for each space

A_T = Total area of monitored spaces in ward (m^2)

s = space in building

n = number of spaces in building

To assess the performance of the various buildings during the winter the monitored air temperatures were compared to the CIBSE guide A hospital ward heating season criterion of 22-24°. In addition to this, the average daily temperature profile was calculated to enable any daily patterns to be identified. For the winter heating season this profile was created by averaging the temperature of every hour between December 2012 and January 2013. For example, the profile would be made by averaging the temperature at 13:00 for every day in December through to February and doing the same for every hour of the day.

Five criteria were deemed useful to quantify the summer thermal performance of the buildings each one having a recommended limit on the number of hours over a specific operative temperature. The first three were of the static Fanger type and the last three were adaptive, i.e. the threshold temperatures increased with increasing external temperature.

The first static criterion used was hours over 25°C. CIBSE Guide A (CIBSE, 2006b) recommends that during warm ambient conditions, an acceptable internal temperature for schools, offices, living areas and retail buildings is 25°C. CIBSE TM 36 (CIBSE, 2005a) suggests that having no more than 5% of occupied hours above 25°C is an acceptable criterion for assessing overheating when analysing the results of a building energy model using design summer year (DSY) weather data. The data in this study was not modelled, nevertheless this criterion was useful as it identified the number of hours for which internal temperature exceed the value that people find comfortable in summer months. The benchmark or indicator that has been used, 5% of the 8760 hours[i] in each year was 438 hours. The measurements were not taken throughout the

[i] Hospital buildings are occupied all hours of the year.

whole year, but the assumption has been made that the majority of hours in which overheating took place during a year were between May and September.

The second static overheating criterion was hours over 28°C. This has been recommended in HTM-03-01 (Department of Health, 2007a) which states that the temperature in a hospital space should not exceed 28°C for more than 50 hours in a year. CIBSE Guide A also uses 28°C as a benchmark, but it states that no more than 1% of the hours in a year (88 hours) should be over 28°C.

The third static criterion was night-time hours over 26°C. CIBSE has set a maximum criterion of no more than 1% of nightly hours over this operational temperature to define summertime overheating in bedroom areas at night. For the purpose of this study the assumption is made that night is from 21:00 to 6:00.

The adaptive thermal comfort overheating criterion was found in BS EN 15251 (British Standard, 2007). In this criterion the operative temperature at which the building is deemed to be uncomfortable changes according to the running mean of the daily average external air temperature. This criterion was designed to be used with measured as well as simulated internal temperature data. It is to be noted that the actual measured temperatures were an approximation of the rooms air temperature, nevertheless the operative temperature still provided a good standard to compare the measurements to. Another feature that added to this criterion's suitability for this work was that it provided categories that have a specific operative temperature for a number of circumstances. The categories used were Category I and II as they were the most suitable for hospital wards. Category I, a "high level of expectation" the narrowest category was designed for people, who are sensitive, elderly, fragile etc. This was perfect for the buildings in this study as they are specifically built for looking after elderly, sick or recovering patients. Category II, a "normal level of expectation" used an operational temperature range that was a little wider than Category I. This was applicable to the monitored buildings as areas such as nurses stations and corridors did not need to have temperatures as particular as the bed-spaces. The difference between the operational temperatures for the different categories can be seen in Figure 3.14. The formulas (British Standard, 2007) for calculating the operative temperature at any point in time for these categories are.

Category I $$T_{i\,max} = 0.33T_{rm} + 18.8 + 2$$

Equation 3.3

Category II $$T_{i\,max} = 0.33T_{rm} + 18.8 + 3$$

Equation 3.4

The running mean outdoor temperature has been calculated using Equation 3.5.

$$T_{rm} = \frac{T_{ed-1} + 0.8T_{ed-2} + 0.6T_{ed-3} + 0.5T_{ed-4} + 0.4T_{ed-5} + 0.3T_{ed-6} + 0.2T_{ed-7}}{3.8}$$

Equation 3.5

Where:

$T_{i\,max}$ = Limit value of indoor operative temperature for today (°C)

T_{rm} = Running mean temperature for today (°C)

T_{rm-1} = Running mean temperature for previous day (°C)

T_{ed-1} = Daily mean external temperature for previous day (°C)

T_{ed-2} = Daily mean external temperature for day before and so on (°C)

An unacceptable amount of overheating is indicated when the temperature exceeds the categories boundaries for more than 3% or 5% of operational hours. For this study, the indicator of 5% was taken which gives a limiting frequency of occurrence of 438hrs.

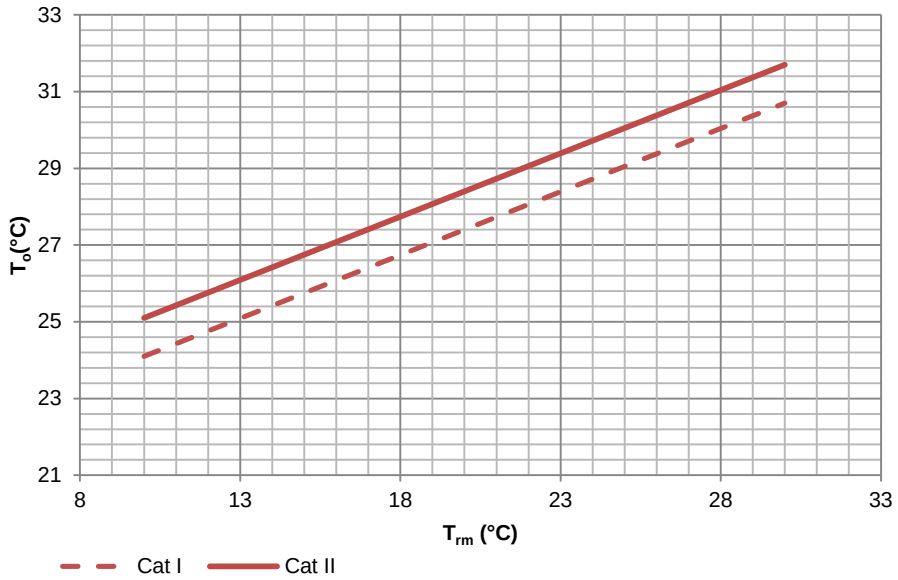


Figure 3.13 – Operative temperatures for Category 1 and 2 from BS EN 15251 thermal comfort guidance

When analysing the measured data according to the above standards, it is important to recognise that the results from the hobo sensors used in the measurements will not actually give a true reading of the operative temperature. The operative temperature is a combination of 50% air and 50% mean radiant temperature within the space. In this

work, the temperatures measured by the hobo sensors were used as a proxy for thermal comfort.

Evidence supporting the acceptability of this assumption for the purpose of this work is demonstrated by a number of studies. In a recent paper (Limbachiya et al., 2012), researchers compared two methods for identifying thermal comfort. The simpler “Silver” method involved using a Hobo sensor placed in the room close to where the participant was seated and it was assumed that the mean radiant temperature was the same as the air temperature. This method was compared to the “Gold” method as defined by international industry standards, which involved measuring air temperature at three heights, and measuring mean radiant temperature at a height of 0.6m with a 150mm diameter globe. It is well known that the mean radiant temperature depends on the construction of the walls in the space. The study was carried out on 17 domestic case study buildings which included terraced, detached and semi-detached homes, with the variety suggesting the buildings would have had a range of constructions. Despite the probable differences in building construction, the results of the comparison between the air temperature measurements (Silver method) and the mean radiant temperature measurements (Gold method), showed that in 75% of cases, there was a difference of 0-1°C and in 19% of cases there was a difference of 1-2°C. The regression line (Figure 3.14) demonstrated that at temperatures typical within hospital spaces (22-24°C), the air temperature tended only to be slightly higher (0.4-0.6°C) than the radiant temperature.

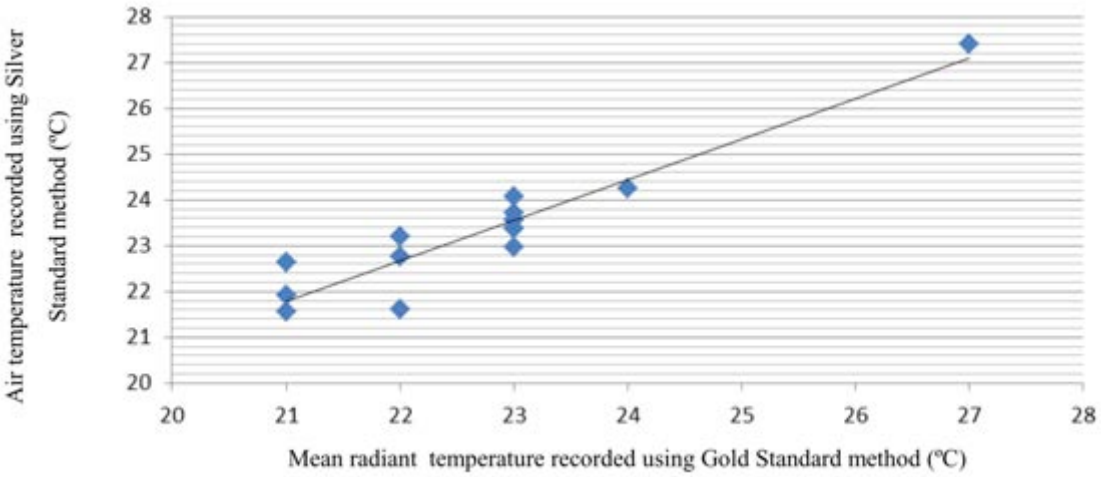


Figure 3.14 – Air temperature measured using the Silver Standard method vs. mean radiant temperature measured using the Gold Standard method (Limbachiya et al., 2012)

In the Limbachiya et al. (2012) study, the hobo sensor was placed in the middle of the room, close to the occupant. In the hospital wards, this is not possible, but rather, the sensor was placed on the wall. The literature suggests that hobo sensors measure 75%

air and 25% radiant temperatures (Deurinck, 2015), with the radiant portion measured being most influenced by the radiant temperature of the surface it is located on (Olesen, 2001).

In another study mean radiant temperature was compared to the air temperature within four different rooms in a building during summer (Walikewitz et al., 2015). The results found that during lower room temperatures (under 25 or 26°C) the difference between air temperature and mean radiant temperature was zero, or the air temperature was higher than measured mean radiant temperature. In general the researchers identified that that the difference between air and mean radiant temperature was negligible as long as minimal amounts of direct solar radiation entered the rooms. With rising temperatures, the radiant temperature increased more than the air temperature. Although this was the general pattern, there were differences between the rooms. Firstly, variable surface temperatures influenced the difference between air and radiant temperatures. Furthermore, the rooms facing southward that had the most solar radiation showed the largest differences between air and mean radiant temperature, hence the study concluded that solar radiation had the greatest impact on mean radiant temperature. The main driving factors determining the difference between air temperature and the mean radiant temperature were the size and exposition of the window and the intensity of the solar radiation entering a room. The study acknowledged its limitations, which were that its results were only applicable for buildings with modern construction during summer conditions (Walikewitz et al., 2015).

It is important to note that both studies described above were undertaken in summer, indicating that the findings are applicable for use in this thesis. Furthermore, the results highlighted that the radiant temperature was typically equal or slightly lower than the air temperature and it is assumed that the hospital buildings studied in this thesis will show similar results. Air temperature has been used as a proxy for operative temperature when assessing thermal comfort in many reputable publications relating to hospital buildings (Giridharan et al., 2013b; Iddon et al., 2015; Lomas & Giridharan, 2012a, 2012b; Oraiopoulos et al., 2015; Short et al., 2012). Therefore, it is expected that this assumption will have limited impact on the findings of this thesis.

CO_2 Levels

The BS EN 15251 standard (British Standard, 2007) contained recommendations for acceptable levels of indoor air quality within a space. Walk around spot CO_2 measurements were assessed against this criterion, Categories I through III were used (Table 3.6) and the assumption was made that the outdoor CO_2 levels were 400ppm. Monthly mean global levels of CO_2 ranged from 391ppm in January 2012 through to 397ppm during the middle of 2014 (ESRL, 2015), the period when the final CO_2 measurements were taken for this study. CO_2 levels in a particular area show daily, weekly and annual variation depending on the amount of anthropogenic activity in the given vicinity, with urban areas generally having higher levels of CO_2 than rural areas, a phenomenon known as the "urban CO_2 dome" (Idso et al., 1998). It is likely that, the levels in Bradford were similar to the global CO_2 levels, so the assumption of 400ppm seems like a reasonable figure. Nevertheless, this assumptions weakness is that it does not take local CO_2 variations into consideration. The literature shows that different cities have diverse degrees of variation in CO_2 levels. In Nottingham, average levels ranged from 345ppm in June/July at 18:00 to 378ppm at 7:00 in February/March (Berry & Colls, 1990). In Boston USA, there was a mean annual difference of 20ppm between the urban and rural areas (Briber et al., 2013). In Kuwait, mean annual diurnal concentrations varied between 367.8ppm and 371ppm (Nasrallah et al., 2003). In New Orleans, Cincinnati and St Louis, there was a max diurnal swing of 62ppm, 85ppm and 12ppm respectively (Clarke & Faoro, 1966). Rome showed fluctuation of 100ppm between May and August 2004 (Gratani & Varone, 2005). These and other (Reid & Steyn, 1997) studies show fluctuation in CO_2 levels which are below 100ppm. On the other hand studies undertaken in the cities of Phoenix, show wider changes in ambient CO_2 levels, up to 250ppm compared to rural area (Idso et al., 2001).

As such it is likely that a smaller city such as Bradford will not have as much emissions and high levels of variation as in Phoenix, and thus show similar changes as those in the previous studies. Taking this into consideration we can make a rough estimate that Bradford's CO_2 levels should vary by no more than 100ppm, providing a figure of 400ppm ± 50. This combined with the accuracy of the readings (±50ppm), gives a combined uncertainty of ±100ppm when interpreting the results against the criterion.

Category	*Explanation*	*BSEN 15251 CO_2 criteria above outdoor levels (ppm)*	*CO_2 criteria used for analysis including outdoor levels of 400ppm (ppm)*
I	High Expectation - Recommended for spaces with very sensitive and fragile persons, i.e. handicapped, sick, very young & elderly	350	750
II	Normal Expectation - Used for new buildings and renovations,	500	900
III	An acceptable Expectation - Used for existing buildings	800	1200
IV	Unacceptable	<800	<1200

Table 3.6 – Recommended BS EN 15251 CO_2 concentrations above outdoor concentration for energy calculations and demand control

It is to be noted that all CO_2 levels mentioned in this thesis from this point forward are absolute, except for those quoted from BS 15251 before conversion or unless otherwise stated.

In addition to the BS EN 15251 criterion, the measured spot CO_2 levels, were used to estimate an indicator of threshold airflow rates, using Equation 3.6 (Persily, 1997).

$$Q_o = \frac{10^6 \times G}{\left(C_{in_{eq}} - C_{out}\right)}$$

Equation 3.6

Q_o= outdoor airflow rate into space (L/s)

G = carbon dioxide generation rate in the space (L/s)

$C_{in_{eq}}$ = equilibrium carbon dioxide concentration in the space (ppm)

C_{out} = outdoor carbon dioxide concentration (ppm)

The carbon dioxide generation rate (G) was taken to be, 0.0052 (L/s) (Guo & Lewis, 2007; Lu, Lu, & Viljanen, 2011), corresponding to the rate generally used in offices for people who are sat down. This has been deemed a suitable estimate for this study as office workers and patients have similar metabolic rates of 1.2 and 0.9MET for office workers and hospital patients respectively. This is a difference of 0.3MET, which can possibly be accounted for by visitors and staff members who regularly visit the ward spaces (CIBSE, 2006b). The outdoor carbon concentration was assumed to be 400ppm, and the equilibrium CO_2 concentration was taken to be the measured CO_2 level measured in the space. It is to be noted, that this method can only be used as a very rough estimate of the threshold of the airflow rate into the space. This is because it is likely that the measured CO_2 levels are a lot lower than the actual equilibrium CO_2

concentration, therefore the results for ventilation will likely be an overestimate. The resulting airflows from the calculations will be compared against the HTM-03-01 and CIBSE criteria of 6ach^{-1} and 10l/s/p as these are the specified airflow rates in the building regulations. The estimation will not be able to verify if criteria are being met, nevertheless, it is useful as it enables one to identify if the system in its present state has the potential to meet the recommendations.

The above method is useful for the walk around spot CO_2 measurements where the level of occupancy is known, however, when considering the long term monitoring, the occupancy of the room will be unknown. Therefore in these cases it will not be possible to use the above method. In addition to this, a portion of the buildings ventilation comes from infiltration through the building fabric. Infiltration rates are generally assessed using tracer gas decay or fan pressurisation techniques. The tracer gas method involves injecting a gas into a space with all windows and ventilation ducts closed while measuring the rate of the decline of the gas which is used to accurately estimate the infiltration rate (Guo & Lewis, 2007). In the fan pressurisation (blower door test) method, the windows and ducts in the room are closed, but in this case, a fan is attached to the sealed door, which is used to pressurise the room. The pressure is then used to calculate the rate of air leaving the space through infiltration (Guo & Lewis, 2007; Sherman, 1987). The limitation with each of these methods is that they are intrusive and require the room to be vacant while measurements are taking place. It was not possible for the hospital spaces to be vacated, as such these methods will not be used in this study.

Window Opening

The data from window monitoring were filtered to identify the number of windows open at any point in time. It was originally logged hourly in the format of inclination, (g) in the x,y,z axis directions. An original recorded signal can be seen in Figure 3.15. As each window had a mechanism which held it opened or closed, the acceleration signal was filtered to determine which position the window was in. When the signal of the sensor was close to 0 the window was taken to be closed, when there was an increase in the displacement to around -0.2, the window was assumed to be opened.

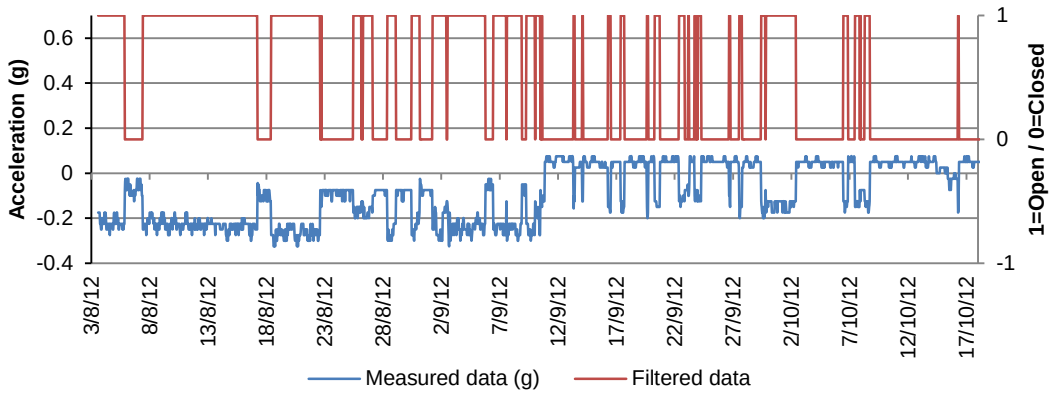


Figure 3.15 - Example of window monitoring data

This filtering process was carried out for the individual windows in a space then their individual results were added together to give a figure for how many windows were opened at any one point in time.

3.4.2 Heating Energy

LTHW

Singer et al., 2009 provided two recommendations for monitoring the LTHW heating consumption of a building over a limited period of time. The first relied on monitoring the space heating under various seasonal weather conditions and the second involved monitoring the heating at a 10-min resolution in order to calculate the heating consumption over an hourly basis. This hourly data could be regressed against outdoor air temperature and the relationship used with an annual outdoor temperature profile to estimate the annual heating energy consumption. Aspects from both methods have been combined in order to monitor the heating load of a single building.

The following paragraphs contain a step-by-step description of how the data from the measurements for the LTHW pipe temperatures and flow rates were processed and analysed to predict the yearly heating energy consumption for the various hospital buildings.

Step 1: Filtering flow rates

The temperature of the LTHW pipes and the flow rates were logged on a minutely basis for periods of up to 7 days at a time. There were often spikes in the readings, up to 5x the magnitude of the general flow. Appendix I details the pilot study undertaken to validate the accuracy of the flow meter and gain a better understanding of the equipment. In the study, similar spikes were found in the flow meter readings when the

flow became unsteady or turbulent. To minimize the effect of these spikes on the results, flow rates were filtered to remove signals resembling those caused by turbulence in the pilot study. An example of the raw and filtered flow rates can be seen in Figure 3.16 and Figure 3.17.

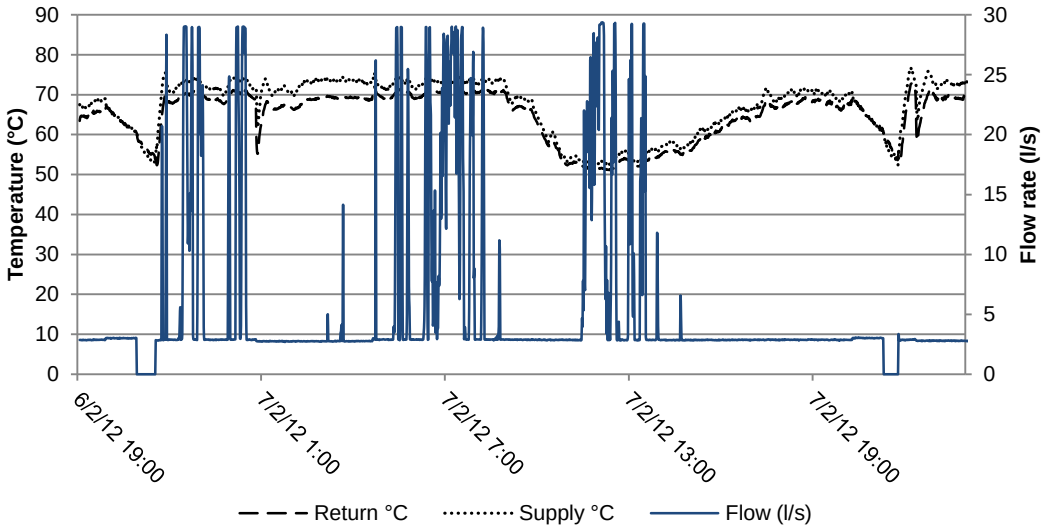


Figure 3.16 – Unfiltered flow rates for LTHW

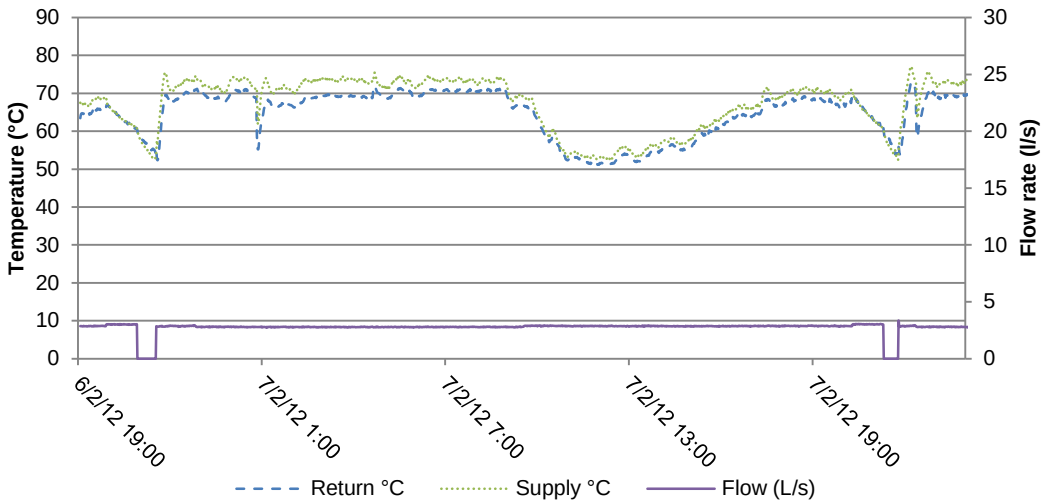


Figure 3.17 – Filtered flow rates for LTHW

Step 2: Daily heating consumption

The filtered data for flow rates and the measured pipe temperatures were put into a spread sheet to calculate the heat consumption for each minute monitored during the day using Equation 3.7 (Cengel, 2003).

$$\dot{Q}_{mLT} = \dot{V}_{LT} \cdot C_{pW} \cdot \rho_W \cdot (T_{sLT} - T_{rLT})$$

Equation 3.7

Where:

$\dot{Q}_{mLT}$ = monitored LTHW heat going into building (kW)

$\dot{V}_{LT}$ = LTHW volume flow rate (m^3/s)

C_{pW}= specific heat capacity of water (kJ/kg K) = 4.813 @ 60°C

ρ_W = density (kg/ m^3) = 986 @ 60°C

T_{sLT}= temperature of supply pipe (˚C)

T_{rLT}= temperature of return pipe (˚C)

Table 3.7 demonstrates that in the minute monitored at 19:05 on 6/2/2012, the LTHW system supplied heat to the building at a rate of 55,490 (W). Using the spread sheet this calculation was repeated for every minute of monitored heat flow data. This information was then used to find the average daily heat consumption of the space from between 00:00 to 23:59.

Time & Date	*Supply (°C)*	*Return (°C)*	*ΔT (only +ve)*	*Flow (L/s)*	*heat (kW)*
06/02/2012 19:05	67.525	63.438	4.087	2.861	55.49

Table 3.7 - Worked example of heat consumption calculation for a particular point in time

Step 3: Performance lines

Each of the buildings were monitored in the different seasons to provide a picture of how their LTHW heating system performed in varying ambient conditions. The average heating consumption for each day monitored was then plotted against the average internal[i] to external temperature difference for the day. This produced a scatter graph, from which regression analysis was used to produce a performance line equation in the form of Equation 3.8, which modelled the performance (Figure 3.18) of the LTHW for the building.

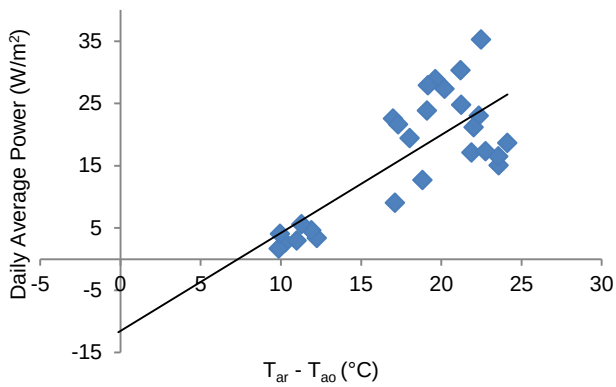


Figure 3.18 - Example performance line

[i] Internal temperature = average weighted internal temperature for heated space.

$$\dot{Q}_{LT} = \mathrm{M}(T_{ar} - T_{ao}) - \mathrm{X}$$

Equation 3.8 (Hammarsten, 1987)

Where:

$\dot{Q}_{LT}$ = heat flow into building estimated by performance line (W/m^2)

M = gradient of performance line

X = value where performance line crosses the y-axis

T_{ao} = ambient air temperature (°C)

T_{ar} = average internal weighted air temperature for space (°C)

A_T = Total area of monitored spaces (m^2)

Step 4: Yearly LTHW energy consumption

The performance line was used to calculate the total annual energy consumption. The average internal weighted temperature from each ward monitored from December 2012 to February 2013 was assumed to be the set-point temperature for the particular space and used as $\boldsymbol{T_{ar}}$. The average hourly heat flow into the building was calculated from April 1st 2012 to March 31st 2013 using the performance line and measured external air temperature ($\boldsymbol{T_{ao}}$) (Table 3.8). From here, the "averageif" function was used in excel to calculate the average daily heat flowing into the building, which was then multiplied by 24 and divided by 1000 to convert from W/m^2 to kWh/m^2. The energy consumption for each day was then added together to estimate the overall energy use for the whole year (Table 3.9).

Date	*Time*	T_{ao}	T_{ar}	*dT(Int-Ext)*	*Hourly heat flow (W/m^2)*
01/04/2012 00:00	00:00:00	1.1	24	22.9	24.791
01/04/2012 00:00	01:00:00	0.6	24	23.4	25.586
01/04/2012 00:00	02:00:00	0.2	24	23.8	26.222
⋮	⋮	⋮	⋮	⋮	⋮
31/03/2013 00:00	21:00:00	1.3	24	22.7	24.473
31/03/2013 00:00	22:00:00	1.1	24	22.9	24.791
31/03/2013 00:00	23:00:00	0.7	24	23.3	25.427

Table 3.8 – Example of hourly LTHW heat flow

Date	*Average daily heat flow (W/m^2)*	*Daily LTHW Energy Use (kWh/m^2)*
01/04/2012 00:00	17.43	0.418335
02/04/2012 00:00	14.43	0.346308
03/04/2012 00:00	17.28	0.414837
04/04/2012 00:00	22.11	0.530589
05/04/2012 00:00	19.32	0.46365
⋮	⋮	⋮
29/03/2013 00:00	26.28	0.630759
30/03/2013 00:00	24.86	0.596574
31/03/2013 00:00	25.77	0.618516
Annual Total	-	120.13

Table 3.9 – Example of daily LTHW heat flow

Air Heating

The energy consumed by the AHU (Q_{AH}) was estimated by using measurements of the supply temperature and external temperatures combined with the AHU measured supply airflow rate to the building. Equation 3.9 was used for calculating the amount of energy needed to raise the temperature of the air (CIBSE Guide B pg 1-9). The data for this analysis were logged at an hourly frequency. It was identified from the estates teams that the AHUs provided air at a single set-point temperature, which was usually around 19°C. A Hobo logger was placed inside the air supply ducting after the heating coil (Figure 3.19) for periods ranging between two weeks to a number of months to measure the supply air temperature to the buildings. These temperature profiles were used to verify the temperature in the BMS system, with the average value providing the set-point temperature to be used in the calculations (T_{ai}). The local weather station was used to supply the external air temperatures (T_{ao}).

To identify the flow rate coming out of the AHU, building operational manuals were consulted to identify which ducts the AHU supplied air to. The airflow rates of these ducts were then measured using the balometer and compared to the design flow rate, it was often found that the figure was slightly lower than the design. The total of all the individual measured flow rates were used for (q_v).

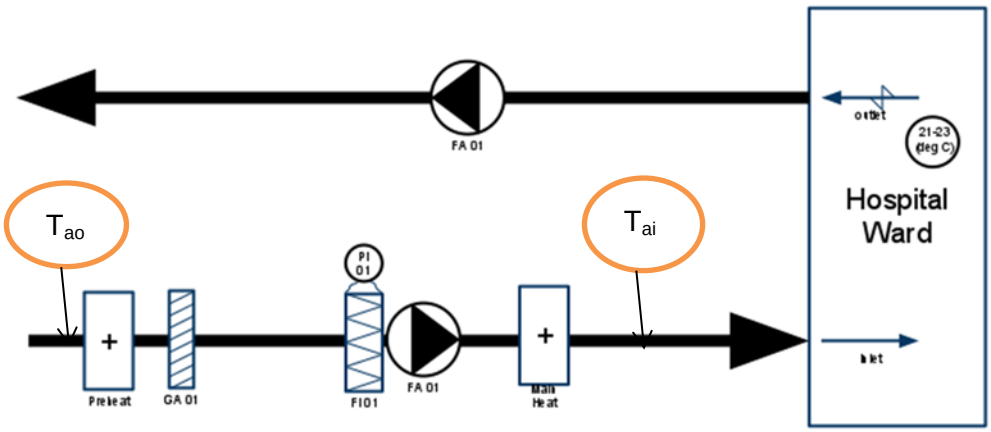


Figure 3.19 - Hospital Ward AHU Schematic with position of air temperature measurements

$$\dot{Q}_{AH} = 1.2 \times \dot{V}_a (T_{ai} - T_{ao})$$

Equation 3.9

Where:

$\dot{Q}_{AH}$ = AHU heat consumption (kW)

$\dot{V}_a$ = volume flow rate of air (m^3/s)

T_{ai} = AHU heating set-point temperature (˚C)

T_{ao} = external air temperature (˚C)

The number '1.2' in Equation 3.9 (CIBSE, 2006b), represents the product of the specific heat capacity and density of air which do not differ much from 1 kJ $kg^{-1}K^{-1}$ and 1.2kg/m^3 respectively. The air heating consumption was calculated for each hour during the year when the external temperature was below the set-point temperature. These figures were added up to produce the yearly energy consumption for air heating in (kWh/year).

Domestic Hot Water

Measuring DHW use is problematic due to the large number of outlets on a circulating system. The literature stated that the energy usage associated with domestic hot water (DHW) was more closely related to occupancy than to climate (Bujak, 2010; Ndoye & Sarr, 2003) Therefore Equation 3.10 (CIBSE, 2012) and figures from the literature were used to estimate results for the different hospital buildings, to compare the measured energy figures to the benchmarks.

$$Q_{DHW} = \frac{V_{DHW} \cdot C_{pW} \cdot \rho_W \cdot (T_{hDH} - T_{cDH})}{3600 \cdot A_f \cdot \eta_s}$$

Equation 3.10

$$V_{DHW} = \frac{105 \cdot N_p \cdot 365}{1000}$$

Equation 3.11

Where:

Q_{DHW} = fossil fuel energy used to heat DHW in building (kWh/m^2/yr)

V_{DHW} = annual DHW consumption (m^3)

C_{pW}= specific heat capacity of water (kJ/kg K) = 4.183 @ 60°C

ρ_W = density of water (kg/ m^3) = 986 @ 60°C

T_{cDH}= temperature of cold water supply (˚C)

T_{hDH}= temperature DHW water is heated to (˚C)

A_f= floor area of building (m^2)

N_p= number of patients in building

η_s = seasonal efficiency of DHW system

The literature pointed out that in Europe the daily usage of DHW was 80-130litres/bed (Bujak, 2010). This number was further supported by Faber and Kell's text book which stated that medical wards use 110 litres/person/day (Martin & Oughton, 1995) which falls close to the middle of the European range of 80-130; i.e. 105l/p/d. Therefore to find the annual DHW consumption, 105l/b/d was multiplied by the number of patients in the area and the number of days in the year, as in Equation 3.11.

Primary Energy Conversion

The previous steps in the method for measuring and estimating the LTHW and AHU heating consumption gives results in the format of kilowatt-hour *heat* usage per year (kWh/yr). The national benchmarks are in the format of kilowatt-hour *fossil fuel* usage per metre squared per year. Therefore to enable the results to be compared to the benchmarks, they needed to be converted into fossil fuels and normalised according to the floor area and location of the building.

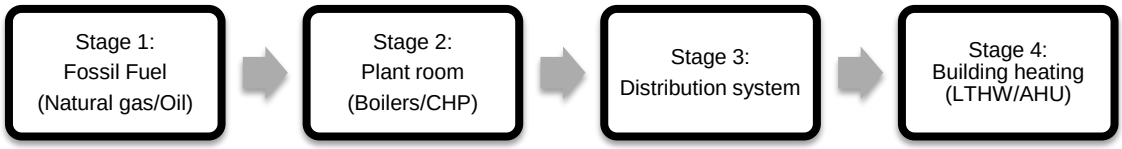


Figure 3.20 - Stages for finding Plant efficiency

There are four stages that the energy arriving at the site in the form of fossil fuels passes through before it becomes heat for the building (Figure 3.20). The heating consumption for the building has been determined (stage 4), however, to identify the actual fossil fuel consumption (stage 1), the efficiency losses at stage 2 and stage 3 need to be calculated. To calculate the efficiency of transferring fossil fuels into heat energy in stage 2 the efficiency of the boilers and CHP need to be determined. Hospital plant rooms use a number of boilers working in unison to meet the heating load, hence the efficiency of the boilers varies during the year depending on the load and the particular boiler being used. With the limited information on the various hospital boiler systems the efficiency is difficult to calculate, however, the literature suggests that an acceptable figure for gas boiler systems in existing buildings is at least 82% (CIBSE, 2012; HM Government, 2013).

The ERIC database discussed in section 3.2.2 contains information on the sites CHP and fossil fuel usage. It details the fossil fuel input into the CHP and how much thermal and electrical energy it produces. These figures are used to calculate the CHP's thermal efficiency (Equation 3.12[i]) using principles of thermodynamics (Cengel & Boles, 2005). To find the total plant room efficiency, both the CHP and boiler use need to be taken into consideration. As well as the fossil fuel input to the CHP, the ERIC data set also reveals how much fossil fuel is consumed by the site (Q_T). In order to calculate the plant efficiency, the assumption has been made that all fossil fuel is burnt

[i] All of the inputs into Equation 3.13 and Equation 3.12 are found in the ERIC database

in the plant room meaning that the fuel will be divided between the boilers and the CHP unit, therefore the plant efficiency can be calculated using Equation 3.13.

$$\eta_{CHP} = \frac{Q_{CHPo}}{Q_{CHPi}}$$

Equation 3.12 (Cengel & Boles, 2005)

$$\eta_p = \frac{Q_{CHPi}}{Q_T} \times \eta_{CHP} + (1 - \frac{Q_{CHPi}}{Q_T}) \times \eta_B$$

Equation 3.13 (Cengel & Boles, 2005)

Where:

Q_{CHPo}= thermal energy out of CHP (kWh)

Q_{CHPi} = total fossil fuel supplied to CHP (kWh)

Q_T = total fossil fuel supplied to site (kWh)

η_p = efficiency of the heating systems in plant room

η_{CHP} = thermal efficiency of the CHP

η_B = efficiency of plant room boilers (0.82)

In order to find the entire efficiency of the heating system it was necessary to combine the plant room efficiency with the distribution efficiency (stage 3). When heat is being transferred to the building from the plant room via means of LTHW or steam, a portion is lost through the piping (Figure 3.21) before it reaches the building. The efficiency of the distribution system (Equation 3.14) is equal to the amount of heat arriving at the building divided by the heat leaving the plant room. Through the performance diagrams for each building, it can be ascertained how much heat is being transferred into the end user building ($\dot{Q}_b$). The heat leaving the plant room ($\dot{Q}_p$) is equal to the heat loss in the distribution system ($\dot{Q}_d$) and the heat arriving at the end user building.

$$\eta_d = \frac{\dot{Q}_b}{\dot{Q}_b + \dot{Q}_d} = \frac{\dot{Q}_b}{\dot{Q}_p}$$

Equation 3.14

Where:

η_d = distribution efficiency

$\dot{Q}_b$= heat arriving at building

$\dot{Q}_p$= heat leaving plant room

$\dot{Q}_d$= heat lost transporting heat from plant room to building

As very little is known about the diameters and length of piping feeding each building, assumptions have been made in order to investigate the heat loss through the pipes during distribution:

- 100mm Diameter pipe (uniform through entire system)
- Pipe thickness = 7mm
- Steam = 125°C
- Air temperature surrounding pipe = 21°C
- Insulation thickness = 75mm
- Heat transfer coefficient of inside of pipe = h_i = 70W/m^{2}K
- Heat transfer coefficient of outside of pipe = h_o = 20W/m^{2}K
- Insulation = 0.038 (W/mK)
- Steel Pipe = 15 (W/mK)
- A = surface area of pipe
- L = length of piping (distance from plant room)

To calculate the heat loss from the distribution system the following heat transfer principles have been used (Cengel, 2003 - pg 402).

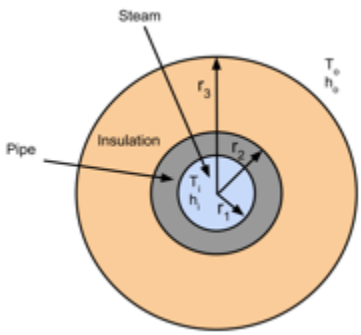


Figure 3.21 - Heat loss though an insulated pipe

$$A_1 = 2\pi r_1 L = 2\pi \times 0.043L = 0.27L$$
$$A_3 = 2\pi r_3 L = 2\pi \times 0.125L = 0.785L$$

$$R_i = R_{conv1} = \frac{1}{h_i A_1} = \frac{1}{70\times 0.27L} = 0.0529L \text{ (m}^2\text{K/W)}$$

$$R_1 = R_{pipe} = \frac{\ln(\frac{r_2}{r_1})}{2\pi k_1 L} = \frac{\ln(\frac{0.05}{0.043})}{2\pi\times 15\times L} = 0.002L \text{ (m}^2\text{K/W)}$$

$$R_2 = R_{insulation} = \frac{\ln(\frac{r_3}{r_2})}{2\pi k_1 L} = \frac{\ln(\frac{0.125}{0.05})}{2\pi\times 0.038\times L} = 3.838L \text{ (m}^2\text{K/W)}$$

$$R_o = R_{conv2} = \frac{1}{h_o A_3} = \frac{1}{20\times 0.785L} = 0.0637L \text{ (m}^2\text{K/W)}$$

$$R_{Total} = R_i + R_1 + R_2 + R_o = 3.957L \text{ (m}^2\text{K/W)}$$

$$Q_d = \frac{T_i - T_o}{R_{Total}} = \frac{125-21}{3.957} = 26.28L \text{ (W)}$$

According to the calculations above, 26.3W of heat are lost for each metre of pipe transferring heat from the plant room to the heated building. This figure is similar to the recommended maximum heat loss from pipes stated in non-domestic building services compliance guide (Table 3.10).

Outside pipe diameter (mm)	*Heatloss (W/m)*
88.9	25.99
114.3	29.32

Table 3.10 - Non-domestic building services compliance guide (HM Government, 2013) - recommended heat losses for direct hot water and heating pipes (insulation thickness has been calculated using ISO12241 standardised assumptions)

The heat supply to the buildings were calculated from the case studies in chapters 5-7. To investigate the efficiencies, the modular and Nightingale buildings at Bradford Royal Infirmary have been considered. The results are presented in Table 3.11, it can be seen that the further the distance the building is away from the plant room, the less the efficiency will be.

	Av measured Daily Heat (W/m^2)	*Floor Area (m)*	*Heat Use in building (W)*	*Distance from Plant (m)*	*Pipe Heat loss (W)*	*Distribution Efficiency* η_d
Modular	6.56	1892	12411.52	180	4734	0.72
Nightingale	13.94	891	12420.54	130	3419	0.78

Table 3.11 – Distribution efficiencies calculated for two buildings monitored in Bradford Royal Infirmary

The efficiencies for the two buildings are 0.72 and 0.78. According to CIBSE Guide F (CIBSE, 2012 - pg 10-9), the typical efficiency for a district heating water system with local calorifiers is stated to be 0.8. It is to be noted that the distribution system in Bradford Royal Infirmary uses plate heat exchangers (PHE) which the manufactures say have a steam to LTHW heat transfer rate of close to 100%, therefore taking Bradford as a rule of thumb due to its use of calorifiers, it is likely that the CIBSE efficiency of 0.8 would be a slight under estimate. This figure is close to the distribution efficiencies calculated for the buildings Table 3.11. Therefore considering the evidence, the distribution efficiencies have been calculated for the individual buildings. It is estimated that they will be 0.78 ±0.05 depending on the distance the building is from the plant room.

Following the previous steps, the plant efficiencies were multiplied by the distribution efficiencies to estimate an efficiency indicator for converting the heat monitored in the system into fossil fuels consumed by the building (Equation 3.16). This formula can be used to convert the heat used for DHW, air heating and LTHW to fossil fuel consumption for the different buildings.

$$\eta_s = \eta_p \times \eta_d$$

Equation 3.15

$$Q_{H(C)} = \frac{Q_H}{\eta_s}$$

Equation 3.16

Where:

η_d = distribution efficiency (0.78 [± 0.05])

η_p = efficiency of the heating systems in plant room

η_s = system efficiency

$Q_{H(C)}$ = annual individual building fossil fuel consumption for AH, DHW or LTHW (centralised) (kWh/yr)

Q_H = annual individual building heat energy consumption for AH, DHW or LTHW (kWh/yr)

The above section showed that CHP is often used to supply part of the hospital's electrical load. In addition to this, renewable energy sources (Q_{Re}) are also used on many sites. The electricity from the CHP (Q_{CHPe}), renewable sources (Q_{Re}) and utility electricity (Q_{Ue}) sum together to equal the total energy used on site (Equation 3.17). The electrical energy consumption has been monitored in each of the case study buildings (Q_{Me}) but the monitored result does not factor in the source of electricity. To find out how much utility electricity (Q_{Ue}) is used in the case study buildings simple ratios can be used. The ratio of utility electricity provided to site compared to that of the other electrical sources of electricity needs to be determined ($\frac{Q_{Ue}}{Q_{Se}}$). This then can be multiplied by the monitored electrical energy use in the case study building to find out how much utility energy was used, this is demonstrated in an equation made to elucidate the procedure (Equation 3.18).

$$Q_{Se} = Q_{Ue} + Q_{Re} + Q_{CHPe}$$

Equation 3.17

$$Q_{Te(C)} = Q_{Me} \times \frac{Q_{Ue}}{Q_{Se}}$$

Equation 3.18

Where:

Q_{Se}= annual total electricity used on site (kWh/yr)

Q_{Ue}= annual utility electricity used on site (kWh/yr)

Q_{Re}= annual renewable electricity used on site (kWh/yr)

Q_{CHPe}= annual electricity output from CHP used on site (kWh/yr)

$Q_{Te(C)}$ = annual utility electricity used in building (centralised plant) (kWh/yr)

Q_{Me} = measured electricity used in building (kWh/yr)

Closing this section on primary energy conversion, it is important to mention that as well as calculating the energy for each building using the centralised CHP plant and site renewables. The energy consumption was also calculated for the single building to simulate how it performed as a standalone building with a localised boiler system. The difference in the calculation was the conversion efficiencies. For fossil fuels, it was assumed that the building used a condenser boiler system with an efficiency of 0.91 (HM Government, 2013) and a distribution efficiency of 0.8 (CIBSE, 2012), providing an overall seasonal efficiency of 0.72 for heating (Equation 3.19). For electricity, rather than being provided by different sources, it would be provided by the utility company, therefore the measured electricity consumption would stay as it was (Equation 3.20).

$$Q_{H(L)} = \frac{Q_H}{0.72}$$

Equation 3.19

$$Q_{Te(L)} = Q_{Me}$$

Equation 3.20

Where:

$Q_{H(L)}$ = annual fossil fuel consumption for AH, DHW or LTHW (local) (kWh/yr)

$Q_{Te(L)}$= annual utility electricity used in building (local) (kWh/yr)

Q_H = annual heat energy consumption for AH, DHW or LTHW (kWh/yr)

Degree-Day Normalisation

In order to compare the different buildings and hospital sites to the benchmarks, the results for fossil fuel consumption were normalised by the floor area, which was found from local hospital estate records, and assessing building floor plans. The second step was to normalise the fossil fuel consumption to local degree-day data using the method from CIBSE TM46.

The degree-day (LHDD) figures used in this work were calculated using measurements from the onsite weather stations. The temperature difference between the ambient temperature and 18.5°C were calculated for every hour when the temperature was less than 18.5°C. Each hourly temperature difference was then divided by 24 and added together to give the local heating degree-day values for the year (Equation 3.21 - CIBSE, 2006a).

$$LHDD = \frac{\sum_{h=1}^{8760}(18.5 - T_{ao})}{24} \text{ for } T_{ao} < 18.5°\text{C}$$

Equation 3.21

The calculated figures for April 2012 to March 2013 have been compared to the typical degree-day figures for the different regions around the U.K (Figure 3.22). These typical figures (Table 3.12) were retrieved from the Vesma energy management organization (Vesma, 2013) specifically for hospital spaces using a base temperature of 18.5°.

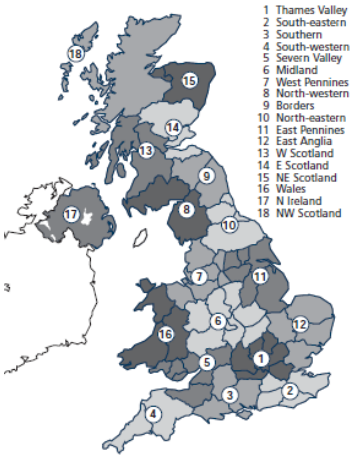


Figure 3.22- Degree-day regions in UK (CIBSE, 2008)

	Calculated		*Regional (VESMA)*	
	Weather Station	Degree-Days	Region	Degree-Days
Bradford	Site (WS-GP1)	3770	1 - East Pennines	4061

Table 3.12 - Degree-day values for monitored site and VESMA (both from April 2012-March 2013)

In each case the calculated degree-days were lower than the typical values. Nevertheless, these have been used for the normalisation calculations as the temperatures measured by the local weather stations present a more accurate picture of what the local temperatures are than of regional figures. Equation 3.22 has been used to normalise the heating energy consumption (CIBSE, 2008).

$$Q_{Ha} = \frac{RHDD}{LHDD} \cdot Q_H$$

Equation 3.22

Where:

LHDD = local heating degree-days

RHDD = reference heating degree-days

T_{ao} = local hourly ambient temperature (°C)

Q_{Ha}= weather adjusted heating energy consumption (kWh/m^2/yr)

$Q_H = Q_{LT} + Q_{AH}$ = heating energy consumption (kWh/m^2/yr)

The reference heating degree-days (RHDD) calculated for a base temperature of 18.5°C are 3070 (Vesma, 2013). They represent the average degree-days for the regions in England, Wales and Northern Ireland between 1991 and 2010. The weather adjusted heating consumption is an estimate of what the heating load would have been if the degree-days in that year were the same as the 20-year average.

3.4.3 Electrical Energy

From the preliminary survey of the hospital wards, it was identified that the electrical energy usage for the buildings was split between the wards and local plant rooms. The internal ward electrical usage was monitored via the distribution boards on at least one floor in each of the case study buildings and it was observed that there were generally two distribution boards with 3-phase power, one essential and the other non-essential. The difference between the two was that a power generator backed up the essential supply, so that emergency electricity could be provided in case of mains power failure.

The plant electrical usage was split between fans, for the air-handling units, pumps, to supply DHW and LTHW and BMS control devices that controlled the 3-port valves and other small plant equipment. In the case of this study, the electricity to control the BMS system was omitted to simplify the data collection.

In a single-phase circuit, there is only one cable supplying the current to the electrical device. In balanced three phase circuits, there are three cables each supplying equal amounts of current to the device. In unbalanced three phase circuits such as the ones found in the distribution boards, there were three cables each supplying three separate and distinct currents. Due to the difference in circuits three different methods were used monitor the power consumption of the devices.

Single Phase

For single-phase systems, the current flowing through the circuit was measured, the voltage was taken as the rated voltage of the circuit and the power was calculated using Equation 3.23 (Paynter & Boydell, 2011). The power factor varied depending on the device monitored, for the motors driving the pumps and fans, it was assumed that the power factor would be 0.85.

$$P = I \times V \times pf$$

Equation 3.23

Where:

P = actual power (W)

I = measured current (A)

V = rated voltage of circuit (V)

pf = power factor

Balanced Three Phase

Some motors driving pumps and fans were powered by a balanced three phase supply. In a balanced three phase circuit, one of the cables were monitored for its current, this current was then placed into Equation 3.24 (Paynter & Boydell, 2011) to calculate the power. In this calculation, it was assumed that the current in each phase would be equal.

$$P = I\sqrt{3}\,pf\,V_{LL}$$

Equation 3.24

Where:

V_{LL} = line voltage for circuit (V)

Unbalanced Three Phase

Each of the phases in the distribution boards provided power for a different item of electrical equipment. As there could be two 415v distribution boards with 3-phases in each one, multiple current transformers were used to monitor each phase separately. The results from these were used with Equation 3.25 (Paynter & Boydell, 2011) to calculate the power at any single point in time. It was found that some of the wards distribution boards had energy meters in them, which monitored all of the key metrics. They showed that the power factor was generally very close to 1, i.e. 0.99 and the line voltage (V_{LL}) was 415V. These figures were used in the wards unbalanced three-phase power calculations as shown in Table 3.13.

$$P = \frac{(I_{ph1}+I_{ph2}+I_{ph3}) \cdot V_{LL} \cdot pf}{\sqrt{3}}$$

Equation 3.25

Where:

$I_{ph...}$= current for each phase (A)

	Essential				*Non-Essential*				*Total*	
	Phase-Current (A)			Power (W)	Phase-Current (A)			Power (W)	Current (A)	Power (W)
	1	2	3		1	2	3			
04/04/2013 13:43:30	8.8	12.3	6.1	6520.5	5.8	2.2	3.3	2721.9	38.6	9257.8
04/04/2013 13:44:00	8.8	12.3	6.1	6517.0	5.9	2.2	3.2	2703.1	38.5	9235.5
04/04/2013 13:44:30	8.9	12.2	6.1	6513.6	5.9	2.2	3.0	2650.5	38.2	9179.3

Table 3.13 – Example of ward unbalanced electrical consumption results

Annual Electrical Energy Consumption

The annual electrical energy consumption is a combination of the annual electrical energy consumptions for the AHU fans, LTHW pumps and ward distribution boards (Equation 3.26).

$$Q_E = Q_{Ep} + Q_{Ef} + Q_{Ew}$$

Equation 3.26

Where:

Q_E = total annual electricity consumption for space (kWh/yr)

Q_{Ep}= LTHW pumps annual electricity consumption for space (kWh/yr)

Q_{Ef}= AHU fans annual electricity consumption for space (kWh/yr)

Q_{Ew}= ward distribution board annual electricity consumption for space (kWh/yr)

It was assumed that the electrical energy consumption of the ward would stay the same year round. Therefore the average power consumption over the periods monitored were multiplied by 8760 the number of hours in the year to get energy consumption in kWh (Equation 3.27). AHU fans in the buildings operated continuously to provide fresh air to the wards. Therefore their yearly electrical energy consumption was calculated by multiplying the average power consumption by 8760 (Equation 3.28).

$$Q_{Ew} = P_w \times 8760$$

Equation 3.27

$$Q_{Ef} = P_f \times 8760$$

Equation 3.28

Where:

P_f = average electrical power used for fans (kW)

P_w = average electrical power used for ward distribution board (kW)

LTHW variable temperature circuit pumps turned on and off depending on the heating demand in the building. Therefore in the summer when there was little demand, these pumps spent a lot of their time turned off. The assumption was made that the pump

turned on when the outdoor temperature dropped below the base temperature. The base temperature for the buildings were calculated by using Equation 3.29 which was a derived by using the energy signature formula found in Equation 3.8 and setting:

$$\dot{Q}_{LT} = 0:$$

$$T_{aB} = T_{ar} - \frac{\mathrm{X}}{\mathrm{M}}$$

Equation 3.29

Where:

$\dot{Q}_{LT}$ = heat flow into building estimated by performance line (W/m^2)

M = gradient of performance line

X = value where performance line crosses the y-axis

T_{aB} = base temperature (°C)

T_{ao} = ambient air temperature (°C)

T_{ar} = average internal weighted air temperature for space (°C)

The annual energy consumption for the LTHW pumps was calculated by multiplying the measured average daily electrical power for the pumps by the number of hours the system was in use (Equation 3.30).

$$Q_{Ep} = P_p \times Hr$$

Equation 3.30

Where:

P_p = average electrical power used for LTHW pumps (kW)

Hr = number of hours in year where $T_{ao} < T_{aB}$

3.4.4 Energy Performance Criteria

Following the steps taken in the methodology, the results for energy consumption were in terms of how much fossil fuel and electrical energy were used in each individual building. The CIBSE benchmarks are however presented in terms of annual energy consumption and carbon emissions. Using the figures from the CIBSE benchmarks, it can be ascertained that the carbon conversion factor to be used is 0.19 and 0.55 kgCO_2 per unit kWh for natural gas and electricity respectively (CIBSE, 2008).

Another set of benchmarks used for assessing hospital energy were the estates code benchmarks (DH Estates and Facilities Division, 2009). These take the volume of the building into consideration as opposed to floor area, presenting the energy consumption in terms of GJ/100m^3. To enable these benchmarks to be used for the work, they were converted into kWh/m^2 taking into consideration that the general floor to ceiling height in the monitored hospital buildings was 2.7m (Chapter 2, Table 2.7 and Table 2.8).

3.5 Error and Uncertainty

There are generally two types of errors in measurement, random and systematic. Random error is demonstrated by a scatter of results for repeated measurements; the extent of this uncertainty can be diminished by repeating measurements (Hughes & Hase, 2010). Systematic uncertainty is where each of the repeated results is affected by the same influence which can produce results that seem accurate but are askew. Therefore, to reduce this type of uncertainty the equipment was checked against others of its type to ensure that the measurements were within reasonable range of each other.

There are a number of statistical methods for quantifying the magnitude of the random uncertainty in the results, the ones which have been used in this study are discussed in this closing section of this methodology chapter. The quantification of the performance of the internal environment, involved monitoring the internal temperatures, airflow rates, CO_2 levels and extent of window opening. Bar the window opening, each of these measurements did not need any data organization, as it was already monitored in the desired format. The error in each of the readings, for the internal temperature and CO_2 levels was as is stated in Table 3.5. As the hobo temperatures were placed in a space, the assumption was made that the measured temperature was the average air temperature within the space.

For the rest of the measurements, i.e. LTHW, air heating, electrical energy and DHW, calculations were used to acquire the final energy use. To find the uncertainty surrounding a metric which was calculated, the following formulas were used.

<u>Uncertainty in Sums, differences, products and quotients</u>

Where the final performance metric used to assess the buildings level of performance (q) is made up of a sum of different measurements (x, z, u, w), the following formulae (Taylor, 1997) were used to find the uncertainty (δq) of the final metric .

Where:

$$q = x + \cdots + z - (u + \cdots + w)$$

$$\delta q = \sqrt{(\delta x)^2 + \cdots + (\delta z)^2 + (\delta u)^2 + \cdots (\delta w)^2}$$

Equation 3.31

Where the final metric is a multiplication or division of a group of measurements then the following formulae (Taylor, 1997) were used to calculate the uncertainties.

Where:

$$q = \frac{x \times \ldots \times z}{u \times \ldots \times w}$$

$$\frac{\delta q}{|q|} = \sqrt{(\frac{\delta x}{x})^2 + \cdots + \left(\frac{\delta z}{z}\right)^2 + \left(\frac{\delta u}{u}\right)^2 + \cdots (\frac{\delta w}{w})^2}$$

Equation 3.32

Both Equation 3.31 and Equation 3.32 were used to calculate the basic error for the air heating, electrical supply and the DHW. They were also used to calculate the uncertainty in the daily LTHW consumption, prior to plotting the results on the performance chart.

Below is an example of how the uncertainty for the airflow heating was calculated.

	Ambient T_{ao} *(°C)*	*Set point* T_{ai} *(°C)*	*Air Flow rate* $\dot{V}_a$ *(m³/s)*	*Floor area* A_F *(m²)*
Measurement	1.1	19.2	0.78	484
Uncertainty (δ)	±0.3°C	± 0.3°C	±5%	±10m²

Table 3.14 - Measurements and their uncertainty for uncertainty calculation example

Use Equation 3.9 to calculate the heat used to raise the temperature of the air being supplied to the building.

$$\dot{Q}_{AH} = 1.2 \times \dot{V}_a(T_{ai} - T_{ao}) = 1.2 \times 0.78(19.2 - 1.1) = 16.94\ (kW)$$

Use Equation 3.31 to find the uncertainty for $(T_{ai} - T_{ao})$,

$$\delta(T_{ai} - T_{ao}) = \sqrt{{T_{ai}}^2 + {T_{ao}}^2} = \sqrt{0.3^2 + 0.3^2} = 0.42(°C)$$

Use Equation 3.32 to find uncertainty for air heating $(\delta\dot{Q}_{AH})$

$$\frac{\delta\dot{Q}_{AH}}{|\dot{Q}_{AH}|} = \sqrt{\left(\frac{\delta\dot{V}_a}{\dot{V}_a}\right)^2 + \left(\frac{\delta(T_{ai} - T_{ao})}{T_{ai} - T_{ao}}\right)^2} = \sqrt{\left(\frac{0.05}{0.78}\right)^2 + \left(\frac{0.42}{18.10}\right)^2} = 0.068 = 6.8\%$$

$$\delta\dot{Q}_{AH} = |\dot{Q}_{AH}| \times 6.8\% = 16.94 \times 6.8\% = 1.152\ (kW)$$

This represents the hourly power demand for air heating supplied to the hospital building. The next step was to convert the hourly power demand into the daily energy consumption, normalised according to the floor area in kWh/m^2.

$$\dot{Q}_{AH} = \frac{16.94\ (kW) \times 24}{484} = 0.84(kWh/m^2/day)$$

$$\frac{\delta \dot{Q}_{AH}}{|\dot{Q}_{AH}|}(kWh/m^2/day) = \sqrt{\left(\frac{\delta \dot{Q}_{AH}}{\dot{Q}_{AH}}(kW)\right)^2 + \left(\frac{\delta(A_F)}{A_F}\right)^2}$$

$$\frac{\delta \dot{Q}_{AH}}{|0.84|} = \sqrt{\left(\frac{1.152}{16.94}\right)^2 + \left(\frac{10}{484}\right)^2} = 0.071 = 7.1\%$$

$$\delta \dot{Q}_{AH} = |0.84| \times 7.1\% = 0.06$$

$$\dot{Q}_{AH} = 0.84 \pm 0.06\ (kWh/m^2/day)$$

In this example, 0.84 kWh/m^2 represents the daily energy consumption. The annual energy consumption would be the sum of the previous calculation undertaken for every day in the year. The uncertainties would also be added together, lets say for this example, the energy consumption and uncertainty was the same everyday of the year. The annual consumption would look like the following:

$$\dot{Q}_{AH} = (0.84 \pm 0.06) \times 365 = 306.6 \pm 21.9\ (kWh/m^2/year)$$

Uncertainty in Linear Regression

Linear regression models can be divided into two main categories, the first for finding the mean value of y for a specific value of x and the second for predicting a y value for a single given value of x (Mendenhall & Sincich, 2003. pg 130). In this work confidence and prediction intervals were used to assess the uncertainty in the LTHW energy performance lines. The confidence interval demonstrated that one could be 95% confident that the line of fit, or performance line would be within the upper and lower boundary. Furthermore, they showed the uncertainty in the mean value of y for a specific value of x from a large number of measurements, i.e. in this example, this would be the uncertainty for the mean amount of heat flowing into the building for *all* days when the temperature was x. The prediction intervals which are slightly wider

than the confidence intervals demonstrated that one could be 95% confident that predictions made from the performance line would fall within the given boundaries.

The confidence and prediction intervals were calculated using the following formulas (Mendenhall & Sincich, 2003. pg 130).

$$\textit{Confidence intervals} = y \pm t_{0.95} \cdot SE \cdot \sqrt{\frac{1}{n} + \frac{(x_p - \bar{\bar{x}})^2}{SS_{xx}}}$$

Equation 3.33 - A 100(1- a)% Confidence interval for the mean value of y for x=xp

$$\textit{Prediction intervals} = y \pm t_{0.95} \cdot SE \cdot \sqrt{1 + \frac{1}{n} + \frac{(x_p - \bar{\bar{x}})^2}{SS_{xx}}}$$

Equation 3.34 - A 100(1- a)% prediction interval for an individual y for x=xp

Where:

n= number of days monitored

$\bar{\bar{x}}$ = mean temperature difference value

x_p= temperature difference

SE= standard error

t_α= t value

$SS_{xx} = \sum (x - \bar{\bar{x}})^2$

In the method for calculating the yearly energy consumption, the performance line was used to predict the daily energy consumption for each day from April 1st 2012 to March 31st 2013. These individual days were summed together to estimate the yearly energy consumption. In a like manner the uncertainty for each day was calculated using the prediction intervals, which were combined using Equation 3.31 to give the uncertainty for the yearly energy.

In addition to being useful for calculating the annual energy consumption, energy performance lines can also be used to calculate other parameters connected with the buildings heating. The gradient of the line, M represented the overall building heat loss coefficient (W/m^{2}K). The uncertainty of this figure can be calculated using Equation 3.35 (Mendenhall & Sincich, 2003. pg 113).

$$\textit{Confidence intervals} = M \pm t_{0.95} \cdot \frac{SE}{\sqrt{SS_{xx}}}$$

Equation 3.35 - A 95% Confidence Interval for the simple linear regression slope M

3.6 Summary

This chapter describes the method used to carry out the research undertaken in this thesis. The method studied a number of key performance metrics; organising and analysing raw measured data against specific hospital performance criteria (Table 3.15). A wide range of measurements were made to assess the various aspects of performance of a number of different hospital buildings. Three main case-study buildings have had their energy consumptions investigated at varying levels of detail. The proceeding chapters contain individual details of the application of the method, discussing the individual analysis, results and their respective uncertainties.

Performance Metric	*Case-Studies*	*Data Collection/ Measurement*	*Analysis*	*Criteria*
Summer Overheating	BMOD	Internal air temperature May-Sept	Count hours over criterion	HTM03-01/CIBSE
			Calculate running mean count hours over criterion	BSEN 15251
Winter Thermal Comfort	BMOD/BNIG BNUC	Internal air temperature Dec-Feb	-	CIBSE Guide A (22-24C)
Indoor Air Quality	BMOD/BNIG BNUC	CO_2 levels	-	BSEN 15251
	BMOD	Window opening		
LTHW	BMOD/BNIG BNUC	Fluid flow rates pipe temperatures	Heat transfer principles linear regression	
Air heating	BMOD/BNUC	Duct air temperatures	Heat transfer principles	
DHW	BMOD/BNIG BNUC	Number of patient beds	CIBSE Guide F & 110 litres/bed/day	CIBSE TM46 & Encode: Cat A/B/C
Ward Electricity	BMOD/BNIG	Current (A) distribution boards [15days]	P=IV	
Plant Electricity	BMOD/BNIG	Current (A) on fans and pumps, spot measurements and up to 5 days logging		
Efficiencies	BMOD/BNIG BNUC	CHP (ERIC) distance from plant room	Plant & Distribution	

Table 3.15 - Summary of Method chapter (BMOD/BNIG/BNUC = Bradford Modular/Nightingale/Nucleus)

4 Hospital Case-Study Sites

As discussed in the literature review, hospitals in the UK tend to be an agglomeration of a number of individual smaller hospital buildings assembled together on a particular site. In the quest to fulfil the aim of this thesis a total of seven buildings were investigated on three hospital sites around the country: four buildings at Bradford Royal Infirmary; a single ward at Glenfield Hospital, Leicestershire: and two buildings at Cambridge University Hospital Trust (also called Addenbrooke's). This chapter contains a general description for each hospital site including its buildings, primary uses and history. These are followed by a description of the overall HVAC strategy and how the monitoring strategy was implemented on the sites.

Figure 4.1 - Location of Hospital Sites (Source: Basarsoft, Google)

This chapter provides context for the individual case-study buildings investigated in chapters 5 to 7 and specifies the energy monitoring being carried out by the NHS thus demonstrating typical hospital monitoring practices in the UK. The chapter also discusses some of the difficulties and limitations of implementing the monitoring method detailed in Chapter 3 by describing some of the failed attempts at monitoring.

4.1 Bradford Royal Infirmary

4.1.1 Site description

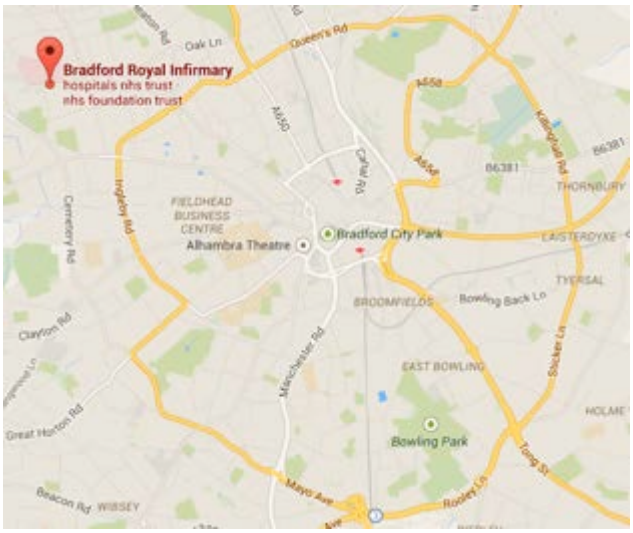


Figure 4.2 – Location of Bradford Royal Infirmary in Bradford (Source: Google)

Bradford Royal Infirmary (BRI) is the main hospital in Bradford, an industrial city situated in the north of England. The city has a moderate climate with a yearly average (1981-2010) temperature of 11.8˚C with a seasonal variation as shown in Figure 4.3a (Office, 2010). The site itself is located at an elevation of 200m above sea level and the prevailing wind measured between 2010 to 2016, was in a west south west direction with an average speed of 10knots (5.14m/s) (Figure 4.3b).

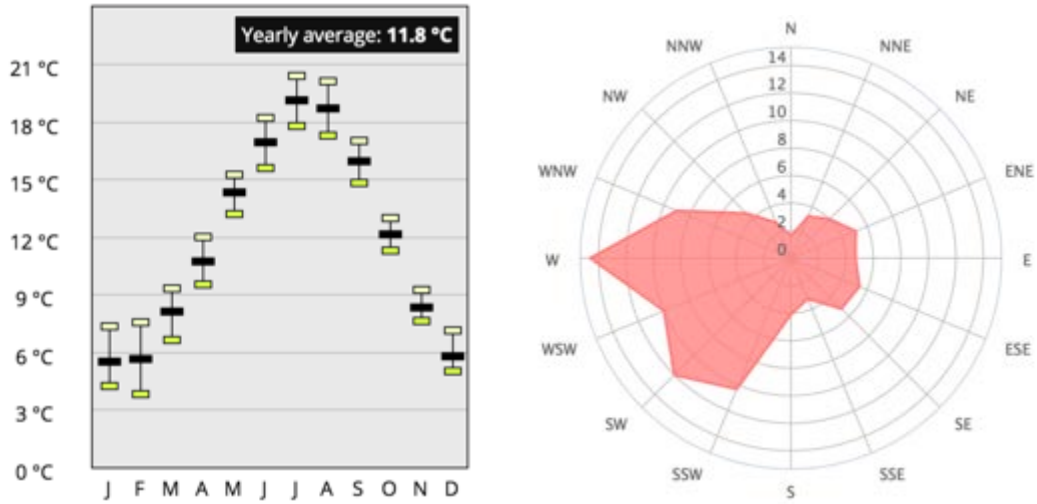
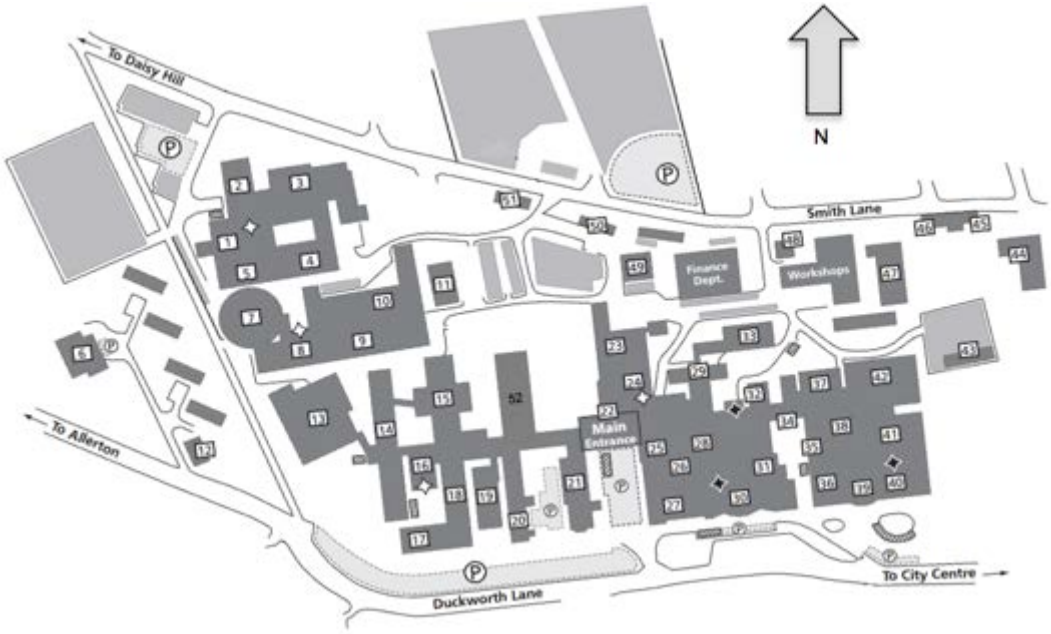


Figure 4.3 – (a) Seasonal variation of Bradford temperature data from 1981 to 2010 (Office, 2010) [left]; (b) Bradford prevailing wind direction from 2010 to 2016 (Windfinder, 2016) [right]



1930s Nightingale – [8-10] = field house educational centre; [14-32] = main site
1960s Tower – [1-4] = Maternity Unit; [35-40] = Ear, Nose and Throat
1980s Nucleus [15]
2000s - [7]= Lecture Theatre; [13]=Modular Building with Theatres (2004); [52]=Modular Wards for Elderly care (2008)
Plant room and estates office [47]
Figure 4.4 - Bradford Royal Infirmary Site Layout (Source: (NHS Bradford, 2015))

BRI is a gathering of different buildings built over a period of time to enhance the health services provided to the local area. This is demonstrated in Figure 4.4 where four different building types from four distinct age groups can be identified. The original buildings built in 1934 were patterned after the Nightingale ward hospital design type. These buildings (Figure 4.5) provided general patient care, consultancy and an A&E department. The original site design incorporated the Field House educational centre (Figure 4.5), providing accommodation and teaching facilities for trainee medical doctors and nurses. Both the original 1934 building and the Field House centre were built at the same time and therefore had a similar structural design constructed with the same materials. In 2009 the educational facilities of the hospital were again developed through the addition of a modern lecture theatre (Figure 4.6).

Figure 4.5 - Main site buildings [Left]; Field house educational centre [Right] (Both nightingale building types)

Figure 4.6 - Lecture Theatre [Left]; Ear, Nose & Throat, (tower on podium design) [Right]

In 1965, the ear nose and throat (E.N.T) building (Figure 4.6) was added to the main building to provide extra services for the hospital. The next addition to the site was the maternity building, which was built in 1967 (Figure 4.7). Both the maternity and E.N.T buildings were built according to the tower on podium design which characterises the district general design of hospitals during that time period. The maternity building served 6,000 women and families each year, providing antenatal care, consultancy and facilities for childbirth. In the '90s the building was extended to provide neonatal care and consequently the building had two different construction types.

Figure 4.7 - Maternity Building [Left]; Nucleus Building [Right]

In 1986, following the UK trend in development of hospital buildings at the time, a nucleus building containing two extra wards and operating theatres was attached to the main building to increase the services and total number of beds on the site (Figure 4.7). The most recent extensions to the site are the two modular buildings (Figure 4.8). The first built in 2004 contained general wards and operating theatres and the second built in 2008, held two wards providing specialist care for the elderly. The first modular building was constructed and fitted at BRI in 2002 and was at that time Europe's largest modular hospital (Hinitt, 2008; Yorkon, 2010). The modular buildings were

constructed using steel beams for structural support with special insulated wall panels providing a façade for the building. The aim was that these buildings were cladded to give a similar appearance to the brickwork of the other buildings on site. The cladding can be seen on the 2004 building (Figure 4.8) and the insulated wall panels can be seen on the 2008 building (Figure 4.8) whose cladding is yet to be fitted. The Bradford Trust has intentions for the construction of another modular building next to the 2008 building, the plans have been pending since 2010 and construction has yet to start in 2014.

In addition to the buildings aforementioned, there were other buildings around the site including office buildings, staff accommodation, plant houses in addition to various support spaces. In total the whole site has 827 beds of which 21% were single rooms, as well as 20 operating theatres and 331 parking spaces for visitors and staff.

Figure 4.8 - Modular Building (2004) [Left], Modular Building (2008) [Right]

The Estates Return Information Collection (ERIC) described earlier on in the thesis includes the age distribution of the buildings in each UK hospital site. The 2011-2012 data for Bradford can be seen in Figure 4.9, they show that the majority of the site was built prior to 1948, and hence the majority of the site is comprised of the Nightingale building design described above. The maternity and E.N.T were built between 1965 and 1975, making up 22% of the site, the nucleus building between 1985 and 1994 taking up 4%, the larger modular building between 1995 and 2004 taking up 7% and the smaller modular building in 2008 making up close to 5% of the site.

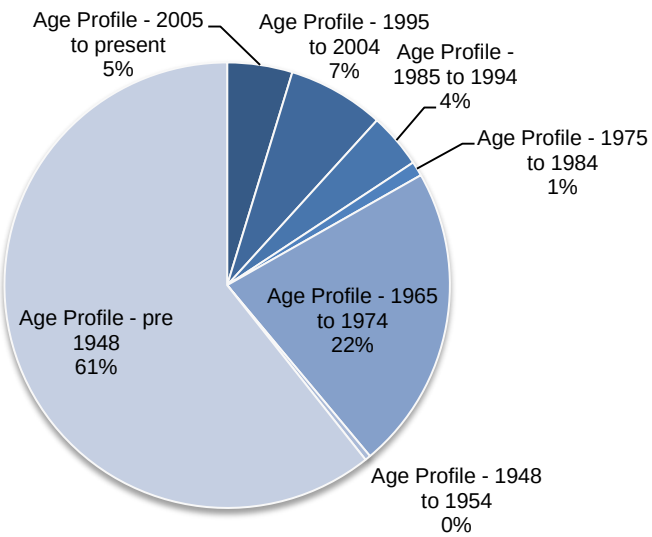


Figure 4.9 – Bradford Royal Infirmary's building age profiles (Source: ERIC)

4.1.2 Monitoring

The basic energy monitoring strategy used by the estates team at BRI was to use utility bills to assess the total electricity and gas energy used on the site. Each of the wards in the 2008 modular building were fitted with advanced electricity meters which had the capability of being linked to a BMS system for continual monitoring. However, the BMS system at BRI was less advanced and unable to utilise the meters to their full potential. Furthermore, it was found that the electricity metering in the modular buildings were an exception, as the rest of the site did not contain any individual building monitoring.

As Bradford contained such a wide range of buildings, which were essentially un-monitored, it posed a great opportunity to use and develop the monitoring method discussed in the previous chapter. For the work, four buildings were chosen which represented each of the different types of buildings found on the site. One of the Nightingale buildings containing wards 22 and 23, the 2008 modular building, wards 20 and 21 in the nucleus building, and the maternity unit tower block. The description of the wards and the results of monitoring for the first three of these buildings can be seen in the forthcoming chapters.

A chapter dedicated to the maternity unit tower block is not featured in this thesis due to problems in monitoring the energy consumption in this building. The intention was to monitor the energy consumption of a number of the different floors. The first problem encountered was due to the building's age, the building was nearly 50 years old, and

the drawings for the building's HVAC system and electrical circuitry had been lost. This made it difficult to locate the places where the different pipes and circuits branched off to feed the particular wards of interest. Through a survey and investigation undertaken on the building with the estates team, it was found that there was a main LTHW pipe, which ran up the service duct and fed each of the floors. This would have provided a suitable place to fit the heat flow meter, however the pipes were insulated with a material containing asbestos, which meant that it could not be removed to install the LTHW monitoring equipment.

As isolating the tower part of the building was not possible, an alternative strategy was to monitor the LTHW consumption for the whole building. The building shared a plant room with the lecture theatre and field house educational centre; it had a pipe with a 100mm diameter, which branched off from the plant room to feed all the different parts of the maternity unit. After monitoring this pipe on a number of occasions, it was found that there was turbulence in the pipe that did not allow for the reliable reading of flow rate. With regards to the electricity demand, the lack of drawings for the electrical circuitry meant that it was not possible to locate a safe place to monitor the electricity going into the building.

4.1.3 Energy consumption

Energy consumption data for the BRI site was sourced from the 2008/09 to 2012/13 ERIC databases (Hospital Estates and Facilities Statistics, 2011). The databases contains a wide range of energy information for all of the sites around the UK, however the results discussed are limited to the utility data for BRI's fossil fuel and electricity use. These have been normalised according to the hospital floor area and heated volume data available in the ERIC database converting them into kWh/m^2/yr to compare them to the CIBSE and Estates Code benchmarks. In addition to this, the fossil fuel data has been normalised to account for variations in local climate due to the location of the hospital sites. This has been accomplished by separating the fossil fuel consumption into DHW water and LTHW heating using the method discussed in Appendix III. The LTHW energy consumption was then normalised according to the TM46 methodology (CIBSE, 2008) using local 18.5°C base temperature degree-day data sourced from Degree-Days Direct Ltd (Vesma, 2013).

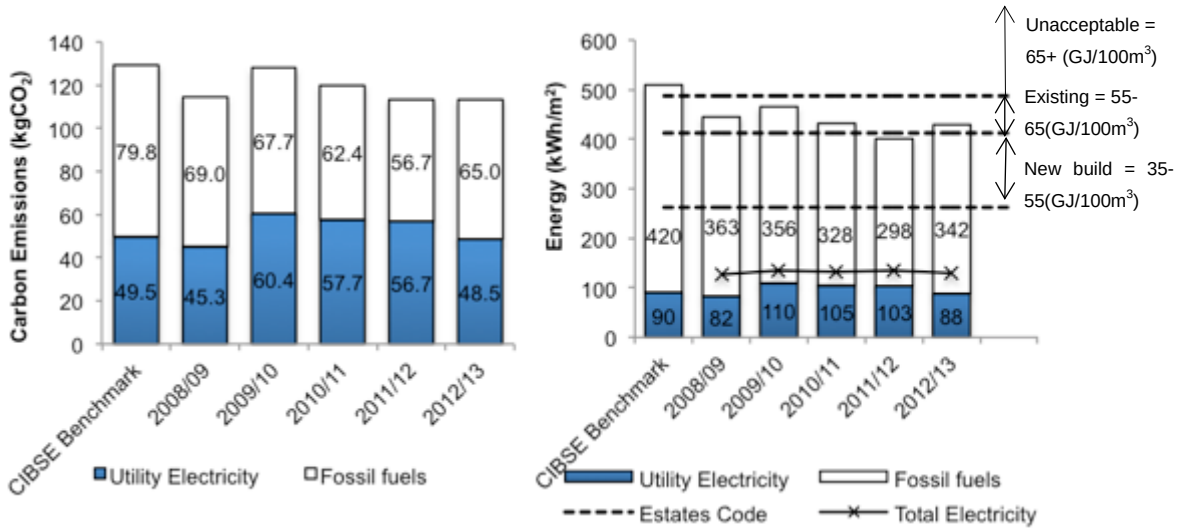


Figure 4.10 – Comparison of Bradford Royal infirmary ERIC data (2008/09 – 2012/13) to benchmarks, (a) carbon emissions [left] and (b) energy consumption [right].

	Heating Degree-Days	*Fossil fuels (kWh)*	*Fossil fuel input to CHP (kWh)*	*(a) Utility Electricity (kWh)*	*(b) Electricity output of the CHP (kWh)*	*(c) Site Renewable Electricity (kWh)*	*Total Electricity/m² (kWh/m²) [a+b+c]*
2008/09	3318	32,024,488	12,507,275	7,399,804	3,953,522	0	11,353,326
2009/10	3171	29,717,922	7,128,819	9,626,862	2,188,159	0	11,815,021
2010/11	3436	29,233,122	7,372,960	9,322,254	2,315,021	0	11,637,275
2011/12	3298	25,873,569	8,722,408	9,155,879	2,908,612	6,202	12,070,693
2012/13	4061	35,472,372	12,832,932	8,193,488	3,965,376	32,000	12,190,864

Table 4.1 – Energy mix for Bradford Royal Infirmary from ERIC 2008/09 to 2012/13

Comparing results to the estate code benchmarks (Figure 4.10b), for all years except 2011/12, the site was performing in category B (55-65GJ/100m^3) the acceptable standard for an existing building. During the year 2011/12, the sites energy consumption dropped into the new build category. Comparing the BRI's total site energy consumption to the CIBSE benchmarks gave some interesting results. They showed that for all 5 years, the total energy consumption and carbon emissions were less than their respective benchmarks. Each year, except 2012/13 the gas consumption reduced and outperformed its benchmark. 2012/13 was an exceptionally cool year (4061 heating degree-days) and it seems as if even after the normalisation of the results, more fossil fuels were used to keep the buildings warm.

Considering the electrical energy consumption, the data showed that starting from the years 2009/10 there was an overall reduction in the use of utility electricity used over the years. The increase in utility electricity use from 2008/09 to 2009/10 is related to a change in the CHP usage during this time period. Fossil fuel input into the CHP unit

decreased by over 5 million kWh, resulting in less electrical output from the CHP and increased use of utility electricity. Although there was a decrease in use of utility electricity, Figure 4.10b Demonstrates that overall, the total electricity consumption over the 5 years varied very little showing no evidence of reduction. This shows that the reduction in use of utility electricity came from an increased use of CHP and renewable electricity suggesting that there were little improvements in the efficiency of electrical use in the buildings on the site. In addition to this, the fact that the electrical use was failing to meet the CIBSE benchmark of 90 kWh/m^2/yr and the gas consumption was significantly lower than its benchmark suggests, that it may be important to focus on gaining improvements in the area of electrical energy consumption as a total site energy reduction strategy.

Considering the energy consumption over the 5 years the performance is very good for a site nearly 100 years old. This level of performance had much to do with the emphasis the leaders in the estates team placed on sustainability within the organisation. Bradford was one of a few hospitals that employed two full-time energy managers who took a proactive approach in developing new means of reducing the energy consumption of the site. In recent years the hospital had become more energy efficient through installing solar panels and adding further insulation to the roofs of the pre-existing maternity and Nightingale buildings. Overall BRI serves as an example that historical and old buildings can meet the building benchmarks.

4.1.4 Efficiencies

In the coming chapters, the energy use of 3 individual buildings on the BRI site will be analysed. The end-use electrical and heating consumption will be measured, however, to enable the results to be compared against the current hospital benchmarks it is important to convert the end-use energy consumption into the same metrics used in the benchmarks. The primary energy use section in the methodology describes how this was achieved. The first step was to calculate the sites overall system efficiency which depended on the distribution efficiency and the plant efficiency over the year. The seasonal efficiency was therefore calculated using the appropriate data from the ERIC 2012/13 database (Table 4.2) and using Equation 3.13 to Equation 3.16 in the primary energy conversion section of the methodology. It was found that with the use of the CHP in the particular year studied, the average overall system efficiency for converting fossil fuels into useable heat in the buildings was 0.53.

Site total fossil (Q_T) *(kWh)*	*Fossil energy input to CHP* (Q_{CHPi}) *(kWh)*	*Thermal energy output of CHP* (Q_{CHPo}) *(kWh)*	*% of fossil fuels used for CHP*	*Thermal efficiency of CHP* (η_{CHP})	*Overall Plant efficiency* (η_p)	*Distribution Efficiency* (η_d)	*Overall system thermal efficiency* (η_s)
35,472,372	12,832,932	6,004,211	36%	0.47	0.68	0.78	0.53

Table 4.2 – Metrics and results for the calculation of the overall systems thermal efficiency for heating buildings at BRI from April 2012 – March 2013 (Source: ERIC)

It is to be emphasised that the CIBSE electrical benchmarks and the BRI electrical usage demonstrated in Table 4.1 only represent the electricity sourced from utility companies. The ERIC data also documents the electricity used that is from non-grid sources which are split between CHP and renewable energy which meet the criteria of DEFRA's carbon measurement guidance (Department for Environment Food and Rural Affairs, 2003). These include sources such as wind, photovoltaic systems and hydropower, which can be located either on or off-site.

In 2012/2013, the largest share of electricity used in the hospital came from utility companies, a small segment came from the solar panels recently installed on the roof of one of the Nightingale buildings and about 1/3 was produced onsite by the CHP unit (Table 4.3). The percentage of electricity from utility will be used to convert the energy measured for each individual building into a metric which is comparable to the benchmark.

Electrical efficiency of CHP	*Electricity output of CHP (kWh)*	*Electricity from renewable (kWh)*	*Electricity from utility (kWh)*	*Total Electricity*	*% Electricity from utility*
0.31	3,965,376	32,000	8,193,488	12,190,864	67%

Table 4.3 - Various sources of electrical energy used in BRI from April 2012 – March 2013 (Source: ERIC)

4.2 Monitoring at Other Sites

4.2.1 Glenfield Hospital

Figure 4.11 - Location of Glenfield Hospital in Leicester City (Source: Google)

The Leicester Glenfield hospital was located just outside of the city of Leicester, it had a floor area of 66,151m^2 with 358 beds making it a medium sized hospital. It provided a range of services for patients and was especially known for being home to three specialist centres, namely cardiology, lung cancer and breast care. The hospital was constructed in the ‘80s and was of the Nucleus hospital design. The site has developed over time, starting with the first phase being built in 1984 and the second phase in 1989. Since then different buildings had been added around the site; in the ‘90s a mental health care centre and in 2011 a new Leicester University clinical research centre.

Figure 4.12 - Panoramic view of Glenfield Hospital (Source: (NHS Glenfield, 2015))

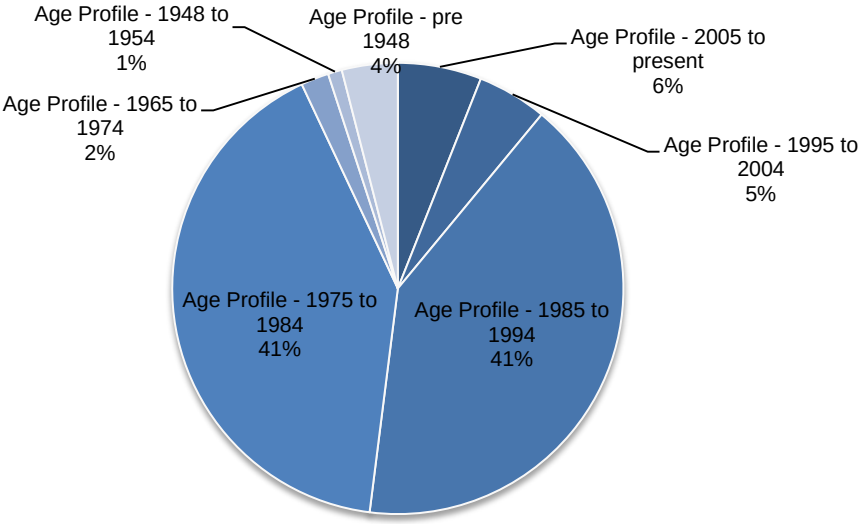


Figure 4.13 - Glenfield Hospital's building age profiles (Source: ERIC)

The site had one main boiler room, which contained two CHP units, and two main boilers that operated using either gas or oil. The site did have a steam boiler, however it was out of use, as the hospital no longer needed steam for sanitary purposes. The main boiler room supplied LTHW to AHU plant on the roofs around the hospital, and plant rooms located on the ground floor of the hospital. These ground floor plant rooms controlled the DHW supply and held pumps, BMS systems and three port valves that controlled the LTHW supplied to wall radiators on each of the different hospital wards. In terms of ventilation, the general approach across all of the wards was to use a mixed mode strategy, with natural ventilation being provided through the windows and mechanical ventilation heating providing additional ventilation to meet the recommended criteria. Each AHU provided ventilation to two or three wards, both supplying fresh air and extracting used air. The extracted air was split between air from toilets and bathrooms, known as 'dirty', and air extracted from general ward use, known as 'clean'. In total, there were three AHUs supporting each ward; supply, dirty extract and clean extract.

Figure 4.14 – Central plant room; CHP [Left], Boilers [Right]

Like Bradford, the site also had its own energy manager who had recently been implementing measures to improve the monitoring strategy on site. Each ward's distribution board was fitted with a metering system very similar to the modular building in Bradford. These panels tracked the current and voltage; however, they did not have any logging function in order to monitor the energy patterns for a period of time. For this reason the energy manager relied on utility data to assess the total performance of the hospital. With regards to fossil fuel use for heating, only the CHP unit was monitored on a regular basis. The hospital had an organised collection of HVAC drawings. This meant that the pipes and ducts for individual buildings could be easily located. In addition to this, there were members of the estates team that had been employed since the opening of the hospital. This gave them a firm grasp on the functioning of the building and knowledge of the different changes, which had taken place since its original commissioning.

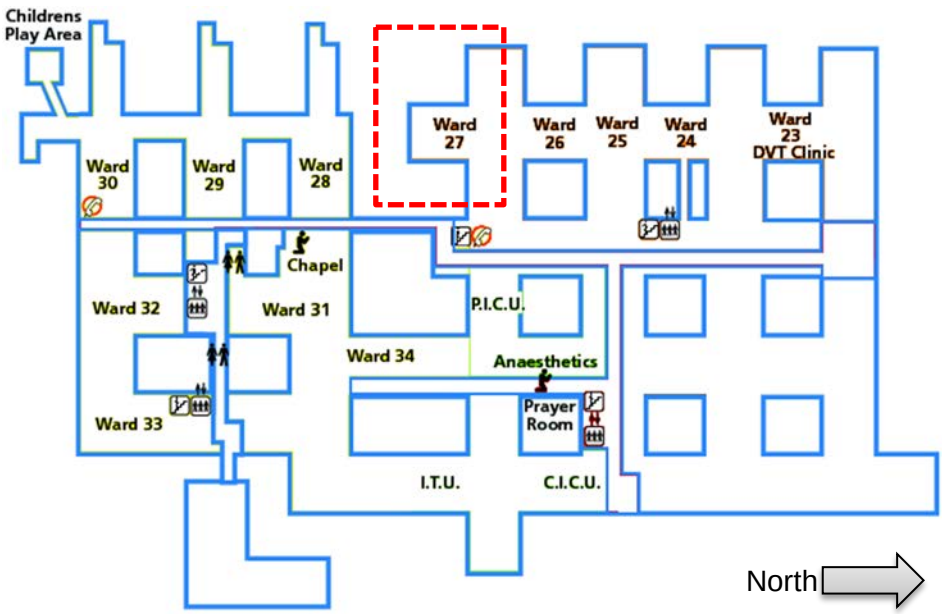


Figure 4.15 - Floor Plan of 1st Floor; Glenfield Hospital (Source:(NHS Glenfield, 2015))

The area of particular interest for this study was Ward 27 (highlighted in dashed box in Figure 4.15), this provided general care for patients admitted to hospital. Like the majority of the Glenfield site, this building was of the Nucleus design type. The energy consumption of the Ward was monitored successfully, but the study was not included in this thesis, due to restrictions on time, nevertheless some of the data gathered was used to support the work presented in the Nucleus chapter.

4.2.2 Cambridge University Hospital Teaching Trust

Figure 4.16 - Location of Addenbrooke's Hospital in Cambridge (Source: Google)

Cambridge University Hospital Teaching Trust has a reputation for being one of the world's leading University teaching hospitals. It has a strong emphasis on bio-medical research and is comprised of the two hospitals, Addenbrooke's and the Rosie maternity unit; Addenbrooke's providing regular acute services and the Rosie hospital provides specialist maternity and general care for women. In addition to serving the local Cambridge area, Addenbrooke's hospital also attracted many patients from around the UK providing specialised treatment in organ transplantation, cancer care and other medical practices.

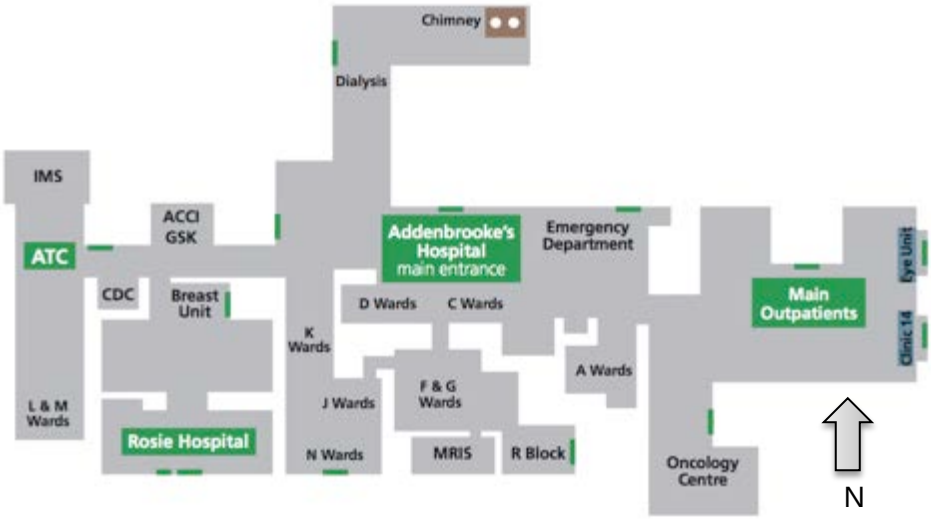


Figure 4.17 - Cambridge Hospital Teaching Trust Site map (Source: (NHS Cambridge, 2014))

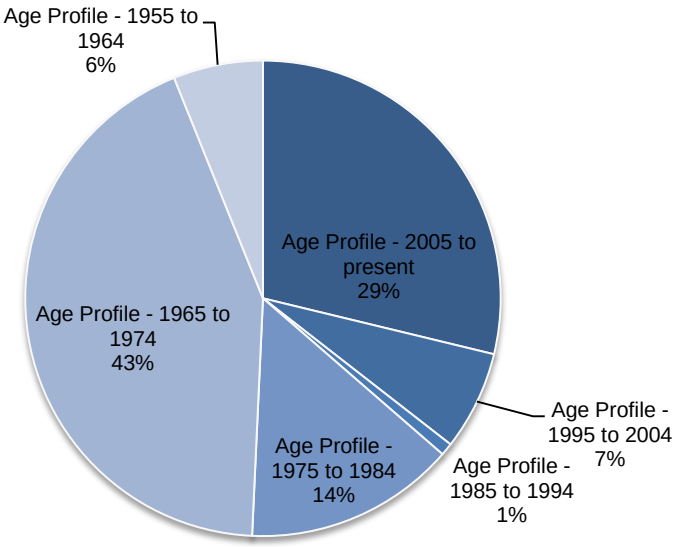


Figure 4.18 - Cambridge University Teaching Hospital building's age profiles (Source: ERIC)

The hospital site is made up of a number of buildings attached to each other (Figure 4.17). The main buildings on the hospital site were completed in two stages, the first in 1962 (not fully reflected in ERIC data) and the second in 1972 (NHS Cambridge, 2014), these buildings were of the district general tower on podium design. In the 80s the site was again extended; the Rosie Maternity building being completed in October 1983 (NHS Cambridge, 2014). In the spring of 2013 an expansion on the Rosie building was completed to double the size of the existing Rosie women's and maternity care unit. When looking at the ERIC age profile for this hospital (Figure 4.18), it can be seen that 29% of the site was constructed since 2005. These buildings were the research facilities, car parks and modern housing facilities for medical students and staff members.

Figure 4.19 - Panoramic stitched view of Cambridge Addenbrooke's Hospital, (BU7 is the large tower in the middle)

Figure 4.20 - Old Rosie Building [Left], New Rosie Building [Right]

The heating on the Addenbrooke's site is provided by a main boiler room in the centre of the site. This boiler room burnt a combination of gas and oil, to produce steam, it was recognisable by its huge chimney which could be seen from miles around (Figure 4.20).

Figure 4.21 - Addenbrooke's Boiler room chimney

The Tower block building also known as BU7 had 9 floors, with its heat provided by steam from the main boiler room on site. This steam was converted into LTHW by three plate heat exchangers in the BU7 basement plant room and then transferred to the rest of the building to provide heating for the radiators and radiant ceiling panels on the wards. Furthermore, LTHW was also supplied to the roof plant room (Figure 4.22), which held the large air-handling units for providing heated ventilation air to the different parts of the building.

Figure 4.22- [Left to right] BU7 AHU Fans, Pumps in basement plant room, scale of ducts providing mechanical ventilation to building

The Rosie building had two sources of heating, it had a set of steam plate heat exchangers transferring energy from steam to LTHW, as well as independent gas boilers which provided heat for the building (Figure 4.23). The building utilised a mixed mode ventilation system to supply the internal areas and corridors of the hospital. The natural ventilation was assisted by the building being designed with an internal courtyard, which allowed a greater area of the building to have windows, this design feature also increased natural lighting into the building. There were three floors in the

building and the mechanical ventilation was split between the east and west side of the building. There were two plant rooms on the ground floor; east and west, each containing three AHUs (Figure 4.23).

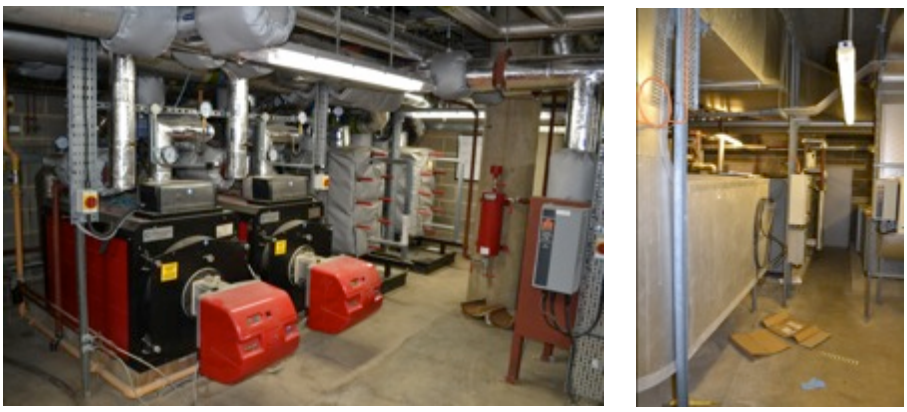


Figure 4.23 - Boilers next to steam to LTHW plate heat exchangers [Left], One of the AHUs in the East mechanical ventilation plant room [Right]

When it came to applying the monitoring methodology in Addenbrooke's, there were difficulties, which prevented the buildings on the site being used as full case-studies. In the BU7 plant room, a number of metrics were being monitored, for example steam going into the plate heat exchangers and electrical transformers supplying the building had meters logging the daily consumptions. Furthermore, the LTHW coming from two out of the three plate heat exchangers was monitored for the purpose of quantifying the heat exchanger efficiency of the plant.

Although the steam going into the building was being monitored, the accuracy of the equipment was unverified and furthermore, the steam readings seemed to be logged in a sporadic fashion, the raw records of 2011 provided by the estates team showed 49% of the daily data missing. It was therefore necessary to supplement the current monitoring, the strategy was to monitor the LTHW coming into the building. This would have provided the energy consumption for both the air heating and space heating energy consumptions for the building.

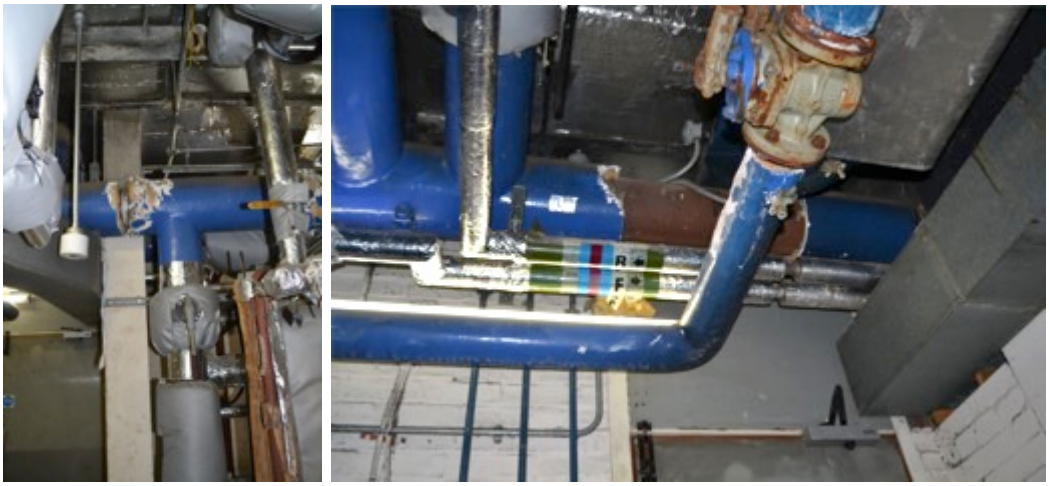


Figure 4.24 - Return pipe to plate heat exchangers, small slit in insulation to fit heat sensor probe [Left]. Supply Pipe to building large removal of insulation to fit flow meter [Right].

The primary piping in the plant room had a 100mm diameter, necessary for providing the large quantity of LTHW to the building. Figure 4.24 shows the position in the piping where insulation was removed to fit the flow monitoring equipment, this piping came directly out of the steam heat exchangers and was the longest section of supply piping in the plant room. Due to the short length of piping; 1200mm, it was expected that it would be difficult to get readings in this space. This building was investigated in the early stages of the project, during the development of the monitoring methodology. An attempt to measure was made despite the shortness of the piping. The results were as expected and readings of the flow were not possible. The original drawings for the building could not be located so it was difficult to identify any other areas available for monitoring the heat supply. There was a section where it seemed like the supply pipe left the plant room and crossed over a corridor into the building. However, the corridor formed an integral part of the Cambridge hospital trusts underground transport system. Closing the corridor in order to install the equipment on a number of occasions as the method required would have caused significant inconveniences for the hospital and hence this option was avoided.

Once the total energy consumption of the build was measured, it was the plan to monitor the air heating energy consumption in order to distinguish it from the space heating. A hobo sensor was placed in the large duct supplying air to the building (Figure 4.25), monitoring took place for a month from 16th April to 16th May 2012 and it was found that the average temperature was 20.62°C, over this time period.

Figure 4.25 - Estates team member looking at duct where air temperature was monitored

The estates team did not have the drawings or commissioning booklets for the air handling unit system, therefore the design flow rates for the building were not available. There were 16 wards in the building and it would have been difficult to measure the flow rates to all the individual wards in the whole building to determine the total flow rate. In addition, this may not have given an accurate reading of what was used at the source, as it is likely that there were leakages in the system. The other option would have been to conduct an airflow probe analysis of air flow at the main duct. It was decided it would not be worth investing the time necessary to do this, as the building would have lacked monitored LTHW heating data meaning that although the air heating energy consumption might be known, an entire picture of the building's energy consumption could not be obtained. Consequently, this building did not yield any useful monitored data and is not studied further in the thesis.

The old Rosie building had sub-meters for the gas boilers, electrical substations and the steam being supplied to the plate heat exchangers in its main plant room. The original aim of the project was to monitor a section of each building type, i.e. a single ward on a floor. The initial aim of monitoring the Rosie building was to target a ward on the first floor as this provided general patient care. The drawings for the Rosie building were available, and it was identified that the pipes for the LTHW came up a duct and then branched off into the section of the building. The piping ran through the ceiling void, but the team was unable to get into the void to fit the flow meter due to restricted spacing. The Rosie building's services were split into two halves, east and west. As monitoring a ward was not possible, the approach was taken that it may be possible to monitor the energy consumption for half of the building. An attempt was made to monitor the heating for mechanical ventilation and then monitor the heating for the LTHW going to the east side of the building. Monitoring of the LTHW took place over 12 days in April and the readings produced an average flow rate of 5.44l/s through the piping. The temperature measurements for the supply and return pipes were also good,

with an average temperature difference of 0.89°C. Although the measurements for the energy consumption of the east side of the building were accurate, the team were unable to be certain about which exact section and floor area of the building this system was heating. This caused too much uncertainty in the calculations for the energy intensity of the building. So the Rosie building was also not used further in the thesis.

Figure 4.26 - Complex system of pumps and piping supplying the LTHW to the Rosie building

4.3 Discussion

4.3.1 Bradford Royal Infirmary Energy Consumption

61% of the BRI site was built prior to 1948 and consequently, one of the sites key characteristics was that it had a large number of traditional Nightingale buildings. These buildings were primarily naturally ventilated which will have contributed to the low overall gas consumption for the site. BRI's site energy consumption fell into the lower end of the NHS Estate Code's existing building category and was 18% lower than the CIBSE benchmark demonstrating that hospital sites with an older building stock can meet modern energy standards. When compared to the benchmarks, the results showed that fossil fuels were performing better than the electrical consumption. This result can be explained by the greater emphasis placed on reducing thermal energy consumption by increasing insulation levels and using more efficient heating systems.

4.3.2 Existing Energy Monitoring

An observation from all the hospitals, which supports the literature discussed earlier in the thesis, is that energy-monitoring systems in hospitals are generally not keeping up with advances in building energy monitoring technology. This was demonstrated at

Bradford and Glenfield, where only utility data was used to assess energy consumption. These hospitals did show traces of advanced monitoring equipment; however, these were often limited to the metering of electricity consumption and were only installed in the newer buildings. Furthermore, in both cases, the metering equipment was not being used to its full capacity as it was not linked to a central computer or logging device which would have enabled the estates team and energy managers to record and analyse the consumption of energy over time. The monitoring at Cambridge Hospital Trust was slightly more advanced with daily readings of the energy consumption for the BU7 and Rosie building. Nevertheless, there was a problem with this data in that close to 50% of metered data from certain years was missing and the floor area for the corresponding consumption was also uncertain.

4.3.3 Limitations of Monitoring Method

One of the key things this chapter highlights is the practical limitations of using the monitoring method proposed for this research in real hospital buildings. The literature has made it clear that it can be difficult to monitor energy consumption in a hospital setting, but it did not point out reasons for this difficulty. The attempts made in this study have helped to point out why and where problems can arise in the monitoring.

The first factor that posed problems was the age of the buildings being monitored. It was found that for the old buildings drawings were not readily available, which meant that the location of pipes was difficult to pin down. In addition to this, the buildings themselves were generally older than the length of time any individual member of the estates team had been working on the sites. Therefore the staff did not understand the energy systems in some buildings at the level of detail necessary to effect an insightful monitoring study. This was not the case at Glenfield Hospital, where the estates team established at the commissioning of the site were still around at the time of this study. Consequently all the building drawings and commissioning manuals were available for use in locating piping and gaining a thorough understanding of the systems. Another limiting factor directly linked to building age was that of asbestos. Older buildings are more likely to have insulation that contains asbestos, which restricts access to key pipes conveying LTHW.

Other areas that posed problems were related to physically accessing areas to install the monitoring equipment, as demonstrated for the BU7 Tower block and Rosie building at Cambridge. Furthermore, in the maternity tower in Bradford there were

difficulties getting the monitoring equipment into the tight spaces that the LTHW piping was squeezed through. This limited monitoring to areas where there was a large enough area to get access to the wiring and piping without creating a health and safety hazard or inconveniences for staff at the hospital. In addition to the studies exposed a key limitation of the method of monitoring LTHW demand, i.e. that it required the heat flow meter to be placed on a sufficiently long length of pipe that turbulence in the water flow was minimal. Some of these problems may have been solved with smaller equipment that could be installed with ease in difficult spaces.

A final point that touches on all of the limitations above, is that the method for assessing the energy consumption of the buildings relies on numerous interdependent factors, i.e. floor area, pipe/air flow rates, pipe temperatures, access to pipes, drawings etc. If any of these factors are unavailable, unknown or immeasurable, the energy consumption for the building may be incomputable. This was the case in the Rosie building where the heat energy going into the building could be measured but the data for floor areas was un-available.

4.4 Summary

The case study sites presented in this chapter have led to a number of conclusions concerning the overall set-up of UK hospitals, their monitoring practices, energy consumptions and limitations of the method described in chapter 3. In general, the case studies showed that there were a variety of buildings used on hospital sites and that the sites were usually heated via a district heating system with ventilation strategies varying between the buildings on the site. Typically, the older buildings (pre-1950s) used natural ventilation, the mid-age buildings (1950-80) mechanical ventilation and the newest buildings (1980-present) utilised mechanical ventilation with heat recovery.

Existing energy monitoring on each site was rudimentary and insufficient to analyse specific parts of a site's energy performance. As a result energy managers relied on utility data to analyse the energy consumption for the entire site. Between April 2012 and March 2013 Bradford's energy demand was significantly lower than the CIBSE benchmarks with lower fossil fuel use than electricity use. Bradford has many old hospital buildings containing naturally ventilated Nightingale wards suggesting there are energy benefits to be had from retaining older, pre-1950s hospital constructions. CIBSE benchmarks and some of the figures in ERIC are based on utility bill data, however as the hospitals generate electricity on-site, the utility bills are a poor

measure of actual electricity used in the buildings, therefore in the coming chapters the source of the energy will be taken into consideration when applying the seasonal efficiencies for the buildings.

Through failed attempts at monitoring it was identified that a large number of co-dependent factors influence whether or not useful energy data could be acquired for a building. These factors included, staff knowledge, availability of drawings, access to services and suitability of equipment. In summary this chapter has provided a foundation on which future chapters can build detail to provide insight into individual buildings' energy performance. The next three chapters of this thesis will be looking at the actual work done to monitor the case-study buildings at Bradford Royal Infirmary. These coming chapters will add to what has been discussed in this chapter providing more depth on the performance of the overall hospital site and demonstrating practical usage of the monitoring method discussed in the methodology chapter.

5 Bradford Nightingale

5.1 Introduction

As discussed in the literature review, Nightingale buildings are the oldest hospital building designs. The literature review highlights a number of papers which discuss this type of building. These papers have a particular focus on the indoor environment of Nightingale buildings, especially summer temperatures (Lomas & Giridharan, 2012a) and indoor air quality (Gilkeson et al., 2013; Gilkeson et al., 2011). This chapter describes the process of, and results from monitoring the indoor environment and energy consumption in a fully functional Nightingale building at Bradford Royal Infirmary in 2012 to 2013. It adds to the established research by defining the energy consumption of an example of this building type, as well as presenting more findings on the performance of the indoor environment. The results are compared with the conclusions presented in the existing literature.

Figure 5.1 – South East face of the Nightingale building (Wards 22 & 23)

5.1.1 Background

The Nightingale building described in this chapter was the oldest building to be investigated in the project. Prior to the formalisation of the National Health Service (NHS) in the 1950s, Nightingale buildings were the predominant form of hospital building type. They are characterised by a spine with narrow pavilions branching off (Figure 5.2). The wards are contained within the pavilions and have beds and windows on each side. When opened on both sides, the windows facilitate natural cross ventilation, which was the principal method of ventilating buildings before the widespread introduction of mechanical ventilation into hospital spaces.

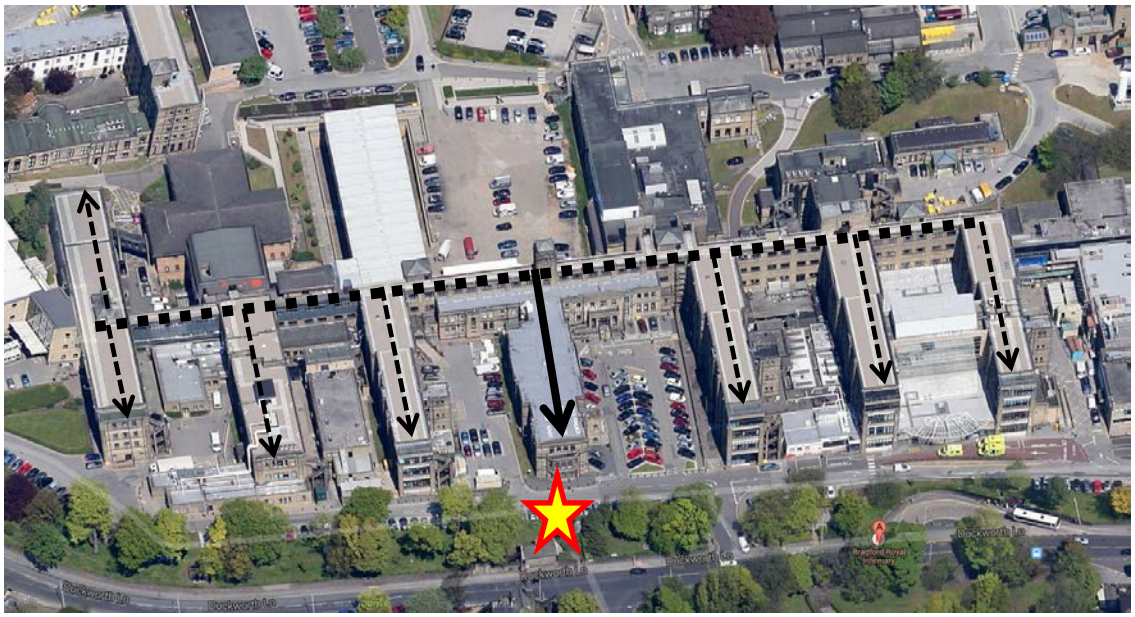


Figure 5.2 - Birdseye view of Bradford Royal Infirmary, demonstrating spine and pavilion Nightingale wards (dotted line = spine, narrow dashed arrows = pavilions, thick arrow = monitored building) (Source: Google)

The Nightingale building investigated in this project was a little different; although part of the original BRI hospital built in 1934, the building was slightly wider than the conventional Nightingale designs. Rather than having one single ward running through the length of the building, the floor was separated into multi and single-bed spaces on each side of the corridor (Figure 5.3). General information about the Nightingale building has been summarised in Table 5.1.

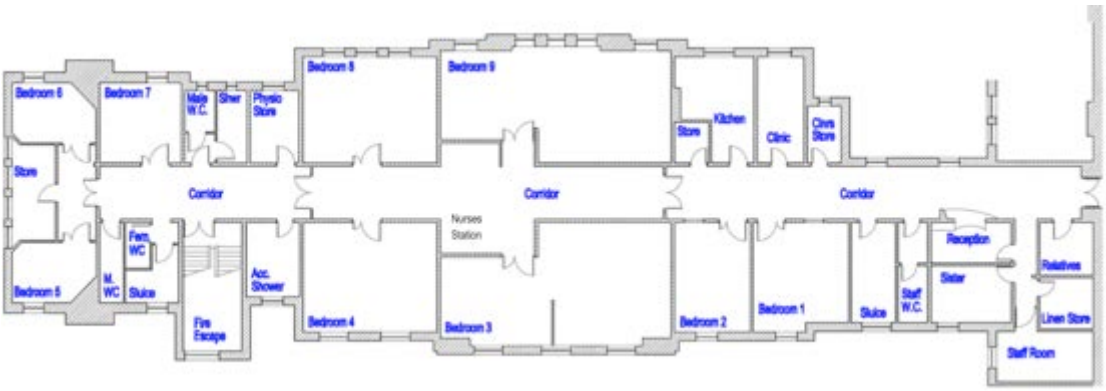


Figure 5.3 - Floor plan of Ward 23 the top floor of monitored building

Type	*Nightingale*
Location	Bradford
Built	1934
Floor area	Level 1: Basement (268m^2) Level 2: Ward 22 (623m^2) Level 3: Ward 23 (660m^2)
Heating	Wall radiators (Rooms and Corridors)
Ventilation	Natural (Windows)
Roof	Flat roofwith195mm insulation (U =0.19W/m^{2}K)[i]
Walls	500mm thick with 150mm stone outer skin, 350-400mm inner skin and rubble infill (U=0.92W/m^{2}K)
Glazing	Openable thermally broken aluminium-framed double glazed (U=2.75W/m^{2}K)[ii]
Ceilings	2.70m
Occupancy	28beds (per floor), Visiting hours 14:00-16:00 & 18:00-20:00.
Room types	3x1bed/ 2x4bed/ 2x2bed/ 2x6
Window orientation	East-west

[i]For calculations see Appendix II, Table A6 Table A7
[ii]Window U-value estimate taken from CIBSE guide A (CIBSE, 2006b)

Table 5.1 - Summary of Nightingale building design and construction

Another difference between this building and other Nightingale buildings on site was that it only had two floors and a basement, whereas the others had up to four floors. The basement of the building contained a tunnel in which the heating was supplied to the building, this area also included some offices and an open area used for Islamic prayers. The first and second floor contained Wards 22 and 23 which provided acute care for patients. Ward 22, was a cardiovascular unit whereas Ward 23 provided general patient care. The main focus of this study was Ward 23; it included bed spaces for 32 patients in a wide variety of room sizes. There were three single bed rooms, two four bed rooms, two two-bed rooms and two large six bed rooms.

5.1.2 Construction

An infra-red photo was taken of the building by the author (Figure 5.4) in the early hours of the morning on 20th November 2012 [02:53 29/11/2012] when the external air temperature was -1.5°C. The roof shows a green/yellow colour representing a cool surface, which means that less heat is escaping compared to the walls and windows,

which are red representing a warmer temperature. More heat escaping from the walls than the roof reflects the previous finding that the U-value for the roof (Table 5.1) was lower than that for the walls.

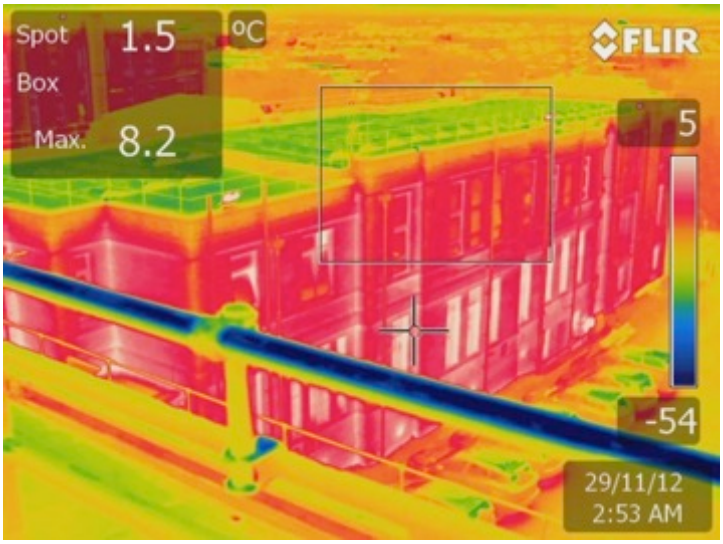


Figure 5.4 - Infra-red image of Nightingale Wards 22 (lower) and 23 (upper).

5.1.3 Heating Ventilation and Air Conditioning Systems

This building has a very simple HVAC system, with the only energy usage being consumed by the LTHW space heating system. The building takes water directly from the main plant room with the pipes running along the main spine of the hospital branching off to the different pavilions. Wards 22 and 23 are supplied slightly differently to the other Nightingale wards which have one supply and one return pipe, with vertical pipes running off this feed loop supplying LTHW to each of the floors. Ward 23 had recently been refurbished and hence had a new LTHW circuit installed. Rather than a single circuit supplying the whole building, two circuits were taken off the main pipeline from the boiler house, one to supply Ward 22 and the other for the supply of Ward 23 (Figure 5.5). Each circuit had its own pump and 3-port valve to control the amount of LTHW supplied, thus controlling the temperature of each ward independently.

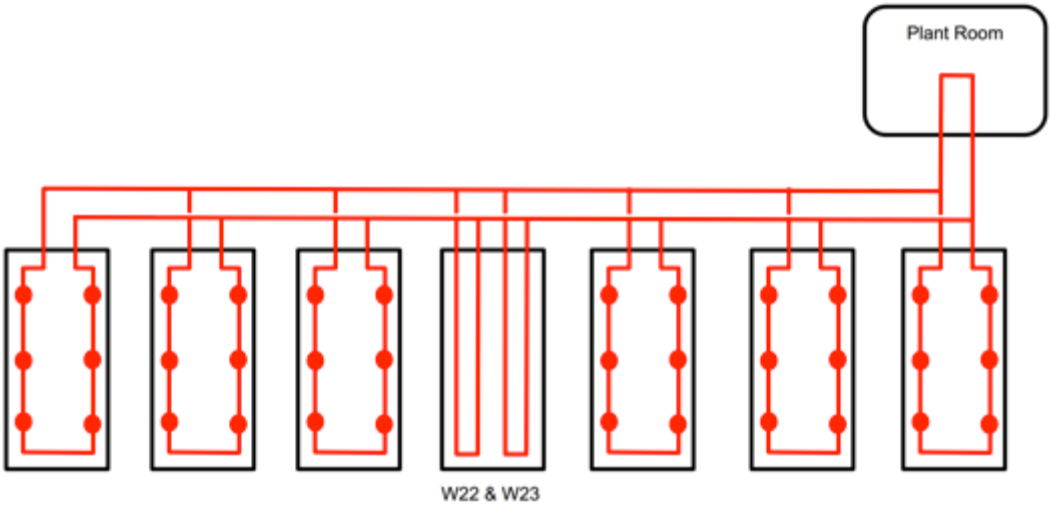


Figure 5.5 - Schematic of LTHW supply for the Nightingale pavilion wards. Each red dot on a circuit show where the piping runs vertically to each floor

Although the inside of the building has recently been refurbished, it still does not utilise any mechanical ventilation. Each space in the building has a number of windows, and these are opened to allow fresh air to enter into the space. In the summer time all the windows are opened and, in addition to this, doors to corridors are also opened to allow cross ventilation through the space. The toilets and bathrooms/showers are on the edge of the building which allow for extractor fans to ventilate these spaces.

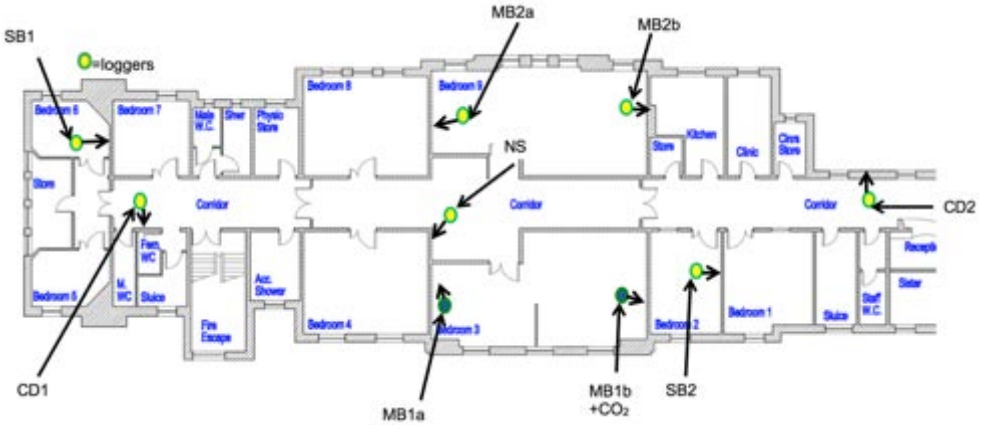
5.2 Monitoring

5.2.1 Internal Environment

The internal air temperature was monitored in a number of different spaces in Ward 23 (Figure 5.6). Only Ward 23 was monitored as it was assumed that the temperatures in the Wards 22 and 23 would be very similar, especially in the heating season when the measurements were most crucial to determine the energy consumption patterns of the building. Some of the rooms that were originally monitored (Figure 5.6) do not appear in this analysis as a number of the sensors fell off the walls and were stored in the nurse station.

CO_2 measurements were also taken to assess the indoor air quality of Ward 23 during the heating season when a lot of the windows were closed. Two methods were used; a CO_2 logging device was installed in MB1 next to the temperature logger on the right hand side of the room (Figure 5.6), this monitored the CO_2 levels for a period of 2 to 3 days. The second test involved taking spot measurements of the CO_2 levels around Ward 23 on May 12th 2014. During this walk around survey, the number of windows

opened and occupied beds were recorded to comprehend the implication of these variables on the CO_2 levels.



Space	*Area (m^2)*
CD1-BE	31.8
CD2-FE	63.3
MB1	66.0
MB2	64.2
SB1	12.6
SB2	22.5
NS	64.5

Figure 5.6 - Ward 23 floor plan demonstrating placement of temperature sensors[i] (MB = Multi-bed, SB = Single bed, CD = corridor, BE/FE = back/front entrance, NS = nurse station) (left); Areas of monitored spaces (right)

5.2.2 LTHW Heating

Although it was assumed that the internal temperatures would be similar in Wards 22 and 23, it was thought that the heating load would be different due to having different levels of heat loss due to one being on the middle floor and the other being on the top floor. Each floor therefore, was monitored separately, for which the portable method for monitoring heat consumption was indispensable. Each floor was monitored for between 5 and 14 days in January, March, April and June of 2013. The positioning of the flow meter and pipe temperature sensors are demonstrated in Figure 5.7.

The daily power demand for each floor (W/m^2) was plotted against the average daily internal to external air temperature difference and linear regression (Step 3, section 3.4.2 of methodology) was used to find the line of best fit for each plot in order to provide a performance line for both floors (Figure 5.21). The average of the equations for each floor was calculated, which represented the relationship between the average daily power consumption and internal to external air temperature difference for both of the floors (Figure 5.22). This formula was used to predict the annual energy consumption for Ward 22 and 23.

[i] Dark blue and green dots represent loggers that did not yield data for use in winter temperature analysis.

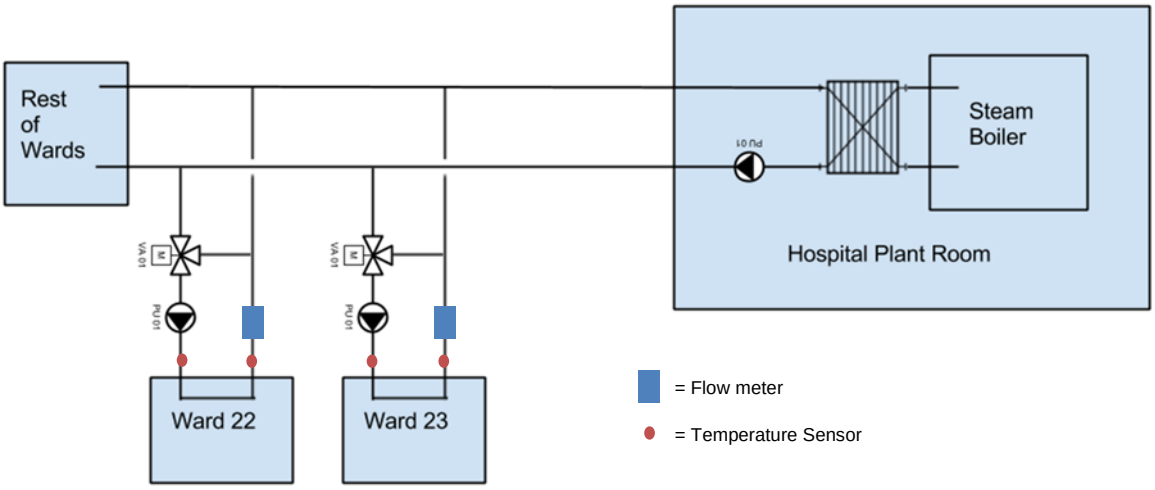


Figure 5.7 - Schematic of LTHW system supplying Ward 22 and 23

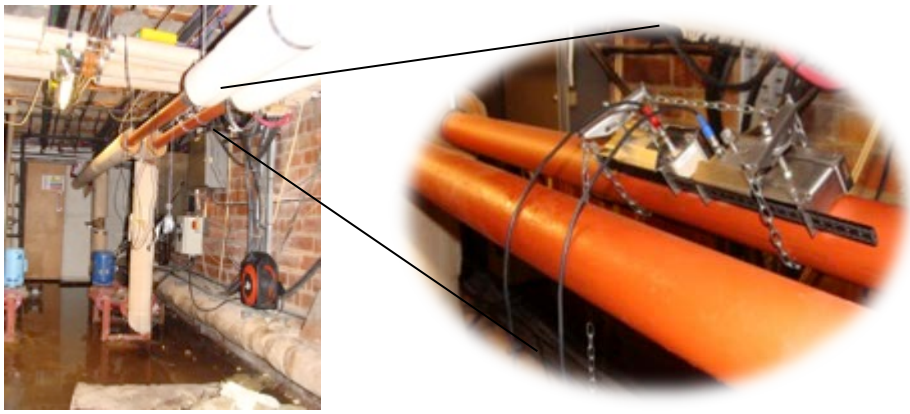


Figure 5.8 - Position of LTHW monitoring equipment for Ward 23 [Left]; Close up view of flow meter transducers [Right];

5.2.3 Electricity

On Ward 23 there was a distribution board that had a 415V three-phase essential supply and a 230V single-phase non-essential supply. All of the lighting plug sockets and electrically powered items including the bathroom extract fans were supplied through this board. In addition to the wards electrical load, there was an individual demand for the pumps that supplied LTHW to the building; these pumps were monitored separately.

The pumps were single phase and therefore one Hobo logger was used to measure the current being drawn by each pump, the pump on Ward 23 was monitored. Ward 22 had the same make and size of pump; it was therefore assumed the current flowing through each pump would be the same. This current was then used to find the power used by the pumps following the method described in the methodology chapter.

Ward 23 was monitored at the distribution board, which was located in a wall panel at corridor level. Access to the distribution board for Ward 22 was challenging being located at ceiling level in the corridor. The assumption was made that the electricity consumption would be the very similar on both floors. The distribution board for Ward 23 was slightly different to all the others investigated during the project. As usual, there was a split between the essential and non-essential supply, however, the essential supply was single phase while the non-essential supply was three-phase. A larger 100A hobo current transformer was used to monitor the current through this larger single-phase supply and three 20A current transformers were used for the 3-phase non-essential circuit. A pilot monitoring study of the distribution board took place in autumn where the 230V non-essential single-phase circuit was monitored for 16 days in October 2012 and the 415V three-phase essential circuit was monitored for 10 days in November 2012. The main monitoring study where both the essential and non-essential circuits were monitored simultaneously took place in summer for a period of 10 days from the 25th June to the 4th July 2013.

5.3 Internal Environmental Results and Analysis

5.3.1 Winter Temperatures

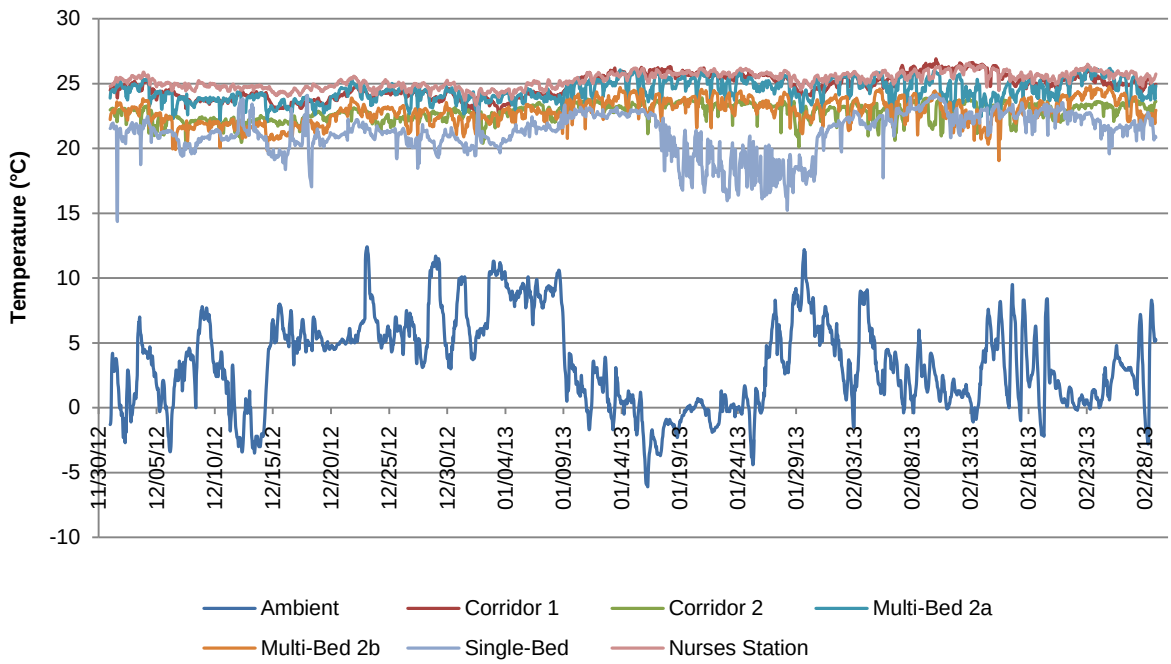


Figure 5.9 - Winter temperatures for Bradford Ward 23 (Dec 12 - Feb 13)

The average weighted temperatures were calculated for the monitored spaces in Ward 23 and it was identified that the average temperature for all the spaces during the winter period was 23.9°C. This temperature was at the upper limit of the CIBSE recommendations of 22-24°C (CIBSE, 2006b), however the histogram in Figure 5.10 points out that there was an unusual spread in the measurements showing that the majority of hours fell between 24-24.5°C and then 23-23.5°C. The high frequency of measurements falling into the 24-24.5°C range suggests that for a significant amount of time the building was being slightly overheated.

	Max temp (°C)	*Min temp (°C)*	*Mean temp (°C)*	*Standard deviation (°C)*	*Hour under 18°C*		*Hours under 22°C*		*Hours between 22 & 24°C*		*Hours over 24°C*	
CD1-BE	26.9	22.4	24.8	0.90	0	0.0%	0	0.0%	464	21.5%	1696	78.5%
CD2-FE	23.9	20.1	22.8	0.65	0	0.0%	229	10.6%	1931	89.4%	0	0.0%
MB2a	26.2	20.6	24.4	0.82	0	0.0%	1	0.0%	718	33.2%	1441	66.7%
MB2b	24.8	19.1	22.9	0.94	0	0.0%	425	19.7%	1464	67.8%	271	12.5%
MB2-Av	25.5	19.8	23.6	0.87	0	0.0%	73	3.4%	1306	60.5%	781	36.2%
SB1	24.1	14.4	21.2	1.58	120	5.6%	1449	67.1%	703	32.5%	8	0.4%
NS	26.5	23.3	25.3	0.58	0	0.0%	0	0.0%	16	0.7%	2144	99.3%
Ward Av	23.9	25.1	22.3	0.61	0	0.0%	0	0.0%	1108	51.3%	1052	48.7%

Table 5.2 – Results for Nightingale Ward 23 temperatures during winter heating season (2160hrs between 1st Dec 2012 and 28th Feb 2013)

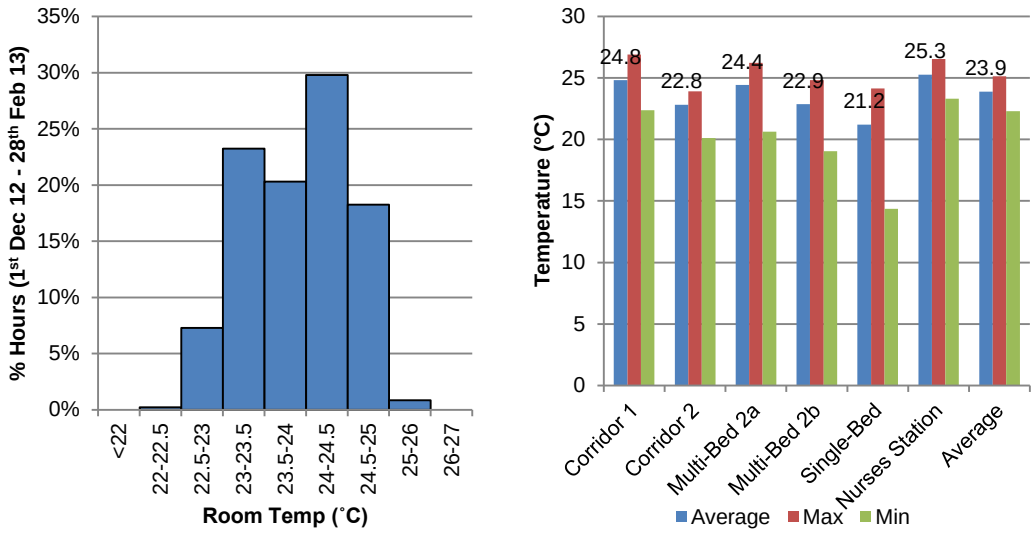


Figure 5.10 - Histogram of Nightingale ward 23 weighted average winter temperatures [Left]; Bar chart of average temperatures in ward 23 [Right]

Considering the individual spaces, the multi-bed bed space had an average temperature of 23.6°C with a standard deviation of 0.87°C which indicates rather good temperature control (Figure 5.9). The nurses' station was the warmest space on the ward for the majority of the winter which may have been due to the thermal heat-gains caused by the large number of staff and the concentration of electrical equipment i.e.

printers, computers in such a small area. Corridor 1 had the second highest temperatures, which can be explained by the fact that it was close to the nursing station and would have therefore been impacted by the gains. In addition to the heat gains, these spaces had no window openings to control the temperatures through ventilation. There was a temperature gradient within multi-bed room 2, with sensor *a* showing a higher reading than sensor b; having 66.7% and 12.5% hours over 24°C respectively (Table 5.2). Sensor *a* was closer to the nurses station, and during visits to the ward it was observed that the doors to multi-bed 2 were opened, suggesting that heat from the nurses station was warming the space.

It seemed to be the general case that spaces closer to windows were cooler. Another example of this was corridor logger 2, which was located close to the windows at the entrance of the ward. This logger had a lower temperature than corridor logger 1, which was stationed away from any windows deeper in the ward.

The single bed space had the lowest temperature throughout the entire ward having a mean of 21.2°C with a larger spread represented by a standard deviation of 1.58°C. This wider spread is in part linked to the drop in temperature that is apparent between 17/1/13 to 30/1/13 (Figure 5.9). This period of 13 days had an average temperature of 18.7°C with a standard deviation of 1.51°C. It is probable that the temperature was cooler in this room because it had one radiator and was located at the corner end of the building having a large wall surface area exposed to the outside, thus increasing its rate of heat loss. When comparing this single room to the large multi-bed spaces it can be seen that the wall surface area is less than double that of the single bed's (Bedroom 5 or 6), yet there is 4 to 5 times more radiators in the space. It is assumed this design decision was due to the larger space in the multi-bed room, nevertheless the multi-bed areas are only slightly over 3 times the size of the single bed spaces.

5.3.2 Summer Temperatures

The analysis of the summer temperatures for the Nightingale building covers four bed spaces, corridor and nurses station. In terms of the bed spaces, there were two large multi-bed rooms with between 6 and 7 beds and two smaller spaces, single-bed 1 and single-bed 2 (which sometimes had two beds). The analysis was conducted on data from June 15th through to September 30th 2012, with the exception of single-bed 1 which only yielded data from 23rd August to September 30th. As the data from single-

bed 1 is significantly smaller than then rest of the dataset it has not been included in the entire analysis.

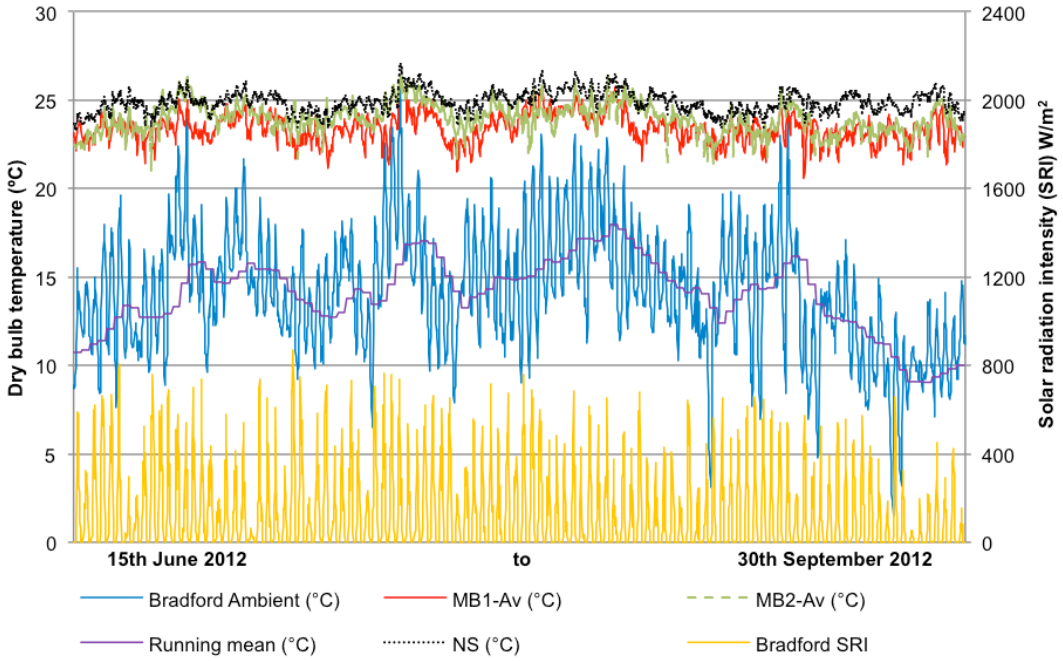


Figure 5.11 - Average internal temperature for Nightingale multi-bed rooms

From initial observations of the data from Figure 5.11 and Figure 5.12 it is apparent that the temperatures within the wards are generally lower than 25°C. Focusing on the multi-bed spaces (Figure 5.11), it can be seen that multi-bed 2 is warmer than multi-bed 1, with the difference between them being 0.6°C (Table 5.3). The results reveal that the smaller spaces have average temperatures which are 0.7°C lower than the larger ones. In addition to this, the single bed spaces had a wider range of temperatures than the multi-bed spaces, showing lows of close to 17°C compared to the multi-bed spaces which did not go under 20°C. The max diurnal range also demonstrates the difference between the two types of room, with single bed spaces and multi-bed spaces having average ranges of 5.3K and 3.6K respectively.

	Max temp (°C) (24hrs)	*Min temp (°C) (24hrs)*	*Mean temp (°C) (7:00-20:00)*	*Mean temp (°C) (21:00-6:00)*	*Max diurnal range (K)*	*Hours over 25°C (24hrs)*		*Hours over 28°C (24hrs)*		*Hours over 24°C (21:00-6:00)*		*Hours over 26°C (21:00-6:00)*	
CD1-BE	25.6	21.5	23.7	23.6	1.8	40	1.5%	0	0.0%	339	13.1%	0	0.0%
CD2-FE	25.3	20.5	23.1	23.1	2.9	9	0.3%	0	0.0%	94	3.6%	0	0.0%
MB1b	26.1	20.2	23.4	23.4	3.8	70	2.7%	0	0.0%	214	8.3%	3	0.1%
MB1a	25.9	20.5	23.4	23.5	4.0	107	4.1%	0	0.0%	256	9.9%	0	0.0%
MB1-Av	26.0	20.3	23.4	23.4	3.5	79	3.0%	0	0.0%	245	9.5%	0	0.0%
MB2a	25.9	20.4	23.5	23.5	4.7	154	5.9%	0	0.0%	313	12.1%	3	0.1%
MB2b	26.8	21.2	24.4	24.4	3.9	577	22.3%	0	0.0%	729	28.1%	69	2.7%
MB2-Av	26.4	20.8	24.0	24.0	3.7	284	11.0%	0	0.0%	518	20.0%	14	0.5%
SB1-BE[i]	24.5	17.0	21.8	21.8	5.1	0.0	0.0%	0.0	0.0%	2.0	0.1%	0.0	0.0%
SB2-FE	25.4	17.1	22.7	22.8	5.5	12	0.5%	0	0.0%	164	6.3%	0	0.0%
NS	27.0	23.4	24.9	24.9	2.4	1117	43.1%	0	0.0%	1004	38.7%	106	4.1%

[i]SB1-BE is measured for 912 hours from 24/08/12 to 31/09/12

Table 5.3 – Results from Nightingale summer monitoring

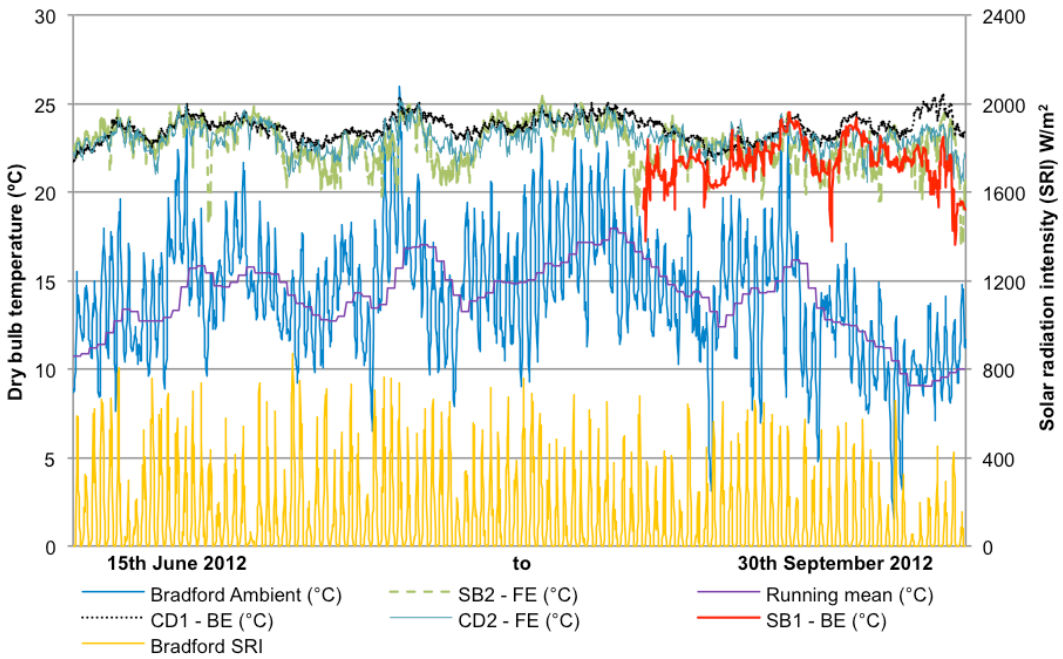


Figure 5.12 - Average internal temperature for Nightingale single bed rooms

Just as in the winter, the warmest space in the ward during the summer was the nurse station. This was likely due to the heat gains from the high density of staff and equipment combined with the lack of window ventilation in the area. The other central areas i.e. the front end of the corridor (CD-FE) and the back end of the corridor (CD-BE) had relatively low temperatures compared to the nurse station. The front end of the corridor was around 0.5°C cooler than the back end, and it is likely this is the case because of the window that was located at the front end of the corridor. The analysis of winter temperatures identified that single-bed 1 was the ward's coolest space in the heating season and although there was not a full data set to analyse single-bed 1's

performance during the summer months, the month of available data did show that in the summer it was also the coolest space in the summer. The back end of the corridor, the space next to single-bed 1, also displayed relatively cool temperatures for an internal space with no windows, suggesting that it could have been influenced by the temperatures in single-bed 1.

Figure 5.13 shows that according to the BS EN 15251 criteria all of the bed spaces except single-bed 2 and part of multi-bed 2 measured by sensor *b* had temperatures that were suitable for patients. Rather than being too warm, single-bed 2 happened to be too cool, with over 20% of the measured hours being lower than Cat I lower. As we are interested in the potential for the building to overheat, this was not a problem, as heating could be adjusted to control the cooler temperatures more closely. The section of multi-bed 2 measured by sensor *b* appears to be too warm for patients for around 8% of the summer period. The other senor in the room (MB2a), is measuring cooler temperatures than this, bringing the overall average hours in the room over the BS EN 15251 criteria, underneath 5%, which is an acceptable figure. This demonstrates that while the overall space is acceptable by the recommended criteria, temperature gradients can exist within a room causing certain areas within it to be unacceptably warm.

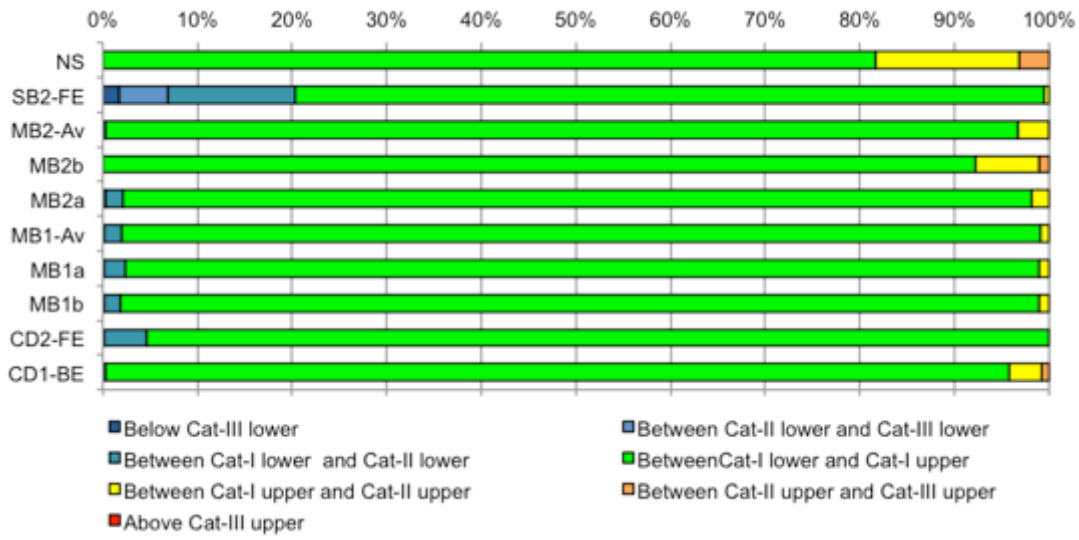


Figure 5.13 - Percentage of all measured summers hours in BSEN15251 for Nightingale building

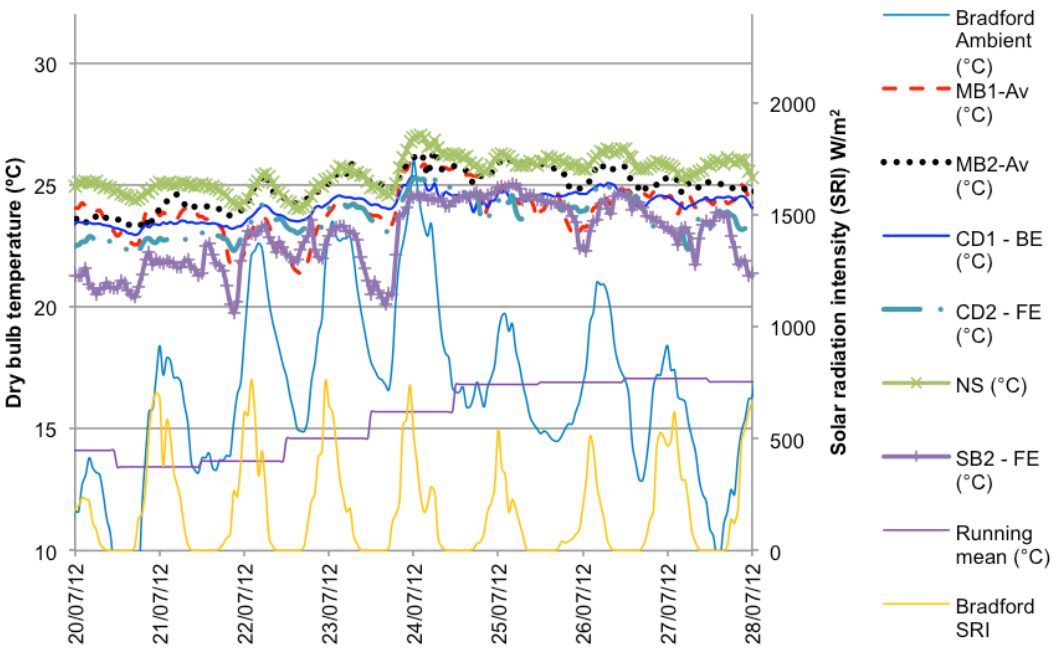


Figure 5.14 – Nightingale performance on warmest day in summer, 24th July 2012, with preceding and proceeding days

Some of the peak internal temperatures were reached on the 24th of July, the warmest day of the year. What is striking about the temperatures during this period (Figure 5.14) is that leading up to the 24th, the internal temperatures respond closely to the ambient temperatures (most visible in single-bed 1 and multi-bed 2). Then, on the days after the 24th when the peak ambient temperatures are significantly lower, the spaces in the building seem to be less responsive to the changes in ambient temperature and remain high until after the 26th. The Nightingale building fabric may explain this phenomenon. The building's walls are made up of 500mm thick stone giving the building a high thermal mass, meaning that the building fabric will absorb and hold heat for a prolonged period of time. It is noticeable that on the 24th the temperature in many of the spaces, including single-bed 2 and multi-bed 1 did not exceed the days maximum ambient temperature, this and the fact that the temperatures were relatively high on the days following, suggests that the building fabric absorbed the ambient heat during 24th and emitted it slowly during the proceeding days.

It was stated earlier that the nurse station was the warmest space in the ward during winter and considering the number of hours it measured over 25°C (43.1%) during summer, it would seem as if the space would be overheating. However, by BS EN 15251 criteria, the space was actually fit for purpose as it had less than 5% of hours above the Cat III upper limit, demonstrating that the performance is acceptable for staff and visitors.

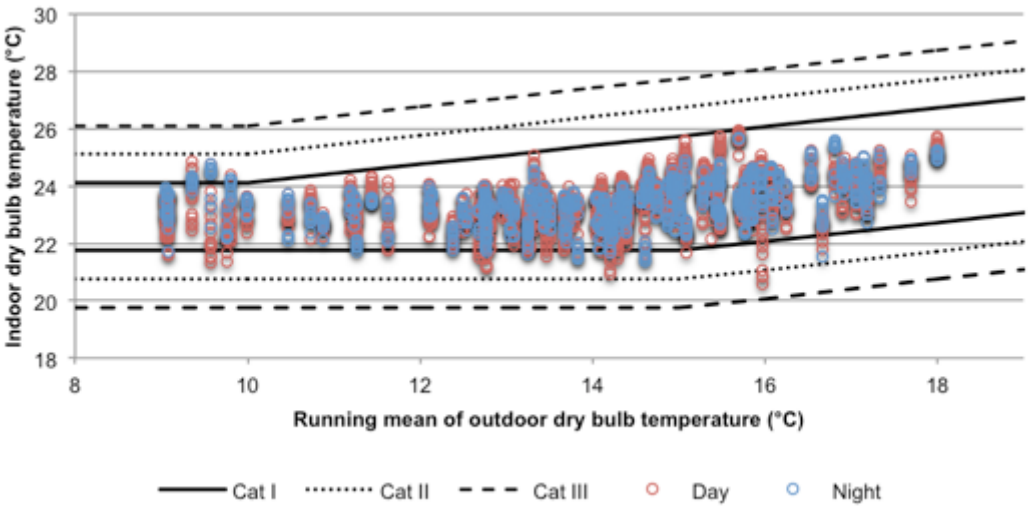


Figure 5.15 - Comparison of measured temperatures with BSEN15251: Nightingale multi-bed 1 Average

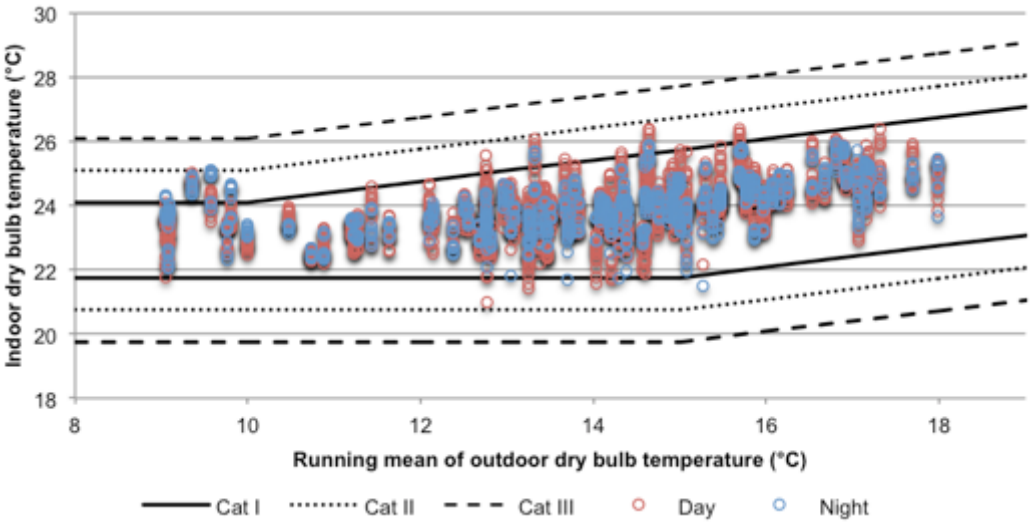


Figure 5.16 - Comparison of measured temperatures with BSEN15251: Nightingale multi-bed 2 Average

The scatter graph for multi-bed space 1 (Figure 5.15) illustrates that the results are quite tightly packed together, indicating that the temperatures in this space are well controlled. The multi-bed 2 room (Figure 5.16) has points scattered over a wider range which signals that the control of the temperature within the space is not as good as that in multi-bed 1. The scatter graph for single-bed 1 (Figure 5.17) contains temperatures from the 912 hours of monitoring in the space. It has been included in the work because when used with the scatter graph for single-bed 2 (Figure 5.18), it helps to demonstrate that the smaller spaces are much cooler than the larger spaces. When looking at the difference between the day and night time temperatures it seems to be the general case that the night temperatures are in the middle of the given range

and the coolest temperatures are during the day. This may be the case because the ambient temperatures have dropped rather suddenly and there is a lag between heating turning on and the room warming up.

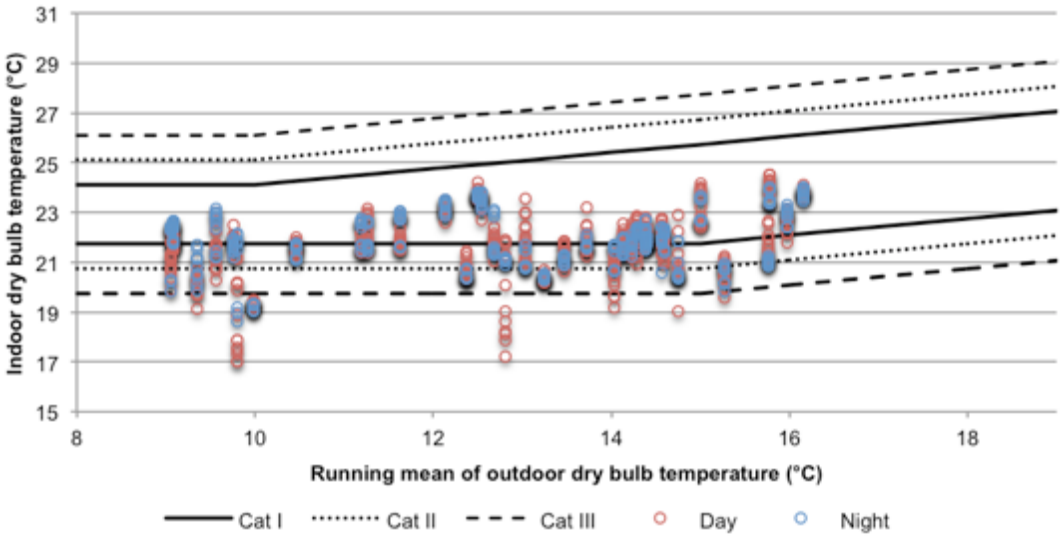


Figure 5.17 - Comparison of measured temperatures with BSEN15251: Nightingale single bed 1 Average

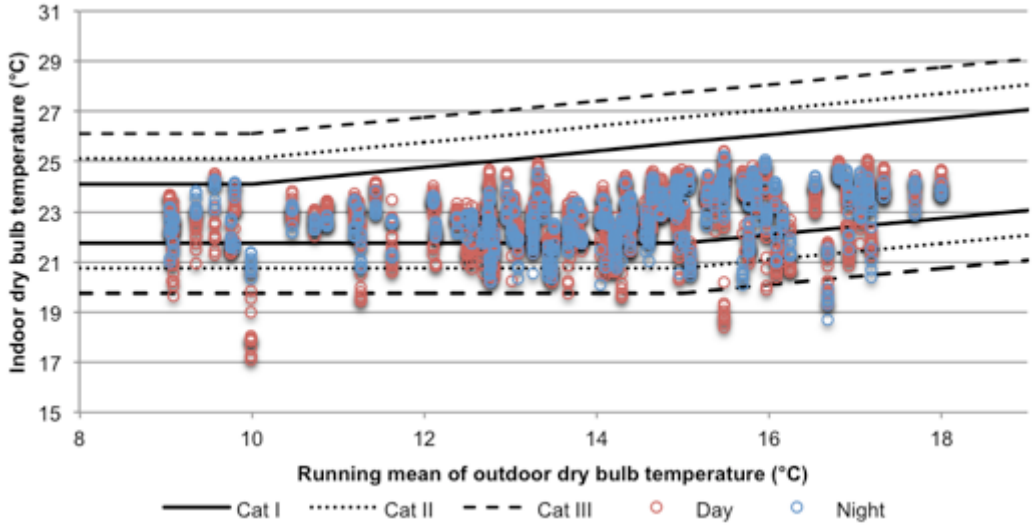


Figure 5.18 - Comparison of measured temperatures with BSEN15251: Nightingale single bed 2 Average

5.3.3 Air Quality

The CO_2 levels were monitored in bedroom 3 on Ward 23 for 2 days in November 2012; the results can be seen in Figure 5.19. Considering the magnitude of the CO_2 levels, it was found that throughout the 53 hours of monitoring, there were 13 hours (24.5%) above Cat III limit (1200ppm), 39 hours (73.6%) above Cat II (900ppm), 45 hours (84.9%) above Cat I (750ppm). The average CO_2 levels during the entire 53 hour period was 1060ppm. In general therefore, it might be concluded that based on the CO_2 levels, bedroom 3 was poorly ventilated.

Although there was not a direct correlation between the temperature and CO_2 levels in the space, there were specific times when there was a visible relationship between the two parameters, (e.g. between 16:00 on the 28th and 02:30 on the 29th and 09:00 and 15:00 on the 30th). Interestingly there were times when the internal temperature peaked at the same time the CO_2 levels peaked (e.g. 20:00 on the 28th, 2 and 20:00 on the 29th and 09:00 and 14:00 on the 30th). These could be due to periods of higher occupancy when additional people in the spaces were emitting heat and exhaling CO_2. The CO_2 reductions after the peaks could be the results of windows being opened.

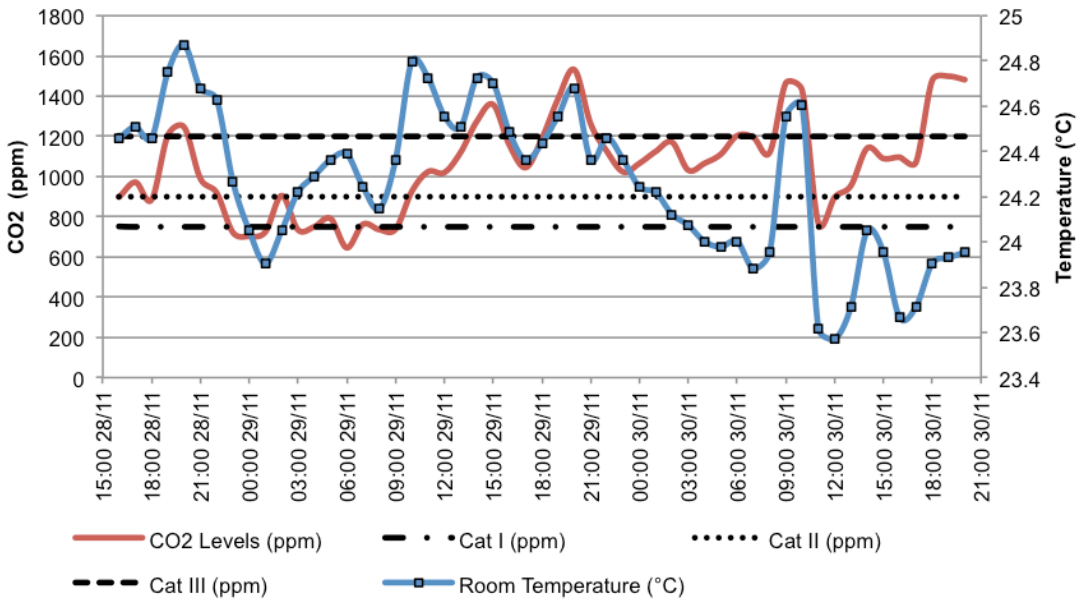


Figure 5.19 - CO_2 levels and air temperature in Ward 23 Bedroom 3 during November 2012

The results from the spot test measurement of CO_2 levels taken on 12/05/14 can be seen on the floor plan in Figure 5.20 and Table 5.4. It shows that the lowest CO_2 levels were found in the bedroom 9 the multi-bed space where three windows were opened and half of its beds occupied. In rooms where no windows were opened the CO_2 levels rose up to 1150ppm. On the day spot measurements occurred, it seemed to be the general pattern that when there was no windows open and at least one occupant in the room, the CO_2 levels were between 844 and 1150ppm. This was above the Cat I criterion suggesting that there may be inadequate ventilation in these spaces for sick patients.

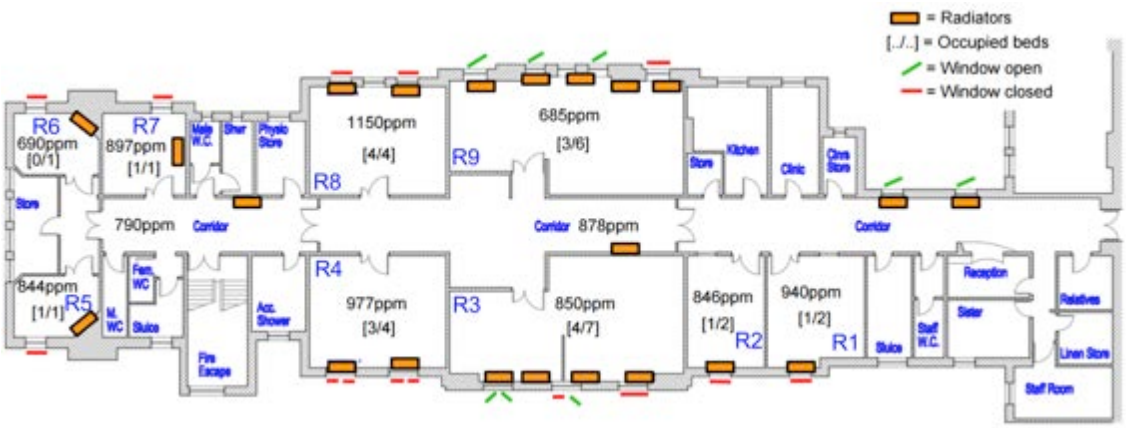


Figure 5.20 - Spot measurement for CO_2 levels in Ward 23 taken May 12th 2014,

When using the simple equilibrium balance formula (Equation 3.6) to estimate the airflow rates based on occupants, it becomes apparent that all of the spaces have estimated air change rates that are below the 6ach^{-1}. This could indicate that there is poor ventilation, but it could also indicate that the rooms are particularly large, thus leading to lower air change rates, therefore the second criterion of 10l/s/p is also useful. When comparing the results to this benchmark, it can be seen that the bedrooms with 3-7 beds did not meet the criterion with the current number of windows opened. However the smaller bedrooms with either one or two beds per space could have the potential to provide sufficient ventilation per person to satisfy, the needs of their maximum patients even in circumstances when the windows were closed.

Space	*Occupants*	*CO_2 Levels (ppm)*	*Windows*	*Q_o (L/s)*	*Volume (m^3)*	*Max ach^{-1}*	*Max l/s/p (current occupancy)*	*Max l/s/p (Max patients)*
R1	1 of 2 +3G	940	0 of 1	37.0	73.5	1.81	9.3	18.5
R2	1 of 2 +1G	846	0 of 1	22.4	60.8	1.33	11.2	11.2
R3	5 of 7	850	3 of 6	55.6	178.1	1.12	11.1	7.9
R4	3 of 4	977	0 of 4	26.0	107.4	0.87	8.7	6.5
R5	1 of 1	844	0 of 1	11.3	34.0	1.19	11.3	11.3
R6	0 of 1	690	0 of 1	0.0	34.0	0.00	/	/
R7	1 of 1	897	0 of 1	10.1	47.5	0.76	10.1	10.1
R8	4 of 4	1150	0 of 2	26.7	103.6	0.93	6.7	6.7
R9	3 of 6	685	3 of 5	52.6	173.3	1.09	17.5	8.8

Table 5.4 - Results from the Nightingale walk around CO_2 survey, with ventilation rates estimated using equilibrium balance equation.

5.4 Energy Results and Analysis

5.4.1 LTHW Heating

As Ward 22 and 23 were monitored individually, it was possible to create a performance line for each of the wards (Figure 5.21). It can be seen that the ground

floor, Ward 22, has the steepest gradient indicating that it had a higher heating demand than Ward 23.

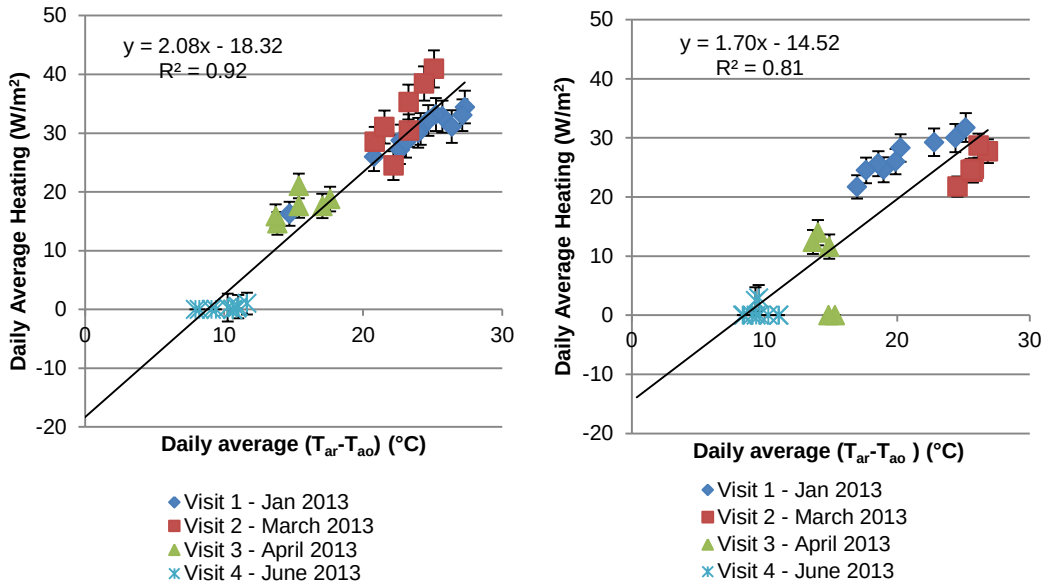


Figure 5.21 – Individual performance lines for Ward 22 [Left] and Ward 23 [Right]

The performance lines for the combined measurements from Ward 22 and Ward 23 were well defined (Figure 5.22) with coefficients of determination (R-squared value) 0.87.

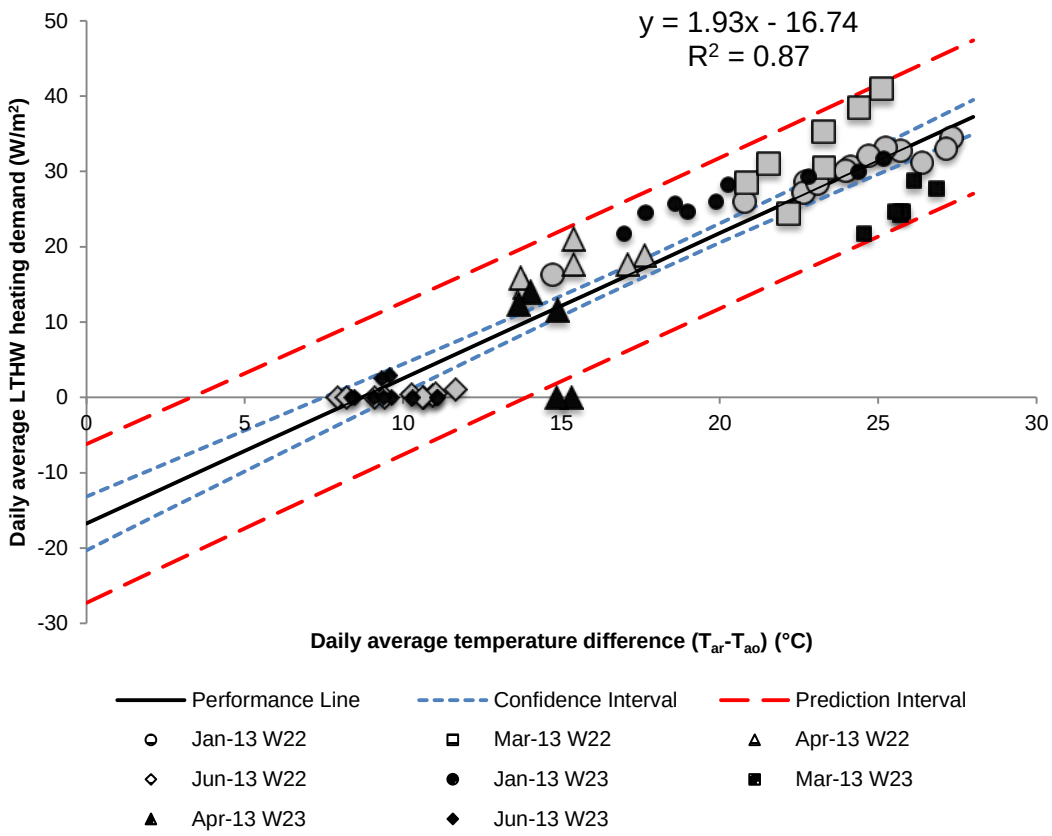


Figure 5.22 – Performance line for Nightingale building based on measurements taken for Ward 22 and 23

The equation for the performance line of the entire Nightingale wing, both Ward 22 and Ward 23 is:

$$Q_{LTHW} = 1.93(T_{ar} - T_{ao}) - 16.74$$

Equation 5.1

When the daily average outside air temperature is equal to the daily average internal air temperature the performance line shows that -16.7W/m^2 of heating is used for Wards 22 and 23. This indicates that the internal heat gains for the wards are, on average, 16.7W/m^2. The performance line for the building crosses the x-axis at 8.67°C (with confidence intervals of ±0.9), indicating that the heating system needs to supply heat to the building when the inside to outside temperature difference is larger than 8°C. Using Equation 5.1, hourly local weather data, the wards average temperature of 23.9°C (Table 5.2) as the set point and local degree-day data for normalisation. The total heating energy for the building was calculated to be 100.3 ± 12.6 kWh/m^2/yr. Using the overall seasonal efficiency of 53%[i] for the centralised heat delivery system, the efficiency losses attributed to LTHW heating were 88.9 kWh/m^2/yr, meaning that the overall fossil fuel use attributed to heating this Nightingale building was estimated to be 189.2 ±18.4 kWh/m^2/yr.

5.4.2 Electricity

The average total daily electrical demand for Ward 23 varied over the 10 days monitored during summer (Figure 5.23). The average demand over the period was 10.33 ±0.83 W/m^2, ranging from 9.74 to 10.77W/m^2. The results suggest that the actual day in the week did not have an impact on the demand, with Tuesday, Wednesday and Thursday showing different demands on the different days they were monitored.

[i] See chapter 4, section 4.1.4, Table 4.2

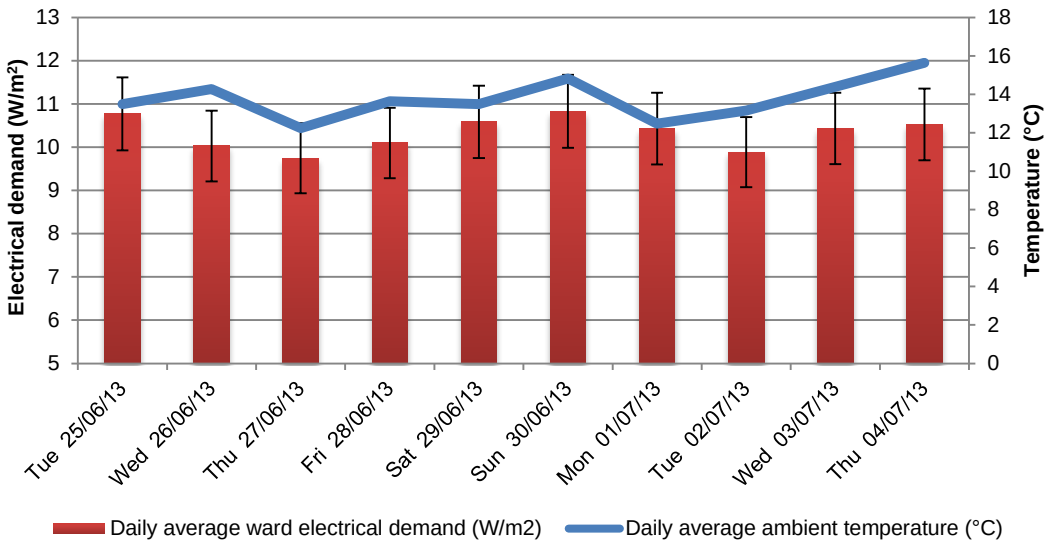


Figure 5.23 – Ward 23 average total summer daily electrical power demand

The power demand from for the essential and non-essential supplies to the ward were monitored in both the autumn and summer months. The single phases monitored in autumn demonstrate that the non-essential phase seems to use a similar amount of energy as the non-essential phase in summer, having average demands of 4.12 and 4.56 W/m^2 respectively (Figure 5.24). There is a wider disparity between the essential circuit measurements in summer and autumn. It could be expected that the electricity demand would show a slight increase with external temperature, however the results show that the essential circuit had a larger demand in autumn than in summer when it was warmer, (8.19 and 5.77 W/m^2 respectively). Although the electrical consumption of Ward 22 was not monitored, it is highly likely that it would have been slightly higher than that for Ward 23, this is because it will have used more electrical equipment to support the needs of the cardiovascular patients.

The method for calculating the yearly ward electrical consumption (Chapter 3, section 3.4.3) involved finding the average demand over the monitoring period and multiplying it by the days in the year. Taking the non-essential and essential demands from both the summer and autumn monitoring into consideration, the total consumption would be 11.32 ± 0.86 W/m^2. Using this figure, the method gave an estimate of the electrical consumption of Ward 23 as 99.16 ±7.53 kWh/m^2/yr.

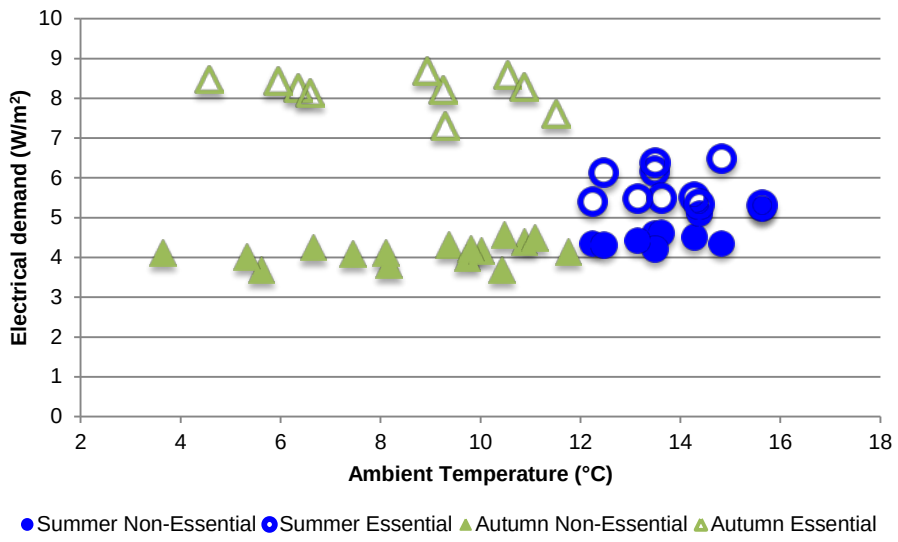


Figure 5.24 – Relationship between average daily ambient temperature and average daily electrical power demand

As the autumn essential and non-essential ward demands were not measured at the same time, they could not be accurately combined together to create a daily energy profile as with the summer measurements (Figure 5.25). During the summer the daily ward demand base load (demand in the night and early hours of the morning) was around 7W/m^2. Just after 06:00 the demand began to rise with a spike occurring at 07:00, then dropping slightly and rising until 10:00, staying between around 10-18W/m^2 until 15:00 when the power consumption gradually declined to 7W/m^2 by midnight.

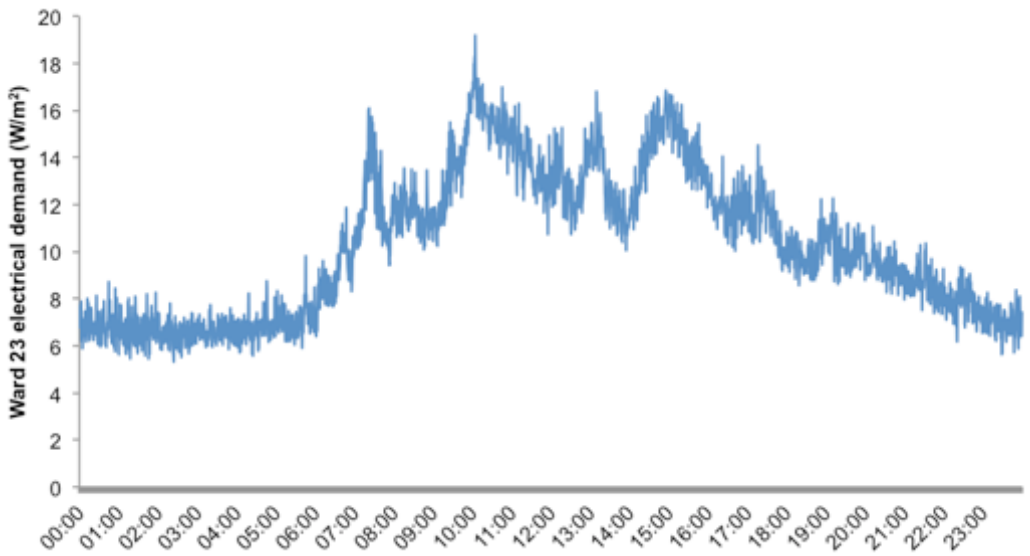


Figure 5.25 – Average hourly electrical power demand profile for Ward 23 over a period of 10 days in June/July 2013

Monitoring the single speed pump showed that it drew 2.65A using a 230V single-phase circuit. As the pumps for Wards 22 and 23 were the same, it was assumed that they drew the same current, therefore the total current for both pumps would be 5.3A. It was also assumed that the pumps only operated when the building needed heating (7675 hours[i]) the annual energy consumption of the pumps was estimated to be 5.1 ±1.15 kWh/m^2/yr (Table 5.5). It is to be noted that this figure only represents the electrical energy needed to move the LTHW around the two wards and does not consider the energy needed to move the LTHW from the main plant room to the building. This factor was only comprehended when assessing the results and consequently the pumps in the main plant room were not measured. Therefore, in order to take a whole view of the energy consumption, it is being assumed that the electrical energy taken to move the heat to the building was 5 kWh/m^2/yr. Overall, from the electrical analysis, it is evident that the pumps only used a fraction of the energy that was used for the ward.

	Average current of measured phases (Amps)	*Phases*	*Voltage (V)*	*Power factor*	*Time in operation (Hours)*	*Floor area (m^2)*	*(kWh/m^2/yr)*
Pumps	5.30	1	230	0.85	7675	1551	**5.13 ±1.15**

Table 5.5 - Nightingale plant room electricity consumption

5.4.3 Overall Energy Consumption and Carbon Emissions

The Nightingale building DHW load and the efficiency losses for both central and local energy systems were calculated according to the method in Chapter 3. It is to be noted that the actual building on the site is supplied by BRI's central plant system which has a combined supply of electricity from the grid, CHP and renewable energy. The local system was included in the analysis to demonstrate the performance of the building if it was standing alone. The difference in the results is based on the efficiencies used[ii]. The energy is presented in Figure 5.26 in terms of fossil fuels and grid electricity, which allows for comparison to the CIBSE benchmarks.

The difference between the building being supplied by the central plant and a local boiler is mainly that the electrical demand from the grid for the building supplied by the central plant is lower, but the heating is higher due to reduced heating efficiencies.

[i] This number was found by counting the number of hours over base temperature of 15.2°C, (see Methodology, Equation 3.27 and set T_{ar}= 23.9°C).

[ii] For seasonal efficiencies see chapter 3, methodology primary energy conversions and chapter 4 section 4.1.4.

Overall, the energy consumption for the building would be lower if it had a local boiler system. On the other hand, when taking into consideration the carbon emissions produced by each scenario (Figure 5.27), it becomes apparent that the output is almost identical with the central and local systems producing 106.6 and 108.7 ($kgCO_2/m^2/yr$) respectively. DEC operational ratings are based on carbon emissions as opposed to energy consumption, therefore when comparing the CIBSE benchmark to the nightingale building performance it is useful to use the format of $kgCO_2/m^2/year$. The results show that the carbon emissions of the Nightingale building (central) are 23.0 $kgCO_2/m^2/year$ less than the CIBSE benchmark.

Considering the energy consumption, the results show that the building is currently performing (56.1GJ/100m^3) at a similar level to the entirety of the BRI site, both having similar fossil fuel and grid electricity consumption falling at the bottom end of the existing hospital category for the Estates Code benchmarks (Figure 5.26). The results for the local Nightingale scenario fall into the new build category, with a consumption of 48.7GJ/100m^3.

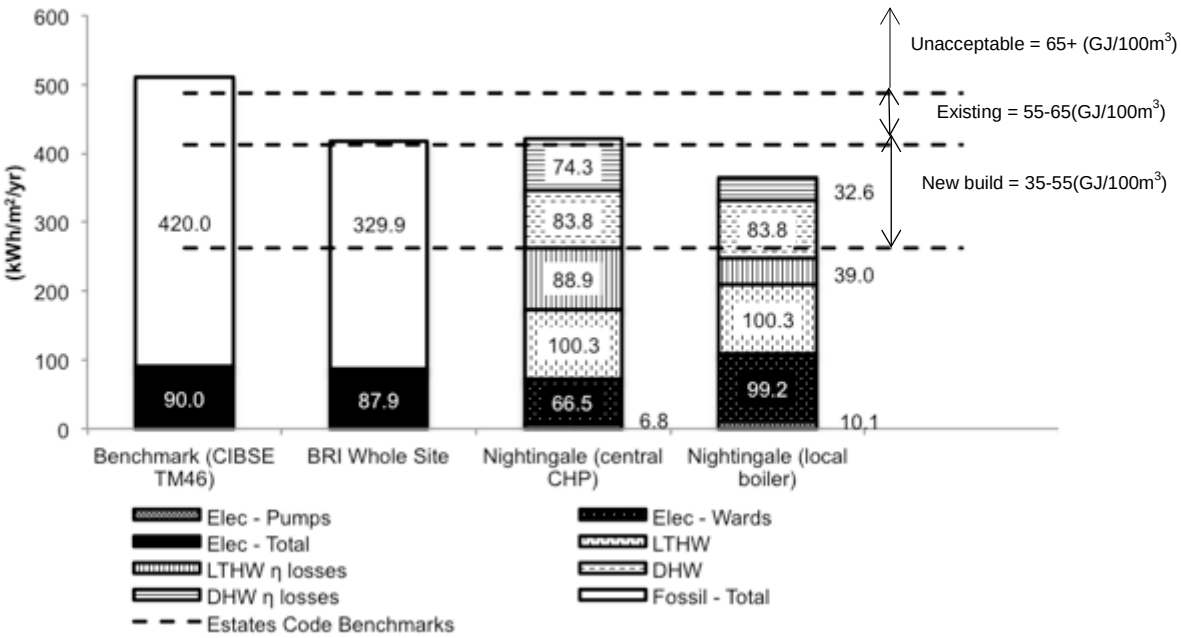


Figure 5.26 - Total energy consumption for the Nightingale Building (April 1st 2012 – March 31st 2013)

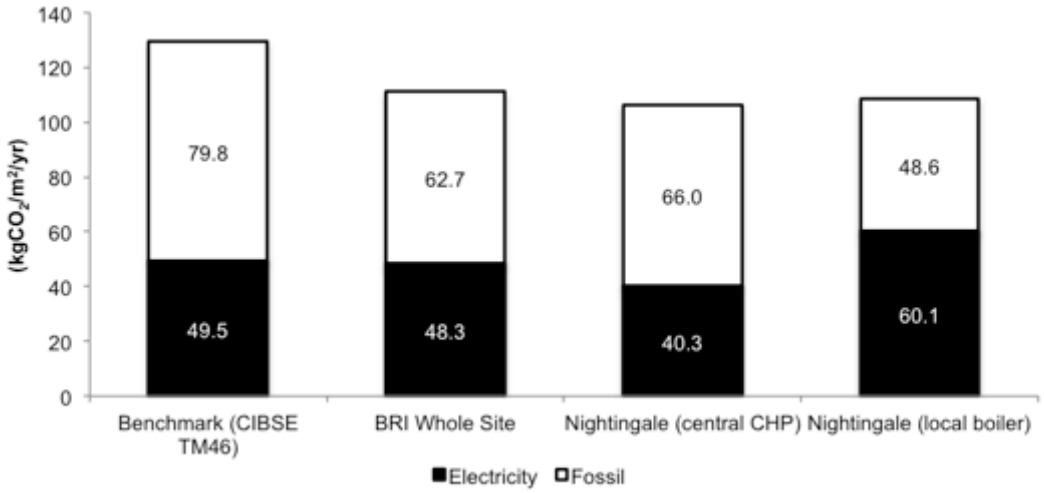


Figure 5.27 - Total Carbon Emission for the Nightingale Building

5.5 Discussion

The first notable point about this building was its low energy consumption. It is a commonly held belief that the old does not perform as well as the new; yet this building constructed in 1923 seems to be an exception to this belief. Built close to 80 years prior to the formation of energy code benchmarks it fell comfortably into the new build category for energy consumption. The question must be asked, why was this building performing so well?

When looking at the energy results in section 5.4.3, it is clear that the heating energy consumption for the building is where the majority of the savings are being made. Space heating demand is closely related to the amount of fresh air entering the building and the level to which the building is insulated. As this building did not have a mechanical ventilation air heating system, a significant proportion of energy was saved. Another important factor explaining the low heating consumption may be the recently installed roof insulation which brings the roofs U-values to similar levels as those recommended for meeting the target emissions rating, as defined in the building regulations (HMGovernment, 2010). This suggests that bringing an old building up to new building standards has the effect of saving energy.

It was interesting that Ward 22, the ground floor, used more energy for heating than Ward 23, the upper floor. This difference in energy consumption may demonstrate the heat transfer between the bottom floor and the top floor through the floor between them. There is however a degree of uncertainty due to the fact that the temperature was not measured on the ground floor and assumed to be the same as the first floor.

The literature has shown that in a particular Nightingale case-study monitored during the summer, there was a difference of about 0.5°C between the two floors (Lomas & Giridharan, 2012a). In this case an uncertainty of 0.5°C would have shifted the temperature difference for each day and had the impact of shifting the performance line to the right or left. In either case, the gradient of the performance line for Ward 22 would remain the same; slightly steeper than the gradient for Ward 23. The encode guidance has recommended that one way to lower energy consumption is to monitor the energy consumed in each department creating energy league tables and making results visible to staff to encourage further savings. The work in this thesis has demonstrated that it is possible to monitor the energy consumption in specific wards. However, this example suggests that the measurements for heating for each ward or space do not necessarily represent the energy used to heat the space. It could be that the space is being heated by a space next to it or below it, or that the energy in the space is being used to heat another space above it. Electrical energy consumption is not affected in this way but items, such as pumps and fans, may not be controllable by staff.

The electrical energy performance of the building was not as good as its performance for heating. The results show a number of peaks especially at times when staff were changing shifts, an example of this is the peak at 7:00. The electricity consumption of this particular building will be discussed in further depth and compared to the electrical consumption from the other monitored buildings (Chapter 8).

It has been discussed in previous chapters that Bradford Royal infirmary as a site has a low energy consumption. Some of the reasons for this have been mentioned in Chapter 4. One more possible reason is that 61% of the entire site was made up of buildings built before 1948. Out of this number, the majority are of the Nightingale design, bar a few small residential units for housing nurses. If it is assumed that this building is representative of the energy consumption of all the other Nightingale buildings on the site. This might explain why the site is energy efficient.

The results suggest however that insufficient fresh air may be being provided to the bed spaces in the winter months, when the majority of windows are closed. The CO_2 monitoring demonstrating that 84.9% of hours were recorded above Cat I, when the building standards BS EN 15251 limits this amount to 5%. The spot measurements suggests that the airflow rates are less than 6ach^{-1} with the estimates ranging from 0.76 – 1.8 ach^{-1}. This could pose a possible risk for infection control, because the

Wells-Riley equation demonstrated in Figure 2.12 shows that at the lowest levels of quanta generation, there is a risk of infection of 0.3 when the ventilation rate is $1ach^{-1}$, and as the quanta rate rises, low rates of ventilation lead to a high probability of infection. In addition to this, a study identified that risk of tuberculosis infection increased for clinical workers, working in a non-isolation space when air change rates fell below $2ach^{-1}$ (Menzies et al., 2000).

When looking at the flow rate per maximum number of potential patients occupying the space, it can be seen that the ventilation rate was around, or just below 10l/s/p. These estimates are likely to be higher than in actuality as the measured CO_2 levels were likely below the equilibrium value. This suggests that actual flow rates were below 10l/s/p, which has the potential to lead to odour problems. Both spot and the longer measurements seem to agree that there could be inadequate ventilation in the rooms for a significant portion of the year.

The results from monitoring in Ward 23 seemed to show a relationship between the room temperature and CO_2 levels. It is also apparent that the temperature and CO_2 levels are influenced by the occupancy of the space. Furthermore, the temperature is also heavily influenced by the solar gains. It can be seen that both CO_2 levels and temperatures rise at times of increased occupancy, a simple measure to reduce the high levels of CO_2 as well as the temperature could be to open the windows. During the period of monitoring the CO_2 level, the peak air temperatures were over 24.6°C. This shows there is some room for the temperatures to reduce and the space remain comfortable.

When examining the temperatures monitored in the ward during the entire winter period it is evident that the overall temperature was higher than the CIBSE recommended value for 30% of the time. If this temperature was lowered, it may further reduce the energy consumption as well as benefitting the staff on the wards who regularly complained that the temperatures were too high. In regards to the distribution of temperatures in the ward, as expected it has been identified that the areas closest to the windows have the lowest temperatures. In addition to this, it seems to be the case that the ratio between radiators in a space and the surface area of the room exposed to the outside of the building may have an impact on a spaces ability to control its internal air temperatures. This suggests that as well as room size, external wall surface area exposure should be taken into consideration when designing heating systems.

When looking at the results from this case-study in the light of the existing literature some interesting points arise. Firstly, this is the first Nightingale building of its type to be studied in this way, the existing literature focuses on Nightingale buildings with open wards, which utilise cross flow ventilation. In one such building with open cross-ventilated wards, the regular airflow when the windows were open and the wind speed was between 1-4 m/s provided 3 to 7 ach^{-1} (Gilkeson et al., 2013), which falls in line with the NHS guidance of 6 ach^{-1} for wards (Department of Health, 2007b). The same NHS guidance states that cross ventilation is only effective when there are clear paths between both sides of the building and that when clear paths are not maintained, mechanical ventilation should be supplied. Considering that this building only used single sided ventilation, and the fact that the windows were not always opened, might explain why the CO_2 levels were above the recommended values of 750ppm for 85% of the time.

Lomas et al conducted a study in which a Nightingale ward with various retrofit measures was modelled in order to reduce the risk of overheating (Lomas & Giridharan, 2012a). The modelling study predicted that in 2010 a relatively cool year with 3 hours when the ambient exceeded 24°C, the energy consumption for the Nightingale building would be around 25GJ/100m^3/yr for heating. It is important to note that the authors mentioned that there were some “crude” adjustments made to compensate for hot water energy and other energy that may not have been modelled. Taking this into account, when comparing the predicted 25GJ/100m^3/yr to the value for the standalone building in this chapter, 48.7GJ/100m^3/yr, it is clear that their predicted values may be a under estimate of the real heating energy demands. Nevertheless, both results demonstrate that Nightingale buildings have a considerably lower energy consumption than the recommended benchmarks.

In their paper Lomas and Giridharan also presented results for the monitoring of the summer temperatures in the wards. The period of monitoring differed from this study in that the building was monitored between June and August of 2010. It is to be mentioned that 2010 had less hot hours than 2012, having no hours over 25°C and only 3 hours over 24°C, whereas 2012 had 5 and 17 hours respectively. With this in mind, the results showed that the ward did not overheat massively, but when compared to the BS EN 15251, the larger spaces exceeded the criterion for 6-7% of the hours and the smaller spaces exceeded the criterion for around 2% of the hours. The pattern of the smaller spaces being cooler seems to be the same as that found in

this chapter, however this chapter differs, in that in Lomas' study, the larger spaces had a wider spread of temperatures than the smaller spaces, having diurnal swings of 5.2-6.9K and 3.5-3.9K respectively. The diurnal swing may be higher in the larger multi-bed spaces in this building due to the traditional Nightingale design utilising cross ventilation, which would have made the building more responsive to ambient temperatures.

Due to the fact that the building was measured for a shorter period of time in a different year than in the study in this chapter, it is not empirically sound to compare the two buildings together in order to say which had the greater performance, what it is possible to say though, is that the both studies point to the conclusion that Nightingale buildings provide relatively stable temperatures in typical weather conditions.

5.6 Conclusions

This chapter has described the procedure used for monitoring the energy consumption in one of the Nightingale buildings at Bradford Royal Infirmary. The monitoring method described in Chapter 3 worked remarkably well in this building. The building had recently been refurbished with a simple building services system that supported ease of implementation of the method. This building was an exception to the other five Nightingale buildings on the BRI site as due to their old design, these buildings had restricted access to the pipes necessary to monitor the LTHW consumption. In addition to these findings, this chapter also highlights the importance of monitoring the heating consumption of all floors in a space. This is due to a disparity in heat usage because of heat gains from other floors.

This chapter provides evidence that Nightingale hospital buildings, constructed in the early 20th century, updated to modern building standards can be very energy efficient. With the current centralised energy supply the building had an energy consumption of 420.8kWh/m^2, which is below the CIBSE benchmark and in the stand-alone scenario, the building had an energy consumption of 365.2kWh/m^2 or 48.7GJ/100m^3, which falls into the Estates Code New build category. This low energy consumption is mainly due to the low heating demand, arising from the lack of mechanical ventilation and updated levels of roof insulation. The work presented also adds to the body of knowledge that Nightingale buildings provide an acceptable thermal environment for patients in current summer months, with the case study showing that in 2012; a year with below typical temperatures, minimal overheating took place. Two other key findings in regards to the summer temperatures were that, the smaller spaces were cooler and more responsive

to ambient temperatures than the larger ones. Secondly, it is hypothesised that the heavy thermal mass of the building distributed the heat from the warmer days, over a wide period of time, reducing the impact of high ambient temperatures, thus providing greater resilience for the building.

Although the energy consumption and resilience to overheating was of a high standard, the hospital space did have the drawback that the current ventilation system led to high indoor CO_2 concentrations, which indicates that the space could potentially have problems with odour and infection risk. Overall, this hospital case-study building demonstrates the efficiency of simple buildings and provides compelling evidence in favour of the argument for refurbishing heritage UK hospital buildings, which goes against the trend of demolishing old facilities to build new ones. Points for further study would be to increase the amount of ventilation to the wards in the winter months without significantly increasing the heating demand and addressing high electrical energy consumption, which is an area that deserves more attention.

6 Bradford Nucleus

6.1 Introduction

The nucleus design of hospital buildings was introduced to the NHS in the aftermath of the oil crisis that took place within the '70s. These buildings generally utilised mixed mode ventilation and were the NHS' first attempt at creating an easily replicated low carbon hospital building. Since their introduction in the '80s over 100 have been constructed around the UK. The energy performance of two of these buildings were studies in the 90's (NHS Estates, 1995a, 1997) and more recently one featured in a study on the building type's summer thermal resilience (Giridharan et al., 2013). This chapter documents and discusses both the energy and internal environmental performance of a nucleus building monitored at a single site in the north of England in 2012 and 2013. It presents and discusses the findings in the light of previous research, enlarging the current knowledge on the performance of this widely used building type.

Figure 6.1 – North East corner of the nucleus building

6.1.1 Background

In the '80s, the Bradford Hospital Trust had the desire to extend their facilities. Choosing the current NHS blueprint for hospital design at the time, they submitted their first intentions for the construction of a nucleus building at Bradford Royal Infirmary to the design team in December 1980. The original plan was to produce a new hospital block with wards on three floors. Discussion of the building design continued through to 1982 when the trust came to the decision that they wanted to make changes to the top floor, so that rather than it holding a ward, it would contain an operating theatre. The full contracts were signed in April 1984 and construction began in September of the same year, continuing for two years until the building was completed in Sept 1986. The completed building comprised of three levels; a basement that contained the medical physics workshop and plant room, the ground floor which held Wards 20 and 21 and the first floor which housed 4 operating theatres.

Ward 20 and 21 provided general short term patient care for those coming in and out of operation. Out of the 8 multi-bed rooms in the building, one on Ward 21 was a high dependency unit where patients who had undergone major surgery could receive specialised care and consequently this room had more electrical equipment than regular rooms.

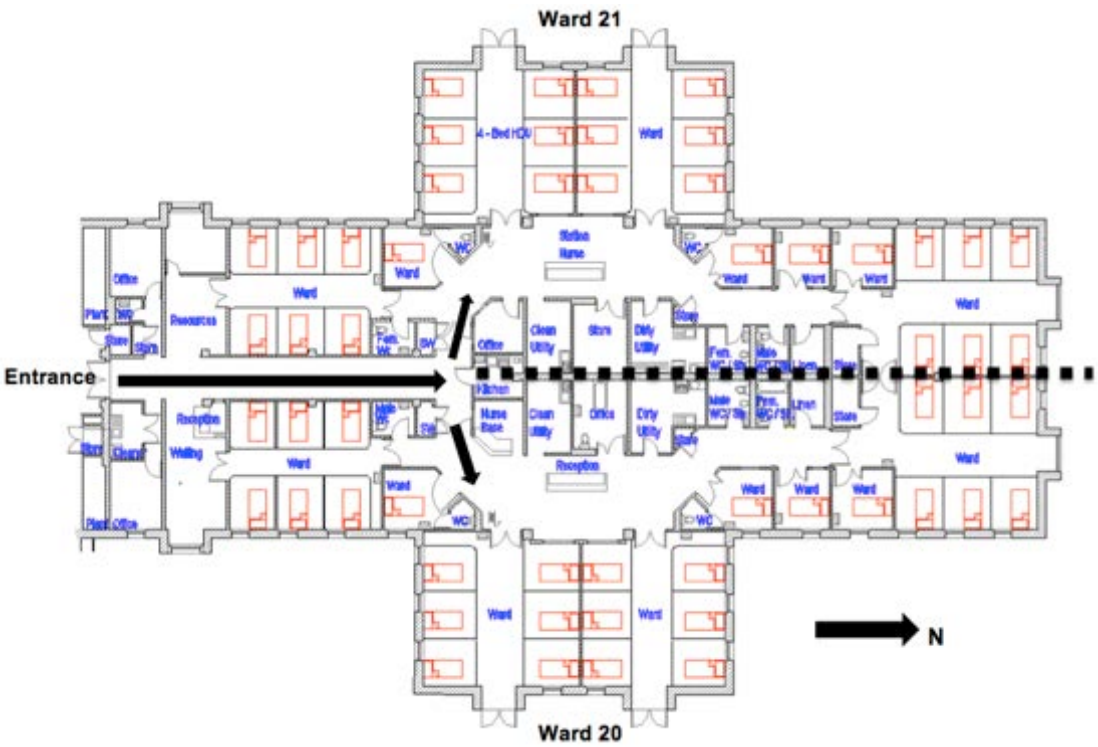


Figure 6.2 - Bradford Nucleus Level 2 floor plan (dashed line denotes divide between Ward 20 & 21)

6.1.2 Construction

The building was constructed with external cavity walls, the outside layer had handmade bricks, with a thickness of 102.5mm. The inside blockwork was made up of 140m thick celcon blocks with the internal gap filled with 50mm of drytherm insulation. The building was covered by a pitched roof, constructed with steel trusses, supporting timber rafters, which were in turn covered by concrete slates.

6.1.3 Heating, Ventilation and Air Conditioning Systems

There were a number of different HVAC strategies to serve the various parts of the building. The theatres were fully air conditioned using air handling units which could be found on the roof. The ward areas utilised a mixed mode ventilation system, with supply and extract ducts being linked to each of the three multi-bed rooms. The nucleus received its heating energy from the existing hospital heating system via

steam from the main boiler room (Figure 6.5). The nucleus had its own plant room which contained heat exchangers to transfer heat in the form of the steam to DHW and LTHW for heating the building. The plant room contained two sets of pumps, one for the constant temperature circuit and the other for the compensated flow temperature system. The constant flow temperature circuit supplied frost coils and heater batteries for the supply air handling units in the plant room on the ground floor and on the roof.

Type	*Nucleus*
Location	Bradford
Built	1986
Floor area	Level 1: Basement (365m^2) Level 2: Wards 20 & 21 (485 & 483m^2) Level 3: Theatres 1-4 (967m^2)
Heating	Wall radiators (Wards) & Heated ceiling panels (Corridors)
Ventilation	Mixed mode
Roof	Pitched roof; (U=0.28W/m^{2}K)[i]
Walls	102.5mm Outer brickwork, 50mm Drytherm cavity insulation, 140mm Inner blockwork; (U=0.37 W/m^{2}K)[ii]
Glazing	Openable thermally broken aluminium-framed double glazed (U=2.75W/m^{2}K)[iii]
Ceilings	2.70m
Occupancy	Ward 20 & 21 = 28 beds (each) Visiting hours 13:00-15:00 & 19:00-20:00
Room types	4x6bed & 4x1bed on each ward

Table 6.1 – Summary of Nucleus building design and construction

The compensated flow heating system used an outside temperature detector to modulate a weather compensating three-way mixing valve which controlled the amount of hot water entering the building. Once the LTHW entered the building it supplied ceiling radiant heating in the corridors and wall mounted radiators in the rooms on the wards.

[i] Minimal information on roof properties therefore pitched roof estimate was taken from CIBSE Guide A Table 3.50, option 3e, 12.5mm plasterboard, 100m mineral wool quilt between ceiling joists, 50mm mineral wool quilt over joists, roof space, tiling (CIBSE, 2006b)

[ii] For calculations see Appendix II Table A8

[iii] Window U-value estimate taken from CIBSE guide A, Table 3.23

There were three different ventilation systems within the building, AHU6 which served the internal rooms on the first floor, AHU7 for the bedrooms in the ward and a system of four AHUs serving the operating theatres on level 2. AHU6 which provided fresh air to the nurses station, office pantry and staff room was built with both cooling and heating abilities, having the summer set-point temperature of 19°C (Figure 6.3). The clean extract system extracted air from staff cloaks and the pantry, and the dirty extract AHU extracted air from the toilets, bathrooms and laundry areas. The floor plan shows that level 1 contained 8 multi-bed rooms. These rooms had two supply vents and two extract vents (Figure 6.18). The air-handling unit that supplied these spaces contained a heater coil and was designed to supply air to each of the rooms at a rate of 3 ach^{-1}. The air handling units for the operating theatres were located in the level 3 plant room, however as operating theatres are beyond the scope of this work, details of their AHU have been omitted from this section.

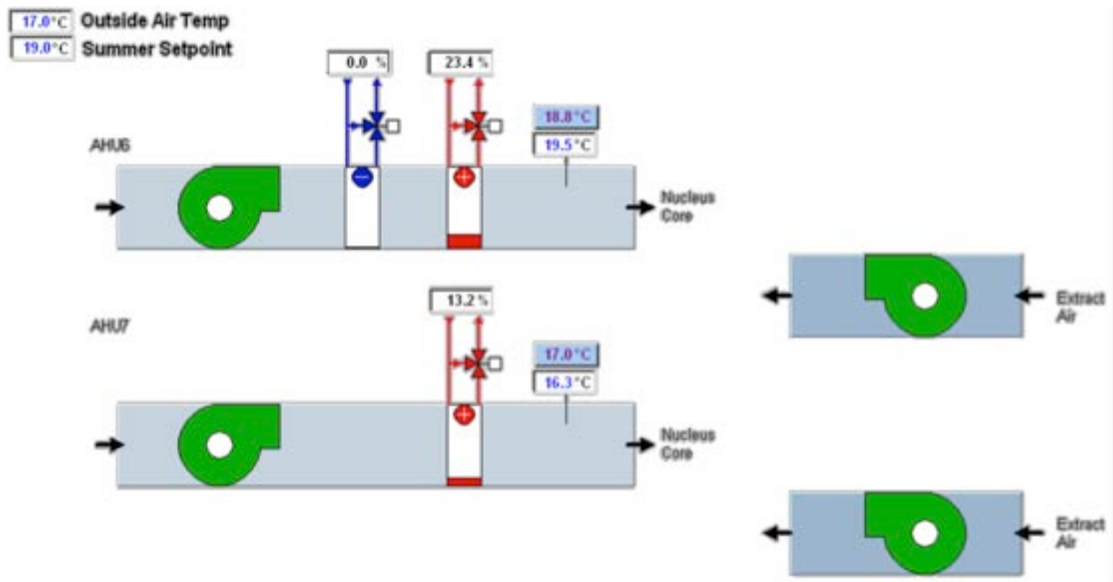
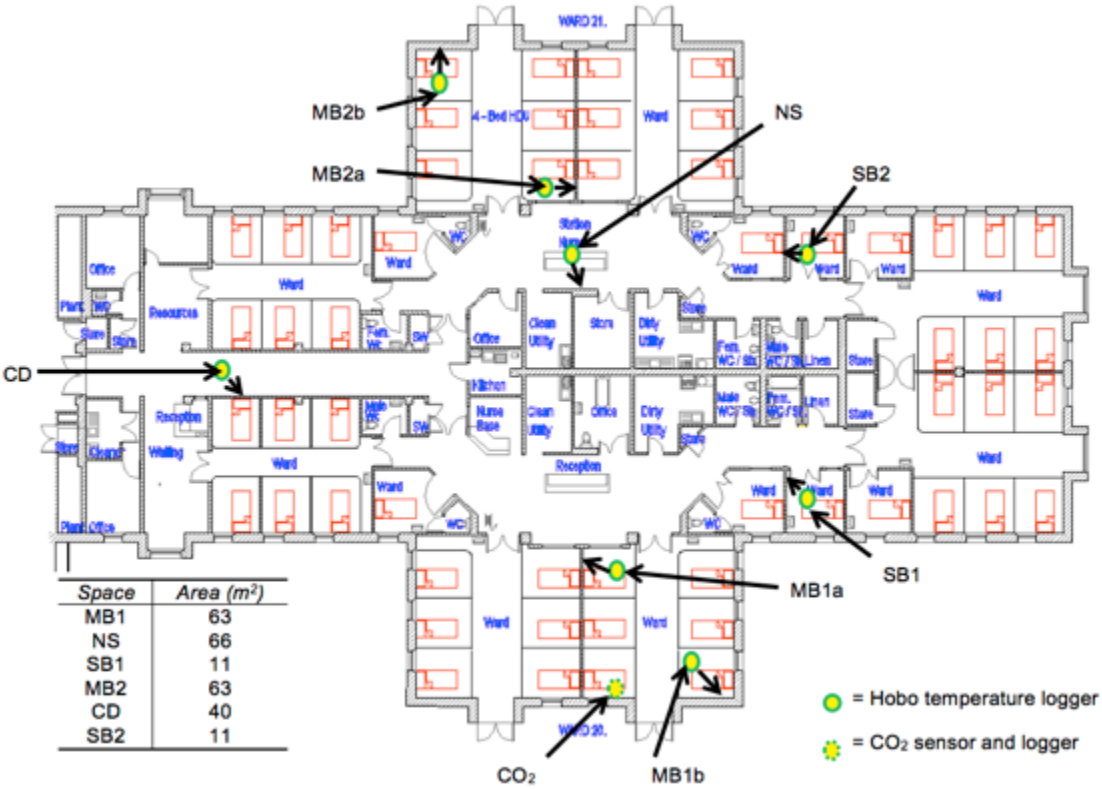


Figure 6.3 - Bradford Nucleus BMS diagram showing AHU6 and AHU7 supplying Ward 20 & 21

6.2 Monitoring Method Details

6.2.1 Internal Environment

To get an understanding of how the internal environment was performing the air temperatures of the different rooms were monitored as well as the CO_2 levels within one of the rooms (Figure 6.4).



Space	Area (m^2)
MB1	63
NS	66
SB1	11
MB2	63
CD	40
SB2	11

Figure 6.4 - Nucleus floor plan demonstrating placement of temperature sensors and areas of monitored spaces (MB = Multi-bed, SB = Single bed, CD = corridor, NS = nurse station)

6.2.2 LTHW Heating

Half of the building was monitored in order to gain an understanding of how much LTHW was being used. After being separated for the purposes of air heating and space heating, the LTHW was pumped through the compensated flow circuit until it split into two channels, one supplying the east side of the building and the other supplying the west side of the building (Figure 6.5). The flow meter needed at least 1.5m length of straight piping to measure accurate readings (Figure 6.6). In the nucleus' LTHW system, piping longer than 1.5m was only available after the supply flow had branched off to feed the two sides of the building. Therefore only one side of the building was monitored, as it was assumed that the energy consumption for each side would be very similar as they had similar levels of heating and rates of heat loss as they were identically symmetrical. The only difference between them being the levels sunlight reaching the building, which would have had minimal impact during the winter as the solar radiation intensity were at its lowest.

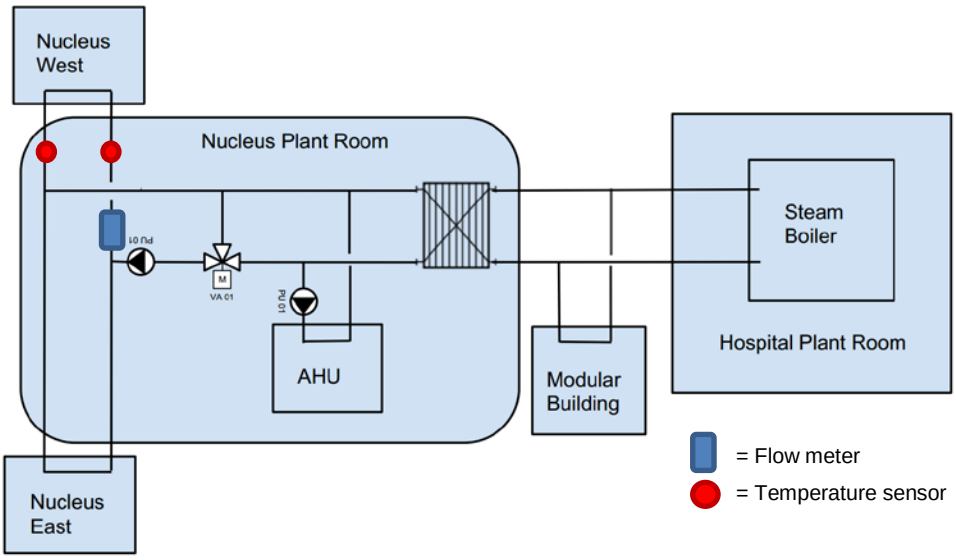


Figure 6.5 - Diagram of Nucleus LTHW plant room

The aim of this work was to identify the amount of energy used on hospital wards through monitoring, therefore the west side of the building was chosen as the specific part of the building to monitor and the heat flow monitoring equipment was fitted after the LTHW pipe had branched off to Ward 21 (Figure 6.5).

Figure 6.6 - Position of LTHW monitoring instrumentation in nucleus plant room

The heated floor area on the second floor Ward 21 was 484m^2, the heated area on the third floor, was 228m^2, as it was only the corridors and waiting areas which were heated (Figure 6.7). The operating theatres were heated through the mechanical ventilation system, so the purpose of the ventilation system was to provide fresh air and keep the room at a specific temperature, fit for operating. As the operating rooms were sealed spaces, and it could be assumed that the temperature difference between the operating rooms and corridors was very small, the air heated in the corridors on the top floor had very little impact on the temperatures inside the operating theatres.

Therefore the heated floor area of the third floor was, 215m^2, giving a total area of the west side of the building heated by LTHW to be 712m^2.

Figure 6.7 – Bradford nucleus floor plans with monitored areas highlighted for ground floor [Left] and first floor [Right]

6.2.3 Mechanical Ventilation

The supply and extract ducts for the mechanical ventilation were located around the ward (Figure 6.18). The building maintenance manual contained the flow rates being supplied to the building by the AHU system, nevertheless the balometer was used to measure the air flow out of the vents in each room in order to validate these supply rates. The temperature of the air supplied to the building was also measured in a duct running from the plant room through to the ward. The temperature of the air and the total airflow rate was used to calculate the amount of energy needed to heat the incoming air.

6.2.4 Electricity

The fans and pumps for the Bradford nucleus AHU and LTHW systems for the wards were located in the plant room in the basement of the building. These were all powered by three-phase motors which were supplied through a distribution board. Clip-on current meters were used to take measurements of a single phase from each piece of equipment for 9 days from the 22nd May to 31st of May 2012 (Figure 6.8).

There was however a limitation when it came to monitoring the electricity consumption for the wards. The distribution board was the original board installed when the building was first built in 1986. It was not therefore designed with monitoring in mind and had wires packed into the box so that there was no space for the current transformers to fit around the three phase cables (red, yellow, blue).

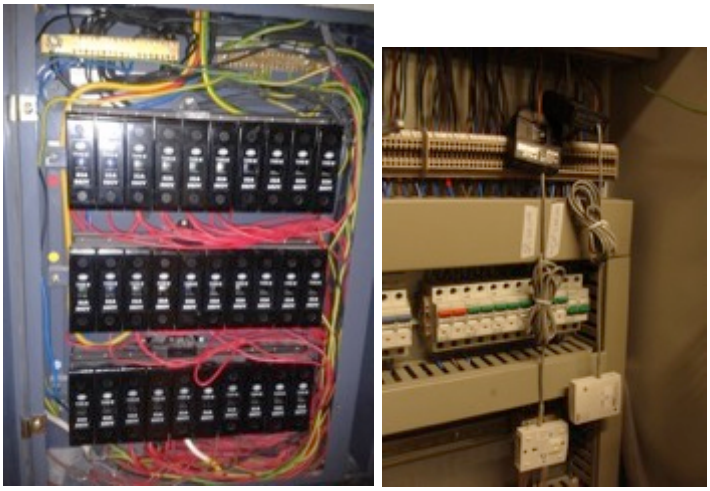


Figure 6.8 – Bradford nucleus electrical distribution boards; Ward 21 [Left], plant room [Right]

For the purpose of comparing the results of this building against benchmarks and the other buildings, the ward electrical power has been assumed to be the same as another nucleus building monitored in the study, but not included in the thesis. This is a fair assumption as it has been identified that ward electrical consumption does not show much variation from ward to ward due to the fact that electrical consumption is very closely related to its usage.

The electrical demand of a nucleus ward was monitored in Ward 27 at Glenfield hospital in Leicester. The ward was built in 1989, had an occupancy of 27 beds and a floor area of 477m^2, characteristics all very similar to the main nucleus building in Bradford. Glenfield Ward 27 was slightly different to the nucleus in Bradford as it had a distribution board which had been retrofitted with an advanced electrical metering system. The meter provided a live reading for power factors, line voltage and current of both the essential and non-essential circuits and had enough space to install the additional current transformers. The electricity consumption was monitored in Glenfield Ward 27 for 6 days from 7th to the 13th March 2013.

6.3 Internal Environmental Results and Analysis

6.3.1 Winter Temperatures

The average winter temperature measured from 1st December 2012 to the 24th February 2013 for Ward 21 was 23.95°C with the majority of the measured hours falling between 23.5°C and 24.5°C as is demonstrated in the histogram (Figure 6.9). 56% of the hours were above 24°C, indicating that the Ward was too warm, for a significant amount of time. The range of average temperatures throughout the Ward

was 0.9°C (Figure 6.9) with the highest temperatures being measured in the corridors and nurses station and the lowest temperature in the multi-bed room space.

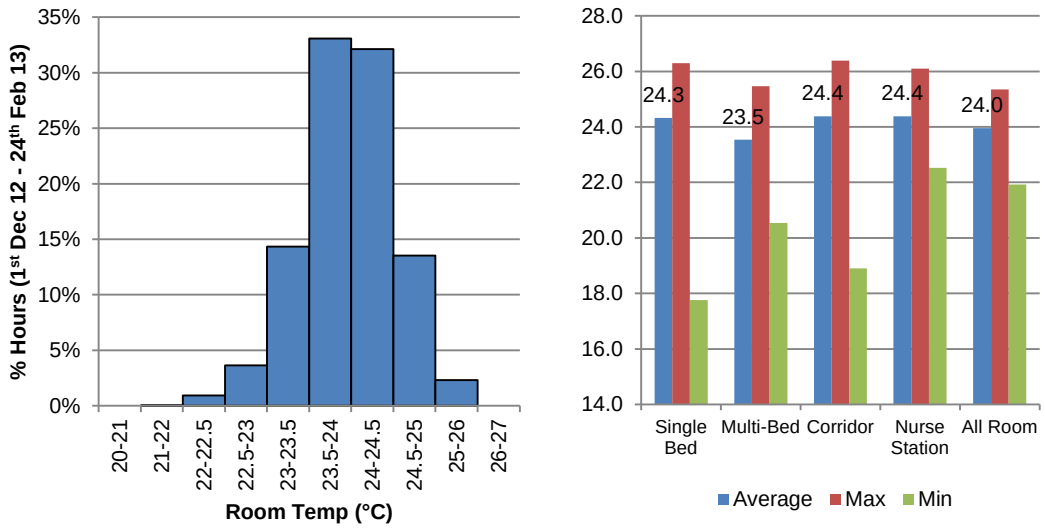


Figure 6.9 – Ward 21: weighted average winter temperatures [Left]; Average temperatures [Right]

	Mean temp (°C)	*Max temp (°C)*	*Min temp (°C)*	*Standard deviation (°C)*	*Hour under 18°C*		*Hours under 22°C*		*Hours between 22 & 24°C*		*Hours over 24°C*	
NS	24.4	26.1	22.5	0.67	0	0.0%	0	0.0%	607	29.4%	1457	70.6%
MB2a	23.3	25.0	20.1	0.72	0	0.0%	133	6.4%	1730	83.8%	201	9.7%
MB2b	23.8	25.9	20.9	0.70	0	0.0%	42	2.0%	1208	58.5%	814	39.4%
MB2-Av	23.5	25.4	20.5	0.70	0	0.0%	93	4.5%	1528	74.0%	443	21.5%
CD	24.4	26.4	18.9	0.93	0	0.0%	47	2.3%	546	26.5%	1471	71.3%
SB2	24.3	26.3	17.8	1.01	1	0.0%	57	2.8%	516	25.0%	1491	72.2%
Ward Av	24.0	25.5	22.0	0.55	0	0.0%	0	0.0%	903	43.8%	1161	56.3%

Table 6.2 – Nucleus Ward 21 temperatures during winter heating season (2064hrs between 1st Dec 2012 and 24th Feb 2013)

The temperatures for the individual spaces show that multi-bed 2 had temperatures which fell into the CIBSE recommendations for 74% of the time, having a standard deviation of 0.7°C (Table 6.2), which indicates the temperatures were well controlled in the space. The temperatures in single-bed 2 had the most hours out of the entire ward which were over 24°C, in addition to this, it had the highest spread in it's temperatures, demonstrated by its standard deviation of 1.01°C. This space was not mechanically ventilated and therefore received ventilation by opening the windows. The balancing act of opening the windows and heating through the wall radiators may have contributed to the wider spread of temperatures in this space. The nurses station and corridor had the highest temperatures in the Ward and it is likely that this was the case because of the internal gains in these areas and the comparatively lower rates of mechanical ventilation.

6.3.2 Summer Temperatures

The internal temperatures in the nucleus building were relatively stable during the summer of 2012 with the majority of hours falling between 22°C and 25°C. The temperatures were similar for both of the two multi-bed spaces monitored (Figure 6.12). On average multi-bed 1 was slightly cooler than multi-bed 2 which had a wider range of temperatures. Early on in the monitoring period, multi-bed 2 showed a large increase in temperatures for a short period. The data showed that this increase was only measured by logger MB2-a, from 16/06/12 01:00 to 17/06/12 07:00, a period of 31 hours. The temperatures measured were sustained between 29.7°C and 30.5°C throughout this period, therefore it is likely that a heater or another piece of heat supplying equipment was placed directly under the logger.

The warmest day in the summer period was on the 24/7/12 where the ambient temperature measured 26°C at 12:00. In all spaces the internal temperatures seemed to be very responsive to the ambient temperatures, i.e. the warmest internal periods were measured when the external temperatures were the warmest. In addition, the temperatures in the bed spaces did not exceed the max ambient temperatures during this warm day. Apart from the exception of multi-bed 1 close to the center of the building (MB1-a), where the max temperature was measured as 26.1°C at 15:00 when the max temp during this day was 26°C. The closeness of the indoor temperatures to the ambient temperatures suggests that there were low internal gains within the building. The corridors leading to the wards had the warmest temperatures, which were consistently higher than in the other spaces.

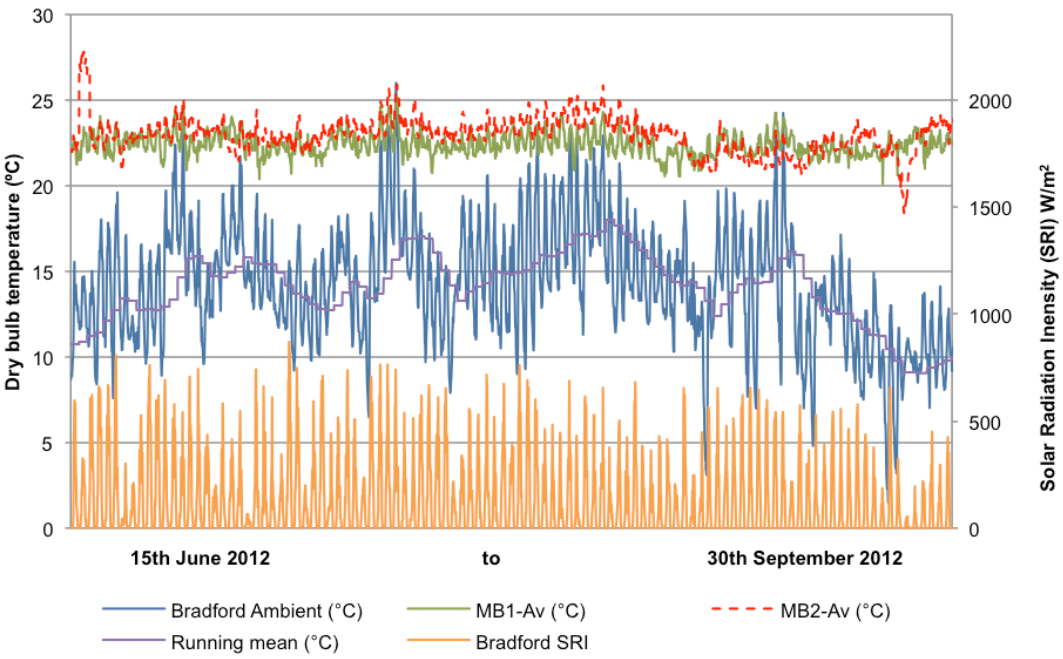


Figure 6.10 - Average internal temperature for nucleus multi-bed rooms

The average temperatures in the single bedrooms were 23.4°C and 23.5°C for rooms 1 and 2 respectively compared to the temperatures for the multi-bed rooms which were 22.6°C and 23.1°C for multi-bed 1 and multi-bed 2 respectively (Table 6.3). This demonstrated that overall, the multi-bed rooms were slightly cooler than the single bedrooms. The single rooms also showed a greater spread in temperatures (Figure 6.11), with the diurnal range for the single beds 1 and 2 being 4.6K and 5.2K respectively whereas the range for the multi-bed 1 and 2 were 3.3K and around 3K respectively.

	Max temp (°C) (24hrs)	*Min temp (°C) (24hrs)*	*Mean temp (°C) (7:00-20:00)*	*Mean temp (°C) (21:00-6:00)*	*Max diurnal range (K)*	*Hours over 25°C (24hrs)*		*Hours over 28°C (24hrs)*		*Hours over 24°C (21:00-6:00)*		*Hours over 26°C (21:00-6:00)*	
MB1a	25.8	20.5	23.0	22.3	3.6	13	0.5%	0	0.0%	5	0.2%	0	0.0%
MB1b	24.7	19.3	22.3	21.9	3.2	0	0.0%	0	0.0%	0	0.0%	0	0.0%
MB1-Av	25.3	20.1	22.6	22.1	3.3	2	0.1%	0	0.0%	0	0.0%	0	0.0%
SB1	26.7	18.8	23.5	23.2	4.6	23	0.9%	0	0.0%	65	2.5%	2	0.1%
SB2	25.9	19.0	23.4	23.4	5.2	55	2.1%	0	0.0%	152[i]	5.9%	0	0.0%
MB2a	32.2	18.1	23.0	22.6	9.0	77	3.0%	31	1.2%	53	2.0%	33	1.3%
MB2b	25.7	18.7	23.2	22.9	2.8	35	1.4%	0	0.0%	71	2.7%	0	0.0%
MB2-Av	27.8	18.4	23.1	22.7	4.9	68	2.6%	0	0.0%	56	2.2%	31	1.2%
CD	27.1	21.4	24.5	24.3	3.2	440	17.0%	0	0.0%	744	28.7%	31	1.2%

Table 6.3- Results from nucleus summer monitoring

[i] MB2a measured 31 hours at an unnaturally high temperature, this must be taken into consideration when looking at its results in Table 6.3

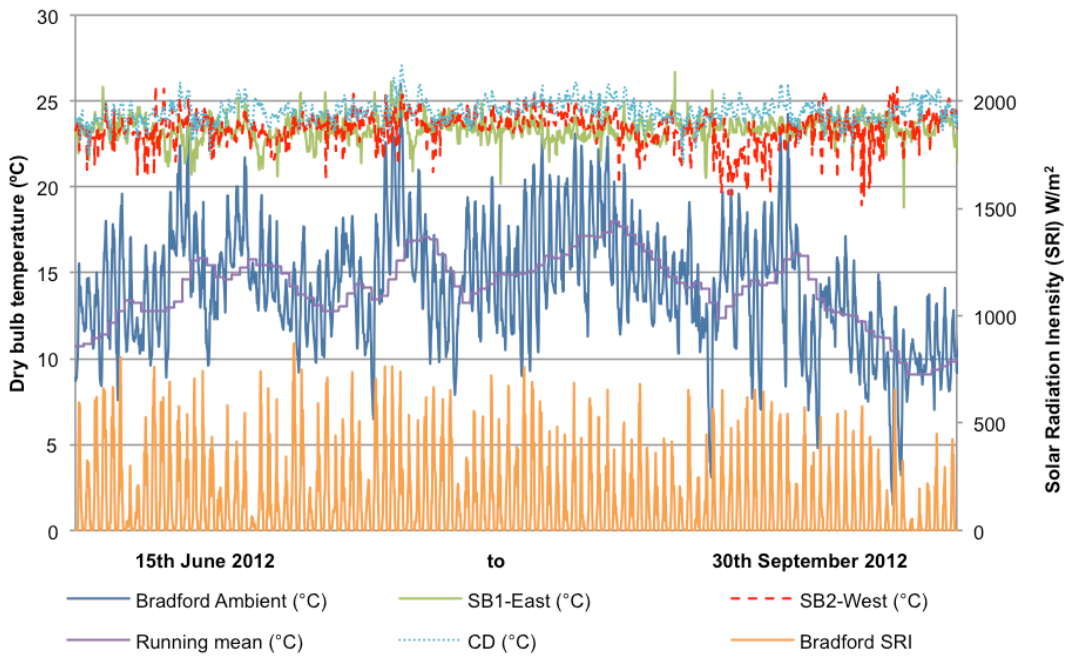


Figure 6.11 - Average internal temperature for nucleus single-bed rooms and corridor

One of the criteria for overheating in hospitals is found in CIBSE TM36 (CIBSE, 2005a) which recommends that no more than 5% of hours exceed 25°C. During this summer period, there were no spaces except the corridor with an unacceptable number of hours above 25°C. In regards to nighttime temperatures, the spaces' general performance was good, with only two hours measured above 26°C at night and this at only 2 hours in each space. The temperature at which it may become uncomfortable for a sleeping person 24°C (CIBSE, 2006b) was only exceeded for a significant amount of time (5% of hours) in single-bed 2, demonstrating that the buildings nighttime performance was very good.

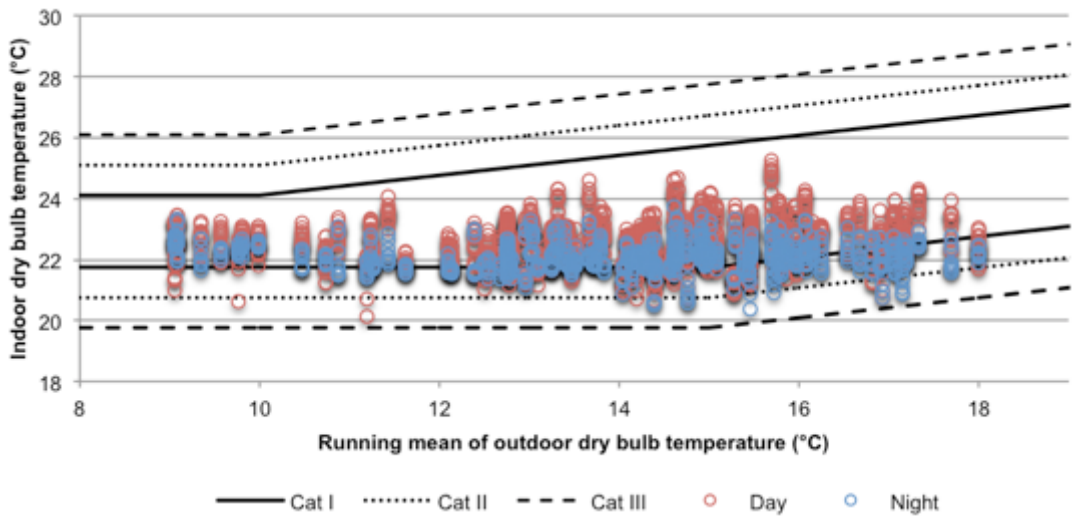


Figure 6.12 - Comparison of measured temperatures with BS EN 15251: MB1-Average

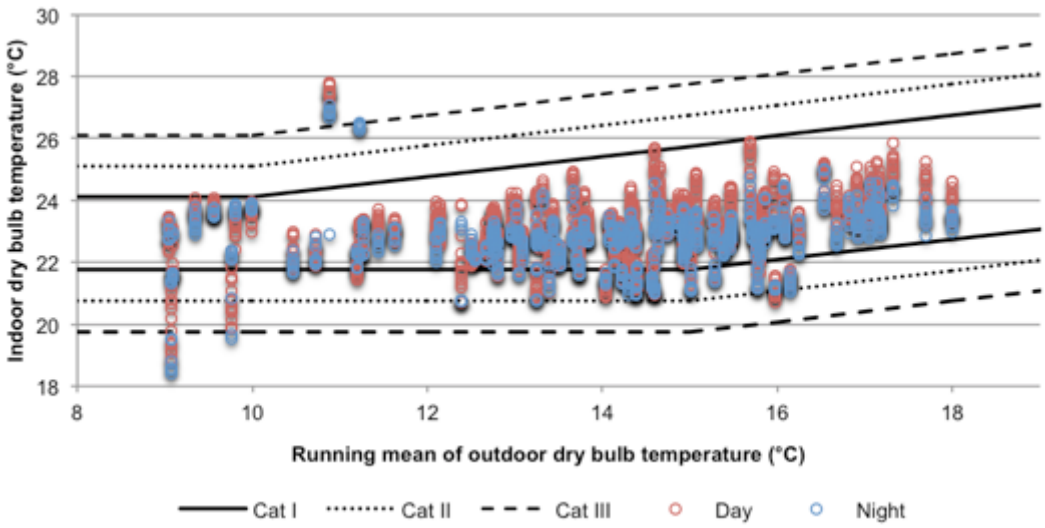


Figure 6.13 - Comparison of measured temperatures with BS EN 15251: MB2-Average

The BS EN 15251 adaptive temperature criterion helps to give more insight into the performance of the building relative to the external temperature. Figures 6.12 to 6.15 compare the day and nighttime temperatures to the adaptive criterion and Figure 6.16 compares all the different spaces to each other, documenting the percentage of hours in each category. The first thing to recognise is that all the bed spaces had the majority of their hours below the Cat I upper threshold, the maximum recommended temperature for sick patients. The exceptions to this were multi-bed 2 (reasons for which have been touched on before) and single-bed 2, where there was a visible number of hours where the temperatures were between Cat I and Cat II, suggesting the temperatures could be too warm for patients, but acceptable for staff or visitors. There were 121 hours (4.7%) in this category, which is within the acceptable limit (5%) for given in BS EN 15251. Figure 6.15 shows that a lot of this overheating took place when the running mean temperature was below 12°C suggesting that the overheating could have been caused by poorly managing the LTHW heating as opposed to heating by high ambient conditions.

The Figures 6.12 to 6.15 seem to show that the results for SB2 and MB2 are more scattered and show greater spread than the results for SB1 and MB1. Another point observable is that there is a significant percentage of hours when the temperature is below the recommended Cat I, most notably in the multi-bed wards (Figure 6.16). On average, MB1 was the coolest with slightly over 20% of the hours when temperatures were lower than Cat I threshold. SB1 was the only space with less than 5% of its hours falling below Cat I suggesting that the building could in fact be too cool for the patients to comfortably recover in.

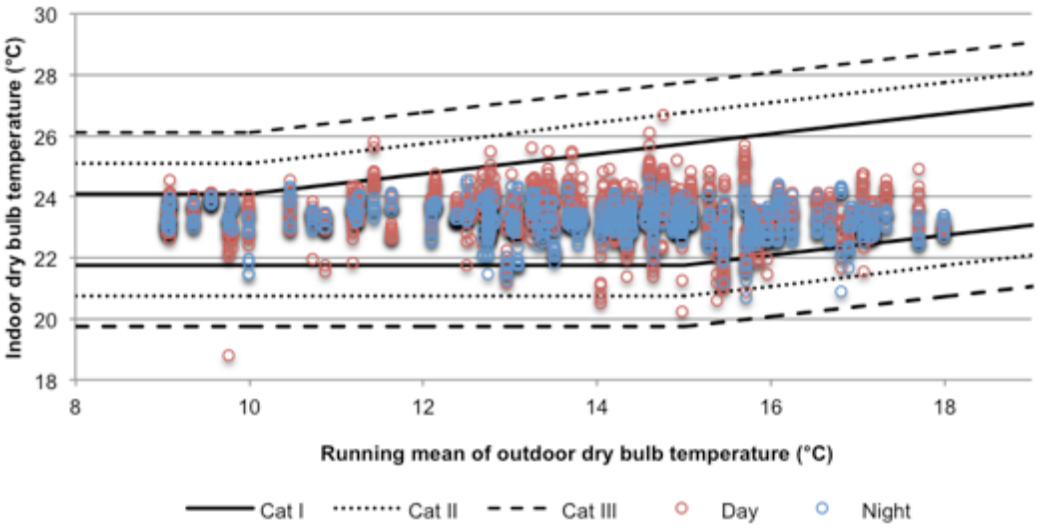


Figure 6.14 - Comparison of measured temperatures with BS EN 15251: SB1

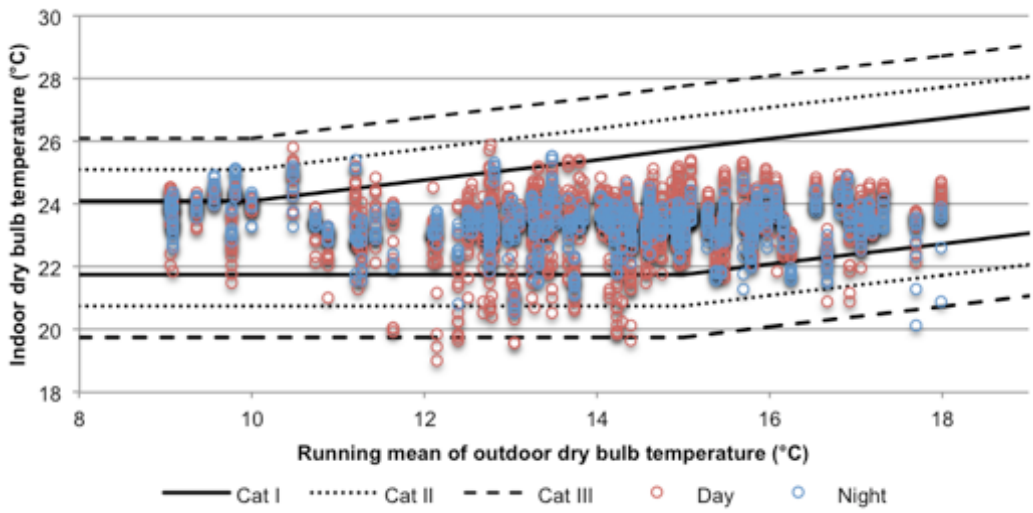


Figure 6.15 - Comparison of measured temperatures with BSEN15251: SB2

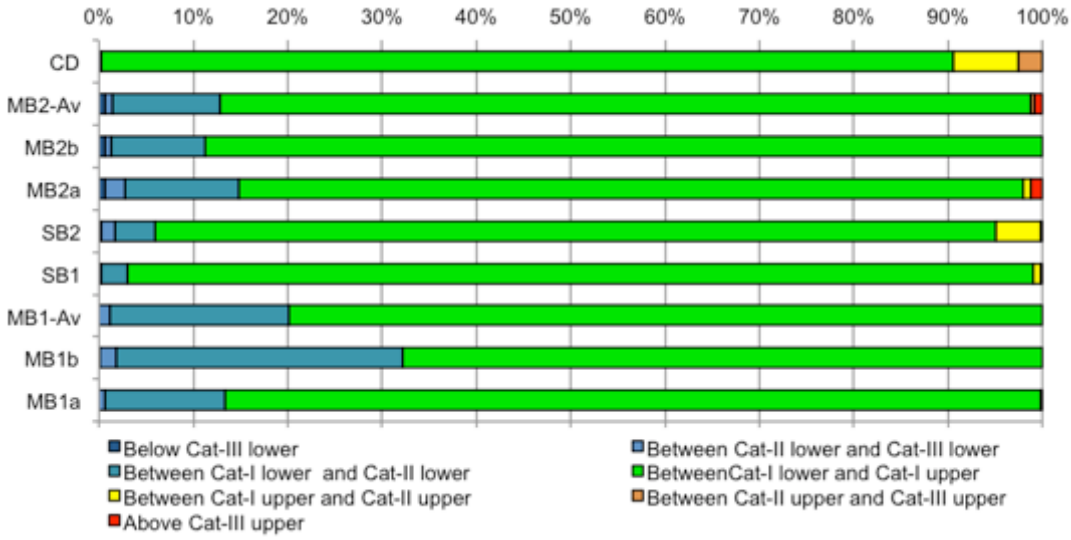


Figure 6.16 - Percentage of all measured summers hours in BSEN15251 for nucleus building

In addition to monitoring the summer temperatures during 2012, a walk around survey was taken in Ward 21 during the heat wave of July 2013 to assess what measures are used to keep the buildings cool in extreme weather situations. Nucleus buildings are designed so that each ward has windows to allow air and sunlight to flow into the space. However, this nucleus building did not promote cross flow ventilation as there were not windows on each side of the ward, nevertheless, at 15:15 on 26th July, when the ambient temperature was 21.3°C the spaces temperature was 25.6°C. All of the windows were opened, and 50% of the doors linking the rooms to the corridors were opened to allow air to flow around the ward. There was only one fan found on this ward and this was a floor fan in one of the multi-bed rooms. In addition, as the Wards were on the ground floor, fire doors were also opened to allow more air to flow into the space.

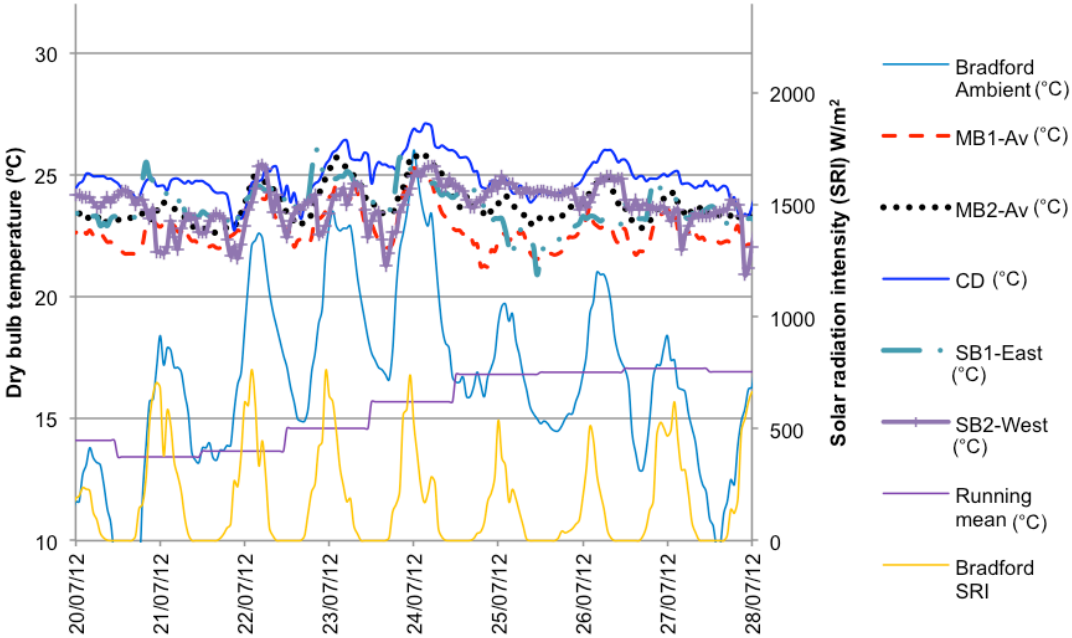


Figure 6.17 – Nucleus performance on warmest day in summer, 24th July 2012, with preceding and proceeding days

The findings from the survey during the 2013 heatwave, are somewhat reflected in the temperature results on 24th of July, the warmest day during 2012 (Figure 5.14). It can be seen that the temperatures in each of the spaces rise above 25°C, but quickly fall with the external temperature returning to below than 24°C by evening. This suggests that, as in the 2013 heatwave, doors and windows were opened to allow warm air to escape. The results also illustrate that the response to the ambient temperatures was different between spaces on the east and west side of the building. MB1 and SB1 on the east temperature's dropped in the 24 to 48 hours following the warmest day. While on the other hand, MB2 and SB2 on the west side of the building had temperatures

which remained significantly higher than the spaces on the east side in the proceeding period.

6.3.3 Air Quality

The measured air extract rate from the Ward 21 was 277 l/s which was less than half of the supply rate into the ward, indicating that overall the ward was positively pressurised. However, when looking at the extract rates in the commissioning manual, it showed that the supply and extract were designed to be the same, thus producing a neutrally pressurised space. The fact that the extract rate was less than half of its designed functionality (592 l/s) (see Table 6.4) was probably due to maintenance issues in that the filters in the extract AHU needed changing and the grills supplying the spaces cleaning. The discrepancy between the measured and the design flow rates for the supply to the multi-bed spaces was much less prominent than with the extract. It is likely that this was the case because air being blown into the building collects less dirt therefore, the system does not get as blocked up. Evidence of this fact was that you could identify the extract grills from the supply grills by the amount of dust on the grill, the extract grill always being covered with dust and the supply grills mostly clean. Although the supply flow rate showed little overall discrepancy, the results do show that on a grill by grill basis the air supply rates did not match the ones stated in the manual. This suggests that over the years of operation the system had fallen out of balance and perhaps was in need of being re-commissioned.

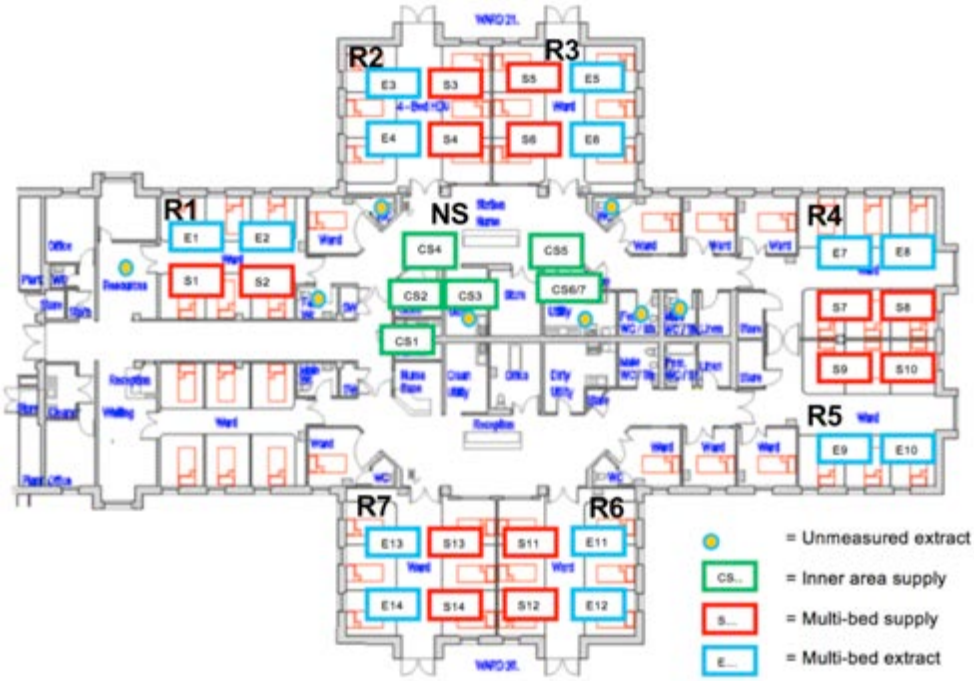


Figure 6.18 – Location of airflow rate measurements in Bradford nucleus' Ward 21 & 20;

Ward Supply	*Measured (l/s)*	*Design (l/s)*
S1	**77**	**74**
S2	**100**	**74**
S3	**57**	**74**
S4	**56**	**74**
S5	**70**	**74**
S6	**76**	**74**
S7	**65**	**74**
S8	**68**	**74**
S9	64	74
S10	70	74
S11	70	74
S12	74	74
S13	48	74
S14	56	74
Total W21	**569**	**592**

Ward Extract	*Measured (l/s)*	*Design (l/s)*
E1	**40**	**74**
E2	**65**	**74**
E3	**28**	**74**
E4	**33**	**74**
E5	**23**	**74**
E6	**30**	**74**
E7	**30**	**74**
E8	**28**	**74**
E9	40	74
E10	?	74
E11	41	74
E12	29	74
E13	26	74
E14	33	74
Total W21	**277**	**592**

Core Supply	*Measured (l/s)*	*Design (l/s)*
CS1	/	43
CS2	24	23
CS3	56	35
CS4	22	20
CS5	/	20
CS6	/	40
CS7	/	30
Total	**/**	**211**

Table 6.4 - Results from measurement of Nucleus Duct Airflow rates (Total Ward 21 is the total flow rates measured primarily for ducts in ward 21, i.e. S1-S8 & E1-E8)

Looking at each individual room, it was identified that for the five spaces monitored, the average measured flow rate to each room was 141l/s, this equates to 507m^3/h. The average size for one of the six bed spaces was 170.6m^3, this gave each of the wards a supply flow rate of 2.97 ach^{-1}.

As with the other case study buildings, an attempt was made to monitor CO_2 levels in the Nucleus building, however in this case the CO_2 monitor used to log the CO_2 concentrations over the period of a week was faulty resulting in the data being unusable. In addition to the long term monitoring, spot measurements were taken (Table 6.5), in a similar fashion to the other wards, however in this building, only the corridor and two of the bed spaces were monitored. The spot measurements were not taken in all of the spaces as it was believed that the long term monitoring would have been sufficient to establish the air quality of the ward.

Space	*Occupants*	*CO_2 Levels*	*Windows*	*Q_o (L/s)*	*Room Volume (m^3)*	*ach^{-1}*	*l/s/p (max occupancy)*
R2	-	631	0	-	170	-	-
R4	4 of 6	579	0	111.7	170	2.4	18.6
NS	-	661	0	-	-	-	-

Table 6.5 - Results from Nucleus CO2 walk around survey with estimates of flow rates [May 2014]

The CO_2 levels were all below the recommendations set by BS EN 15251 of 750ppm (Table 6.5). The results also show that the estimated flow rates for room R4 is relatively similar to the measured value, 111.7l/s compared to 133l/s (total of S7 & S8).

6.4 Energy Results and Analysis

6.4.1 LTHW Heating

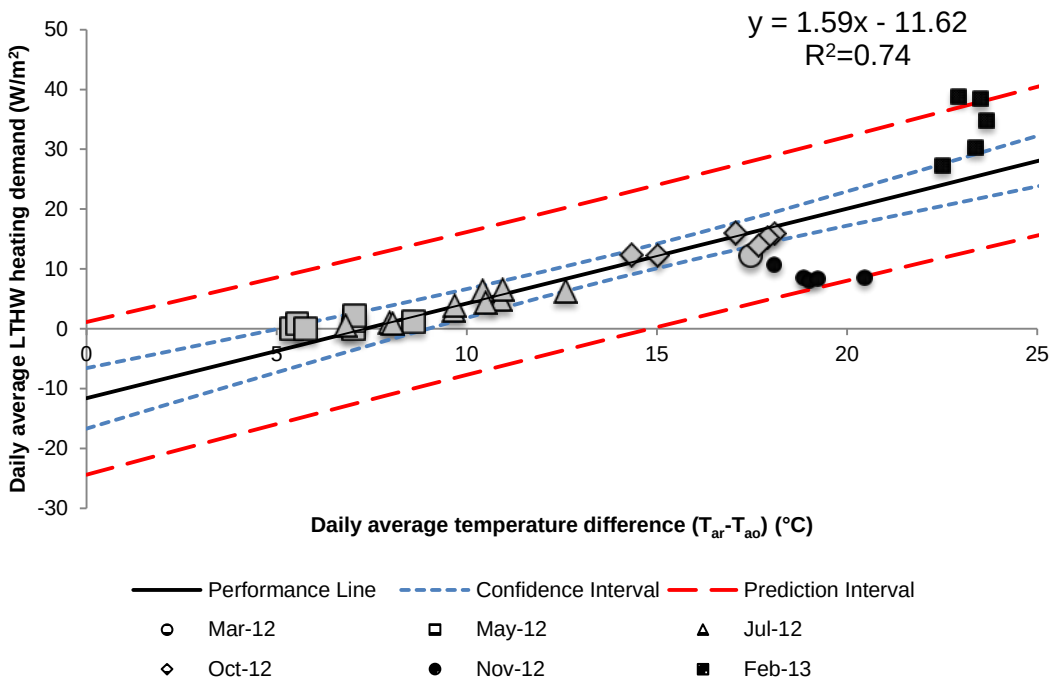


Figure 6.19 – Performance line for nucleus building based on measurements taken in west side of building

The heating was monitored on 6 separate occasions in 2012/2013. The least squared regression line, was drawn through all of the points on the plot and gave the formula relating the amount of energy used for LTHW and the internal to external air temperature difference.

$$Q_{LTHW} = 1.59(T_{ar} - T_{ao}) - 11.62 \quad (\mathrm{W/m^2})$$

Equation 6.1

By substituting the average ward temperature of 24.95°C and the average ambient temperature measured at Bradford Royal infirmary from April 2012-March 2013 (8.26°C) into Equation 6.1 and then normalising the result according to local degree day data. It was calculated that the yearly energy consumption for the nucleus building was 96.8 ± 20.2 kWh/m^2, and then by taking the efficiency losses for a centralised system into account the total amounted to 182.6 ± 24.0 kWh/m^2.

The regression line displays an R^2 value of 0.74, showing that there is a reasonably small amount of variance between the model for the building and the actual measured data points. The measurements taken in Nov 12 shows slight deviation from the rest of the results, it shows that the daily energy consumption remained at around 8.5 W/m^2 for each day monitored, despite the internal external temperature difference changing.

6.4.2 Ventilation

The air supply temperature to the multi-bed spaces was monitored just after it had left the AHU. Monitoring took place for a period of 8 days from 23/5/12 to 31/5/12 and it was found that the average airflow temperature in the duct was 19.2°C. The ambient temperature had an average value of 17.1°C over the same time period. Figure 6.20 shows that the air temperature supplied to the multi-bed wards was often lower than the ambient temperature on hot days, i.e. when the ambient temperature rose above 20°C. Both the operational manual and estates team stated that there was no cooling supplied to the multi-bed spaces, however it is likely that the cooler temperatures measured in the supply duct could be explained by the fact that the inlet to the AHU was placed in a shaded area between the nucleus building and adjacent constructions. This is a viable justification as shaded canyons are recommended as good locations to place the inlets to the AHU due to their cooling properties caused by local urban heat island effect (Graves et al., 2001).

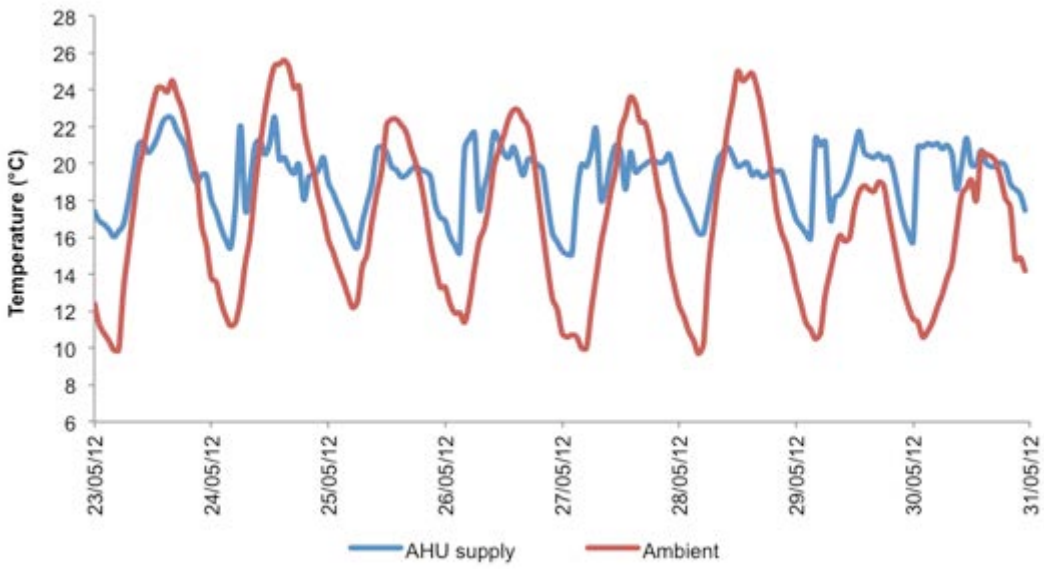


Figure 6.20 - Bradford Nucleus AHU air supply temperature to multi-bed spaces

The mechanical ventilation rate to the multi-bed space and the inner areas of the Ward 21 was 780l/s. Using this flow rate, the average yearly ambient temperature from April 2012-March 2013, and the average measured air supply rate, it was estimated that after normalising the energy consumption to local weather data, 157.13 kWh/m^2 pa was used to heat air coming into the building. When including efficiency losses, the total estimated energy demand was 296.47 ±23.3 kWh/m^2. AHU7 supplying the inner areas of the ward used cooling when the external temperature rose above 19°C. The

cooling energy was not within the scope of this work and has been omitted from the study.

6.4.3 Electricity

The electricity for wards was monitored at Glenfield hospital Ward 27 to provide a picture of the ward energy consumption patterns in Nucleus buildings. It is likely that the actual Bradford nucleus buildings electrical consumption would have been slightly higher than the building at Glenfield as it contained a high dependency unit that used a greater density of electrical equipment. Nevertheless, considering the data for the Bradford nucleus was not available, the Glenfield nucleus results provide a general picture for electrical consumption in nucleus buildings. It was found that the system was supplied with a voltage of 415V and had a power factor that fluctuated between 1 and 0.999. The current was measured over a period of 6 days from the 7/3/2013 – 13/3/2013. In the early mornings and late evening the electrical energy averaged at about 6W/m^2. This rose to around 12.5W/m^2 at 7:00 and remained at this level throughout the day except for four main spikes, two large ones at 12:30 and 17:30 and a smaller spike at 9:00 and 14:30 (Figure 6.21).

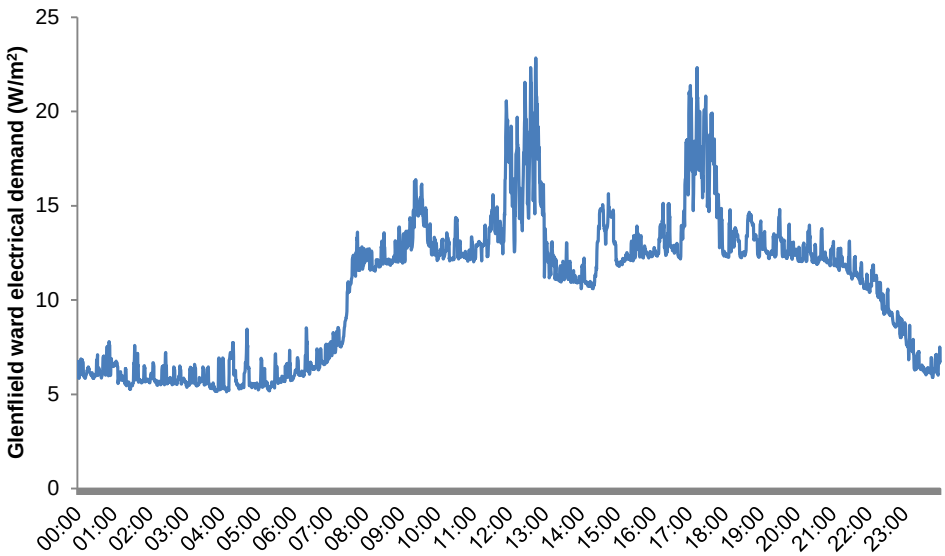


Figure 6.21 - Average daily energy consumption measured at Glenfield nucleus Ward 27 between 7/3/13-13/3/13

The average power usage over this time period was 10.60 ±1.3W/m^2. Using this figure, and making the assumption that the wards power usage was the same throughout the year, the wards consumption was estimated to be 92.9 ±11.4 kWh/m^2/yr. This figure was slightly larger than the electrical energy consumption for the plant room (Figure 6.22).

	Average current of measured phases (Amps)	*Phases*	*Voltage (V)*	*Power factor*	*Time in operation*	*Floor area*	*(kWh/m²/yr)*
Pump - Constant Temp	4.9	3	415	0.85	8057	2204.0	**10.94**
Pump - Variable Flow	5.8	3	415	0.85	8057	2204.0	**12.95**
Fans - Supply Ward	3.24	3	415	0.85	8760	969.0	**17.90**
Fans - Supply Core	1.09	3	415	0.85	8760	969.0	**6.02**
Fans - Extract	5.2	3	415	0.85	8760	969.0	**28.72**
						Total	**76.54 ± 10.7**

Figure 6.22 – Bradford nucleus plant room electricity consumption

Taking the electrical sources for BRI into consideration[i], the utility electricity used for the building would be, 51.3 and 62.2 kWh/m^2/yr for the plant and ward respectively.

6.4.4 Overall Energy Consumption and Carbon Emissions

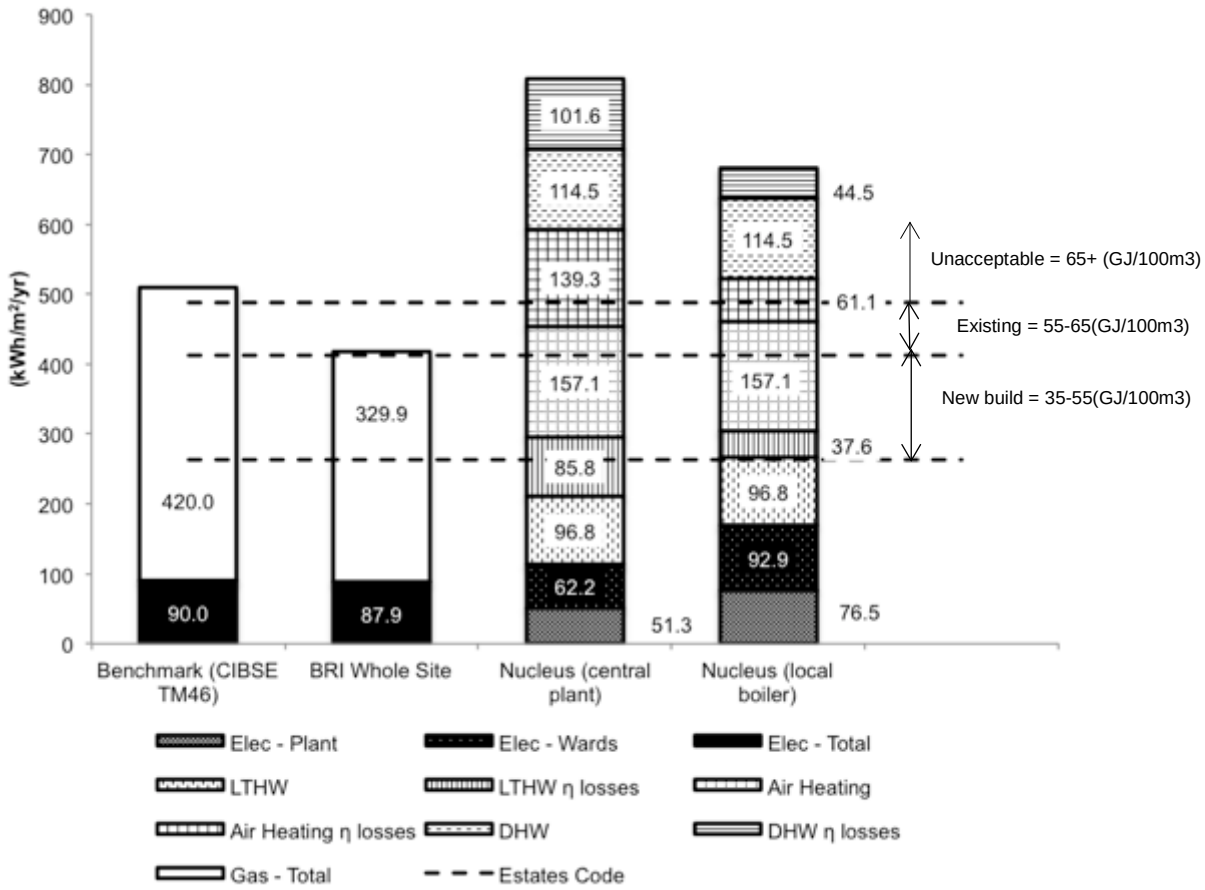


Figure 6.23 – End-use energy consumption for Nucleus building, compared to the CIBSE benchmarks, BRI site and Estates Code benchmarks (assumed roof height of 2.7m to convert between kWh/m^2/yr and GJ/100m^3)

[i] See equation 3.15 and 3.16 in primary energy conversion section of the methodology and chapter 4, section 4.1.4.

Combining the various heating and electrical energy demands, the results for the overall energy consumption of this nucleus building show that its energy consumption is considerably larger than the CIBSE benchmark and categorised as unacceptable by the Estates Code benchmarks. The centrally supplied building consumes 808.7kWh/m^2/yr (107GJ/100m^3) of energy which is nearly double that of the average across the BRI site. The largest contributor to the energy consumption is air heating, with its associated efficiency losses. It is also apparent that the DHW load, is also relatively high, with more energy being used for this purpose than for actual LTHW.

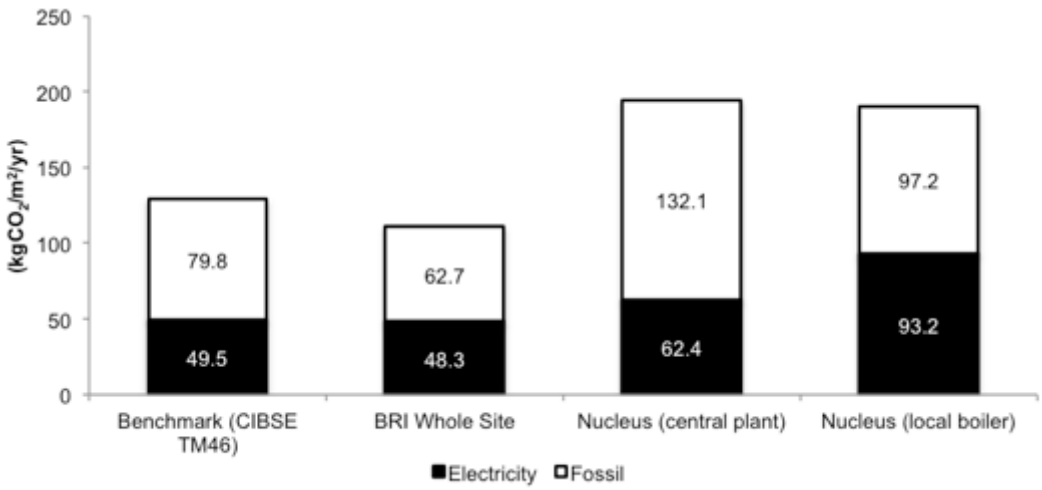


Figure 6.24 - Total Carbon emissions for Bradford Nucleus building

Both scenarios for the nucleus building are producing more than 190 kgCO$_2$/m^2/yr, which happens to be 61 kgCO$_2$/m^2/yr larger than the CIBSE benchmark and 80 kgCO$_2$/m^2/yr more carbon emissions than the average emissions on site.

6.5 Discussion

An ideal place to begin the discussion is the high energy consumption of the building. According to the literature (NHS Estates, 1995a), a standard nucleus building to had an energy consumption of around 720kWh/m^2/yr which falls between the consumptions estimated for the centrally and locally supplied building at Bradford (Figure 6.23). However, in this same study which was designed to test the implementation of energy lowering features in nucleus buildings (NHS Estates, 1995a), it was found that with a number of changes including increasing levels of insulation, improved control over the building services, the addition of heat recovery ventilation etc. It was possible to reduce the energy consumption to around 407kWh/m^2/yr which is below the CIBSE benchmark for hospitals and at the lower end of the existing category for the Estates Code benchmark. This suggests that although the

consumption of the Bradford nucleus building is currently high, there is great potential for improvements in the energy consumption.

The key contributor to the high energy consumption of this nucleus building was the mechanical ventilation system which impacted the gas-heating load as well as the electrical load to power the fans. Although the mechanical ventilation system did use a large amount of energy, spot measurements offer evidence that the system can keep CO_2 levels below 750ppm, which according to BS EN 15251 provides an environment which is suitable for sick and vulnerable occupants. In addition, each of the spaces had a designed ventilation rate of 148l/s, or a measured rate of between 94l/s (R7) and 177l/s (R1). This rate had the potential of supplying the 6 patients with over 10l/s/p, as well as covering the additional ventilation requirements of visitors or hospitals staff. Furthermore, according to HTM-03-01 this rate of ventilation is also sufficient for controlling odour.

The flow rate of the mechanical ventilation was 2.97 ach^{-1}. The hospital guidance HTM-03-01 recommends that single and multi-bed spaces on hospital wards are provided with an air supply rate of 6 ach^{-1}. Recent literature reporting a study on a mechanically ventilated hospital ward, found that when designed to that standard, it may be impossible to meet the NHS targets of between 55-65GJ/100m^3 (Short et al., 2012). This nucleus building used 3 ach^{-1} yet the energy consumption of the building was still considerably higher than the NHS targets of 55-65GJ/100m^3, suggesting that reducing the flow rate to 3 ach^{-1} still may not be enough to meet the NHS targets.

In regards to infection control, air changes per hour, are relatively low suggesting that even though the building is mechanically ventilated, there may still be a risk of infection. This is because although rates are above 2ach^{-1}, (ventilation rates below 2ach^{-1} are linked with increased risk of infection (Menzies et al., 2000)), it is still below the recommended 6ach^{-1}.

The analysis of the winter temperatures demonstrated that the average internal air temperature measured in the multi-bed and single-bed spaces was 23.5°C and 24.3°C respectively. The observation that the temperatures in the naturally ventilated single bed space were higher and had a larger standard deviation than the multi-bed space indicates that the HVAC system was helpful in modulating the air temperature. The overall temperature within the ward (24.0°C) was at the high end of the CIBSE recommendations and resulted in the total heating load for ventilation and LTHW being

479.1kWh/m^2. It could be possible to reduce this by lowering the average temperature on the ward and reducing the mechanical air supply temperature. In addition a further and possibly more plausible method to reduce the heating consumption, would have been to use heat recovery in the mechanical ventilation system. The literature review pointed out that nucleus buildings were built after the energy crisis in the 1970s. One of their purposes was to save energy on the district general designed hospitals. One of the key features to be included in nucleus buildings was heat recovery ventilation systems, examples of these were found in the St Mary's low energy hospital study (NHS Estates, 1994b). Heat recovery would have been especially useful in the wards in this building, as the large volume of air which was extracted at a relatively warm temperature (24.0°C) could have been passed through a heat-exchanger to heat the incoming air. In a previous study in a nucleus building the implementation of heat recovery device into a mechanical ventilation system reduced the demand by 15% (NHS Estates, 1995b). A reduction of this magnitude in this building could bring the energy demand closer to the targets.

The mechanical ventilation system also had a positive impact on building performance when it came to it's resilience against overheating. The analysis of summer temperature data from 2012 demonstrated that the multi-bed rooms which were mechanically ventilated, showed cooler and more stable temperatures than in the single bed spaces that were naturally ventilated through opening windows. There was however a degree of uncertainty as to why this was the case. The results from monitoring the internal supply temperature to the multi-bed wards during a warm spell in May showed that the air supplied to the wards was less than ambient temperatures on the warm days. This gives the impression that the air was cooled before being supplied to the ward, which was not the case, as there was no direct cooling in the system. It is possible however, that the cool supply temperature could have been linked to there being shading around the inlets to AHU. The temperatures may have shown a wider spread in the single beds because as the windows were opened regularly to provide ventilation, the rooms would have been impacted by changes in external temperatures. While on the other hand, in the multi-bed spaces it was likely that the windows would have been closed for the majority of the year, except in the case of extreme ambient temperatures. The walk around survey conducted during the heat wave of 2013 did find that in very hot periods, windows and even doors were opened in the multi-bed space to control the temperatures.

The results demonstrated that multi-bed 2 and single-bed 2, the rooms on the west facing side of the building were slightly warmer than multi-bed 1 and single-bed 1, the rooms on the east side of the building. A previous studies on nucleus hospital constructions showed that the building reached its maximum temperatures on the days proceeding high ambient temperatures, demonstrating that there was often a lag between high ambient temperatures and high internal temperatures (Giridharan et al., 2013). This however was not the case with this nucleus building, and peak temperatures were always found on days when the ambient temperatures were the highest.

There were three main limitations to the study conducted on this building. The first is there was no ward electrical energy consumption recorded for this building due to limited access to the electrical distribution board in the hospital ward. Therefore, it was not possible to get an understanding of the actual electrical energy usage patterns in this particular building. Data from measurements taken at a nucleus building in Glenfield, with very similar ward usage patterns have been used to demonstrate the patterns in a nucleus type building. It shows that as expected the electrical energy usage varies according to the time of the day, with peak energy use taking place at 12:00 and 17:00, the main meal times. The annual ward electrical energy demand estimated from the measurements has been used, as it provides a rough figure which enables the rest of the results to be compared to the benchmarks.

The second limitation is linked to the electrical energy for cooling. On first assessment of the buildings to be studied it was decided to focus on the energy consumption of the general wards spaces, which do not have any cooling. It was later discovered that the nucleus building had cooling in the inner areas, the method in the study did not account for monitoring the cooling consumption and therefore the energy associated with cooling in the nucleus building was omitted. The electrical consumption of the plant is similar to the estimated electrical demand of the ward. Cooling was supplied to a small segment of the building, for a small portion of the year, however, if cooling was factored in, it is likely that the plants electrical consumption would have been higher than that of the wards (Figure 6.23).

The third limitation is the heat energy usage associated with the AHU. In the study of this nucleus building, the AHU heating demand was estimated based on direct measurements of the airflow into the building and the temperature of the supply. The measurement of the volume of air flowing into the building showed high levels of

accuracy, however the temperature of air flowing into the building was only measured for seven days in a very warm period during the year. The system had two control inputs, the main one which was set at 19°C and the low limit override at 15°C. The period monitored showed air flow temperatures between 22.4 and 14.3°C, in essence, the set point temperature (19.2°C), the average measured air temperature used to estimate the yearly energy consumption is likely to have been slightly high as it was measured during a warm time of the year, therefore the air heating consumption could be slightly high too. If the monitoring was to be undertaken again, it would be recommended to monitor the air flow into the ward in different seasons, in the same way as was done with the LTHW.

Finally, it is important to point out that the energy consumption measured for this building did not include the consumption of the operating theatres on the second floor. However, this is not a limitation in the scope of this study, which is primarily focusing on the energy consumption and internal environmental performance of ward areas in individual hospital buildings.

6.6 Conclusions

This chapter presented an investigation of the Bradford nucleus building, the second building type to be studied in this thesis. The case study building was constructed in the ‘80s with a mixed mode ventilation system, providing multi-bed rooms with heated mechanical ventilation and single-bedrooms with natural ventilation. The consequence of this system in terms of energy consumption was that this building’s energy consumption was considerably larger than CIBSE benchmark due to the large volume of air being heated and the electrical demand for the additional fans needed to move the air around the building. The new energy monitoring method used throughout this thesis provided good results for the LTHW heating demand as well as plant electrical usage. However, it was limited when it came to monitoring the ward electrical consumption and the heating and cooling loads for the mechanical ventilation system. These limitations have stimulated areas for future development of the methodology, specifically monitoring electrical circuits in tight spaces and accurately monitoring AHU heating and cooling loads.

Although the energy consumption was significantly larger than the benchmarks, and categorised as unacceptable by the estates code standard. It did have a positive side to it in that it maintained CO_2 levels and temperatures which were below the BS EN 15251 Cat I and supplied the space with more than 10l/s/patient, demonstrating that

the internal environment could be suitable for vulnerable patients and odour would not be a problem. The efficacy of the mechanical ventilation system was also demonstrated by the case that it supplied the multi-bed rooms which remained cooler than the rest of the spaces in the ward during the summer months. Conversely, when it came to infection control, the spaces were ventilated at a rate of $3ach^{-1}$, which was below the recommended $6ach^{-1}$, indicating that the ventilation system may not have been capable of reducing the risk of airborne infection. The main suggestion for improving the performance of this building would be in the implementation of a heat recovery unit to the existing mechanical ventilation system.

7 Bradford Modular Building

7.1 Introduction

This chapter presents the first study of its kind on the performance of modular hospital buildings. Out of the four case studies to be discussed in the coming chapters this building was studied in the most depth. The literature has documented work on all of the other hospital building types being investigated in this work, especially focusing on the summer thermal environment and indoor air quality of the wards spaces. As the modular hospital building concept is relatively new there is a limited amount of information in the literature on this building type. Studying the performance of this building was therefore perceived as an important opportunity to develop the field of research in low carbon hospitals in order to examine its potential for contributing to the NHS' wider goals of reducing their building stocks energy consumption. This chapter's investigation describes the buildings construction, functioning and energy consumption as well as its internal environmental performance, specifically focusing on indoor temperatures, air quality and window opening patterns.

Figure 7.1 – East facing façade of the 2008 modular building

7.1.1 Background

The modular building was built in 2008 as a response to an increase in demand for bed space. Bradford Hospital Trust needed to make an extension to the existing hospital and the construction options available to them were a modular block or a traditionally constructed three-floor extension building. The modular building was slightly more expensive but it offered the advantage of completion in just six months compared to eighteen months for the traditionally construction building (Hinitt, 2008). The design team also sought to produce an energy efficient building.

The modular building was divided into two floors, the bottom containing Ward 29 and the top floor Ward 30, both of which provided care for elderly patients. On each ward there were four multi-bed rooms each containing 4 beds, as well as 12 single bedrooms, which could provide isolation care for highly infectious patients. In total, there were 56 beds in the building that were fully occupied for most of the time. Electrical equipment on the ward was very basic with one television in each of the bed spaces. Visiting time took place at two separate times during the day, 14:00-15:30 and 18:00-19:00. In general, the wards functioned like a standard hospital ward with doctors and nurses providing care for the patients with an average of about 4 patients per nurse. Three meals were served on the wards each day; these meals were prepared elsewhere in the hospital and transported to the ward. Despite this, there were two small kitchens on the wards, one for making drinks and one for washing up after meal times.

Type	*Modular*
Location	Bradford
Built	2008
Floor area	Level 1: Ward 29 (946m^2) Level 2: Wards 30 (946m^2)
Heating	Heated ceiling panels
Ventilation	Bedrooms (natural) Corridors (mechanical heat recovery)
Roof	Flat roof with Kingspan Thermaproof TR31 & Isowool insulation (U-value=0.11W/m^{2}K)[i]
Walls	Prefabricated Kingspan KS1000 Insulated wall with added insulation (U-value=0.15W/m^{2}K) (permeability=5m^3/h.m^2)[ii]
Glazing	Openable Double glazed, toughened glass argon filled cavity (U-value=1.5W/m^{2}K) [iii]
Ceilings	2.70m
Occupancy	Ward 29 & 30 = 28 beds (each) Visiting 14:00-16:00 & 18:00-19:00
Room types	4x4bed & 12x1bed on each ward
Window orientation	East-West

[i] For calculations see Appendix II

[ii] From Bradford maintenance manuals (Bradford Estates, 2012)

[iii] Window U-value estimate taken from CIBSE guide A, Table 3.23 (CIBSE, 2006b)

Table 7.1 - Summary of Modular building design and construction

7.1.2 Construction

The buildings fabric was highly insulated throughout, with U-values lower than the building regulations in every aspect, with the exception of the ground floor which had slightly higher U-values. The building was constructed using steel beams and seated on beams which kept it 3-4m above the ground. The visible façade of grey panels (Figure 7.1) was produced and manufactured off-site by Kingspan (Figure 7.2). They claimed that the panels complied with Part L2a of the building regulations (HMGovernment, 2010), had a guaranteed U-value life cycle, air leakage of 5(m^3/hr/m^2) at 50Pa, 100% reliable thermal performance and insulation continuity with no cavities, cold bridges or condensation risk (Bradford Estates, 2012). As the panels were designed for off-site construction, they contained a concealed single fix joint which reduced the build time by up to 50%. Finally, the product was guaranteed long-term performance, with up to 25 years for first maintenance and an overall life expectancy of 40 years.

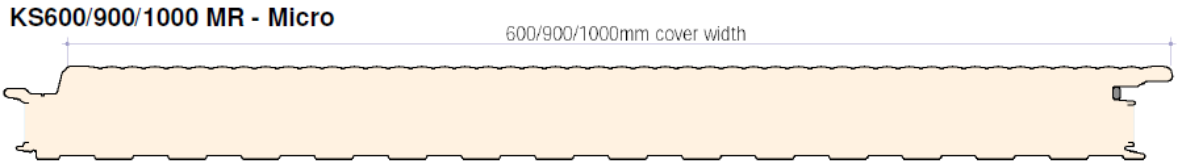


Figure 7.2 - Cross-section of Kingspan panels used in construction of Modular building (Source: Bradford Estates, 2012)

7.1.3 Heating Ventilation and Air Conditioning Systems

The heating was split into three distinct circuits. Firstly, the steam and condensate system, which was responsible for transferring the energy of the steam from the central site plant room to the modular building. Secondly the primary circuit, which allowed water to flow through the heat exchanger at a constant rate. Thirdly the variable temperature circuit which enabled LTHW at different temperatures and flow rates to be supplied to the building. Thermostats were placed in each room within the building, directly controlling the amount of heat being transferred to the heated ceiling panels in each room.

The primary section was connected to the variable temperature circuit via a low loss header; a piece of equipment which is often found in hospital heating systems where a heat exchanger is involved. The header acts as an interface between the primary and secondary circuit to maintain a flow through the plate heat exchanger at all times and improve the heat exchange efficiency.

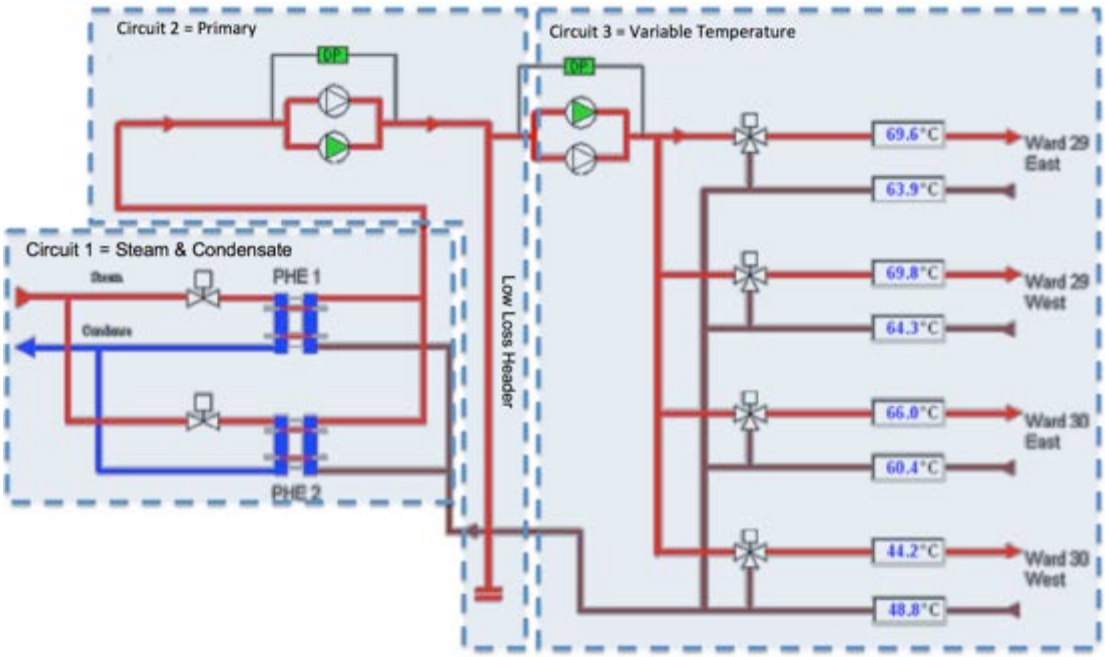


Figure 7.3 - Layout of the Modular Building Heating system (Source: Bradford Estates BMS)

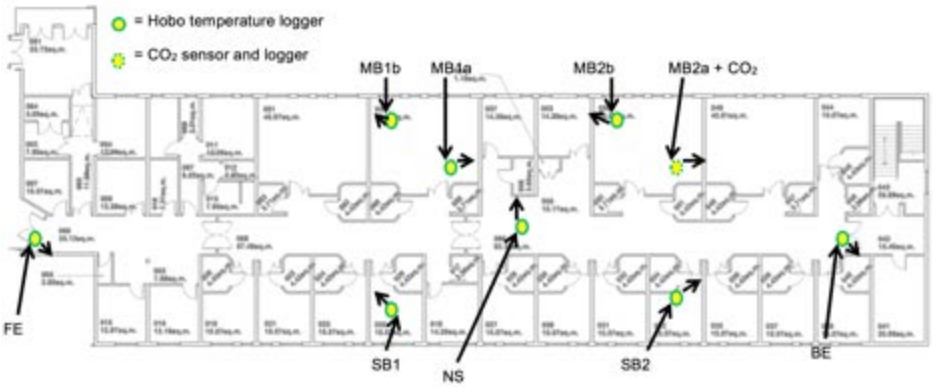
The bedrooms in the building were provided with natural ventilation through the operable windows whereas the corridors and other special areas were ventilated mechanically. The mechanical ventilation system incorporated a recuperator (a cross-plate heat exchanger) that reclaimed heat from the extracted air to preheat the air supplied to the building. It was designed to maintain a constant flow rate of air and the temperatures were modulated using an air bypass damper to stay as close to 19◦C as possible. The estates team stated that the recuperator could heat incoming air adequately until the external air temperatures dropped to -5◦C. This was possible as a larger volume of air was extracted (0.775 m^3/s) from the bathrooms and toilets on the ward than was being supplied (0.575 m^3/s) to the corridors and two storage spaces. Thus the building had a slightly negative pressure ensuring that flow through open doors and windows was always inwards and into the bathrooms and toilets. This reduces the risk of airborne infections travelling around the wards.

7.2 Monitoring

7.2.1 Internal Environment

Temperature sensors were placed on the top floor of the building (Ward 30) and a weather station was installed at the hospital to measure the external climate and ambient temperatures. A combination of nurse stations, multi-bed and single bed rooms were chosen to quantify the temperature variations in the different parts of the Ward (Figure 7.4). A CO_2 sensor and window monitoring devices were set up in one of

the multi-bed rooms to monitor how effectively the natural ventilation strategy was working.



Space	*Area (m^2)*
MB1	45.6
MB2	45.8
SB1	15.57
SB2	15.57
FE	40
BE	30

Figure 7.4 – Modular building Ward 30 floor plan demonstrating placement of temperature sensors (MB = Mixed bed, SB = Single bed, FE/BE = front/back entrance, NS = nurse station) [Left]; Areas of monitored spaces [Right]

The window opening patterns in one of the modular building multi bed wards were monitored. The window layout can be seen in Figure 7.5 the diagram describes that not all the windows were able to open, six Hobo accelerometers were attached to the windows that open, one on the top left, one on the bottom left, one on the centre left and so on. The monitoring took place over the period of 5-6 months spanning from August 2012 – February 2013.

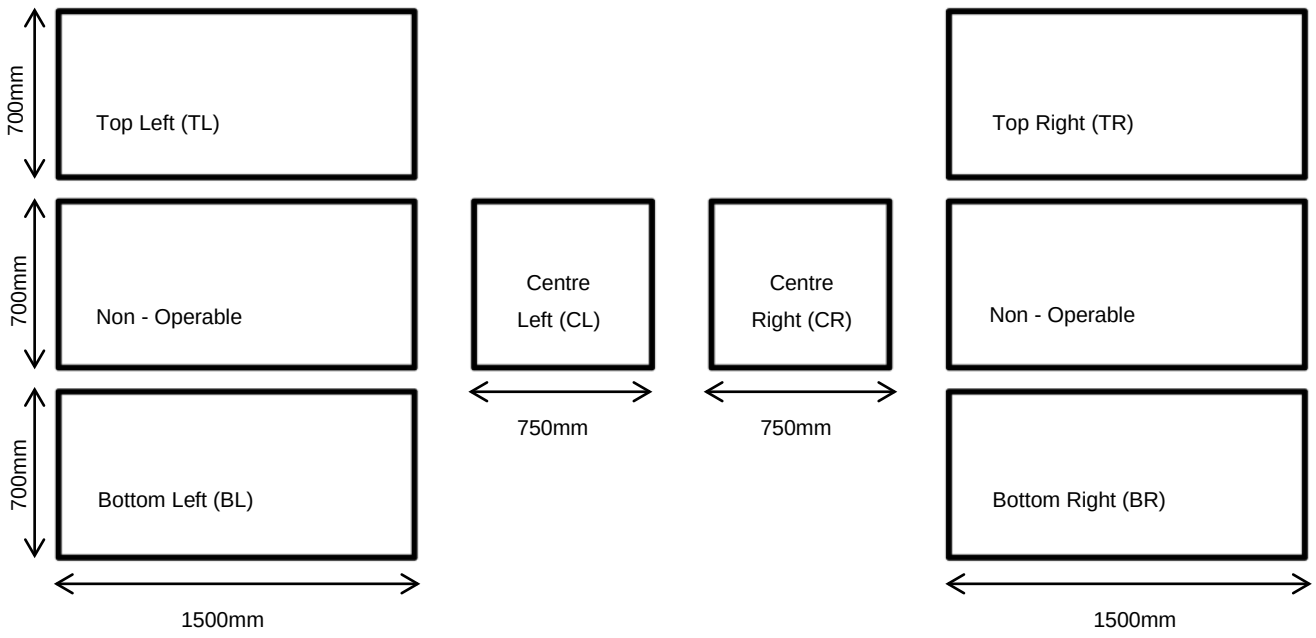


Figure 7.5 – Window layout in a multi-bed modular ward, Operable windows are TL, BL, CL, CR, TR and BL.

Each window had a mechanism that held them either opened at 100mm or closed (Figure 7.6) therefore when assessing the results it was assumed that the window was either fully opened or fully closed. Windows were monitored and the total windows opened were logged for each hour. The centre windows were ½ the width of the side windows, therefore when opened, they counted for ½ a window. In total, the maximum number of windows which could be opened was 5; 4 side windows and 2 central ½ windows.

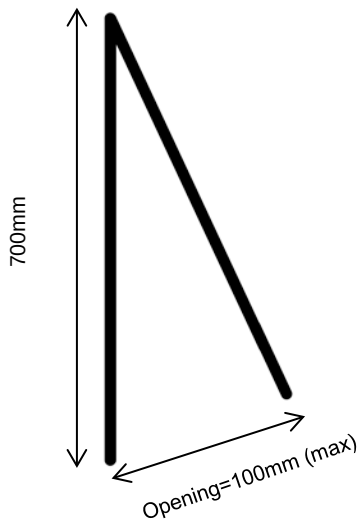


Figure 7.6 - Window opening

7.2.2 Electricity Consumption

The electrical energy use for the building was divided into two areas, the wards and the heating and ventilation plant. Electricity was supplied to the ward via two distribution boards: one essential supply and the other non-essential supply. The essential board was connected to a power supply which was backed up by a generator to provide continual energy even if there was a power failure; this is crucial in a hospital environment, where patients' lives are dependent on electrically powered equipment. The essential board supplied emergency lighting as well as plug sockets that were labelled red. The non-essential board supplied the rest of the lighting and plug sockets. Both of the boards were 415V. The plant room contained a distribution board which controlled the primary and secondary LTHW pumps as well as the fans for the mechanical ventilation units.

The electricity for the ward was measured by putting six Hobo CTV-C current transformers (Onset, 2013) onto the individual phases in the distribution boards, Figure 7.7, i.e. three Hobos on the essential and three on the non-essential board of

Ward 29 (bottom floor of building, the assumption was made that electricity use would be very similar on each floor). These were left for a period of 15 days in February and 15 days in June. Ward 29 also had a meter installed in the distribution board, but this only measured the cumulative energy consumption and not the actual daily electrical patterns. The cumulative energy use in the June monitoring period was compared with the results recorded at the electricity boards. It was found that the measured results showed (±) 2% variation from the metered results, indicating that the Hobo CTV current transformer equipment was well calibrated.

Figure 7.7 - Placement of current transformers in Modular distribution board

7.2.3 LTHW Heating

The setup of the flow meter instrumentation can be seen in Figure 7.8 and Figure 7.9, the flow meter was attached onto the supply pipe which went down from the rooftop plant room to provide heating for the ceiling panels in the wards. Monitoring of the ward took place on six separate occasions, Feb, May, July of 2012 and Feb, March, April of 2013. This provided enough data to be able to produce a performance line characterising the heating energy consumption.

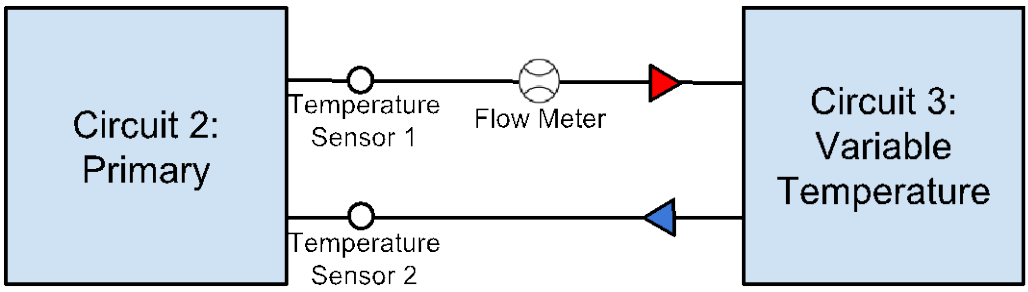


Figure 7.8 - Schematic demonstrating placement of LTHW measurement equipment in modular building heating system

Figure 7.9 - Instrumentation installed in modular building

7.2.4 Mechanical Ventilation

Due to its heat recuperator the AHU did not consume any energy for heating; nevertheless, Hobo temperature sensors were placed in the supply duct to monitor the temperature of the air supplied to the building (Figure 7.10). The AHU drawings containing the design flow rates were available for the building and the figures on this were verified by conducting actual flow measurements of the air coming out of the ducts using a balometer. An estimate of the energy consumption used for heat reclaim was calculated using the temperature difference between the internal side of the extract (extract inside) and the external side of the extract (extract outside).

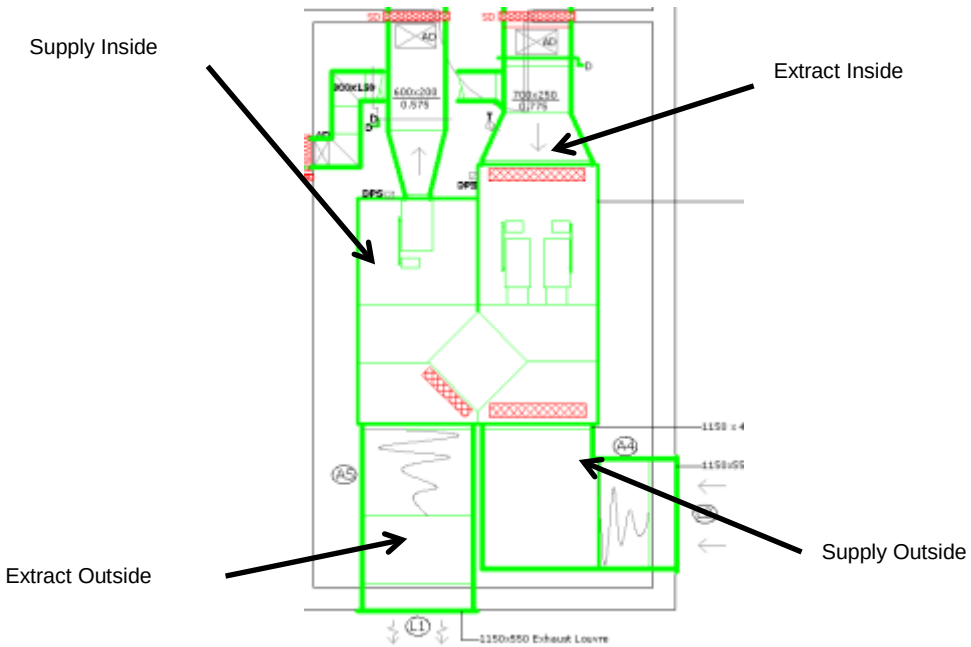


Figure 7.10 - Close up of AHU Plant with location of 4 Hobo Sensors (Source: Bradford Estates, 2012)

7.3 Internal Environmental Results and Analysis

7.3.1 Internal Winter Temperatures

Analysis of the internal air temperatures from months December 2012 to February 2013 was carried out to determine if the heating system was providing the correct thermal environment for the building during the winter months. The average space temperature for the ward was 23.2°C, which is close to the middle of the CIBSE recommendations of 22-24°C. In addition, the ward only spent 8.4% of its hours above 24°C and had a standard deviation of 0.57°C suggesting that its temperatures were well controlled.

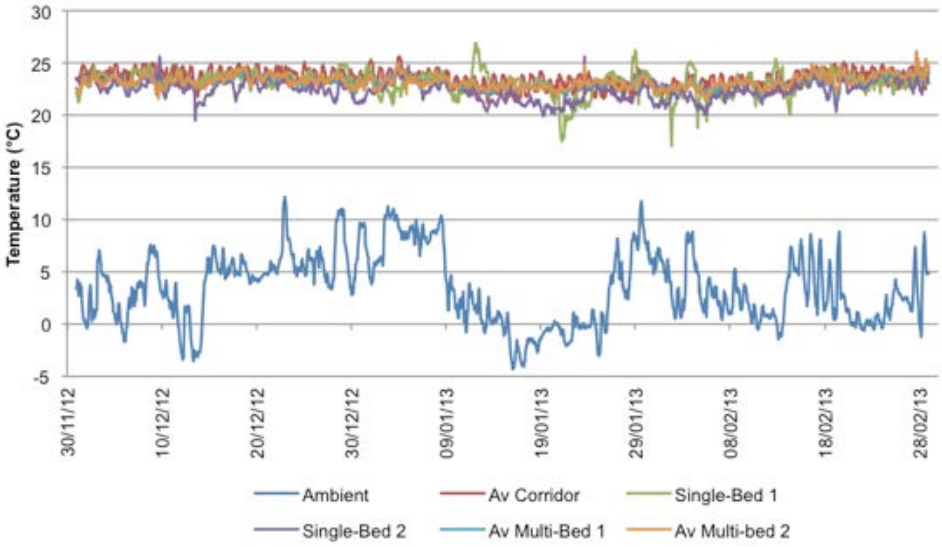


Figure 7.11 - Measured ward and ambient winter temperatures for Bradford Modular building (Dec 2012 - Feb 2013)

The building showed good control over the temperatures throughout the ward in that the average, maximum and minimum temperatures were very similar in nearly all the monitored spaces. The only space that deviated from this pattern was single-bed 1, where the maximum and minimum temperatures showed spikes on certain days (Figure 7.11). When comparing the multi-bed to the single-bed spaces, it becomes apparent that that the standard deviation for the single-bed spaces was higher than that for the multi-bed, demonstrating that the temperatures in the multi-bed spaces had closer control than the single-bed spaces. The single bed spaces were also slightly cooler than the multi-bed spaces (Table 7.2).

	Mean temp (°C)	*Max temp (°C)*	*Min temp (°C)*	*Standard deviation (°C)*	*Hour under 18°C*		*Hours under 22°C*		*Hours between 22 & 24°C*		*Hours over 24°C*	
CD-FE	23.9	26.5	20.6	0.94	0	0.0%	54	2.5%	1114	51.6%	992	45.9%
SB1	23.1	26.9	17.1	1.11	9	0.4%	302	14.0%	1480	68.5%	378	17.5%
SB2	22.4	25.6	19.5	0.91	0	0.0%	678	31.4%	1455	67.4%	27	1.3%
CD-BE	23.0	25.8	20.5	0.88	0	0.0%	291	13.5%	1559	72.2%	310	14.4%
MB2a	24.1	26.2	22.1	0.66	0	0.0%	0	0.0%	994	46.0%	1166	54.0%
MB2b	22.3	25.8	19.4	0.77	0	0.0%	689	31.9%	1443	66.8%	28	1.3%
MB2-Av	23.2	26.0	21.5	0.57	0	0.0%	12	0.6%	1968	91.1%	181	8.4%
MB1a	23.0	26.3	20.6	0.70	0	0.0%	140	6.5%	1825	84.5%	195	9.0%
MB1b	23.3	26.0	21.2	0.69	0	0.0%	65	3.0%	1779	82.4%	316	14.6%
MB1-Av	23.2	26.1	21.6	0.56	0	0.0%	12	0.6%	1999	92.5%	149	6.9%
Ward Av	23.2	24.9	21.7	0.57	0	0.0%	22	1.0%	1956	90.6%	182	8.4%

Table 7.2 – Results for modular building Ward 30 temperatures during winter heating season (2160hrs between 1st Dec 2012 and 28th Feb 2013)

7.3.2 Summer Temperatures

The Bradford modular building had the largest set of temperature data available out of the three main case study buildings being monitored. The temperatures were monitored from June 2010 through to September 2012, with some observations also taken in the summer of 2013. The results for the modular building summer overheating analysis is therefore split into three sections. The first section shows results for the two wards (29 and 30) for years 2010 to 2011 and Ward 30 for 2012. The periods monitored for 2011 and 2012 were from May to September, however the period for 2010 was slightly shorter, from June to September. The second section undertakes a detailed analysis of the summer temperatures in Ward 30 during summer 2012 from June 15th to September 30th 2012. Finally, the third shares some findings from observations of the building's performance from general visits and a survey undertaken in the heat wave in July 2013.

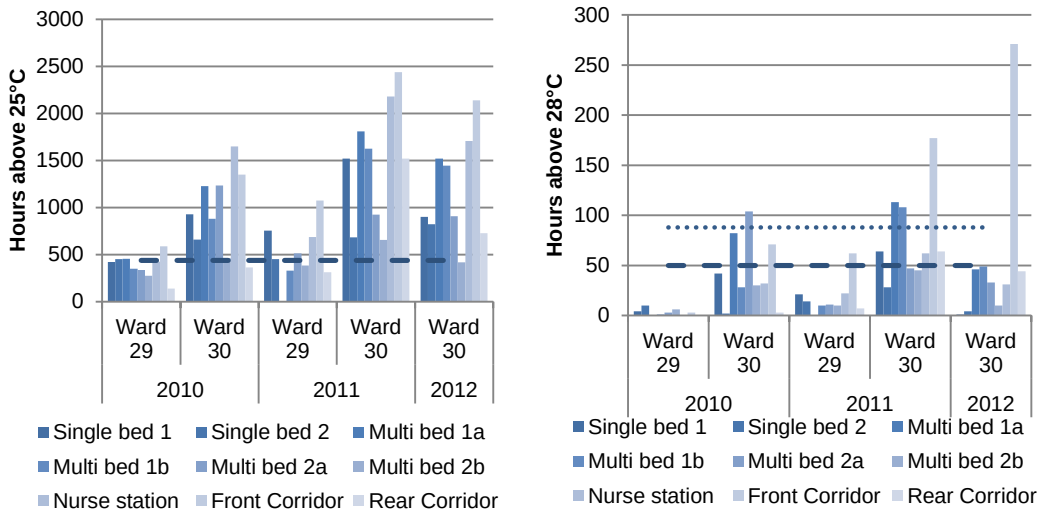


Figure 7.12 - Modular building overheating assessment; [Left] - number of hours above 25°C, Benchmark is 438hrs (5% of year); [Right] - number of hours above 28°C, Benchmarks are 50hrs (HTM03) and 88hrs CIBSE Guide A (1% of year)

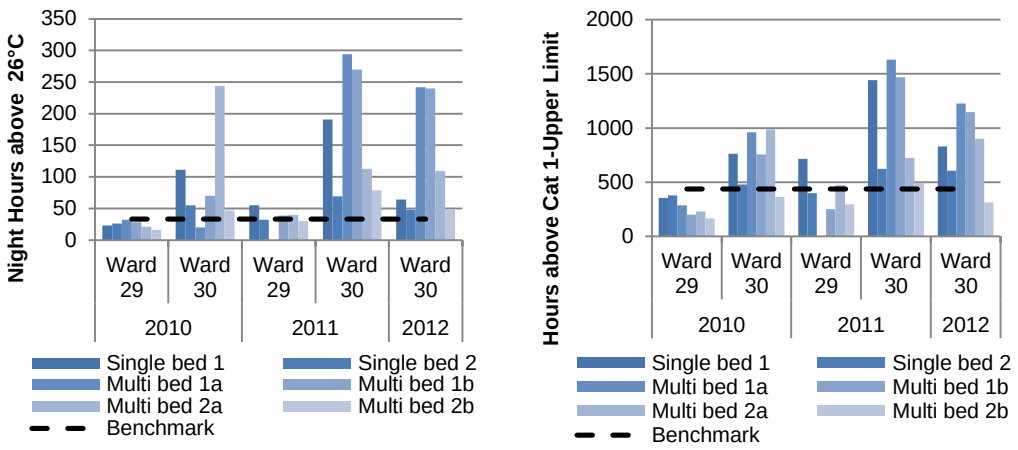
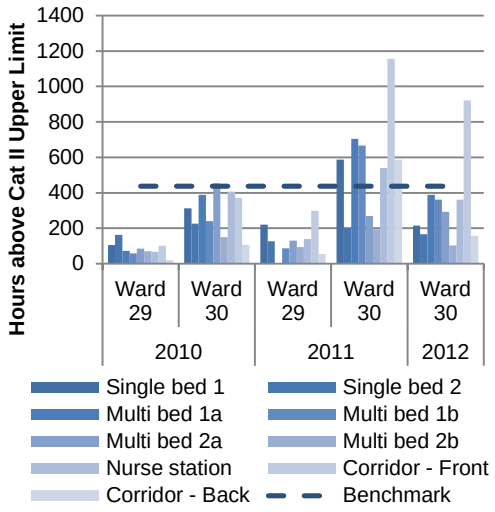


Figure 7.13 - Modular Building overheating assessment; [Left] - number of night hours (21:00-6:00) above 26°C, Benchmark is 33hrs (CIBSE Guide A); [Right] - number hours above BSEN 15251, Cat 1, Benchmark 438hrs



Ambient Temp °C	*TRY*	*2010*	*2011*	*2012*	*2013*
Average	12.61	13.48	13.56	13.09	13.09
Max	31.6	24.9	27.6	25.5	27.9
Min	0.9	2.9	3.3	0.2	0.7
Hours >= 24	61	3	31	17	54
Hours >= 25	38	0	19	5	31
Hours >= 26	24	0	7	0	15
Hours >= 27	18	0	1	0	4
Hours >= 28	16	0	0	0	0

Figure 7.14 - Modular Building overheating assessment; [Left] - number hours above BSEN 15251, Cat 11, Benchmark 438hrs; [Right] – Ambient temperature for each of the years monitored

Figure 7.12 shows how many hours were above 25°C in the monitoring period. The first element which stands out in Figure 7.12 is that the majority of spaces in each year have more than 438 hours above 25°C. This indicates that the ward is uncomfortable for a significant amount of time. Next it can be seen that when comparing Wards 29 and 30, the top floor of Ward 30 has a greater degree of overheating.

Considering the bedrooms, single-bed 1 seemed to be warmer than single-bed 2 and multi-bed 1 warmer than multi-bed 2. Overall the nurse station and corridor tended to overheat the most, however, it was noted that there was a large disparity between the amounts of overheating from one end of the corridor to the other. The front part of the corridor was significantly warmer than the back end of the corridor. Furthermore, when looking at the temperature variation in the multi-bed rooms it was found that in most

cases sensor *a* was reading warmer temperatures than sensor *b*. Sensor *a*, was located towards the inside of the building, whereas sensor *b* was closest to the window. This suggests that within each room there is a temperature gradient influenced by the cooling effect of opening the windows.

The second graph in Figure 7.12 shows the number of hours over 28°C, on this graph there are two sets of criteria. HTM-03-01's no more than 50 hours in a year above 28°C and CIBSE guide A's limit of 1% of the hours in a year (88 hours). When looking at the graph it is noticeable that the bedrooms in Ward 29 did not exceed any of the criteria in both 2010 and 2011. Ward 30 had more hours where the temperature was unacceptable, however, it can be seen that this was only the case in some of the rooms. In 2010 multi-bed 2a exceeded CIBSE's 88 hours and part of multi-bed 1a exceeded HTM 03-01's 50 hours. In 2011 both sensors in multi-bed 1 read over 88hrs above 28°C and overall there was no clear pattern between the individual rooms and overheating. Generally, the results show that according to the 28°C criterion, the hospital may not have been overheating as badly as expected as only one of the rooms (i.e. Ward 30 Multi-bed room 1, in 2011) had more than 88 hours above 28°C.

When looking at the night-time temperatures in Figure 7.13, single room 1 is always warmer than single room 2. In 2010 multi-bed 2 had more hours over 26°C than multi-bed 1: but in 2011 the multi-bed 1 overheated more than multi-bed 2. In general, what is distinct about this graph is that Ward 30 overheats considerably at night.

The final chart assessing the summer time temperatures in 2010 and 2011 shows how the ward performed against the BS EN 15251 adaptive thermal comfort criteria (Figure 7.14). An unacceptable amount of overheating was indicated when the temperature would exceed the categories boundaries for more than 5% of operational hours. The results for Category I show that in Ward 30 all of the rooms were operating at too high a temperature for vulnerable patients. The performance of Ward 29 was more acceptable; nevertheless in 2011 the warmest year out of the three, single bedroom 1 had a significant number of hours where the temperature exceeded Category I. The results for Category II in the BSEN criteria are displayed in Figure 7.14. They indicate that in 2010, the cooler year, the building did not overheat to uncomfortable levels for healthy individuals, i.e. nurses, doctors, cleaners, visitors etc. However, in 2011, when the temperature was slightly warmer, all of the monitored areas in Ward 30 were shown to be overheating except single bed 2 and multi-bed 2. This demonstrates that

in warm conditions, the nurse's station, corridors and rooms would be deemed uncomfortable for staff and people visiting the wards.

The main analysis for the case-studies in this thesis covers the year from April 2012 to May 2013. This section contributes to the larger thesis by analysing the modular buildings performance during the summer of 2012 to compare its performance to the performance of the Nightingale and nucleus case-study buildings in chapter 8. The period of interest covers 2592 hours from June 15th through to September 30th.

Considering the temperatures in the multi-bed wards during the majority of the period (Figure 7.15), it was apparent that multi-bed 1 was warmer than multi-bed 2 with temperatures in multi-bed 1 rising above 25°C, even on relatively cool days when the ambient temperature was below 17°C. The difference between the two spaces is demonstrated by the average daily temperatures during the period, where multi-bed 1 is 1.1°C warmer than multi-bed 2 (Table 7.3).

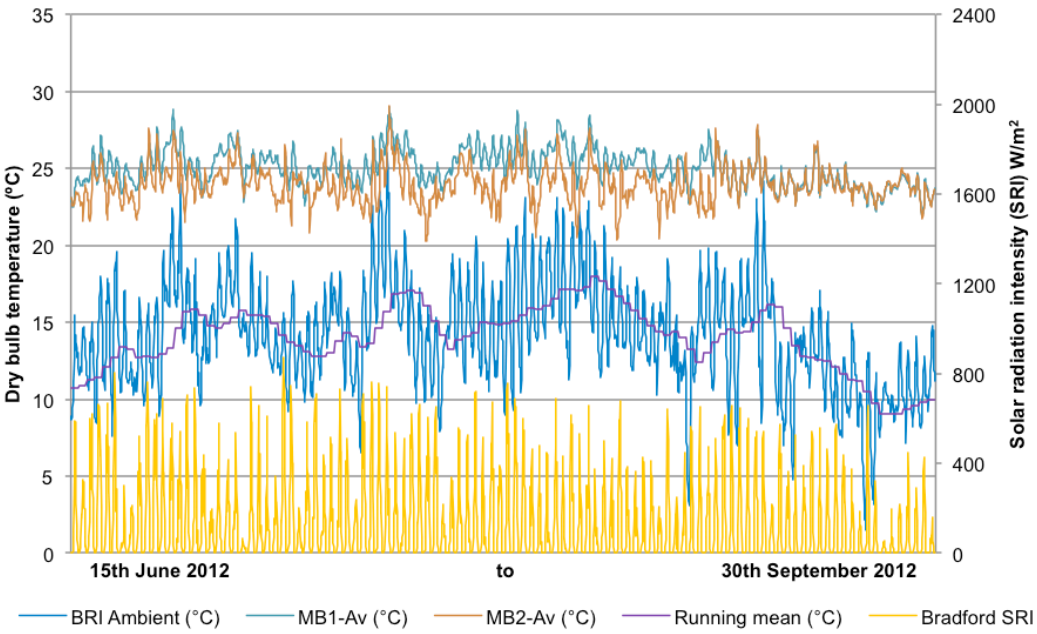


Figure 7.15 - Average internal temperature for modular multi-bed rooms

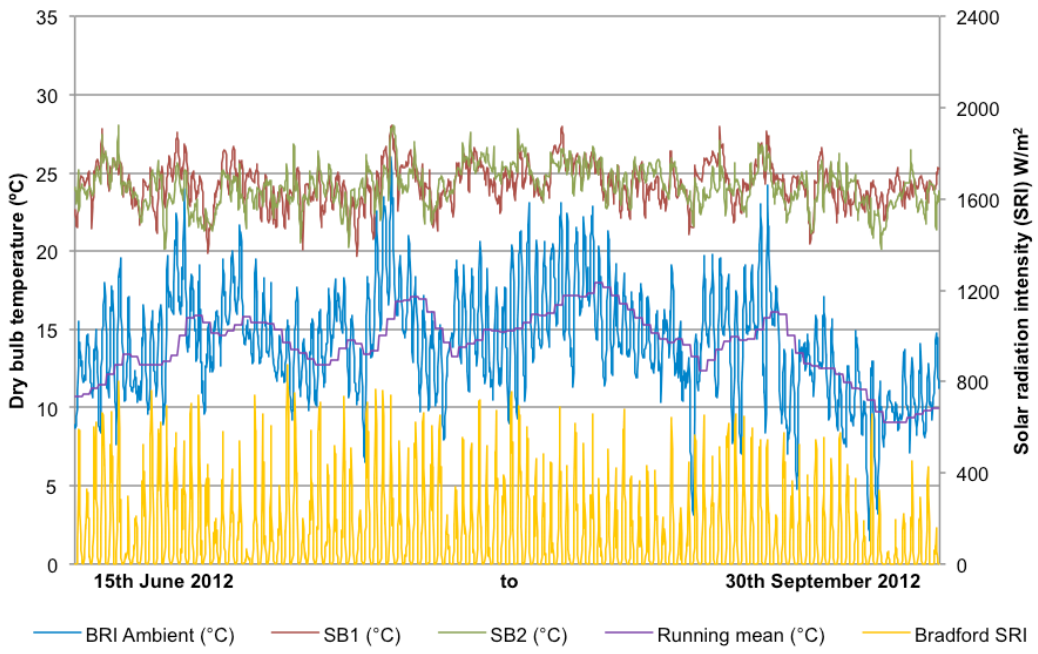


Figure 7.16 - Average internal temperature for modular single bed spaces

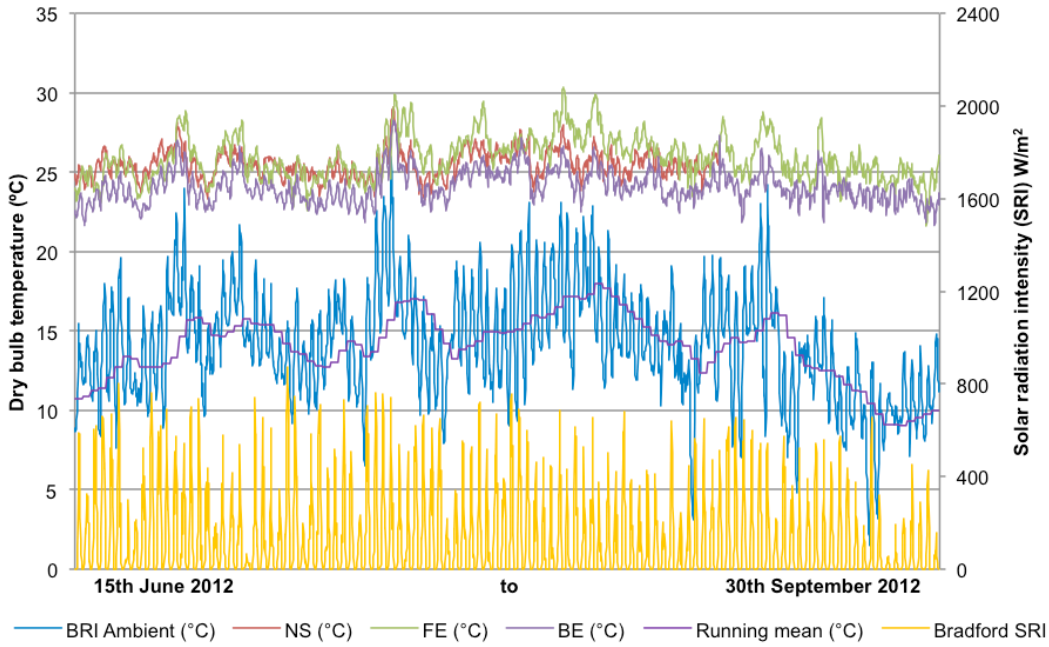


Figure 7.17 - Average internal temperature for modular corridor and nurses station

There was less of a noticeable difference between the temperatures within the two single bed spaces (Figure 7.16) than with the multi-bed spaces. In fact, the diurnal swing, max, min and average temperature results for the single-bed spaces were very similar (Table 7.3). As with the 2010/11 data, it was found that the nurses station and corridors had the highest temperatures on the ward and the front end of the corridor was the warmest space in the building (Figure 7.17).

The warmest day during the summer period fell on July 24th where it can be seen that multi-bed 1 responded the least to ambient temperatures (Figure 7.18). Its temperature remained relatively high during the early morning hours, whereas the rest of the bed spaces cooled down to below 25°C. The figure also highlights that as expected, the east facing single bed wards heated up and cooled down earlier than the west facing multi-bed space. Furthermore, it shows that the front entrance of the corridor was the warmest space, with its temperatures staying elevated until after midnight. Out of the bed spaces, multi-bed 1 had the highest temperatures and was at the front of the building, which suggests that the heat from the front end of the corridor may have had an influence on its temperatures.

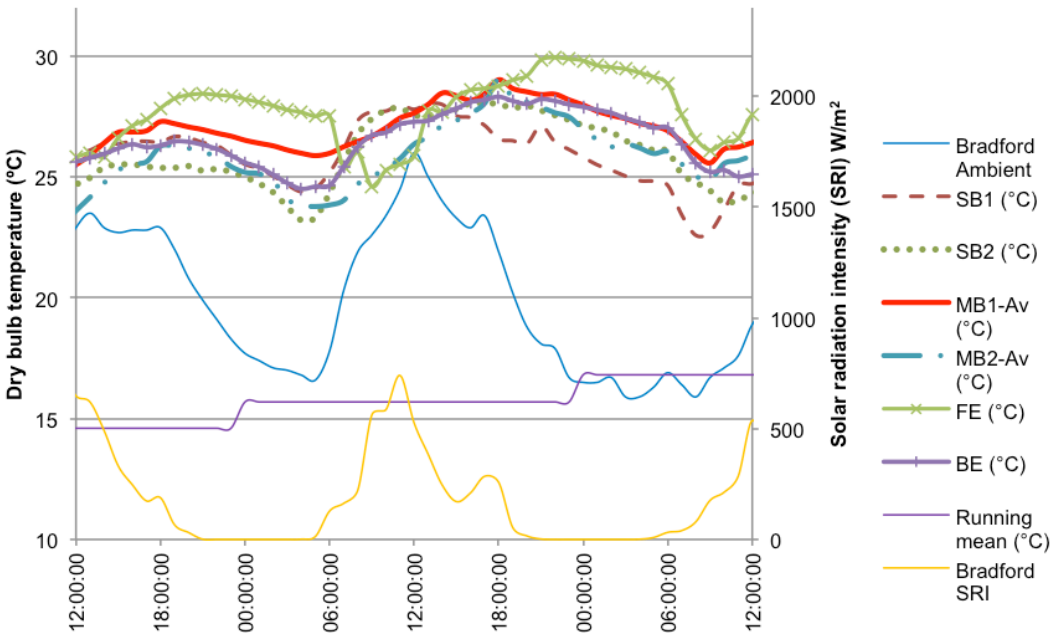


Figure 7.18 - Warmest day during summer, 24th July 2012, with day before and after

The pattern of warmer rooms at the front of the building is not reflected with the single bed spaces. Single bed 1 the space at the front end of the building, is the coolest and responds the most to outdoor temperatures, single-bed 2 temperatures are similar to the multi-bed 2. This indicates that the impact of the corridors on single bed spaces is not as predictable as on multi-bed spaces. It is likely that this is the case because single bed spaces are isolated for infection control and therefore have their doors closed to reduce the spread of infection. On the other hand, during visits to the ward it was observed that multi-bed rooms regularly had their doors opened which would have allowed the free mixing of air between them and the corridor.

	Max temp (°C) (24hrs)	*Min temp (°C) (24hrs)*	*Mean temp (°C) (7:00-20:00)*	*Mean temp (°C) (21:00-6:00)*	*Max diurnal range (K)*	*Hours over 25°C (24hrs)*		*Hours over 28°C (24hrs)*		*Hours over 24°C (21:00-6:00)*		*Hours over 26°C (21:00-6:00)*	
SB1	28.0	19.7	24.5	24.0	4.8	733	28%	1	0%	558	22%	255	10%
SB2	28.0	20.1	24.3	24.0	4.8	675	26%	4	0%	547	21%	178	7%
MB1a	29.1	20.6	25.1	25.0	4.0	1352	52%	35	1%	858	33%	633	24%
MB1b	29.0	21.6	25.1	25.0	4.7	1243	48%	30	1%	887	34%	588	23%
MB1-Av	29.0	21.1	25.1	25.0	4.0	1289	50%	33	1%	848	33%	581	22%
MB2a	29.3	20.6	24.4	24.3	6.2	650	25%	6	0%	663	26%	211	8%
MB2b	28.8	19.5	23.6	23.5	5.5	319	12%	1	0%	334	13%	109	4%
MB2-Av	29.0	20.0	24.0	23.9	5.8	418	16%	4	0%	461	18%	141	5%
NS	29.1	23.3	25.5	25.5	3.6	1362	53%	15	1%	797	31%	541	21%
CD-FE	30.4	21.6	25.8	26.1	5.3	1866	72%	234	9%	1022	39%	1147	44%
CD-BE	28.3	21.7	24.1	24.1	4.1	501	19%	7	0%	558	22%	107	4%

Table 7.3 - Results from monitoring summer temperatures in Bradford Modular building from June 15th 2012 to Sept 30th 2012

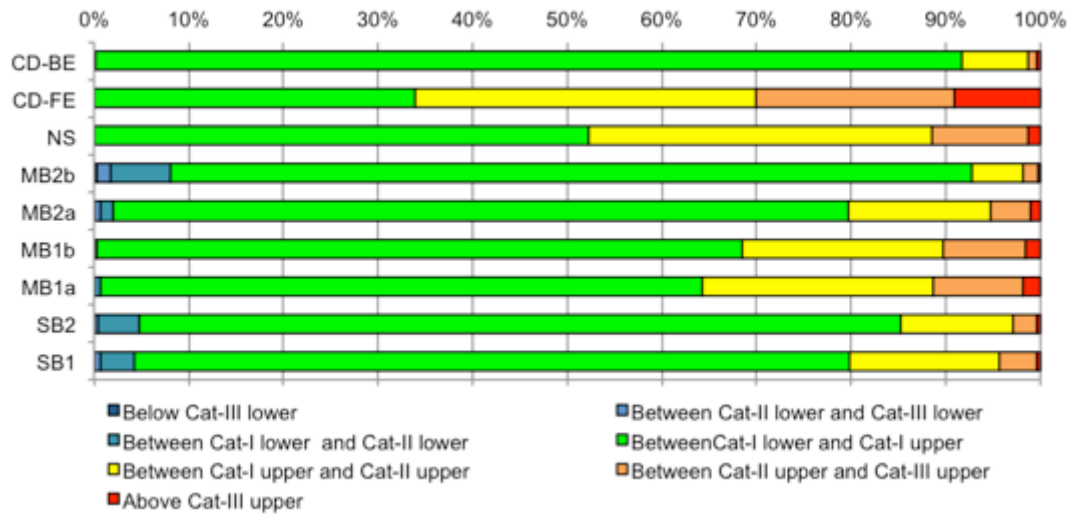


Figure 7.19 - Percentage of all measured summers hours in BSEN15251 for modular building

To meet the BS EN 15251 criterion, no more than 5% of the summer hours could be in excess of the Cat I upper limit, which represents the ideal environment for sick and vulnerable patients (Figure 7.19). Temperatures between Cat I upper and Cat II upper is acceptable for staff and visitors and the orange/red bars represent a case which is unacceptable for a hospital environment. Figure 7.19 shows that even in 2012, a relatively cool year, every available space is unfit for patients. Furthermore, it demonstrated that the only spaces which are acceptable for hospital staff and visitors are multi-bed 2, the two single bed spaces and the end of the corridor.

The scatter graphs below show the measurements for each hour, in either the day or night compared against the BS EN 15251 criterion during the summer period. Multi-bed 1 (Figure 7.20), the warmer out of the two multi-bed spaces has its temperatures

scattered higher on the graph than multi-bed 2 (Figure 7.21); however, multi-bed 2 has a larger spread, which is demonstrated by their respective maximum diurnal swings, (MB1=4K, MB2=5.8K) (Table 7.3). In regards to the spread of the temperatures during day and night, both spaces show the warmest temperatures during the day, albeit, other than the extreme warm temperatures during the day, there does not seem to be much difference between the spread of the day time temperatures and the night temperatures, as many of the coolest temperatures have been measured during the day. Overall, for the mixed bed spaces, most of the night temperatures fall into the middle range; for multi-bed 1, this happens to be above Cat I and often Cat II, meaning the building is overheating at night, and for multi-bed 2, most of the night temperatures are below the Cat I and II boundaries.

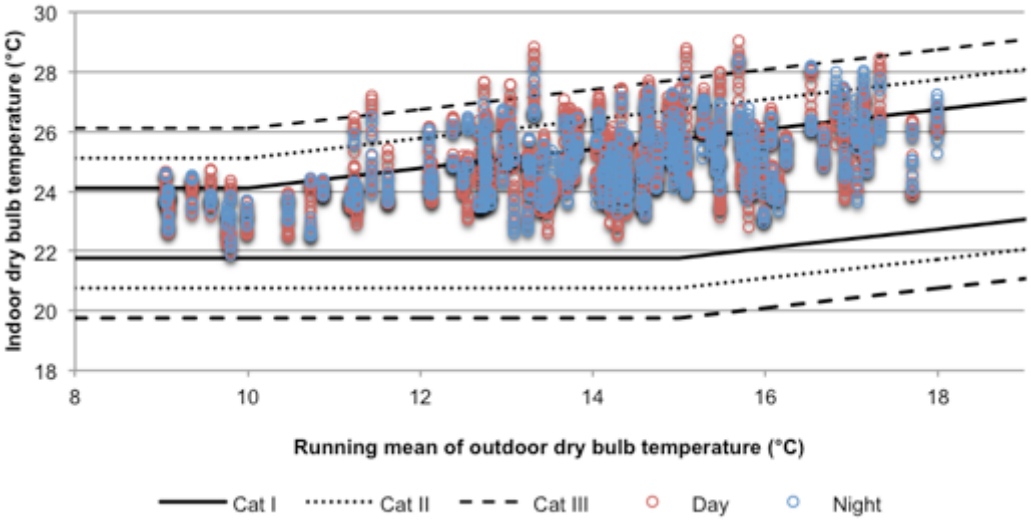


Figure 7.20 - Comparison of measured temperatures with BSEN15251: modular multi-bed 1 Average

The scatter graphs for single-bed wards (Figures 7.22 and 7.23) show that their performance during this summer period was very similar, both had a similar number of hours when the temperature fell outside of the Cat I criterion and they both had the same max diurnal range, 4.8K. Although their max diurnal swing was not as large as the one for multi-bed 2 (5.8K), it seems to be that the average distribution of temperature measurements is wider for the single-beds than the multi-bed spaces. In addition, the single-bed spaces show more distinction between the night temperatures and the day time temperatures; this is most apparent for single-bed 2 where there is a dense spread of cool temperatures, plotted in blue (Figure 7.23).

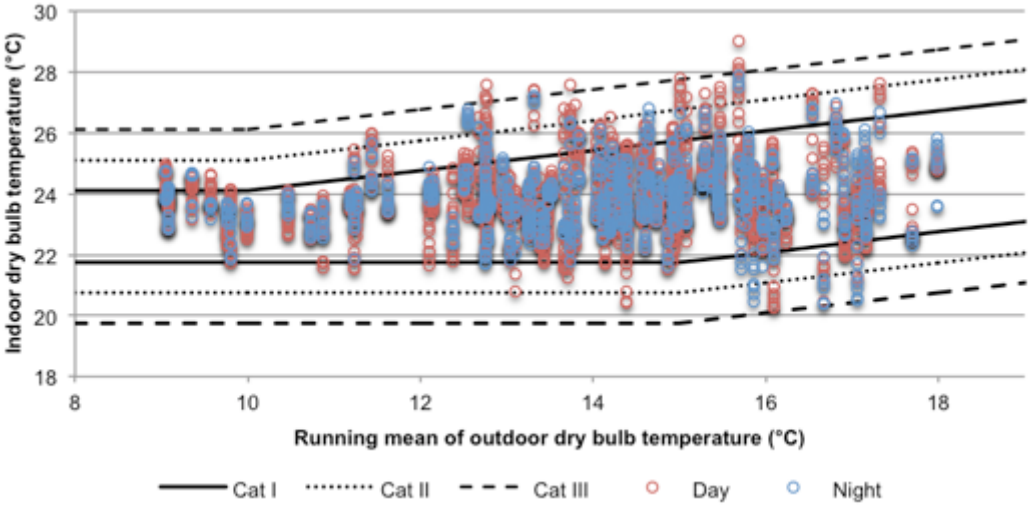


Figure 7.21 - Comparison of measured temperatures with BSEN15251: modular multi-bed 2 average

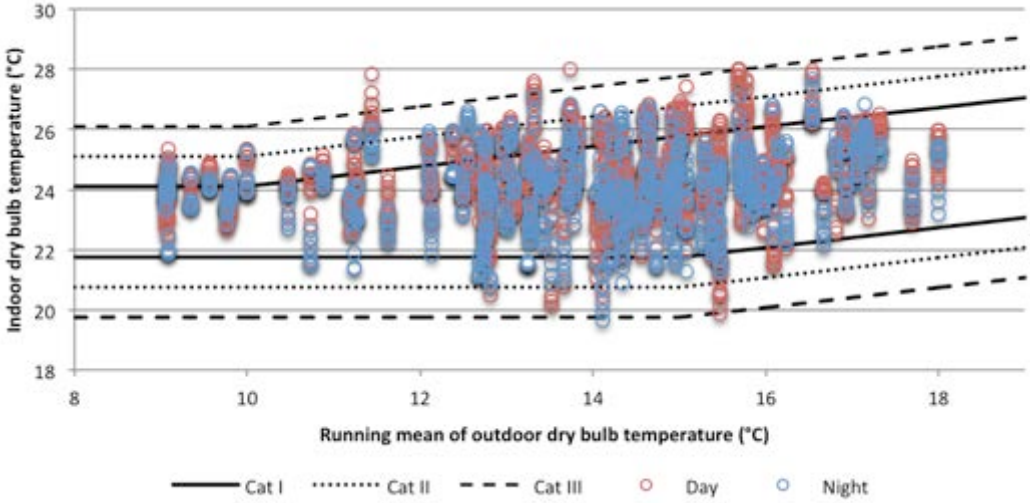


Figure 7.22 - Comparison of measured temperatures with BSEN15251: modular single bed 1 average

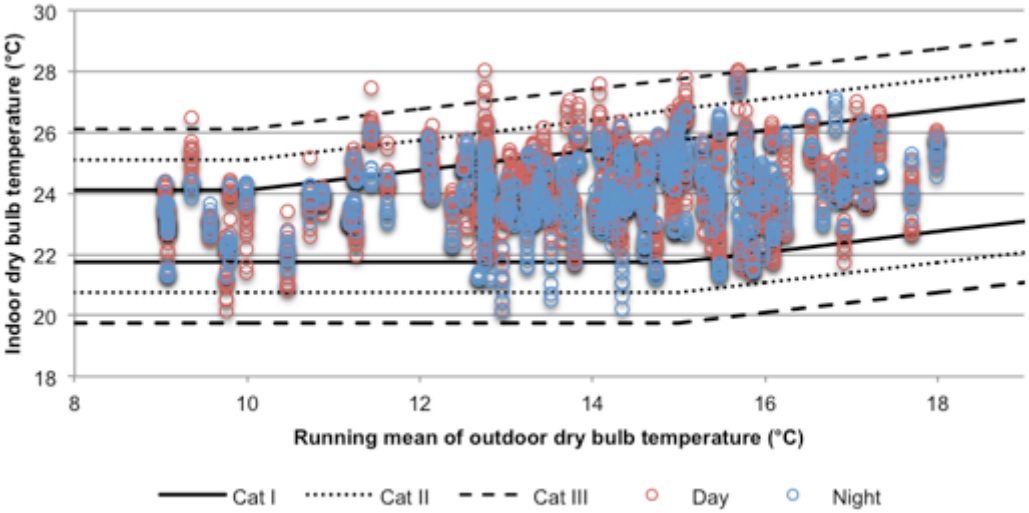


Figure 7.23 - Comparison of measured temperatures with BSEN15251: modular single bed 2 average

The observations made while visiting the modular building help to substantiate the quantitative analysis. When visiting the various wards and buildings around BRI it was noted that in the summer periods the modular building always felt warmer than the others on site. In addition, there were multitudinous complaints from staff i.e. estates, doctors, nurses on the wards that this building did get very hot. Another indicator of this was that when visiting the building in 2011 and 2012, the staff had requested that fans be placed in bedrooms and corridors on the wards. In 2013 on the final visit to the ward during a heat wave which took place in July, it was found that there were not only fans in the wards but also portable air conditioning units placed in all four of the multi-bed wards in both floor 1 (Ward 29) and floor 2 (Ward 30) (Figure 7.24). These were the only wards throughout the whole hospital where this had taken place, suggesting that the building was overheating and unable to provide a satisfactory environment for the staff and patients.

Figure 7.24 - Portable air conditioning unit in modular buildings multi-bed rooms

7.3.3 Natural Ventilation

Figure 7.25 shows the relationship between the ambient air temperature and the number of windows opened in multi-bed 2 Ward 30, monitored over a period of 183 days from August 2012 to January 2013. It shows that the number of windows opened increases as the ambient temperature increases, up to a temperature of about 18°C when all the windows are open. Unlike the relationship with ambient temperatures, there was not a strong correlation between window opening and the indoor air temperatures (Figure 7.26).

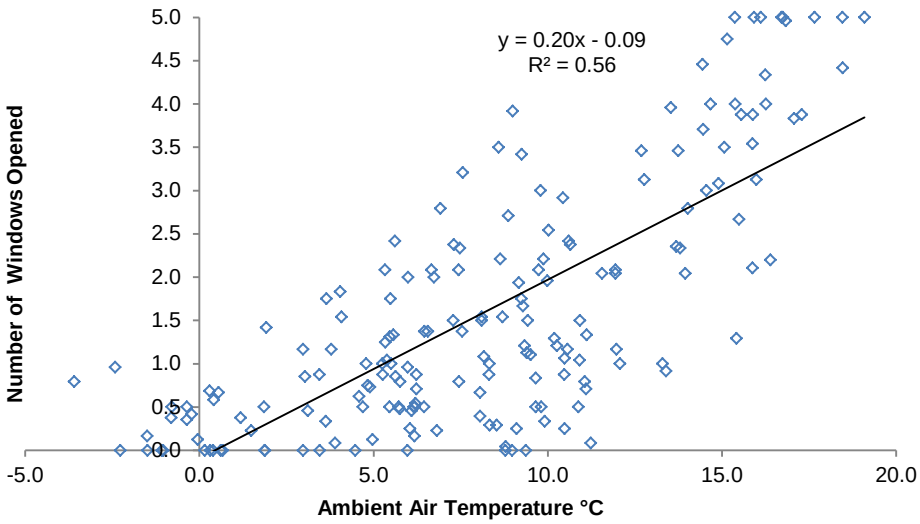


Figure 7.25 - Daily average ambient temperature compared to the daily average number of windows in modular building multi-bed room 2.

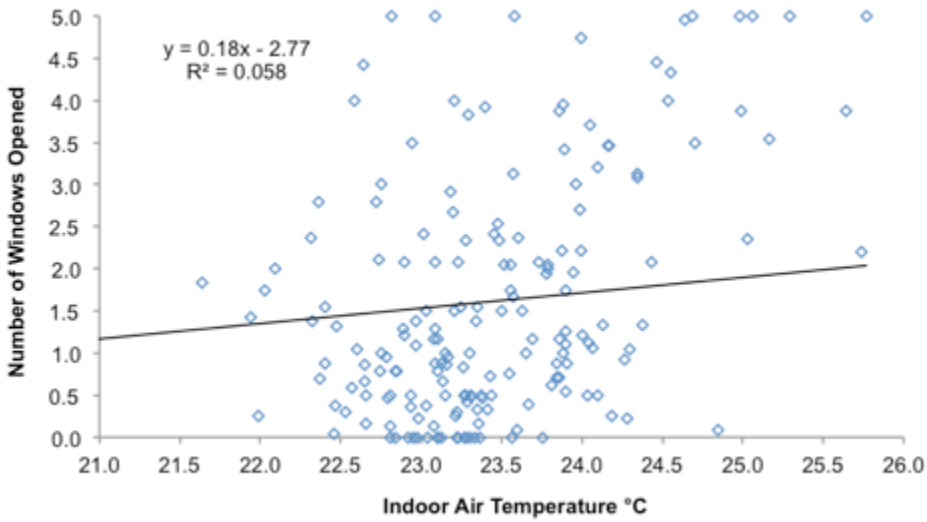


Figure 7.26 - Daily average indoor temperature compared to the daily average number of windows in modular building multi-bed room 2.

The measured hourly CO_2 levels in the room can be seen in Figure 7.27. The results show that the maximum measured CO_2 level in the room was 1960ppm, which was measured when just one of the windows was opened halfway. The minimum CO_2 level was 509ppm, and on average when all of the windows were closed the CO_2 levels were 1099ppm; this is 699ppm above the ambient level. This average was under the recommendation for Category III (i.e. 800ppm), however, the results do show that 11.9% of the measured hours were above 1200ppm. This performance is not inside the recommended criterion for acceptable deviation in BS EN 15251, which states that:

"The different parameters for the indoor environment of the building meet the criteria of a specified category when: The parameter in the rooms representing 95 % of the occupied space is not more than as example 3 % (or 5 %) of occupied hours a day, a week, a month and a year outside the limits of the specified category."(British Standard, 2007)

As was expected, the CO_2 levels decreased as more windows were opened. The measurements were taken in the winter months when windows were rarely opened. The results do show however, that when there were between 3 and 4 windows opened, the levels of CO_2 dropped below 750ppm, therefore according to this criterion, the ventilation to the room is insufficient for vulnerable patients unless more than 3 windows are opened (Figure 7.27).

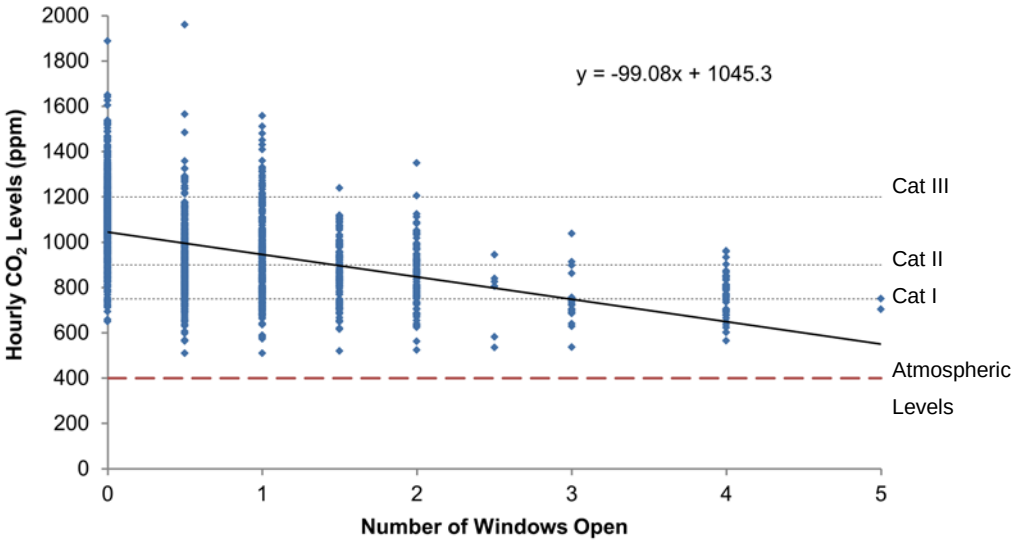


Figure 7.27 – Impact number of window opened has on hourly averages for CO_2 levels in multi-bed 2 between 23/11/12 & 31/1/13

When relating the results from the two graphs above together, (Figure 7.25 and Figure 7.27), it can be inferred that as it gets warmer outside more windows are opened and as more windows are opened, the ventilation is increased and CO_2 levels go down. This suggests that in the warmer months there will be sufficient ventilation, but in the winter months ventilation may be unsatisfactory. When looking at Figure 7.25, we can see that when the daily average ambient temperature rises above 15°C, there is an average of 3 or more windows opened and at this point sufficient ventilation is provided to satisfy the needs of the hospital patients. In 2012, there were 314 days when the average daily temperature was below 15°C, hence using the graphs above it

can be roughly estimated that in this year there would be insufficient fresh air for the patients in the multi-bed room 2 for 86% of the year.

It is also interesting to consider the variation of CO_2 levels with time of day; Figure 7.28 demonstrates average window openings and CO_2 levels at each hour in a multi-bed room in the modular building taken from the 2 months of monitoring (23/11/2012 to 31/01/2013). It shows that on average the CO_2 levels are just over 950ppm at night, then when patients wake up and more nurses come onto their shift, the CO_2 levels rise to 1025ppm, then drop back down. At this point in time, 8:00, there is a slight increase in the number of the windows open and the CO_2 level drops to close to 950ppm. The next significant increase in the CO_2 levels is at 14:00, which reaches a peak at 15:00 where the window opening plot shows that more windows were opened. This lasts until about 16:00. Again, at 18:00 another increase is seen in CO_2 level which reaches a peak at 19:00, generally at 19:00 the number of windows opened decreases. The CO_2 levels drop to their lowest after the peaks, however, this does not correspond to the opening of windows. This is interesting as it would have been expected that the lowest CO_2 levels would have been recorded in the night, as the nurses would have been at the nurses' stations and there would have only been four patients in the room. The CO_2 levels show that it may be useful to use occupant specific ventilation which adapts the level of ventilation to the number of people in a space, or the time of day.

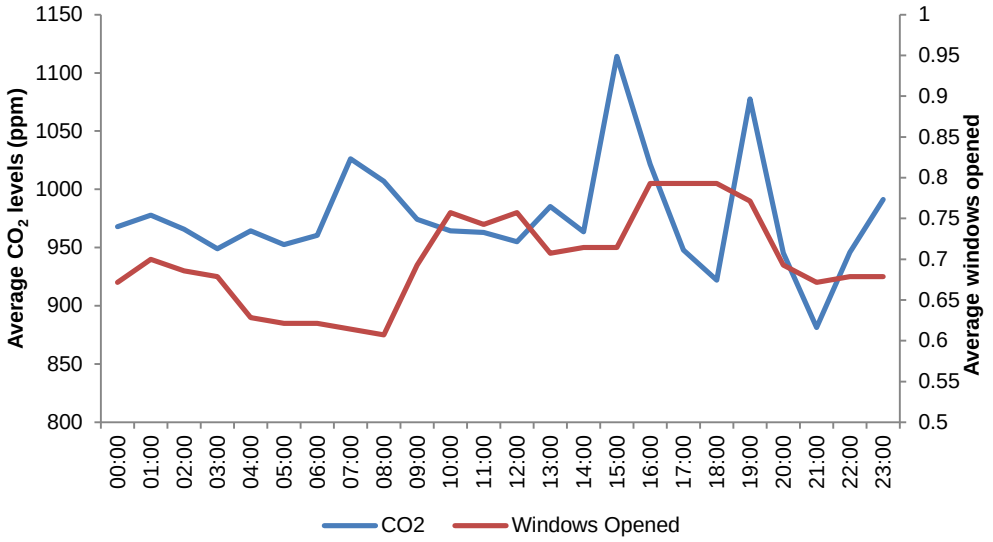


Figure 7.28 - Average hourly window opening and CO_2 (ppm) level over in Ward 30 Multi-bed room 2 (23/11/2012-31/01/2013)

In addition to the long term monitoring, CO_2 spot measurements were taken in both single and multi-bedrooms on Ward 29 (lower floor) and Ward 30 (upper floor) in May 2014. As previously stated, there were upto 5 windows openable in the multi-bed

rooms, and in single bed rooms there were 2.5 windows openable. The results show the number of windows opened during the time of the measurements given as a fraction of the total windows (Table 7.4). The CO_2 measurements were used with the equilibrium balance equation (Equation 3.6) to estimate the flow rates for each space. It can be observed that all of the rooms had air change rates considerably lower than 6ach^{-1}, with the largest flow rates being found in the multi-bed spaces on the upper floor (2-2.2ach^{-1}), when 0.2 to 0.5 of the windows were opened. Considering the airflow rate per person, it can be identified that when the windows were slightly opened in the single spaces, the flow rate was generally between 8.2 – 18.9 l/s/p. In addition to the windows opened, the single bed spaces had extract vents in the rooms en-suite which extracted air at the rate of 10l/s providing the patient in the space, with a air flow rate of 10l/s/p, when no staff or visitors were in the room. It is interesting to observe that when the windows were closed, the estimated flow rates in the single bedrooms were close to 10l/s/p, this suggests that air was being drawn from the corridor into the single-bed rooms due to the extract in the en-suites.

It is likely that in room W30R9, the space where four guests were visiting a patient and all windows were closed, that although the CO_2 levels were high, the space was far from reaching equilibrium, meaning that given more time the CO_2 levels would have risen considerably more leading to the effect of lowing the estimated, airflow rate. Nevertheless, this space is interesting as it showed the impact guests can have on the CO_2 levels in a space. It can be seen that the CO_2 levels rose to 1600ppm, when all of the windows were closed, this lead to an estimated flow rate per person of 4.2l/s/p, which is below satisfactory.

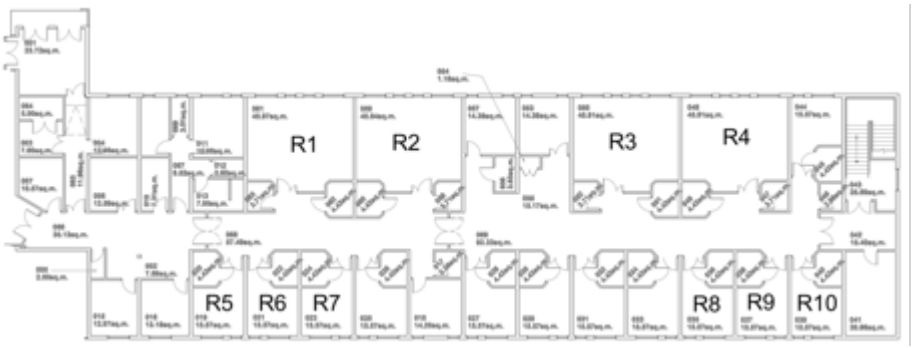


Figure 7.29 – Room names for Table 7.4

Space	*Beds*	*Floor*	*Occupants*	*CO_2 (ppm)*	*Windows*	*Qo (L/s)*	*Volume (m^3)*	*Max ACH^{-1}*	*Max L/s/p (current occupancy)*
W29R1	Multi	Lower	4 of 4	910	0.1	39.2	123.1	1.1	9.8
W29R2	Multi	Lower	4 of 4	1010	0.4	32.8	123.1	1.0	8.2
W29R3	Multi	Lower	4 of 4	922	0.2	38.3	123.1	1.1	9.6
W29R4	Multi	Lower	4 of 4	1180	0	25.6	123.1	0.7	6.4
W30R1	Multi	Upper	4 of 4	665	0.2	75.5	123.1	2.2	18.9
W30R2	Multi	Upper	4 of 4	683	0.5	70.7	123.1	2.1	17.7
W30R4	Multi	Upper	4 of 4	687	0.3	69.7	123.1	2.0	17.4
W29R5	Single	Lower	1 of 1	972	0.2	8.7	42.0	0.7	8.7
W29R6	Single	Lower	1 of 1	763	0	13.8	42.0	1.2	13.8
W29R7	Single	Lower	1 of 1	805	0.4	12.3	42.0	1.1	12.3
W29R8	Single	Lower	1 of 1	863	0	10.8	42.0	0.9	10.8
W29R9	Single	Lower	1 of 1	976	0.2	8.7	42.0	0.7	8.7
W29R10	Single	Lower	1 of 1	1049	0	7.7	42.0	0.7	7.7
W30R9	Single	Upper	1 of 1 +4G	1600	0	20.8	42.0	1.8	4.2
W30R10	Single	Upper	1 of 1	726	0.4	15.3	42.0	1.3	15.3

Table 7.4 - Results for Modular building walk around CO_2 survey (May 2014) [Room names found in Figure 7.29]

A further observation is that the estimated maximum flow rates seem to be higher for the upper floor than for the lower floor when the same amount of windows are opened. This can be seen for the single bed spaces, W29R7 and W30R10, which both had 0.4 windows opened, but had ventilation rates of 12.3 and 15.3L/s respectively. The same can be seen for the multi bed spaces, where when 0.2 of the windows in the space were opened, W29R3 had a flow rate of 38.3l/s, yet W30R1 had a higher flow rate of 75.5l/s, nearly double of its counterpart on the lower floor.

7.3.4 Mechanical Ventilation

The temperature of the ventilation air supplied to the corridors from the AHU can be seen in Figure 7.30. Over the monitored period of 231 days, the average air supply temperature was 19.7°C, with a range of daily average temperatures from 13.4°C to 25.6°C. From the hourly averages of the air supply temperature, it was found that there were a total of 5 hours (0.09%) when the supply temperature was above 28°C. From monitoring the flow rate of the system using the balometer it was found that the total flow rates for supply and extract matched the design flow rates which were 0.575 m^3/s and 0.775 m^3/s respectively. The flow rate to the corridor was 0.459m^3/s, which equates to 2.95 ach^{-1}.

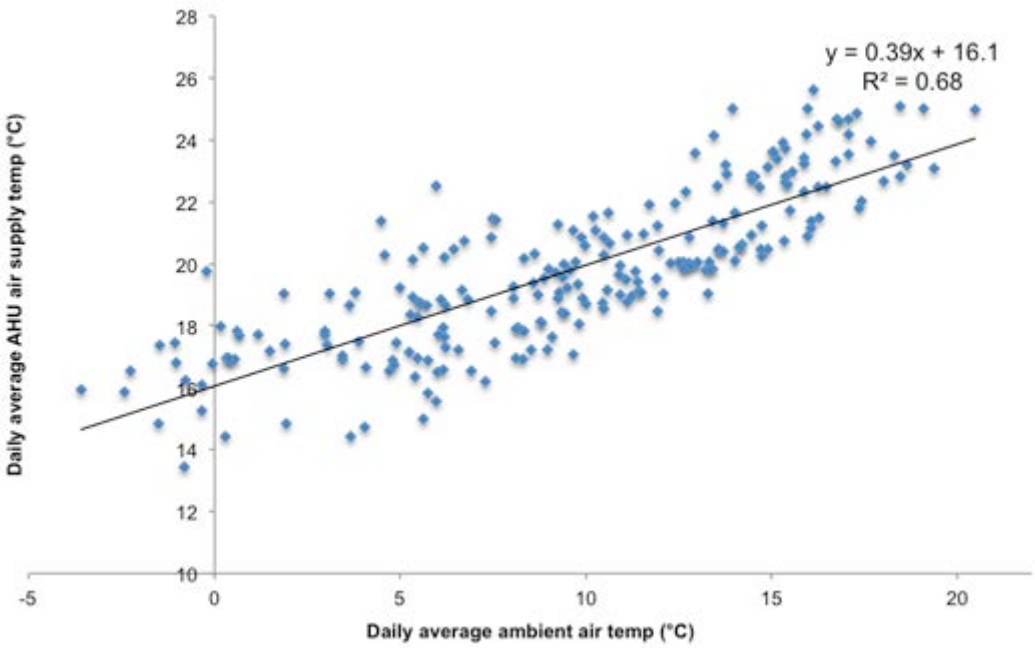


Figure 7.30 – Daily average ambient air temperature against daily averages of air supplied by AHU between 13/06/12 & 29/01/13

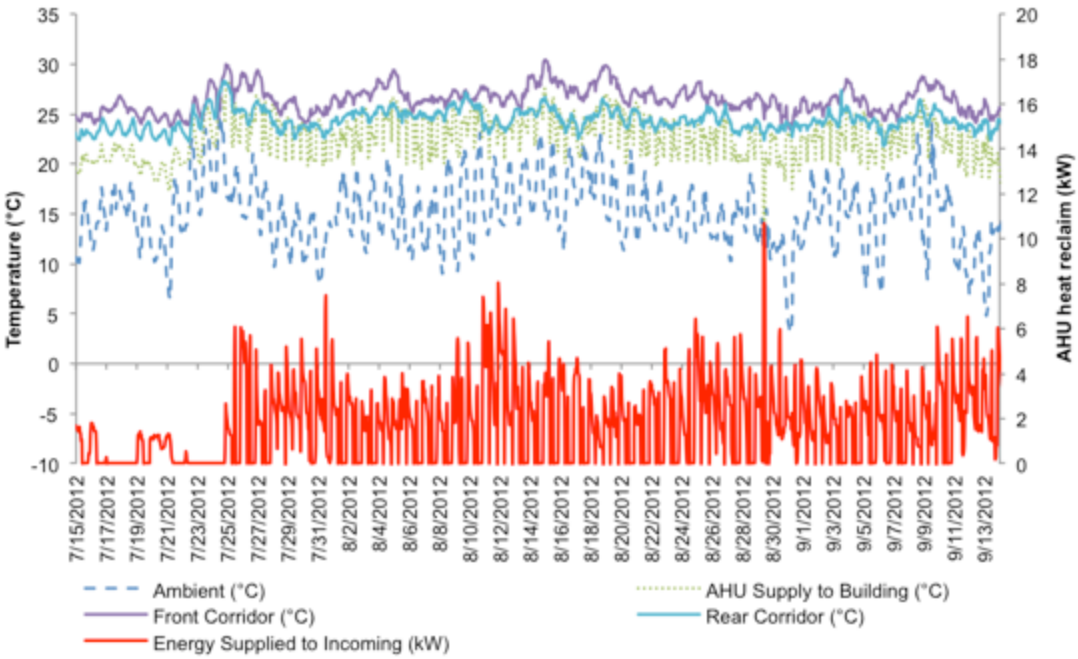


Figure 7.31 - Summer 2012 AHU supply and corridor temperatures with the heat reclaimed to warm incoming air supply (July-Sept)

Figure 7.31 is taken from the warmest period of the year, from mid-July through to the end of September. The chart shows a number of periods where the external temperature rises to over 20°C and on these days, the temperature of the supply increases close to about 25°C. When comparing the AHU supply temperature to the corridor temperatures it is apparent that the back end of the corridor is cooler than the

front end, and that the temperatures of the back end of the corridor are very similar to the AHU supply temperature. The graph shows that the front end of the corridor is continuously warmer than the back end, this reflects the results in the wards overheating analysis where there was a greater number of hours over 25°C and 28°C in the front part of the corridor, in all years and on both floors monitored (Figure 7.12). Figure 7.31 shows that each day, the supply temperature goes up and down in relation to the ambient air temperatures. It can be seen that although the maximum supply temperatures directly impact the temperature at the rear end of the corridor, the rear corridor's temperatures do not respond to dips in the supply air temperature at times when the AHU supply temperature to the building is low, the heat which is warming the corridor is coming from elsewhere.

The accuracy of the measurements of the 'external supply to AHU' were questionable as Figure 7.32 shows that the 'external supply to AHU' (sensor inside the duct before the heat exchanger) measurements were considerably higher than ambient. It is to be noted, that there is no pre-heat facility within the system, which suggests the sensor is monitoring heat gains from an unknown source or that the incoming air is being heated by the adjacent extract duct; the implication being that the sensors readings may not be an accurate measure of the temperature of the air entering the heat exchanger. The measurements of the air leaving and coming into the AHU are verified as they are similar to the temperatures of the corridors. These points have been highlighted to identify that the measurement of the air temperature of the extract duct after the heat exchanger maybe an imprecise measure of the temperature of the air. The method for calculating the heat-reclaimed energy supplied to the incoming air uses the air temperature of the extract duct (Equation 3.9), therefore, as this may not be a precise measurement, it would influence the accuracy of the magnitude of heat extracted from the outgoing air. Nevertheless, what the calculations for heat-reclaimed energy do clearly show is if the by-pass system is either on or off.

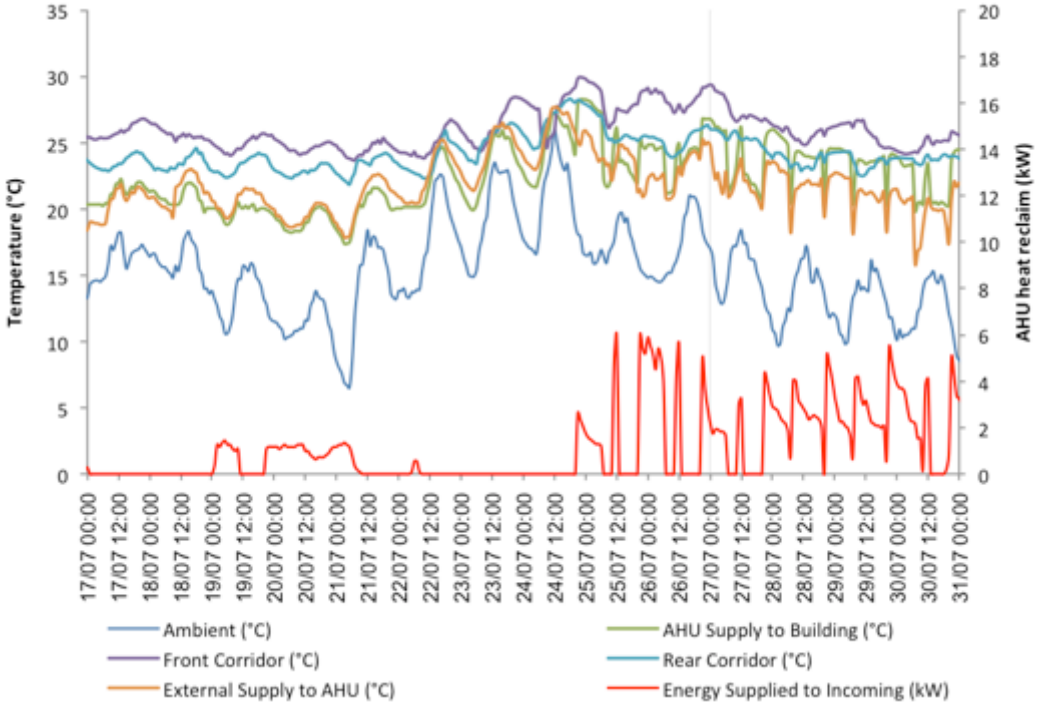


Figure 7.32 – July 2012 Summer AHU and corridor temperatures with the heat reclaimed to warm incoming air supply

From late June through to the 25th of July only minimal amounts of energy were supplied to the incoming air. The heating pattern of the AHU temperatures changed after the 25th of July. The heat supply to the incoming air via the heat exchanger seemed to turn on around 19:00 each day and run through the night with the energy being used declining until it reached a minimum at 07:00 in the morning and then increasing again. Figure 7.31 shows that this pattern repeated itself throughout the whole of the summer period. Prior to the 25th of July, the external supply to the AHU showed similar results to the temperature of the AHU supply to the building, this would be anticipated as no energy was used to heat the incoming supply. However, after the 25th the impact of the heat supplied by the heat reclaim system shows that the temperature of the supply air from the AHU to the building was often significantly higher than the external supply to the AHU. This suggests that the heating of the building during the summer time could have contributed to the overheating of some of the spaces in the ward. It also suggests that if the heat reclaim was completely by-passed during this time period the problem off overheating could have been alleviated.

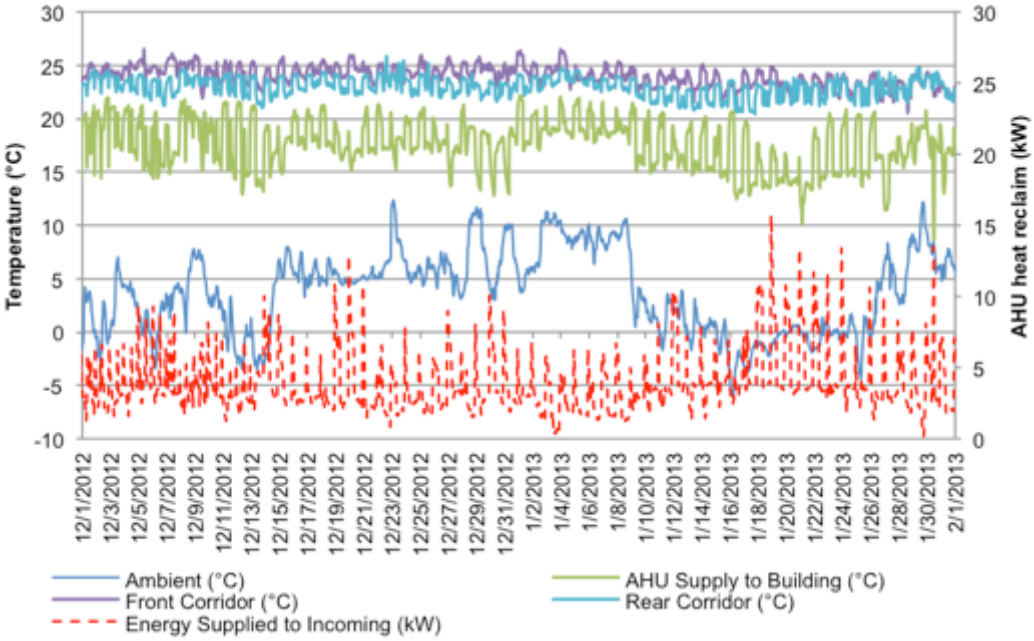


Figure 7.33 - Winter 2012/13 AHU Supply and Corridor Temperatures with the heat reclaimed to warm incoming air supply (Dec-Jan)

Figure 7.33 shows how the colder winter ambient temperatures impact the mechanical air supply to the building. In the winter there was 358 hours when the ambient temperature was below zero. The minimum ambient temperature recorded was -6.1 on the 16th January 2012. On this day the supply temperature remained above 10°C. The winter control of the heat-reclaim system followed a similar intermittent pattern to that found in the summer. The amount of heat transferred tended to hover around 3kW during the day and then rise to over 10kW from 20:00 and stay rather high until 08:00 in the morning when it returned to around 3kW (Figure 7.33).

Hospitals typically supply mechanical ventilation at 19 to 20°C; HTM-03-01 states that when heating a building in winter there should not be more than a +10°C temperature difference between the supply air and the room air temperature so as to avoids spots which are uncomfortably hot underneath the air outlets. In addition to this, the guide also states that in summer the air supply should not be more than 7°C less than the room air temperature to avoid draughts. In the building the winter supply temperature was always lower than the temperature of the corridor. The results show that throughout the monitored period there were 870 hours when the air supply temperature was more than 7°C below the room temperature. If we apply summer comfort criteria for the air supply conditions, then this points out that the differential between the supply and space temperature was too high and could have possibly caused discomfort for staff on the wards.

7.4 Energy Results and Analysis

7.4.1 LTHW Heating

Figure 7.34 shows the results and respective performance line for five different measurement periods. The resulting formula relating the power to air temperature difference is shown in Equation 7.1.

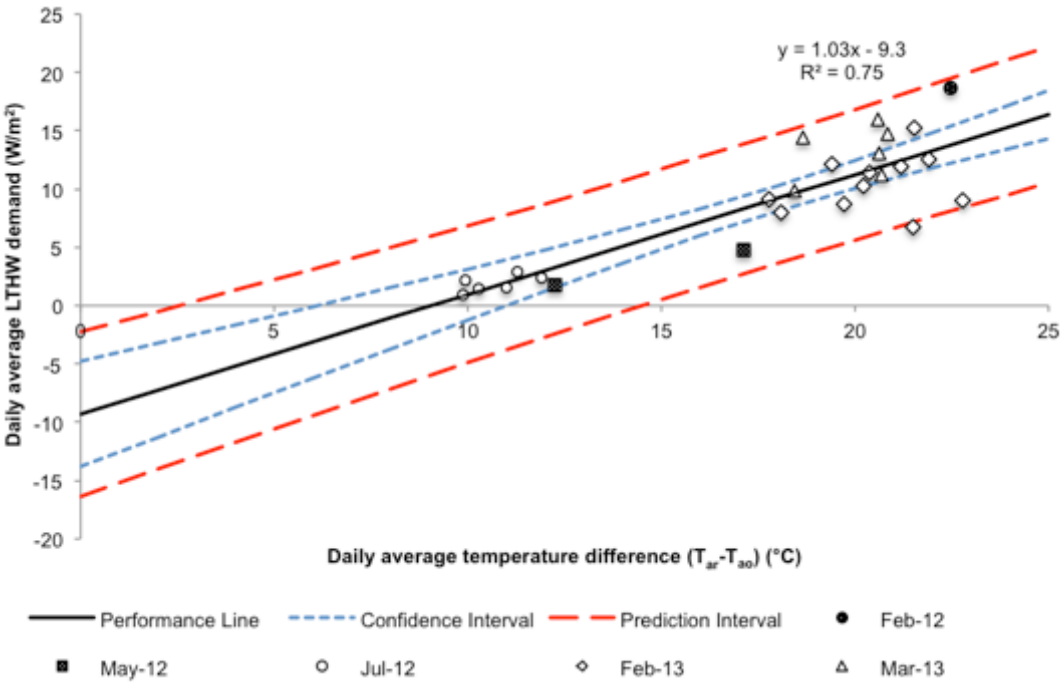


Figure 7.34 - Performance line for Modular building based on average daily measurements taken between April 12 and March 13.

$$Modular\ Q_{LTHW} = 1.03(T_{ar} - T_{ao}) - 9.30$$

Equation 7.1

The average winter temperature for the ward (23.2°C) and the daily average ambient air temperatures between 1st April 2012 and 31st March 2013 were substituted into Equation 7.1 and the result was normalised to account for degree-days (method presented in chapter 3). It is calculated that the building has an annual heat consumption of 46.82 ±12.78 kWh/m^2/yr. Taking into consideration the efficiency losses of 0.53 from the centralized system, it can be estimated that the modular building used 88.33 ± 14.24 kWh/m^2/yr of fossil fuels in that year.

7.4.2 Electricity

The averaged minutely electrical energy consumption in Ward 29 showed peaks in the electrical power at 9:30 and 14:00 as well as variations between the power

consumption of the two monitored months. June had the highest average energy consumption with 10.38 ±0.92 W/m^2 and February had the lower consumption of 9.06 ±0.84W/m^2. Using these figures the yearly ward electrical energy consumption can be estimated to be, 85.15 ±7.7 kWh/m^2 (Figure 7.35).

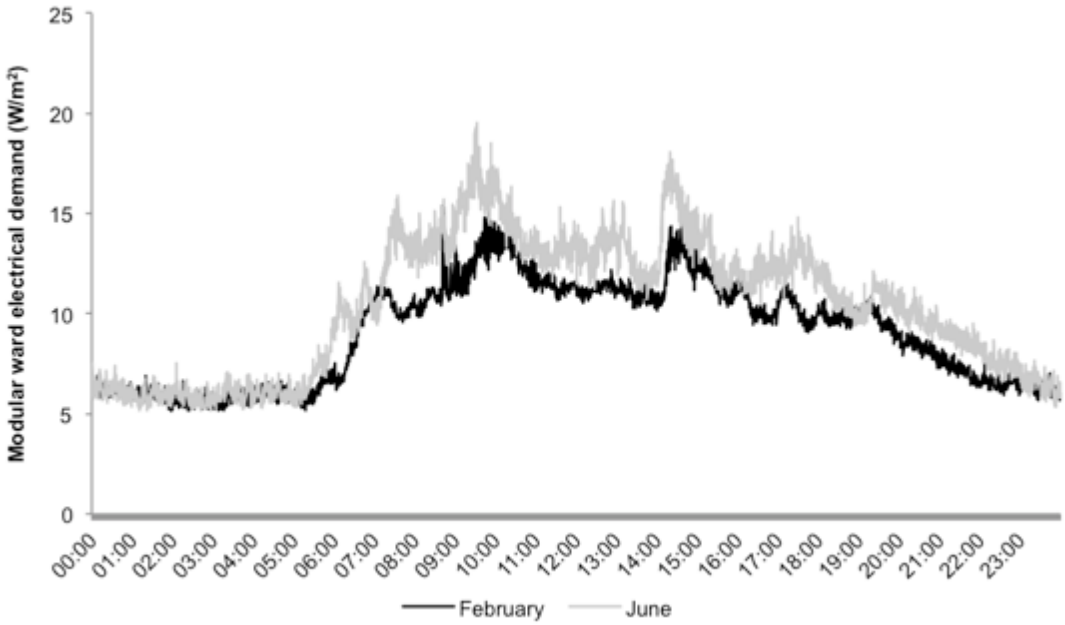


Figure 7.35 - Ward average minutely power consumption monitored over 15 days in February and June 2013

Table 7.5 exemplifies the values that were used in the calculations of the electrical energy consumption of the items in the plant room. When comparing the annual electrical energy consumption for the building from the different sources of use, it is apparent that the wards consume more electrical energy than the pumps and fans used to heat and ventilate the building

	Average current of measured phases (Amps)	*Phases*	*Voltage (V)*	*Power factor*	*Time in operation*	*Floor area*	*(kWh/m^2/yr)*
Pump - Constant Flow	2.82	3	415	0.85	8725	1892.0	**7.93**
Pump - Variable Flow	2.15	3	415	0.85	8725	1892.0	**6.06**
Fans - Supply	2.40	3	415	0.85	8760	946.0	**13.58**
Fans - Extract	3.91	3	415	0.85	8760	946.0	**22.12**
						Total	**49.69 ± 9.01**

Table 7.5 - Modular plant room electricity consumption

7.4.3 Overall Energy Consumption and Carbon Emissions

The results for the modular buildings measured energy consumption and carbon emissions are illustrated in Figure 7.36 and Figure 7.37 respectively. The Modular building DHW load and the efficiency losses for both central and local energy systems were calculated according to the method in Chapter 3. In total, the building currently operating at Bradford (central CHP) consumes 289.0 kWh/m^2/yr (38.5GJ/100m^3) with the locally supplied scenario's performance being similar, consuming 281.1 kWh/m^2/yr (37.5GJ/100m^3). For both scenarios it is apparent that the building has an excellent energy performance on the borderline of the Estates code new build category and being considerably lower than the CIBSE benchmark.

From both Figure 7.36 and Figure 7.37, it is clear that the low energy consumption can be attributed to the heating and fossil fuel consumption which in both scenarios was less than half of the CIBSE benchmark. The electrical consumption on the other hand is larger than the benchmark identifying that this would be the key area to focus on for reducing the energy consumption in this building.

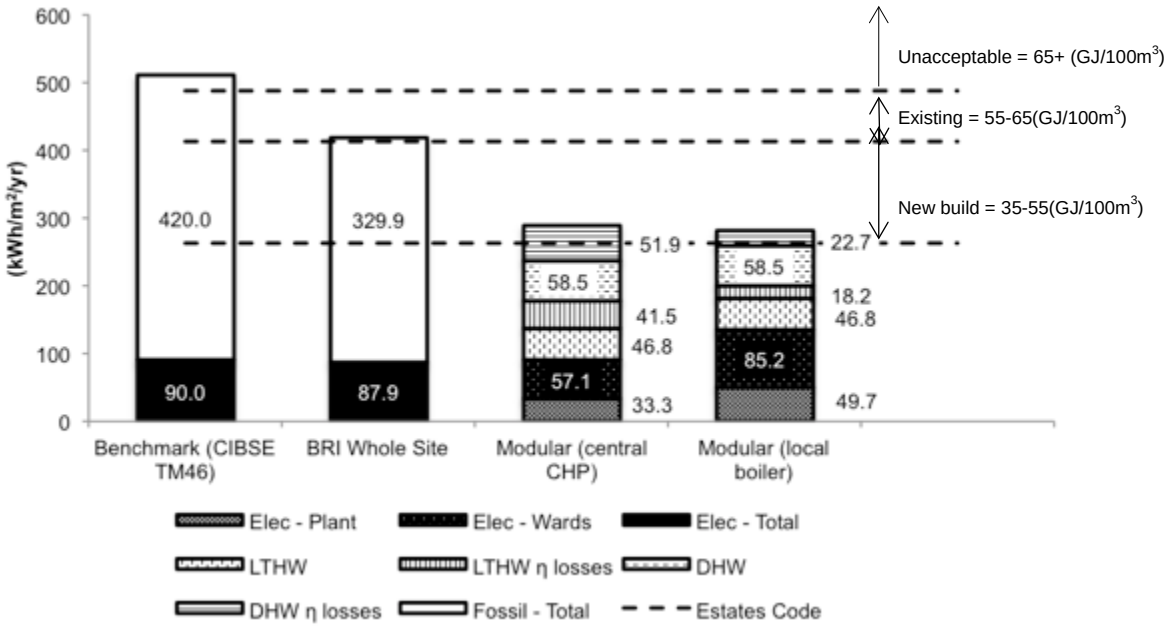


Figure 7.36 - Comparison of results for Yearly energy consumption, for BRI and Modular building against CIBSE TM46 and Encode Hospital benchmarks (GJ/100m^3)

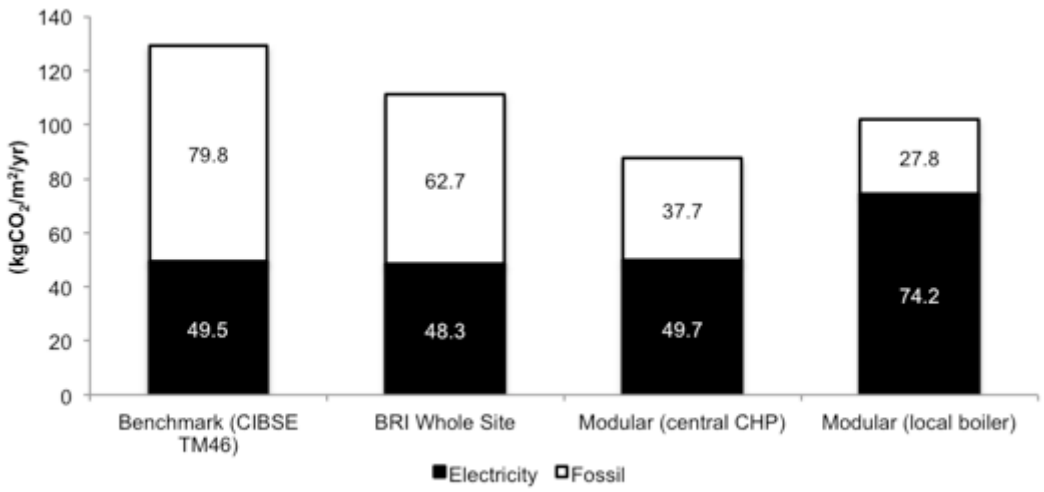


Figure 7.37 - Total carbon emissions for the modular building compared against BRI site and CIBSE benchmark

7.5 Discussion

The results show that the modular building is very efficient when it comes to energy use. When looking at Figure 7.36 it becomes clear that the buildings energy consumption was lower primarily because of its gas heating consumption. There were a number of factors which contributed to this low gas consumption; the first was that the modular building's fabric had been designed with high levels of insulation and low rates of infiltration, far surpassing the criteria in Part 2LA (literature review Table 2.9) which meant that more heat would remain in the building.

In addition to the buildings insulated and air tight fabric, it had an efficient AHU system. The system reclaimed heat from the extracted air and used this energy to heat the incoming air to the building. This meant that there was no energy needed from LTHW heating coils to heat the air and very little heat was wasted when air was extracted from the building.

Although the AHU system was highly energy efficient, there were concerns that it could not provide comfortable air temperatures when ambient air was at the extreme ends of the temperature spectrum, i.e. cold winter and hot summer. In the summer it was found that the AHU supplied air to the building's corridors at temperatures higher than ambient. When looking at the summer overheating analysis, it can be seen that the corridors were the warmest places in the building. The AHU was stationed in a room close to the rear end of the corridor, therefore the air coming out of the AHU first passed into this space. The results show that the air supply temperature from the AHU was very similar to the temperature for the rear of the corridor. The corridor was over

50m long, hence to travel from the AHU to the front end, the air had to pass through a long length of ducting in the ceiling void. The ceiling void contains heated ceiling panels and their piping, in addition to this, heat gains from the occupants and their equipment rise through the ceiling thus further heating the AHU ducts. These all have the combined effect of providing heat gains to the air inside the ducting; consequently the further away the ducting was from the AHU, the more heat it gained. This is demonstrated in the results, which point out that the front part of the corridor was always warmer than the rear. Furthermore single and multi-bedroom 1 towards the front of the building overheated significantly more than the single and multi-bedroom 2 rooms towards the rear of the building. These findings imply that there was a close relationship between the AHU supply, corridor and the bedroom temperatures.

In the winter the air supply temperature to the building was generally above 15°C, even when the temperature outside dropped below zero; however, design guidance HTM03-01 suggests that supply temperatures should not drop more than 7°C below the room temperature. The set point for the building was around 23°C and in the monitoring period, the supply temperature fell below 16°C for 870 hours. This suggested that discomfort may have been felt by persons positioned close to the supply ducts. Nevertheless, when considering that there would be heat gains to the air supply along the duct, it can be assumed that the majority of the air entering the corridor would be slightly warmer than the measured supply temperature in the AHU. It is quite outstanding that even when the daily average external temperature was 0°C, the AHU was able to heat the incoming air to a daily average of 16°C (Figure 7.30). The main reason this was possible was that there is a larger volume of air being extracted from the building than being supplied to the building, 0.775m^3/s compared to 0.555m^3/s.

The results showed that during the summer of 2012 two control strategies were used for controlling the AHU's heat reclaim system. The first strategy involved reclaimed heat being used to heat incoming air during the night, i.e. 19:00 to 7:00, and the second involved the heat-reclaim system being bypassed. The temperature measurements showed that at times when by-passed was not operational, the temperature in the corridors rose proportionally to the increase in AHU supply temperature. The implications of these findings are that the high temperatures in the ward may have been alleviated if the control functions for the AHU were set to by-pass during the night as well as at other times.

Another control related observation was that in the winter the amount of heat being reclaimed varied intermittently. During the day 3kW of heat was reclaimed which increased to 7kW during the night. The corridor temperatures responded to the amount of heat being reclaimed, with warmer temperatures being measured when more heat was reclaimed. These findings suggest that if the heat reclaim system was used to its full capacity, less LTHW heating would need to be used for the heated ceiling panels in the corridors. Overall, with improved control functions of the AHU reclaim system, it seems as if the building could have saved heating energy in the winter and reduced the extent of summer overheating.

It was found that the temperature in Ward 30, the 2nd floor of the building was always higher than that in ward 29, the 1st floor of the building. It was likely that this would be the case because of heat gains in the lower floor rising to heat 2nd floor of the building. The construction properties of the dividing floor between the two floors had a low thermal mass and no insulation allowing heat to pass through efficiently. As a consequence Ward 29 did not overheat in any of the spaces, except single bed 1. In the main 2012 analysis of summer temperatures, Ward 30 had minimal hours over 28°C, thus meeting the recommended HTM-03-01 criterion for overheating in hospital spaces. However, all of the spaces in the ward had a considerable amount of hours over the Cat I threshold, failing to meet the recommended conditions for sick patients. This overheating in a relatively cool year suggests that unless action is taken to change the building's physical form or HVAC system, the building will overheat in future years due to the impact of climate change. Methods which may be useful on this building, are chilled ceiling panels, shading devices, internally fitted ceiling fans shading on the windows, increasing the thermal mass of the building and implementing night cooling.

When looking at the electrical energy consumption, the results show that the larger proportion of the electrical energy of the building went to supplying the ward with a power supply which varied at different times during the day. Spikes in electrical energy consumption showed connection to occupant activities on ward, the arrival of Nurses, lunch time and patient visitations all produced spikes at 9:00, 12:00-13:00 and 14:00-15:00 relatively. The results showed that more power was used in June than February. It is very likely that the extra energy used had much to do with portable fans being used to cool the wards down. The electrical energy usage allocated to the wards is close to double that of the mechanical services suggesting the ward should be a focus for reducing electrical energy consumption.

The literature points out that ventilation in wards plays a crucial role in reducing the spread of infections. A number of hospital designs use natural ventilation, however the concern with the modular building was that, with a fabric allowing minimal amounts of infiltration, there would be insufficient ventilation to provide an optimal environment for patients. The main source of ventilation to the multi bedrooms was the windows; results from monitoring their opening patterns showed that in cooler weather more were closed. It was measured that when there were more than 3 windows open, the CO_2 levels would meet Cat I recommendations of the BS EN 15251 guidance. On the other hand, continually having 3 windows open would increase the heating needed for the building. When all the windows were closed, there were a large number of hours where the CO_2 levels were above the Cat III boundary, which the guidance says is unsuitable for existing buildings. A further solution would be to incorporate more mechanical ventilation into the building. However, depending on the magnitude of the increase in air being supplied to the building, the heat exchanger may not be able to extract enough heat from the return air supply to heat the incoming air. This would result in an additional heat source being needed to warm the larger volume of air entering the building and additional electrical energy to power a larger fan.

The results of monitoring window openings were positively correlated to the ambient temperature, showing a stochastic process. These findings help to confirm that similar window opening patterns can be found between hospital spaces and office buildings where more windows are opened as the ambient temperatures increase (Nicol, 2001; Zhang & Barrett, 2012). The correlation between window opening and CO_2 levels (Figure 7.27) was also as expected, with CO_2 levels dropping when more windows were opened. However, when considering the daily profile of CO_2 levels within multi-bedroom 2, it was observed that although the expected relationship between the CO_2 levels and windows opened was found for the majority of the daily profile, at around 14:00 and 18:00 the times of visitations on the wards, there was increase in CO_2 levels and the amount of windows opened. It is clear that the increase in CO_2 levels arose from the increase in occupant density within the space at this time, however there are a number of mechanisms that may explain the increase in windows opened.

It is important to remember that patients are often incapacitated, limiting their ability to open windows themselves. As visitors enter the room, there are more occupants in the space who have ready access to windows, thus increasing the probability of them being opened. The use of window opening as a tool to control the internal environment

has two main functions, one, to increase the freshness of the air and two to reduce the air temperature. In regards to air freshness, it should be considered that visitors are not adapted to the unpleasant odours which are often found in wards and would possibly open the windows on entrance to alleviate the odours. When considering the control of internal temperatures, the results demonstrated that there was a slight increase in the average daily temperature profile of the multi-bed spaces during the wards allocated visiting times. The results section highlighted that these peaks in temperature occurred one hour after the commencement of the visiting periods, suggesting that it took a while for the air temperature to be impacted by the increase in occupancy.

The building regulations guidance for hospitals found in HTM-03-01 states that 6ach^{-1} or 10l/s/p should be used in hospitals spaces (Department of Health, 2007b; HM Government, 2014). The estimate of the air flow rates show that the rooms are failing to meet the 6ach^{-1} but could potential meet the 10l/s/p criterion which HTM-03-01 specifies is for the purpose of odour control. When it comes to the accuracy of the estimates, the literature (Persily, 1997) is clear that the results must be correctly interpreted due to the likelihood that equilibrium conditions will not be met. Nevertheless, the same literature states that the estimates can be used to identify the inadequacy of a rooms ventilation. Considering this, the CO_2 spot measurement help to give supporting evidence that a flow rate of close to 10l/s/p is actually being supplied to the single bed rooms even when windows are closed.

It was observed that the upper floor spaces had a higher flow rate than the lower spaces for both single and multi-bed rooms on either side of the building. This suggests that the rooms on the upper floor were exposed to more wind pressure than the other spaces, possibly due to the influence of there being fewer obstructions to wind flow as the upper rooms would have been at least 3m above the lower spaces.

From observing the functioning of the Modular building, it is clear that infection control was a key factor in the mind of the designers. The single bed rooms have a negatively pressurised extract duct providing 10l/s/p, with corridors positively pressurised to stop air filtering out into the corridor, this has been stated to be a key factor in the design of hospital ward infection control (Tang et al., 2005). It has been identified that the air change rate provided to the corridor was 2.95ach^{-1}. When assessing the air change rate for the single bed room, it becomes apparent that when taking the floor area, ceiling height and extract speed of the en-suite area as 4.42m^2, 2.7m and 10l/s

respectively, the air change rate for the en-suite area is 3 ach^{-1}. This air change rate matches the recommended rate given for single room WC's in the HTM-03-01 guidance. This observation has a number of implications, the first is that it suggests that the extract feature has specifically been designed for the purpose of extracting air out of the toilet and not for infection control in the room, this leads to the second point that it seems as if the single bed room was designed for the purpose of being naturally ventilated. The HTM-03-01 guidance recommends that infectious disease isolation rooms are supplied with an extract removing air at a rate of 10ach^{-1}. The results show that the majority of the estimated air change rates in both the multi and single bed spaces were below 2ach^{-1}, according to the literature this suggests that there could be an increased risk of airborne infection (Menzies et al., 2000; Qian et al., 2010). Overall the positively pressurised corridors are likely to help keep contaminated air within the isolation rooms, and the fact that infected patients are isolated and specialised hygiene practiced by nurses is likely to reduce the risk of cross infection. However, as the air change rates are not likely to meet 10ach^{-1} when windows are closed, it does seem like there could be risk of airborne pathogens remaining in the space, thus increasing risk of infection for other building occupants. This shows that the side rooms provide some additional protection, but not that of a full isolation room and are designed to "barrier nurse" a patient who may have an infection such as MRSA.

It has been mentioned earlier in this discussion section that the elevated levels of CO_2 in bed spaces may benefit from mechanical ventilation. The findings that the CO_2 levels and room temperatures vary according to the level of occupancy suggests that it would be useful to install, time specific ventilation, which varied the airflow and temperature into the spaces at different times during the day. This would have the result of reducing the CO_2 levels in the bed-spaces while at the same time using less energy than a standard ventilation system that provided a constant rate of heat and air.

7.6 Conclusions

The analysis contained in this chapter provides insight into the energy performance and internal thermal conditions in a modular hospital building in the north of England. Monitoring conducted over two winters showed that the building had exceptionally low energy consumption meeting the new-build benchmark category set by the NHS. The work has identified that this low energy consumption is directly related to specific design features; namely, the high levels of insulation and air tightness, heat recovery

incorporated in the mechanical ventilation system, and natural ventilation in the bedroom spaces.

Although the building has low energy consumption, measurements made during the cool summers of 2010 to 2012 demonstrated overheating as indicated by the CIBSE, HTM-03-01 and BS EN 15251 adaptive comfort criteria. To combat this portable cooling devices were temporarily used on the wards, resulting in higher electrical energy consumption in summer than in winter. AHU supply temperatures had an observable impact on the corridor areas, which in turn impacted bed room temperatures. Weaknesses in the AHU heat-recovery control strategy were identified; the by-pass was not fully operational in summer and maximum heat recovery was not in use in winter. If rectified this could have an impact of reducing summer cooling and winter heating demands.

This study was one of the first to document the window opening patterns in a simple naturally ventilated hospital space, CO_2 levels were measured in a multi-bed room and the relationship between CO_2 levels and window openings was determined. The results indicated that for over 100 days each year the air quality within the bed spaces would fail to meet the recommendations in BS EN 15251. In addition to this, the spaces often fail to meet the HTM-03-01 recommend 6ach^{-1} which suggests there could be a risk of odour problems in the spaces. Furthermore, although the ward has specific isolation rooms which are operated at negative pressure so that air travels into them from connecting areas, the evidence suggest that the air change rates could be lower than the building regulations recommendations, which increases the risk of infection via the airborne transmission route.

The mechanical heat recovery ventilation system provided sufficient ventilation to toilets, shower rooms and corridors maintaining acceptable temperatures during the winter months. Overall, it would seem that modular hospital buildings of the type monitored, can be low energy, but that they are at serious risk of overheating even in relatively cool summers. Further research into reducing overheating and improving ventilation to bed areas is needed to make this form of building more widely acceptable within the NHS.

8 Comparison and Discussion of Case Studies

In the previous chapters, the energy and internal environmental performance of the monitored case-study buildings was presented. This chapter compares the results from these case studies to identify emerging patterns in hospital building performance. It considers: the implementation of the monitoring method- assessing its successes and areas for improvement; the results for the internal environmental conditions comprising the winter and summer thermal comfort and air quality; and the buildings' energy demand in light of the other aspects of design and performance. Following this, the performance lines for each building are used to investigate the effects of simple energy reduction measures on the buildings LTHW consumption. In closing, the evidence from each of the case study buildings are compiled in order to answer the original research questions and provide recommendations for the NHS.

8.1 Monitoring

A fundamental objective of this thesis was to develop a monitoring method to quantify the energy and environmental performance of existing hospital buildings. This section compares what was learnt from the application of the monitoring method in the different case study buildings. The monitoring of the ward air temperatures was relatively easy to achieve. Occasionally, the data logging temperature sensors would go missing, or be moved to a location that did not represent the intended space; the data from such sensors was omitted from the study. However, the main limitation of the method was that it was time consuming to collect the data from individual sensors and there was no option to get remote or real time access to the data.

To investigate air quality the CO_2 loggers were placed in one room in each ward. The success of using this method varied between the different wards. The logging device was larger and heavier than the devices used for monitoring temperature and this caused some difficulties in finding suitable locations. Also, the batteries required changing more frequently. When monitoring the modular building these difficulties were overcome by installing strong wall fixings and a mains power supply.

The results presented for the LTHW heating in the previous chapters demonstrate that the monitoring method was successful in obtaining the heating energy consumption for the different wards. There were however, a number of difficulties encountered with measuring water temperatures and flow rates. Pipework was often insulated using

materials containing asbestos and locating pipes could be challenging due to missing service drawings. The Nightingale building monitored in this work fell into the old building category, but fortunately in this case, the heating system for Ward 22 and 23 had recently been refurbished without asbestos insulation and the system was simple enough to locate the pipes to each ward.

The AHU ducts in the modular and nucleus building were easily accessed for monitoring the temperature of the air. The monitoring of the airflow rate at outlets using the balometer was also relatively simple with difficulties only being encountered in smaller spaces such as showers and bathrooms where railings limited contact between the balometer and the duct. The accuracy of grills' air flow measurements were verified by the commissioning manuals for the modular building. Measurements of ventilation in the naturally ventilated rooms of the modular and Nightingale buildings were not possible. In addition, the air supply temperatures measured for calculating the nucleus buildings annual mechanical ventilation consumption were recorded during one period and the assumption made that the temperature was the same throughout the year.

For the measurement of electricity consumption, access to the distribution boards varied from ward to ward. However, in nearly all cases it was possible to measure the ward's electricity demand. The study of the wards' electricity consumption was limited in that the wards were only monitored for one or two periods during the year. For the modular building these measurements highlighted that the electricity demand was higher in summer and lower in winter. Improvements could have been made in this part of the method by monitoring the electrical energy consumption on a seasonal basis in a similar manner as the LTHW consumption.

The method of measuring the electrical current to the fans and pumps in the plant rooms of the various buildings worked well as the electrical supplies to the pumps and fans were easily accessible for monitoring. There was however, a shortcoming in the method for assessing the total pumps electrical demand allocated to the Nightingale building, which was realised when analysing the results. The method focused on monitoring the electricity consumption of the plant localised at the individual building itself. This omitted the energy used by the distribution pump at the central plant room to transport the LTHW to the Nightingale building. This however did not impact the modular and nucleus building, as they were supplied by steam from the main plant room that did not use any pumps to move the steam to the necessary location on the

site. To enable a fair comparison of energy demands it was assumed that the pump at the central plant room which distributed LTHW to the Nightingale building consumed a similar amount of energy as the pump in the building: 5 kWh/m^2/yr.

8.2 Indoor Environment

The indoor environment in hospital spaces is off the utmost importance. It is essential that buildings meet the recommended comfort criteria in order to create an environment that is conducive for health and recovery. This section compares the performance of the winter and summer temperatures and air quality in each of the building types investigated.

8.2.1 Winter Temperatures

The recommended temperature range for hospital wards during the heating season is 22-24°C (CIBSE, 2006b), with the ideal falling into the middle of this range (23°C). The modular building achieved the average optimal temperatures (Table 8.1) as it had thermostats in each of the rooms, enabling the system to control each room's temperature. The building with the least control over the internal temperatures was the Nightingale building as in contrast to the modular building, its BMS was only able to set an overall set-point temperature for the ward.

	Nightingale		***Nucleus***		***Modular***	
	Mean temp (°C)	*Stand dev (°C)*	*Mean temp (°C)*	*Stand dev (°C)*	*Mean temp (°C)*	*Stand dev (°C)*
Weighted average	23.9	0.61	24.0	0.55	23.2	0.57
Nurse-station	25.3	0.58	24.4	0.67	n/m[i]	n/m
Corridor	24.8 / 22.8	0.9/0.65	24.4	0.93	23.4	0.91
Single bed	21.2	1.58	24.3	1.01	23.1 / 22.4	1.11/0.91
Multi-bed	23.6	0.87	23.5	0.70	23.2	0.57

[i]Modular nurse station temperatures not monitored during this period.

Table 8.1 - Average temperature measured in each of the spaces in the monitored wards between 1st December 2012 - 28th February 2013 (Nucleus measured up until 24th February 2013)

The warmest spaces in all of the buildings were generally found to be the nurse-stations and corridors. These tended to have similar temperatures, as the nurse-station was a desk within the corridor.

The bed spaces with the lowest temperatures varied according to the building. In the modular and Nightingale buildings whose spaces were naturally ventilated, the single bed spaces were cooler than the multi-bed spaces. Conversely, in the nucleus building, the multi-bed rooms were mechanically ventilated and were cooler than the single bed

spaces. The fresh air was supplied to the wards at a temperature of 19°C suggesting that the mechanical ventilation may have helped to control the temperatures.

Considering the control of the temperatures, it is apparent that in all spaces, the single bed spaces have a larger standard deviation in temperature than the multi-bed spaces. It is unclear why this is the case, but it is possible that it could be linked to the opening of windows. Patients in single-bed spaces have greater control over the window opening, than patients in multi-bed spaces. Therefore, one patient staying in the space may like the windows closed at all times, whereas the next patient occupying the space may like the windows opened. Because there are a number of patients in a multi-bed space no single patient would be inclined to exercise control.

8.2.2 Summer Temperatures

The summer temperatures were monitored in the various wards from June 15th to September 30th 2012. They were compared against thermal comfort criteria from HTM-03-01, CIBSE guides and the BS EN 15251 standards. The first static criterion, from CIBSE TM36, states that no more than 5% of the occupied hours (438hrs) in the year should exceed 25°C. This criterion was met in all of the patient rooms except for those in the modular building where all spaces exceeded the criterion except for one multi-bed room which marginally fitted the criterion with 418 hours over 25°C. The next two criteria used were the HTM-03-01 and CIBSE guide A benchmarks which recommended that there be no more than 50 and 88 hours above 28°C each year respectively. The year 2012 was relatively cool with the ambient temperature exceeding 24°C for only 17 hours and 25°C for 5 hours. The maximum measured internal temperatures were not much higher than 28°C, with the modular multi-bed rooms being the only spaces exceeding this temperature. CIBSE Guide A recommends that no more than 1% of the hours exceed 26°C during the night. Again the modular building failed to meet this criterion whereas the nucleus and Nightingale buildings successfully met it.

Many of the hours when the ambient temperature was over 24°C took place on the 24th of July, the warmest day in 2012. On this day the ambient temperature reached a maximum of 26°C which presented an opportunity to compare the performance of the individual wards on a warm summer's day (Figure 8.1 and Figure 8.2). It is apparent that the modular building had warmer spaces than the Nightingale and nucleus buildings. The results show that in general (Table 8.2) and on the warm summer's day

(Figure 8.1) the nucleus multi-bed rooms were cooler than the nightingale multi-bed rooms. As in winter, this seems to be because of the nucleus' mechanical ventilation system.

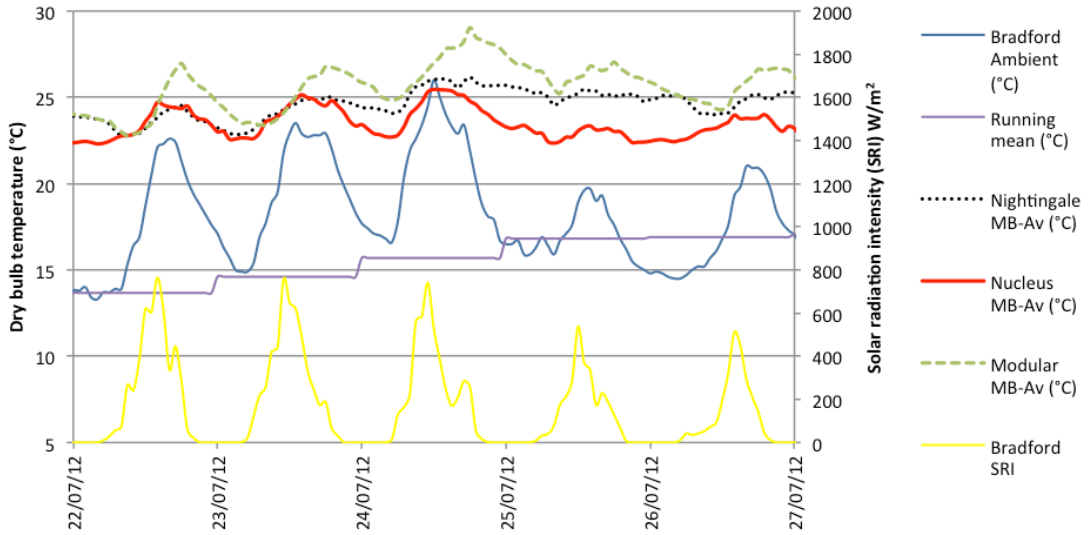


Figure 8.1 – Performance of multi-bed spaces on warmest day in summer, 24th July 2012, with preceding and proceeding days

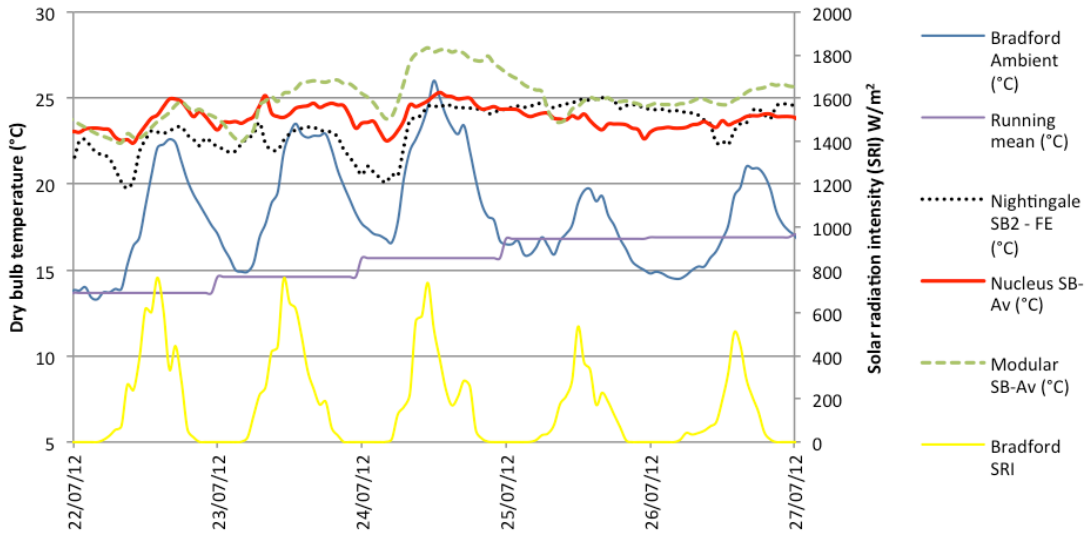


Figure 8.2 – Performance of single bed spaces on warmest day in summer, 24th July 2012, with preceding and proceeding days

		Max temp (°C) (24hrs)	Min temp (°C) (24hrs)	Mean temp (°C) (7:00-20:00)	Mean temp (°C) (21:00-6:00)	Max diurnal range (K)	Hours over 25°C (24hrs)		Hours over 28°C (24hrs)		Hours over 24°C (21:00-6:00)		Hours over 26°C (21:00-6:00)	
Single Bed	Mod 1	28.0	19.7	24.5	24.0	4.8	733	28%	1	0%	558	22%	255	10%
	Mod 2	28.0	20.1	24.3	24.0	4.8	675	26%	4	0%	547	21%	178	7%
	Night 1	24.5	17.0	21.8	21.8	5.1	0	0%	0	0%	2	0%	0	0%
	Night 2	25.4	17.1	22.7	22.8	5.5	12	0%	0	0%	164	6%	0	0%
	Nuc 1	26.7	18.8	23.5	23.2	4.6	23	1%	0	0%	65	3%	2	0%
	Nuc 2	25.9	19.0	23.4	23.4	5.2	55	2%	0	0%	152	6%	0	0%
Mixed-bed	Mod 1	29.0	21.1	25.1	25.0	4.0	1289	50%	33	1%	848	33%	581	22%
	Mod 2	29.0	20.0	24.0	23.9	5.8	418	16%	4	0%	461	18%	141	5%
	Night 1	26.0	20.3	23.4	23.4	3.5	79	3%	0	0%	245	9%	0	0%
	Night 2	26.4	20.8	24.0	24.0	3.7	284	11%	0	0%	518	20%	14	1%
	Nuc 1	25.3	20.1	22.6	22.1	3.3	2	0%	0	0%	0	0%	0	0%
	Nuc 2	27.8	18.4	23.1	22.7	4.9	68	3%	0	0%	56	2%	31	1%
Central Spaces	Mod - NS	29.1	23.3	25.5	25.5	3.6	1362	53%	15	1%	N/A	N/A	N/A	N/A
	Mod - CD-FE	30.4	21.6	25.8	26.1	5.3	1866	72%	234	9%	N/A	N/A	N/A	N/A
	Mod - CD-BE	28.3	21.7	24.1	24.1	4.1	501	19%	7	0%	N/A	N/A	N/A	N/A
	Night - NS	27.0	23.4	24.9	24.9	2.4	1117	43%	0	0%	N/A	N/A	N/A	N/A
	Night - CD1	25.6	21.5	23.7	23.6	1.8	40	2%	0	0%	N/A	N/A	N/A	N/A
	Night CD2	25.3	20.5	23.1	23.1	2.9	9	0%	0	0%	N/A	N/A	N/A	N/A
	Nuc CD	27.1	21.4	24.5	24.3	3.2	440	17%	0	0%	N/A	N/A	N/A	N/A

Table 8.2 - Results from monitoring of summer indoor temperatures for Nightingale, nucleus and modular wards from 15th June to 30th September 2012 (CD=corridor, FE/BE=front/back entrance) Highlighted sections represent spaces which fail to meet the CIBSE TM36 (5%,25°C) and CIBSE Guide A (1%, 26°C) criteria.

Considering the single bed spaces, the Nightingale building had the coolest temperatures on the warmest day (Figure 8.2) and generally throughout the monitoring period (Table 8.2). One of the building design variables which was likely to have had an impact on the summertime indoor air temperatures was the thermal properties of the building's fabric. The modular building was made with a steel frame and insulated panels creating a well-sealed, lightweight structure, with low U-values and infiltration rates. The Nightingale building had relatively low levels of insulation, but was constructed with a 500mm thick wall made up of stone and rubble, producing a heavy weight construction with higher U-values and rates of infiltration. The nucleus' fabric construction fell somewhere in the middle of these two buildings, having a brick and mortar construction with cavity insulation.

The modular building's high levels of insulation and low rates of infiltration increased the amount of heat accumulating in the building and potentially contributed to its overheating. The Nightingale's fabric would have allowed less heat to build up and its

heavy weight structure may have absorbed some of the ambient heat, allowing it to be released into the building at a slower rate. Evidence for this is demonstrated by the reduced variability in the Nightingale ward temperatures in the days following July 24th. In contrast, the other space's temperatures showed a visible drop with ambient temperatures, which is the most evident with the lightweight modular building. The nucleus building demonstrated a gradual reduction in temperature due to its medium to heavy weight masonry structure which had a higher thermal mass than the modular building.

The final analysis of the summer temperatures used the BS EN 15251 adaptive thermal comfort criteria. The target for each hospital space was to have no more than 5% of the measured hours above of the Category I (Cat-I) upper boundary, which is suitable for patient rooms and the Category II (Cat-II) upper boundary, which is appropriate for other occupied areas. For the central spaces it can be seen that all of the spaces in the Nightingale and nucleus building meet the standard with less than 5% of hours above Cat II upper (Figure 8.3). It is also apparent that the back entrance for the modular building meets the criterion, however, the nurses' station and the front of the corridor exceed the 5% boundary with around 12% and 30% of hours above the recommended criterion for the spaces respectively. In addition to this, it can be seen that compared to the Nightingale building's central areas, there is a larger variation in the degree of overheating in the central areas of the modular building, suggesting the temperatures in the central areas of the building are not controlled as well as in the Nightingale building.

In regards to the bed areas, all of the Nightingale and nucleus spaces meet the recommended criterion having less than 5% of their hours above the upper limit for Cat I. They may however, become too cool during certain periods, with the mechanically ventilated multi-bed spaces in the nucleus building and the single bed spaces in the Nightingale building being the coolest. The nucleus multi-bed rooms were coolest in both the summer and winter, which suggested that it's mechanical ventilation system, had a cooling effect on the spaces temperatures. Again, the modular building failed to meet the criterion for all bed spaces, showing the greatest degree of overheating in the single bed 1 and multi-bed 1, the spaces closer to the front end of the corridor.

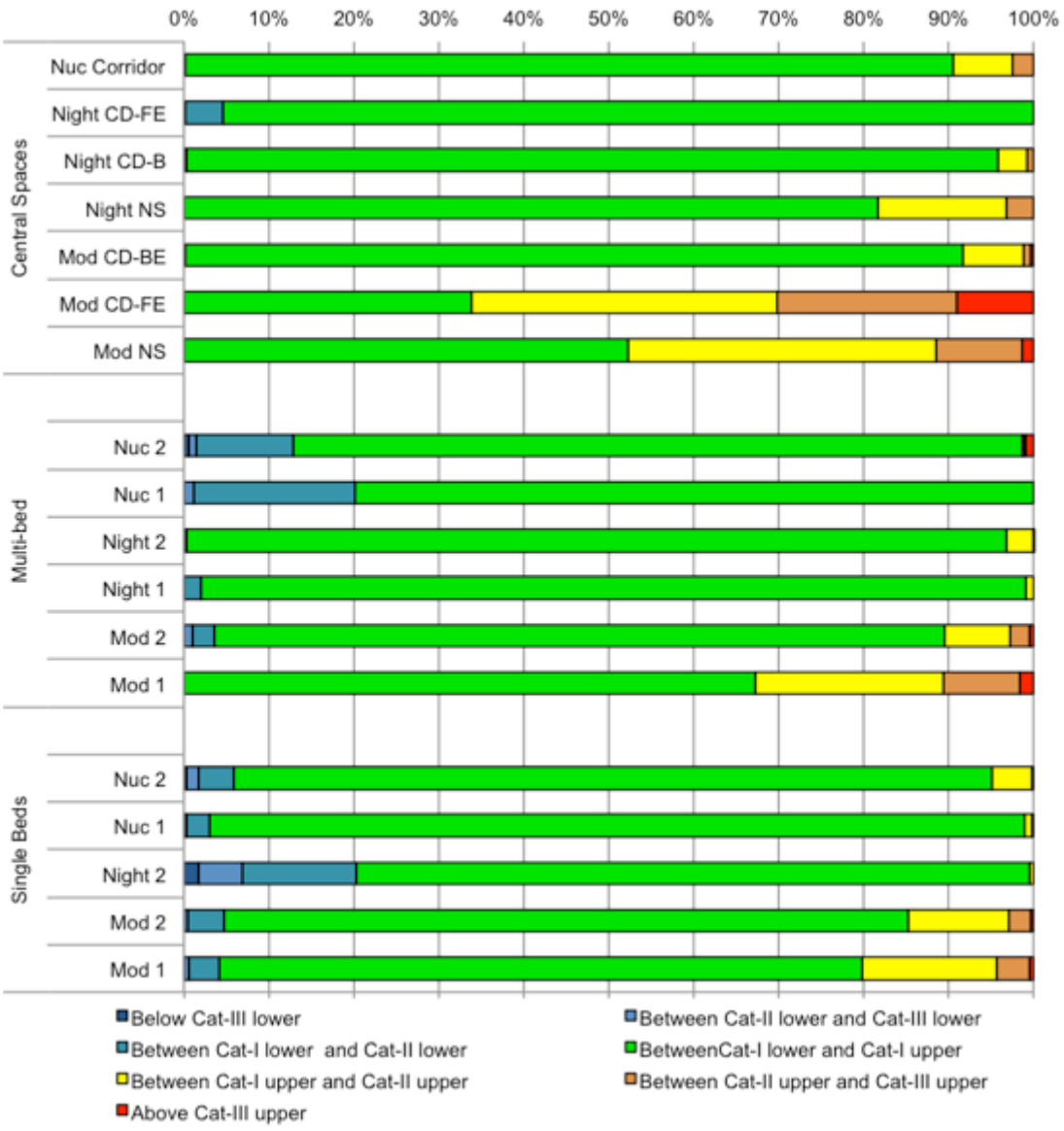


Figure 8.3 - Comparison of percentage of hours in each BS EN 15251 category for each hospital building

In recent years, extensive work has been undertaken through the DeDeRHECC project to investigate the resilience of hospital buildings to overheating. To gain context for the results in this thesis, it is important to demonstrate how its findings line up with those in the wider literature. The DeDeRHECC has published papers touching on thermal resilience of all of the building types discussed in this work, Nightingale buildings (Lomas & Giridharan, 2012a), nucleus (Giridharan et al., 2013b), and a range of other buildings including the modular building type (Iddon et al., 2015). The findings from this report seem to validate the work done in these previous studies.

During the relatively cool summer of 2010, another nightingale building was studied at BRI (Lomas & Giridharan, 2012a). The wards studied were on separate floors, with

layouts based on the traditional Nightingale design, with a slightly lowered ceiling and ventilation vents removed from the edge of the rooms. The study measured temperatures that were within the HTM-03-01 guideline and BSEN 15251 Cat I criterion for vulnerable patients and through modelling demonstrated that this type of building could be resilient in the future warming climate. The main difference between the Nightingale in this thesis and that in the Lomas study was that it did not utilise traditional Nightingale ward design, which favoured cross ventilation. Rather, the rooms had ventilation on one side of the room, producing different levels of through flow ventilation depending on window and door openings to corridors. The results from both this thesis and the Lomas study suggest that naturally ventilated pavilion building hospital types can reduce levels of overheating in a moderate climate regardless of the ward layout and specific natural ventilation strategy.

The DeDeRHECC study on nucleus buildings also showed similarities to the results in this work. In this thesis the nucleus building demonstrated what could be argued the most optimal thermal temperatures during the monitored summer period. Likewise in the research undertaken at a nucleus building in Leicester (Giridharan et al., 2013b), results showed that the nucleus hospital performed well with all patient spaces meeting the HTM-03-01 and BS EN 15251 criteria. The study noted that this performance coincided with a ventilation flow rate of 1.5ach^{-1}, hence Giridharan came to the conclusion that air changes lower than the recommended 6ach^{-1}, even possibly as low as 1.2ach^{-1} could help to increase resilience to overheating. The Bradford nucleus in this thesis seems to support this finding as it's 3ach^{-1} supported the building in maintaining comfortable temperatures throughout the monitored period.

The warmest parts in the buildings tended to be the internal spaces, i.e. nurses stations and corridors (Figure 8.3), a number of papers (Giridharan et al., 2013b; Lomas & Giridharan, 2012a, 2012b) identified this same finding explaining that they were the warmest spaces in the building due to internal gains and lack of windows. As well as the internal spaces, the monitored temperatures in the modular building failed to meet the BS EN 15251 recommendations. One of the most recent papers on the thermal resilience of hospitals modelled the performance of the Bradford modular building using the 2010 data analysed in this thesis (Iddon et al., 2015). The numerical model predicted that in the 2006 heatwave, the building would have 20 or more hours each day over 28°C. The conclusion from Iddon et al, on the modular building type lines up with those in this thesis, but adds that lightweight buildings should not be used for hospitals as they are unsafe due to their tendency for overheating.

In addition to the assessment of the thermal resilience of various hospital building types, the literature from the DeDeRHECC project discussed the impact of retrofit measures to reduce overheating in hospitals. They concluded that light touch carbon interventions such as the introduction of ceiling fans into the wards could enable the nucleus and Nightingale buildings produce comfortable conditions into the 2050s. These results were identified using modelling, which was out of the scope of this work, the literature is yet to study retrofit measures for the modular building which could be an interesting area for further work.

8.2.3 Air Quality

The results from monitoring the modular building demonstrated a positive correlation between ambient temperatures and the number of windows opened. Many of the bed spaces in the wards were naturally ventilated, therefore it was a concern that when the windows were closed in the winter there would be insufficient fresh air provided for the patients.

Building	*Nightingale*	*Modular*
Date of Measurements	28/11/12 - 30/11/12	23/11/2012 - 31/01/2013
Average ambient temp °C	1.2	3.78
Hours monitored	53	1680
Room Type Monitored	6 Bed	4 Bed
Ventilation System	Natural	Natural
Room Size (m^2)	71.3	45.64
Day time [07:00-21:00] average CO_2 levels (ppm)	1126.0	990.5
Night [21:00-07:00] Average CO_2 levels (ppm)	953.5	955.7
Daily average CO_2 levels (24hrs) (ppm)	1060.9	976.0
Max CO_2 levels (ppm)	1531	1960.8
Hours over CAT I [750ppm]	84.9%	88.5%
Hours over CAT II [900ppm]	73.6%	62.5%
Hours over ASHRAE [1100ppm]	43.4%	24.6%
Hours over CAT III [1200ppm]	24.5%	12.0%

Table 8.3 - Results for the stationary monitoring of air quality in each of the buildings

The air quality in the rooms was monitored in autumn and winter, with the periods varying due to difficulties being found with leaving the CO_2 sensors in the wards. The modular building had a prolonged monitoring period of 1680 hours, whereas

monitoring in the Nightingale building was significantly shorter at 53 hours due to disruptions by ward occupants. The reduced period is not optimal for creating a frequency distribution but it helps to demonstrate the overall performance of the ventilation systems (Figure 8.4).

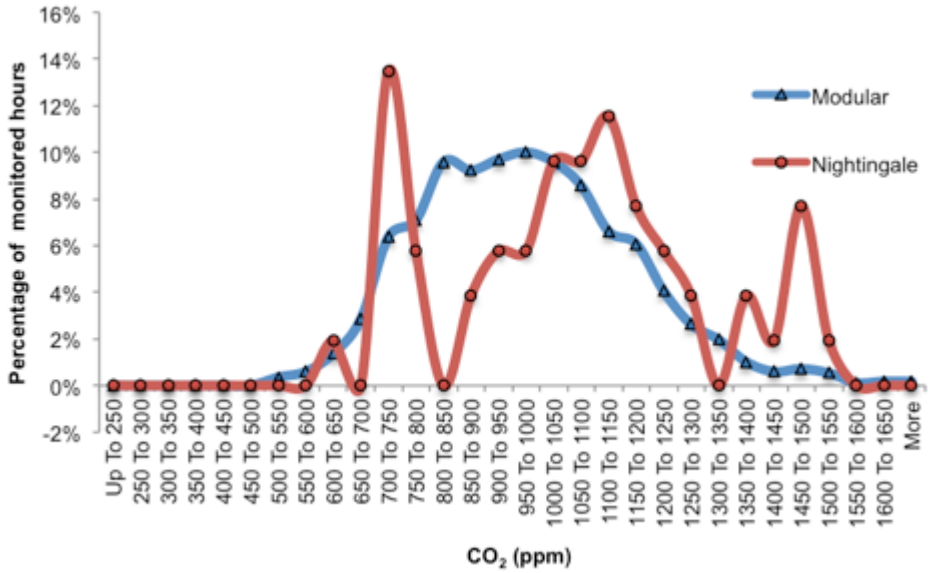


Figure 8.4 – Histogram frequency plots for building CO_2 levels

Comparing the CO_2 levels to the BS EN 15251 limit of no more than 5% of hours above 750ppm. The modular and Nightingale buildings had over 80% of their hours above 750ppm, furthermore, their monitored spaces failed to meet the ASHRAE standard of 1100ppm (ASHRAE, 2001), having 25% and 43% of their respective hours above the recommendation. The results also show that there is a definite difference between the CO_2 levels in the day and night. It seems to be the case that this is related to the occupancy of the building as the results for the modular and Nightingale show that the average hourly CO_2 levels for the night are between 40ppm and 60ppm lower than in the day.

Walk around surveys were conducted to investigate whether the results from the stationary monitoring of the CO_2 levels were representative of the other spaces in the wards. Key points from surveying each of the buildings were:

Nightingale:

- 8 rooms measured
- CO_2 levels ranged from 685ppm to 1150ppm
- Estimated upper limit for air changes = 0.87 to 1.81 ach^{-1}
- Estimated upper limit for flow rates = 6.5 to 18.5 l/s/p

Nucleus:

- 2 bedrooms and 1 corridor measured
- CO_2 levels ranged from 579 to 661ppm
- Rooms supplying 3ach^{-1}
- Measured flow rate to space is larger than 10l/s/p in each room

Modular:

- 10 rooms measured lower floor, 5 rooms measured upper floor
- Lower floor CO_2 levels higher than upper floor
- Multi bed rooms:
    - 665 to 1180ppm;
    - Estimated upper limits = 0.7 to 2.2ach^{-1}; 6.4 to 18.9 l/s/p;
- Single bed:
    - 726 to 1600ppm;
    - Estimated upper limits = 0.7 to 1.3ach^{-1}; 7.7 to 15.3 l/s/p;

When comparing the CO_2 levels, it is clear that the measurements suggest that the Nucleus building had levels suitable for the comfort of hospital patients, this is as expected as the system was mechanically ventilated. The naturally ventilated modular and Nightingale buildings had slightly higher CO_2 levels, with the modular building having none of the single bed spaces below 750ppm, and only 3 of the 7 measured multi-bed spaces achieving levels under this criterion, it is interesting to note, these were all on the upper floor. Conversely, the Nightingale ward had 2 out of the 9 spaces monitored under 750ppm, one of which had no occupants. These results show that the majority of measured spaces had CO_2 levels higher than 750ppm which aligns with the longer term monitoring which demonstrated that the over 80% of hours monitored were above 750ppm.

The guidance recommends that CO_2 levels remain below 1200ppm (ASHRAE, 2001) and flow rates above 10l/s/p (Department of Health, 2007a) to secure odour control. The nucleus building comfortably met these criteria in each of its spaces. The naturally ventilated spaces varied, but both the Nightingale and modular building managed to keep CO_2 levels below 1200ppm, except in the case of one modular single bed space, where there were 4 additional visitors and windows were closed. The estimated upper limits for the flow rates of the naturally ventilated spaces ranged from 6.4 to 18.9 l/s/p

with an average of slightly over 10 l/s/p. The literature review demonstrated that these estimates show a rather large degree of uncertainty, but they can be helpful to show a ballpark figure of what flow rates the ventilation system is providing. Taking this into consideration, it is likely that in the majority of situations, the spaces are providing just enough ventilation to keep odour under control.

Considering infection control, the literature review highlighted that higher air change rates accompanied by infection isolation rooms are the primary ways for reducing the transmission of airborne nosocomial infection. The guidance recommends that 6ach^{-1} is the minimum air change rate for hospital bed spaces (Department of Health, 2007a), which according to the Wells-Riley equation, reduces infection risk to less than 0.1 at low quanta generation rates (Qian et al., 2010). The World Health Organisation recommends that isolation spaces should have an hourly average flow rate of 160l/s/patient, with 60l/s/patient in general ward spaces (WHO, 2009). In addition to this, there is evidence to suggest that air change rates below 2ach^{-1} can greatly increase the risk of infection (Menzies et al., 2000). Comparing the wards to these markers, it becomes apparent that all may be underperforming. The mechanically ventilated nucleus building is doing the best, with 3ach^{-1}, which is above the 2ach^{-1} found in the work of Menzies et al, but is still below 6ach^{-1} recommended by the Department of Health. The naturally ventilated buildings generally have estimated upper limits for their air change rates that are less than 2.2ach^{-1} on the high end and 0.7ach^{-1} on the lower end. It is to be acknowledged that the estimates of air change rate for the naturally ventilated buildings act as a guide. Using them in this way seems to suggests that if there were an infected patient in the ward, there could be a high rate of infection transfer. The modular building does have the added advantage of having naturally ventilated isolation rooms which may have a positive impact of keeping the infected air away from other patients, but even in these spaces, the estimated upper limit for air changes is below 2ach^{-1} and it's estimated 15l/s/patient is drastically under the WHO's 160l/s/patients recommendation for infection control. These observations coupled with the estimated flow rates for all of the ward spaces being below the WHO's recommendation of 60l/s/patient suggests that all spaces measured in BRI may be promoting the transfer of airborne infection.

Bringing the results for the indoor environmental performance of the three case studies together, it is apparent that, overall, the nucleus building had the optimal performance. Out of the three buildings, it was the one that was the most heavily serviced, providing moderate temperatures in summer and fresh air in the wards. The Nightingale and

modular buildings were on par with regards to the poor level of air quality in their naturally ventilated bed spaces. Nevertheless, the Nightingale out performed the modular building in regards to the summer thermal performance. The modular building used advanced technology, which was successful at controlling winter temperatures, but was unsuccessful at minimising overheating. The combination of its poorly controlled mechanical ventilation system and high levels of thermal insulation caused overheating. The combination of these findings demonstrates that servicing buildings with well controlled systems can provide the best indoor environment. In addition to this, the results show that there are traditional structures which do have benefits, and old buildings can perform as well as, or better than new ones.

8.3 Energy Performance

One of the main contributions to knowledge this thesis offers is the quantification of the energy consumption of different building types. This section compares the results from monitoring the energy demands for LTHW, mechanical ventilation and electricity in each of the case-study buildings at Bradford.

8.3.1 LTHW Heating

Each hospital building had its own performance line which identified the amount of energy it used for space heating. From Figure 8.5, it is apparent that the 95% confidence intervals are wider for the modular and nucleus buildings than the Nightingale, especially when the daily average difference between the inside and outside temperature diminishes. The Nightingale building has a larger number of measurements and a higher R^2 value than the two other buildings demonstrating that increasing the number of measurement points enhances confidence in the estimated results.

Building	*Nightingale*	*Nucleus*	*Modular*
Monitored Area	1st Floor 622m^2 2nd Floor 659m^2	1st & 2nd Floor on the left wing of building (484.5m^2 & 483.5m^2 respectively)	1st & 2nd Floors (1892m^2)
LTHW monitored to form Energy demand line[i]	y=1.93x-16.74	y = 1.59x - 11.62	y=1.03x - 9.31
Days in regression	68	34	24
R^2 value	0.87	0.74	0.76
Average internal temperature (°C)	23.9	24	23.2
Space heat loss coefficient (W/m^{2}K)	1.93 ± 0.19	1.59 ± 0.33	1.03 ± 0.25
Normalised heat consumption for LTHW (kWh/m^2/yr)	100.3	96.8	46.8

[i]Where x is the daily average internal to external air temperature difference (T_{ar}-T_{ao}) and y is the daily average LTHW heating energy demand

Table 8.4 - Different results from the monitoring of LTHW

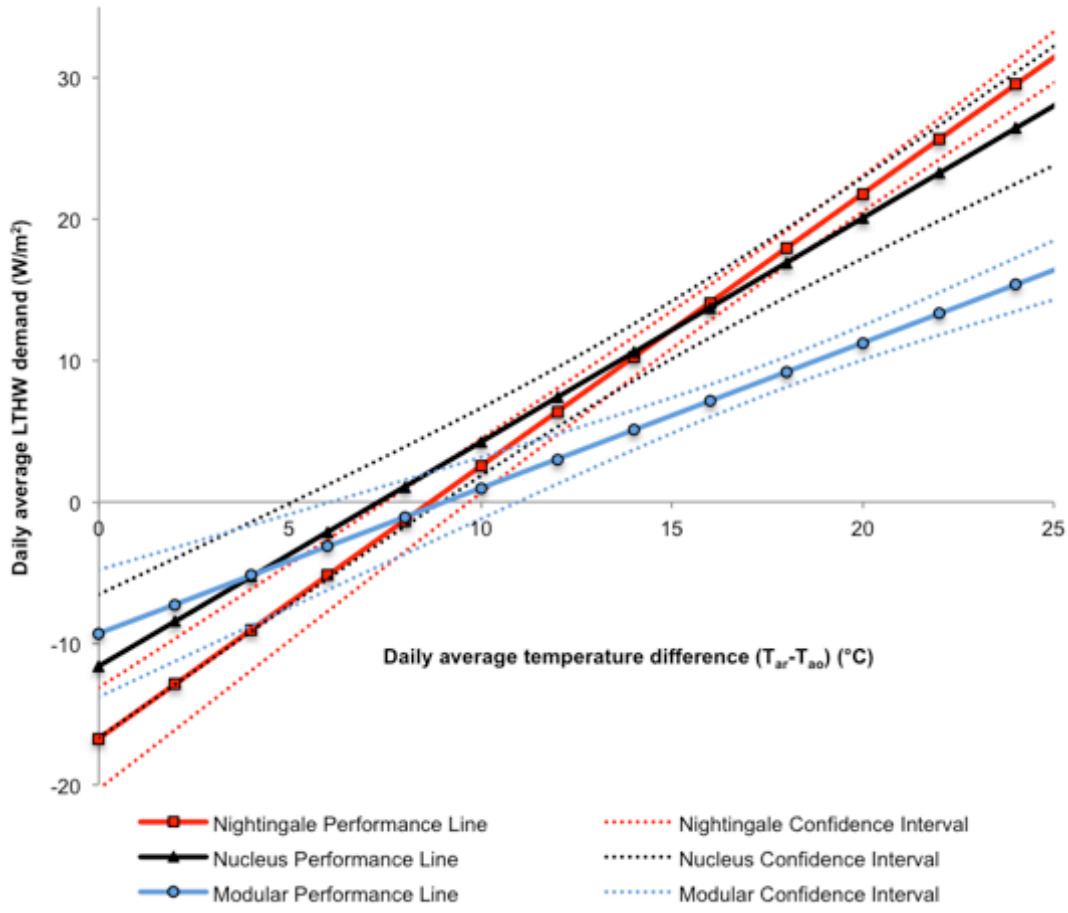


Figure 8.5 - Comparison between energy signatures and 95% confidence intervals for each of the buildings

There is a predictable trend in the U-values of the buildings; the older the building, the higher its U-values as newer buildings reflect the progression in the building regulations. The modular building had the lowest U-values, followed by the nucleus

and then Nightingale buildings. It is to be noted, that the Nightingale building's roof was retrofitted with 120mm of additional insulation in 2010 which reduced the U-value from 0.43 to 0.19 W/m^{2}K.

Building (w/m^{2}K)	*Nightingale*	*Nucleus*	*Modular*	*Part L2a*
Wall	0.92	0.37	0.15	0.25
Roof	0.19	0.28	0.11	0.35
Ground	/	/	0.14	0.25
Windows	2.75	2.75	1.2	2.2
Average U-value	0.69	0.44	0.18	/

Average U-value calculations take into consideration the roof, walls and windows, using the measured surface area of the roof and walls and assuming windows take up 10% of the total surface area.

Table 8.5 - Estimated U-values for different parts of monitored buildings

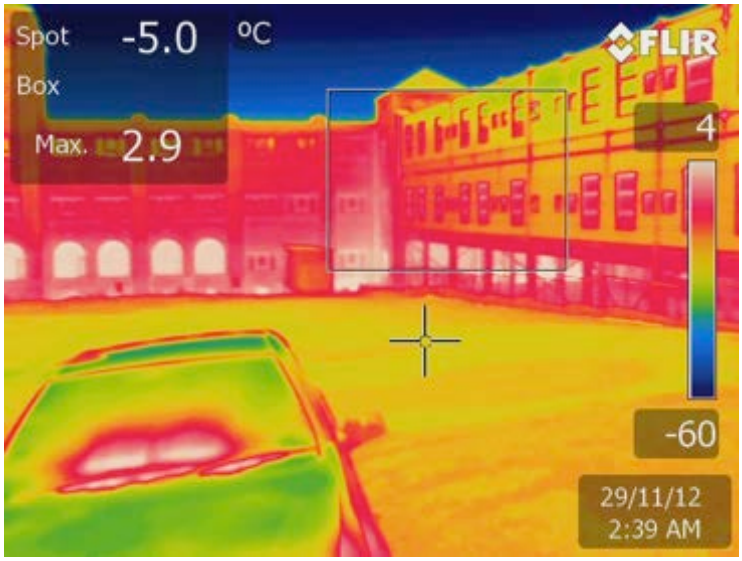


Figure 8.6 - Thermal image showing the heat loss from the nightingale buildings (left) and modular building (right) lighter colour of modular building indicates lower temperature and less heat loss

The gradient of the performance line represents an estimate of the building's space heat-loss coefficient; a metric showing the rate at which heat escapes from the building through convection and conduction. The uncertainty of the line was calculated using Equation 3.35 this provided confidence limits for the heat-loss coefficients. The overall fabric U-value was calculated using the U-values and areas for the walls, roof and windows. There was a positive correlation between the space heat loss coefficient (Table 8.4) and the overall U-value (Figure 8.7). Furthermore, the modular building with the lowest overall U-value had the lowest energy consumption. Comparatively, the nucleus and Nightingale buildings that had higher overall U-values (Table 8.5), had an energy consumption of 96.3 and 100.3kWh/m^2 respectively, which was close to double that of the modular building (46.8kWh/m^2) (Table 8.4).

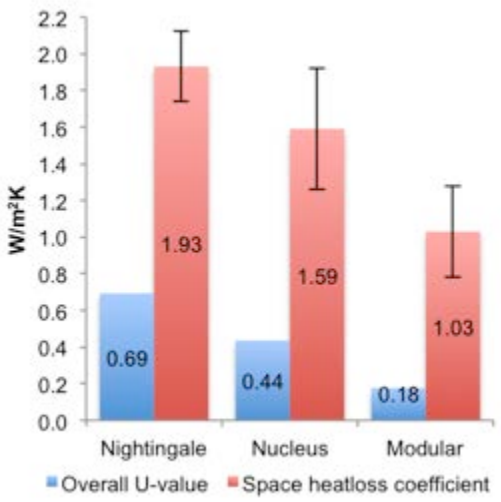


Figure 8.7 – Comparison of overall U-value and space heat loss coefficient for each building

8.3.2 Mechanical Ventilation

The modular building's ventilation system did not incorporate any heating element, therefore the carbon emissions associated with mechanical ventilation were less than a third of the emissions produced by the nucleus building (Table 8.6). The modular building did however, have carbon emissions attributed to the electricity used for the fans.

A close relationship was identified between the modular building's AHU supply air temperature and the ambient air temperature. As it got warmer outside, the temperature of the supply air would rise, increasing the rate of summer overheating. Furthermore, in the winter, supply temperatures would be rather cool; on the coldest day in winter 2012/13 the ambient temperature was -6°C and after passing through the heat exchanger the supply temperature was 10°C.

The nucleus building had the greatest carbon emissions from mechanical ventilation as it was mechanically ventilated with no heat recovery. It was interesting to find that when measured the extract rates were less than half of their design values. This problem could be down to filters not being changed and the lack of regular system maintenance. When visiting the various plant rooms across the case-study sites (Chapter 4), the estates teams often identified that filters on the extract fans were old, partially blocked and needed replacing.

	Nightingale	*Nucleus*	*Modular*
Ventilation system	**Natural** Wards ventilated through bedroom windows, simple mini extract fans fitted in toilets and bathrooms	**Mechanical** All multi-bed rooms ventilated mechanically with supply and extract ducts, single bed rooms ventilated through windows	**Mixed mode** (Bedroom = natural ventilation through windows, Internal corridors = mechanical ventilation)
Heat recovery	N/A	**None**	**Plate heat exchanger** AHU has no heating coils all incoming air heat is taken from extract
Supply flow rate (m^3/s)	N/A	Core = 0.211 Wards = 0.569	0.575
Extract flow rate (m^3/s)	N/A	0.277	0.775
Supply flow rate (ach^{-1})	N/A	Multi-bed = 2.97	Corridor = 2.95
Average air supply temp (°C)	N/A	19.2	19.7
Energy consumption for air heating[i] ($kWh/m^2/yr$)	0	218.2	0
Electrical consumption for AHU Fans ($kWh/m^2/yr$)	0	52.6	35.7
Total carbon emissions for ventilation ($kgCO_2/m^2/yr$)	0	70.4	19.6

[i]Local boiler efficiency = 0.72

Table 8.6 - Results from the monitoring of mechanical ventilation systems

8.3.3 Electricity

The average daily electrical energy profiles were compared for the Nightingale, modular and Glenfield nucleus[i] buildings (Figure 8.8). A similar pattern was found in all the wards closely reflecting the general ward occupancy profile (Figure 8.9). A possible explanation for the pattern is as follows; the energy consumption increases at 07:00 when the nurses first shift begins and lights are fully turned on. The wards each have a night lighting system where the lights are dimmed so patients can sleep. As the day progresses, cleaning staff come onto the ward and begin to use their equipment, doctors come on at 09:00 and begin to use computers and other plug in devices, throughout all this time nurses take short breaks to get cups of tea, which uses

[i] It was not possible to monitor the ward distribution board in the Bradford nucleus building, therefore results from a Glenfield nucleus building were used for comparison in this analysis.

electrical energy to heat the water. Other major events causing noticeable spikes in the consumption can be seen at lunch and dinner times. This energy consumption comes from a dining station used to serve warm food to patients and water heaters used to boil water for hot drinks and washing dishes. From 18:00 until 00:00, the electrical consumption decreases in all of the wards until it reaches the base level, for each ward this falls in line with nurses going onto night shift, and then putting patients to bed and progressively turning lights off.

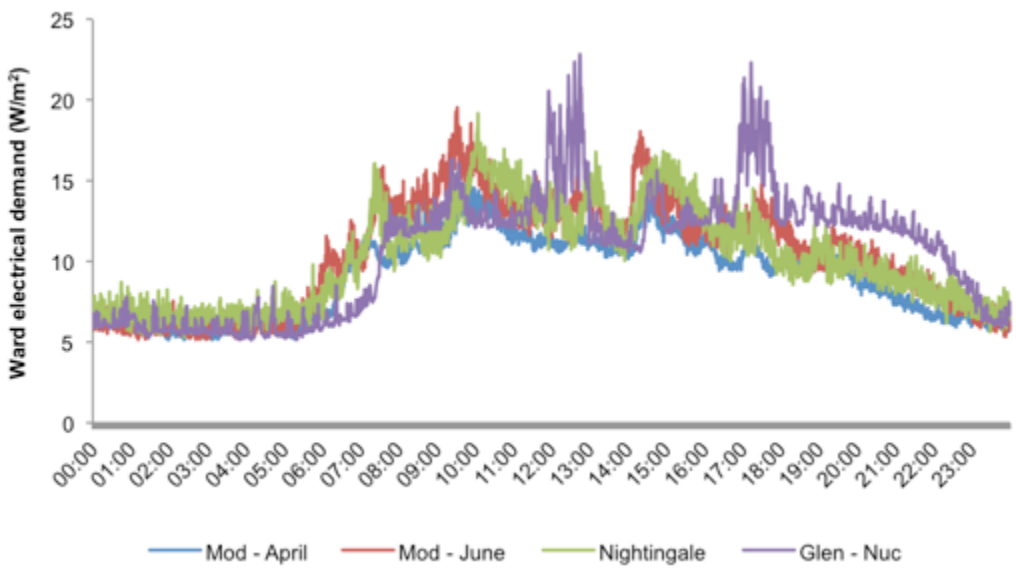


Figure 8.8 - Comparison between the average daily ward electrical profile for each of the different monitored buildings

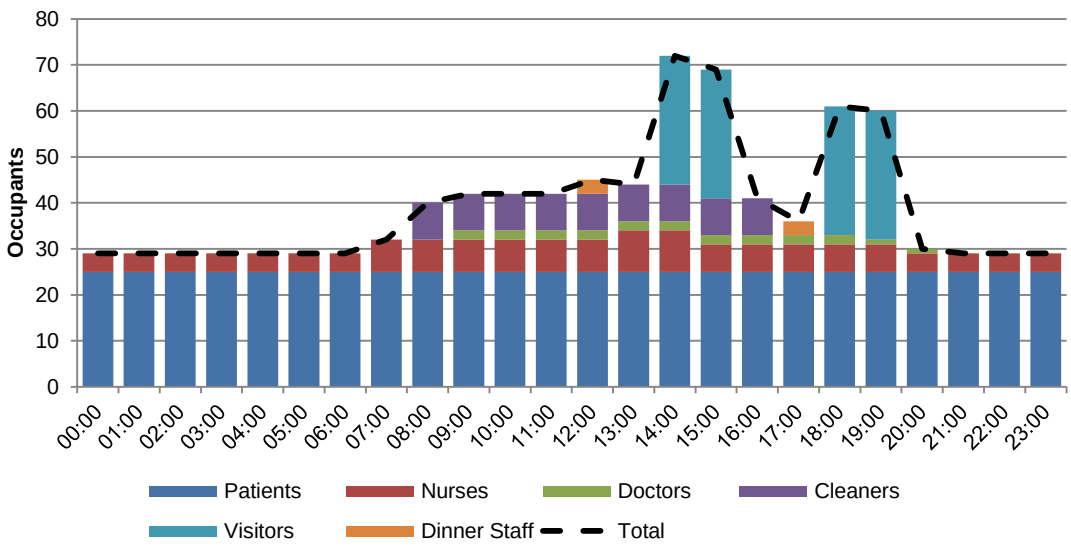


Figure 8.9 - General occupancy profile for all of the monitored Buildings

Overall the nucleus building had the largest electrical energy consumption, followed by the Nightingale and modular building (Table 8.7). This was due to it having higher

mechanical supply and extract rates, increasing the electricity used for fans, as well as having increased pump loads necessary to pump hot water through its AHUs.

(kWh/m²/yr)	*Nightingale*	*Nucleus*	*Modular*
Ward	99.2	(92.9)	84.3
Pumps	5.1+(5)	23.9	14.0
Supply Fans	0.0	23.9	13.6
Extract Fans	0.0	28.7	22.1
Total Plant	**10.1**	**76.5**	**49.7**
Total	109.3	169.1	134.0

Table 8.7 - Electricity consumption for each of the hospital buildings (figures in brackets indicate these were assumed, to enable comparison)

8.4 Total Energy and CO_2 emissions

This section of the report brings the energy consumption results for the different buildings together. It assists in tackling one of the original objectives of the thesis; to identify the energy consumption for individual building types within the NHS.

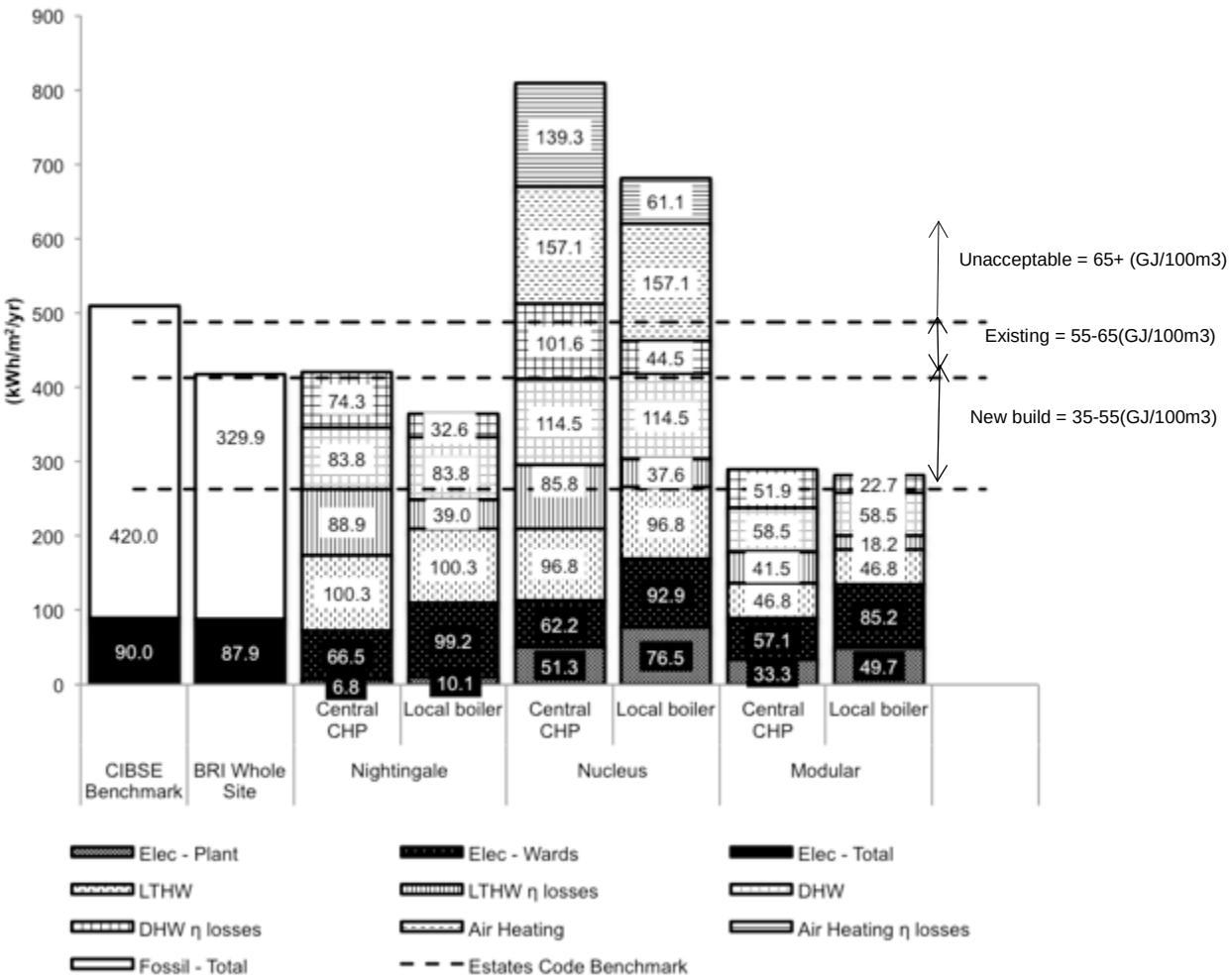


Figure 8.10 - Comparison between overall energy consumption for the different individual hospital buildings, alongside Bradford's total site energy consumption and the CISBE Benchmark

The modular building had the lowest energy consumption falling into the new build category of the Estates Code benchmark (Figure 8.10). The Nightingale building had the second lowest consumption, with the centrally supplied scenario just falling on the borderline of the new-build/existing category and the hypothetical locally supplied system falling into the new build category. This is exceptional for the Nightingale building which was built close to 90 years before the modular building. When comparing the two it can be seen that the main difference between them is that the LTHW use for the modular building is less than half of the amount for the Nightingale building, which is primarily due to higher levels of insulation being found in the modular building.

The nucleus building had considerably larger energy consumption than the two others. This can be attributed to its mechanical ventilation system which placed a weighty load on both the gas consumption used to heat the air and the electrical power consumption necessary for the fans used to move the air around the building. The building fell into the unacceptable category with an energy consumption of over 65GJ/100m^3/yr.

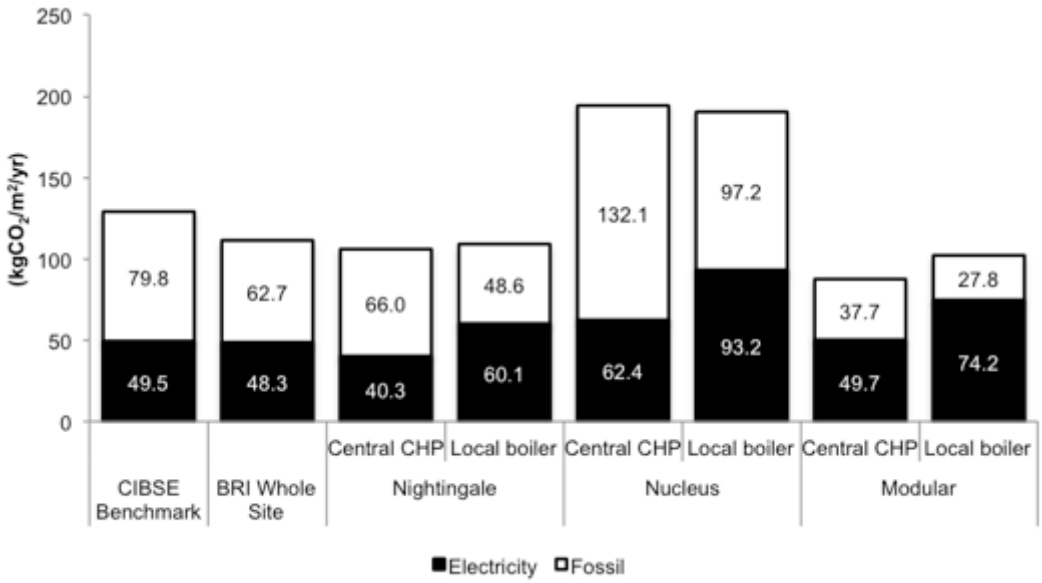


Figure 8.11 - Comparison between overall carbon emissions for the different individual hospital buildings, alongside Bradford's total site energy consumption and the CISBE Benchmark

The carbon emissions followed a similar pattern to that of the energy consumption with the main difference being that each of the buildings did not perform as well when compared to the CIBSE benchmark (Figure 8.11). Another noticeable point is that the electrical emissions for the individual buildings supplied from the CHP unit were closer

to the emissions for the BRI site, than the emissions for the individual buildings supplied from the scenario using a local boiler. However, when looking at the energy consumption, the hypothetical locally supplied buildings had lower energy consumptions. This demonstrates that the way in which a building is supplied, i.e. via central plant with CHP, local boiler etc. plays a large role into the distribution between electrical and fossil fuel energy use in a building and therefore its overall carbon emissions. In all cases, except for the nucleus building, it is marginally preferable to use the centralised CHP plant, even though it has high distribution efficiency losses for the hot water. The only example where it may not be viable is where a building such as the nucleus building has a very high heating load. When considering future benchmarks for hospitals or other large buildings it may be useful to consider the source of the energy, raising the heating benchmark and lowering the electrical benchmark when CHP is used and doing the opposite when locally supplied.

In addition to the nucleus building's mechanical ventilation, another aspect of its energy consumption which was higher than the two other buildings was its DHW. The total for the nucleus building was 216.1kWh/m^2/yr whereas the total for the Nightingale and modular buildings were 158.1 and 110.4 kWh/m^2/yr respectively. The DHW was estimated according to the number of beds in each ward with each of the wards in the buildings holding 28 patients. The energy consumption of the building was normalised according to the floor area of the building in order to compare them to the CIBSE and Estates Code benchmarks. This placed the nucleus building at a disadvantage because it's wards were 484m^2 which was smaller than the nightingale and modular buildings, each having floor areas of, 622m^2 and 946m^2 respectively. The DHW energy consumption was normalised to appear smaller for the modular building as the energy was spread across its larger floor area. This demonstrates that only using floor area may not be the best way to assess the energy performance of a hospital building and currently the two main forms of hospital benchmarks do not take occupancy into consideration.

There are a few examples in the literature where hospital buildings energy consumption have been identified through either monitoring or modelling. In Giridharan and Lomas' paper (2012b) on Nightingale buildings, a model was produced which predicted that a Nightingale building in its existing format, i.e. no shading, regular Nightingale ward arrangement, ventilation through windows and perimeter heating would consume around 25GJ/100m3/yr. This result is below the one found in this study, and it is expected this is the case as plant efficiencies do not seem to have

been taken into consideration. Nevertheless, the result helps to support the view that existing Nightingale buildings can have energy consumption levels similar to those of new builds. In terms of mechanically ventilated buildings, the literature showed that a modelled tower block building demonstrated an energy consumption of 101GJ/100m^3 and two nucleus buildings, one retrofitted and the other in its original form demonstrated monitored energy consumptions of 407kWh/m^2 (54GJ/100m^3) and 720kWh/m^2 (96GJ/100m^3) respectively (NHS Estates, 1995a). These results show that the nucleus building in this thesis is performing on a similar level to other mechanically ventilated buildings in the UK. The NHS Estates, 1995a study demonstrates that through the implementation of heat recovery and a few other energy reduction measures, the nucleus' energy consumption was reduced from 720kWh/m^2 to 407kWh/m^2 . This helps to highlight that retrofit measures could be implemented in BRI's nucleus building to reduce its high energy consumption. The author has been unable to identify any published material on the energy consumption of modular buildings, but when comparing the results for the modular monitored in this study to other buildings utilising some form of mechanical ventilation, it becomes clear that the use of heat recovery ventilation can significantly diminish the energy footprint of a hospital building.

Normalising the buildings energy consumptions according to occupancy considerably alters the way they compare against each other (Figure 8.12). Using the metric of annual energy consumption per patient (kWh/patient/yr), the nucleus building's consumption is reduced significantly and the modular building is on par with the Nightingale. Considering the annual carbon emissions per patient (kgCO_2/patient/yr) (Figure 8.13), the pattern changed even more with Nightingale having the lowest emissions and the nucleus and modular buildings having emissions which were similar to each other.

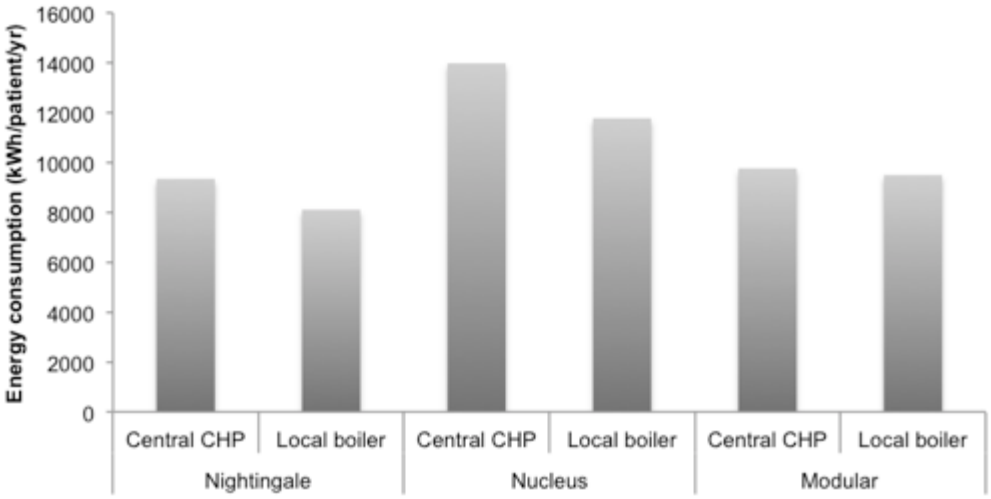


Figure 8.12 - Energy consumption per patient for each building

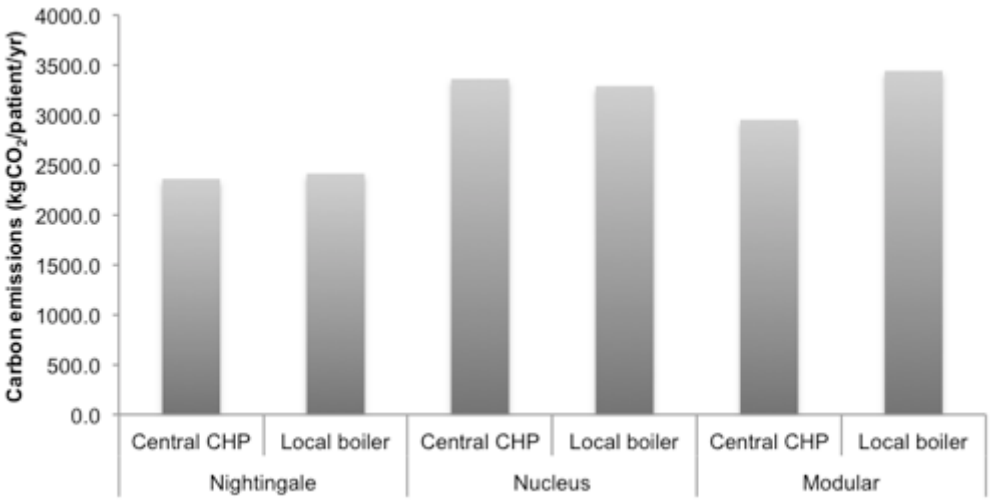


Figure 8.13 – Annual carbon emissions per patient for each building

Table 8.8 demonstrates the amount of floor area each building's ward has per patient. The modular building has 33.8m^2, the Nightingale has 23.5m^2, and the nucleus has 17.3m^2. The modular building uses close to double the nucleus' floor area to serve the same number of patients. This means twice as much space needs to be serviced, explaining why, when looking at the energy consumption in terms of the amount used for each patient, the modular building is the highest. There are a number of reasons why the modular building has a larger floor area; firstly, it has more single bed spaces, which use more space to hold patients than multi-bed spaces. Secondly, the modular building provides more space for each patient for both its multi and single bed spaces, giving 12.5m^2 and 20m^2 for multi and single bed respectively compared to the Nightingale and nucleus which were less in both circumstances. Thirdly, the nucleus building, uses the least space for corridors, storage and nurse facilities and largest

percentage of space for patient care. With the nucleus using 67% and the Nightingale and modular using 53% and 46% respectively.

	Ward area (m^2)	*Total patients*	*Single beds*	*Area per patient (m^2/P)*			*Ward area*		
				Ward	Multi	Single	Multi-bed	Single bed	Other
Nightingale	659	28	3	23.5	11.7	15.3	46%	7%	47%
Nucleus	484	28	4	17.3	11.3	12.9	56%	11%	34%
Modular	946	28	12	33.8	12.5	20.0	21%	25%	54%

Table 8.8 - Ward floor area distributions

These examples demonstrate two critical points: one, that it is not enough to simply design a low carbon building with the most efficient technologies and highest quality insulation. But rather, the function for the building needs to be taken into consideration and it's floor plan needs to be designed as specifically as possible for the particular purpose. The modular building is a very generic shape using a construction method that is universal and can be used for a number of different types of building. The nucleus building, on the other hand, has been designed specifically for hospitals and for providing services to the patients; the patient bedrooms surrounding the nurses station to provide nurses with the quickest access to each of the spaces. The second point is that when comparing building energy consumptions to each other, using floor area for normalisation may not always be relied upon to illustrate which building has been designed the most effectively.

8.5 Reduction Measures

In order to investigate the impact of changing the set point temperature in each of the different buildings, a number of temperatures at increments of 0.2°C were substituted into each of the building's energy signature formulas to calculate the yearly energy consumption of the buildings (Figure 8.14)

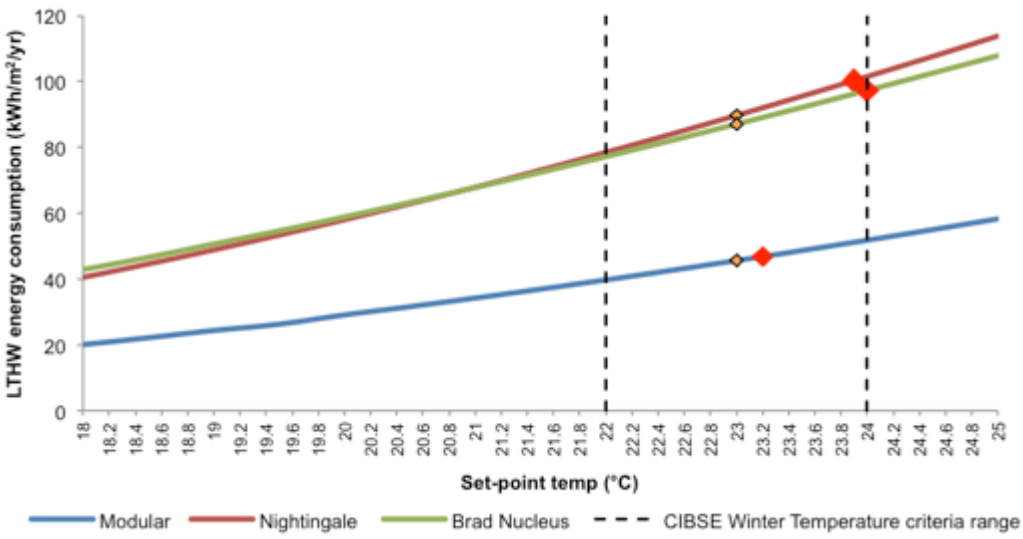


Figure 8.14 - Influence ward set point temperature has on annual LTHW energy consumption; (red dots = measured set-point temperature, yellow dot = ideal set-point temperature CIBSE)

The modular building's average temperature was 0.2°C higher than the CIBSE guidelines ideal. If the temperature was reduced to 23°C the energy consumption for space heating would have been reduced from 46.82 to 45.6 kWh/m^2/yr a reduction of 1.22 kWh/m^2/yr. The other wards were heated to a higher temperature than the modular building and had steeper performance lines (Figure 8.5). Therefore, if the average temperature of the wards was reduced to 23°C, more energy would be saved. It was found that 10.61 and 10.42 kWh/m^2/yr could be saved for the Nightingale and nucleus buildings respectively. In terms of the percentages of total fossil fuel consumption for the buildings supplied by the centralised CHP, the reductions in average ward temperature could save 1% for the modular building, and 3.1% and 1.5% of the Nightingale and nucleus buildings respectively.

In addition to lowering the average ward temperatures as close to 23°C as possible, the literature demonstrated that two other thermostat set-point methods have been successful in lowering the heating energy consumption; zonal heating control and heating temperature set-back time periods (Moon & Han, 2011; Vine, 1986). Applying zonal heating control to the case studies in this report, it may be useful to set an individual set-point temperature for the different areas, i.e. one set-point temperature for the actual bed spaces, one for the nurses' station and one for the corridors.

The following heating control scenarios have been tested to investigate how much energy can be saved on the LTHW load (Table 8.9).

Scenario	*Area*	*Set Point temperatures*
(S1) 23°C	Whole ward	23°C >>> Constant
(S2) Moderate Set-back	Whole ward	23°C >>> 06:00 – 23:00 21°C >>> 23:00 – 06:00
(S3) Large Set-back	Whole ward	23°C >>> 06:00 – 23:00 19°C >>> 23:00 – 06:00
(S4) Zonal	Patient Bedroom/Toilet & Bathroom areas	23°C >>> Constant
	Rest of ward	19°C >>> Constant
(S5) Zonal Set-back	Patient Bedroom/Toilet & Bathroom areas	23°C >>> 06:00 – 23:00 19°C >>> 23:00 – 06:00
	Nurses Area	21°C >>> 06:00 – 23:00 19°C >>> 23:00 – 06:00
	Rest of ward	19°C >>> 06:00 – 23:00 18°C >>> 23:00 – 06:00

Table 8.9 - Ward heating control intervention scenarios

Scenarios 1 and 2

The first scenario (S1), discussed above, involves lowering the set-point temperature to 23°C according to the recommendations laid down in the CIBSE guidance. The second scenario (S2) investigates the impact of a moderate setback temperature. The daytime temperature of the ward was set to 23°C and the night time which was defined as from 23:00 to 06:00 was set at a temperature of 21°C. At the latest patients were put to bed at mid-night, therefore turning the heating down from 23:00 gives the opportunity for the temperature to decrease to 21°C by 00:00.The first morning shift starts at 07:00; turning the heating up from 06:00 allows one hour for the heating to reach the desired temperature.

Scenario 3 – Large Set back

In this scenario, the night time temperature was set to 19°C. The night time period and the daytime temperature was the same as scenario 2.

Scenario 4 – Zonal

This scenario splits each hospital ward into two zones; zone one is for the patient areas, i.e. bedrooms, toilets and bathrooms and zone two is for everything else, i.e. corridors, nurses stations, circulation areas etc. In zone one the patient areas were set to 23°C and the other areas were set to a temperature of 19°C, which is deemed

acceptable as CIBSE Guide A suggests that circulation spaces have a temperature range from 19-24°C and nurses stations have a range from 19-22°C. The lower end of these recommendations were chosen for the set point as people in these spaces, generally were moving around, i.e. walking through corridors which increased their metabolic activity level; in addition to this people moved through these areas to other areas of importance i.e. patient bedroom or nurses station. The results for the measured temperatures demonstrate that the nurse stations were among the warmest spaces in the wards. Therefore having a low set point temperature would not have a large impact on the staff as these areas had the most thermal gains.

Scenario 5 – Zonal Set-Back temperatures

This final scenario applies different set-back temperatures to three different zones. In zone one the bedrooms had their temperatures reduced to 19°C at night, which was close to the minimal temperature in HTM-03-01 and at the high end of the temperature range recommended by CIBSE for domestic bedroom areas (17-19°C) (CIBSE, 2005b). The second zone was specifically for the nurses who were on night duty. From discussing the role of nurses on night duty with a number of NHS staff, it was identified that after putting the last of the patients to bed at the latest time of midnight, the nurses return to the nurses station or office where they carry out paper work and review patient records etc. They do this until the specified time when they need to check on each of the patients which takes place at a minimum of once every 4 hours. As the nurses carry out office-like functions during the night shift, the temperature in their area was set to be 21°C. In all of the wards, the average size of the offices and nurses area was 16m^2, this provided enough working space for the 4 members of staff which usually worked at this time. The third zone incorporated the circulation spaces and had the temperature reduced from 19°C during the day to 18°C at night.

One of the requisites to implementing zonal heating is that there needs to be thermal barriers between the individual zones to maintain their set temperatures. These barriers are as simple as closing doors, which stops airflow, the primary heat transfer medium moving between the spaces. Changing insulation levels of walls and doors has negligible impact on energy savings as heat transfer through internal barriers are insignificant compared to the heat transfer from the building to the outside (Ingersoll & Huang, 1985). Considering the mechanically ventilated buildings, no changes would need to be made to their existing mechanical ventilation systems, as they typically have space specific supply and extracts providing air at less than or equal to 19°C.

To calculate the result for each scenario the energy data for each set-point temperature found in Figure 8.14 was multiplied by the percentage of hours in use. For zonal scenarios this was then multiplied by the percentage area distribution within each hospital ward.

Ward Floor area	*Bedroom & bathroom*	*Nurse station*	*Rest of ward*
Nightingale	53%	2.4%	52.1%
Nucleus	67%	3.3%	34.3%
Modular	46%	1.7%	50.2%

Table 8.10 – Distribution of floor area on in each building

Heating Scenario	**LTHW Energy Consumption (kWh/m^2/yr) and Energy Savings (%)**										
	Original	(S1) 23°C		(S2) Moderate Set-back		(S3) Extreme Set-back		(S4) Zonal		(S5) Zonal Set-back	
Nightingale	100.3	89.7	10.6%	83.3	16.9%	77.8	22.5%	70.5	29.7%	63.4	36.8%
Nucleus	96.3	87.1	9.6%	81.4	15.4%	76.4	20.6%	75.0	22.1%	67.6	29.8%
Modular	46.8	45.6	2.6%	42.3	9.7%	39.4	15.8%	34.1	27.1%	30.8	34.3%

Table 8.11 – Effect of changing the heating profiles in each ward on energy demand for LTHW heating, with percentage change from the original result.

The results show that the LTHW energy consumption can be reduced considerably by implementing the simple heating control measures stated above. As expected, the more measures undertaken, the more energy saved, and for the most stringent measures, the heating energy consumption could be reduced by close to 35%. However, due to complications with scenario 5, i.e. opening and closing of doors and slight increases in ward temperature at specific times to meet occupants requests it may not be possible to save as much as has been predicted. Nevertheless, scenarios 3 and 4, extreme set-back and zonal are very much achievable with wards as they are today; they indicate that with the poorer performing buildings it may be possible to save at least 25% on heating energy through the implementation of these simple control measures.

Another facet this work brings to light is that, when using zonal temperature control, the ward with the bedrooms taking up the largest percentage of the space will have the largest energy consumption. These wards, therefore, are the ones which will benefit the most from measures similar to scenario 5 which implements both the zonal and set-back temperature control aspects.

8.6 Recommendations

This section of the chapter uses the findings discussed in the previous sections to provide recommendations regarding the improvement of monitoring in the NHS and the design of new hospital buildings.

8.6.1 Monitoring

The results have demonstrated that the monitoring method can be used successfully to monitor the energy consumption of existing individual buildings of diverse age and type. The method can therefore be recommended to estates teams in the NHS as it allows them to specify which buildings are performing inefficiently and where they should focus their efforts to implement energy reduction measures.

The LTHW performance line method is useful for the NHS, however to increase ease of operation it would be necessary for the NHS estates team to create monitoring points; places on pipes where insulation is removed so that equipment can be installed quickly and efficiently. This would require that correct drawings are identified, in addition to the safe removal of insulation which may contain asbestos.

For mechanical ventilation, the method used in the thesis would be improved by monitoring the air supply temperature over different seasons, this could be done in parallel with LTHW monitoring and the monitoring of the electrical consumption for the wards and plant. The method could be implemented if the hospital estates team brought a single heat flow meter, a dozen current transformers and ward temperature monitors. This equipment could be fitted for a week in each building in each season of the year. One of the limitations of the method was that hooks and other devices had to be installed to hold sensors. If monitoring points were already in place in anticipation for the use of the method, much time and effort would be saved and less equipment would be lost.

As the buildings types within the NHS are different, it may not be wise to benchmark them against each other as they have different factors limiting their consumption. Instead, the analysis of the annual and seasonal data monitored for an individual building could be compared against its performance in previous years to enable energy managers to quantify the impact of energy reduction measures on the building. It is important to emphasis that it would be important to monitor the LTHW on a building-to-building level rather than on a ward level as the study showed that there

was often heat transfer between wards in a building meaning that it is near impossible to actually identify how much energy is being used on each ward.

As the energy consumption of different building types varies so much, when it comes to assessing the NHS's energy consumption as a whole, it may be useful to provide benchmarks and energy reduction guidance for each type of existing building. The benchmarks could be for traditional Nightingale buildings, 1960 general district hospitals which include tower block and courtyard hospitals which have high ventilation rates. Another category could be nucleus buildings and the final type could be hospitals built in recent years, which would include the modular building and any other recently built building.

Although the results from the study demonstrated that assessing the carbon emissions per patient changed the profile of results. In the method which has been recommended above, the building would be compared to buildings of its type which would eliminate the impact occupant density had on the energy emissions and therefore it would be fair to use floor area as a method to normalise the energy consumption from year to year, or one building to another in a different location.

8.6.2 Building Design

This section addresses the final research question presented in the introduction chapter of the thesis; "Which principles from existing hospital building design can be carried forward into the design of new low carbon hospital buildings?" Building form and its engineering features are the two central features that contribute to a hospital buildings design. The following recommendations will focus on these areas breaking them down into built form and layout, building fabric, heating systems, ventilation and monitoring.

Both the modular and Nightingale buildings in the study were rather long and narrow which allowed the rooms on the outside of the building to obtain natural ventilation and lighting. They had their length running from the south to the north with their rooms facing in the east-west direction obtaining similar amounts of solar radiation throughout the entirety of the day. On the other hand the nucleus building had a cruciform layout with wards facing north, east and west, each wing having windows which had the potential to provide natural ventilation as effectively as the other two buildings. When comparing the buildings performance, the results suggested that none of the building

forms provided significant advantage over the others in terms of their indoor environmental conditions. While when assessing the buildings energy consumption in terms of energy use per patient, the nucleus buildings energy performance stood out due to its efficient use of space within the ward. Consequently, following the example of the nucleus building, it is recommended that low carbon hospital design should strive to minimise the space that is not used for patients. This tends to conflict with the move towards single bed spaces which are preferred for many non-energy related reasons.

The results demonstrated that the building fabric had a large impact on the buildings performance. The modular building with the lighter weight fabric responded the most to ambient temperatures in the summer months. Furthermore, with the highest levels of insulation and lowest levels of infiltration, it overheated the most. Comparatively, the nucleus and Nightingale buildings had a masonry construction, and were less responsive to warm ambient temperatures due to their heavier thermal masses. In addition to summer thermal comfort, the building fabric also had a profound effect on the amount of LTHW heating used. The modular building, with the highest levels of insulation, used substantially less heating than the Nightingale and nucleus buildings, proposing that it is well worth having high levels of insulation to reduce the winter heating load, which could be reduced by close to 50%. In conclusion, it is recommended that the optimal building would have high levels of insulation, with a heavy weight structure to provide good thermal mass to stabilise the temperatures in warm ambient temperatures.

Comparing the internal air temperatures during the heating season demonstrated that the modular building contained temperatures closest to the CIBSE target due to its LTHW system, which controlled the temperatures in each space. In addition, the energy reduction section, which investigated different control measures on the LTHW consumption showed that close control of the temperatures and an advanced heating control system could reduce the energy consumption for LTHW. Therefore it is recommended that the LTHW hot water system uses a zonal temperature control system combined with a BMS system to provide space specific set-back temperatures related to the needs of the occupants.

Assessing the case studies revealed that ventilation was a problematic area for each of the buildings. The modular and Nightingale buildings bedrooms were naturally ventilated but were unable to provide sufficient levels of ventilation during the heating

season, while the nucleus building was able to provide high levels of air quality, but at the cost of a high energy consumption. Viewing the problem on both sides of the spectrum, ventilation is an area well worth carrying out further investigations. Although there were negative aspects associated with each building's ventilation system, there were positive lessons that could be drawn from each of the systems. The nucleus' mechanical ventilation system provided high levels of air quality using a rate of 2.95ach^{-1} as well as offering some cooling potential due to the inlets being positioned in a shaded area on the outside of the building. In addition to naturally ventilating the bedrooms, the modular building also used a heat recovery ventilation system which did not use any water heating to warm the air coming into the building, this provided fresh air into the corridor areas of the building only using energy for fans to move the air. One disadvantage of this system was that due to poor control of the bypass, heat was recovered in the system during the summer, causing overheating. Finally, from monitoring the window opening patterns in the modular building, it was identified that when 3 out of 5 of the windows were opened, suitable levels of ventilation could be provided naturally.

Using the above findings, it would be recommended that the optimal building would use a mechanical ventilation system with heat recovery to provide air at a rate of up to 3ach^{-1} to the bed spaces. For the heat recovery system to work effectively more air would need to be extracted than supplied in order for enough heat energy to be supplied to incoming air, therefore it would be useful to have the extract ducts in each of the spaces providing a slightly negatively pressurised environment. As the CO_2 levels varied throughout the day and the ability to ventilate naturally was dependant on the number of windows opened, which was in turn related to the ambient temperature. It would be beneficial for the system to have a mixed mode operation with variable air volume (VAV) control so the flow rate supplied to the bed-spaces could change depending on the levels of CO_2 in the space, thus saving energy used for the electrical fans. Furthermore, if the system were to be used in summer, it would be recommended that the inlets to the system be placed in a position with minimal heat gains. The recommendations above focus on mechanical ventilation, it is to be noted that advanced natural ventilation may also provide similar levels of air quality, with minimal energy consumption, however, the investigation of this type of system was out of the scope of the study.

Recommendations for monitoring discussed above have focused on existing hospital buildings. However, for the optimal building, it would be important to include monitoring

from the conception stage of the building design. It is recommended that localised monitoring equipment be installed when the building is constructed. This would simply involve permanent heat flow meters on the LTHW pipework supplying the building. As well as meters on the fans for the VAV ventilation system and distribution boards supplying the wards energy. These monitoring devices would be directly connected to the main hospital BMS system which would log the data on a set basis, enabling the energy manager to analyse the performance of the building and make changes as is necessary.

8.7 Summary

This chapter has compared the three case study buildings and identified patterns in their internal environmental and energy performances, specifically identifying their summer and winter thermal performance, air quality, LTHW heating, mechanical ventilation and electrical consumption. Out of the three buildings, the modular building provided the best winter temperatures due to its advanced BMS control system. Winter temperatures were directly related to the LTHW energy consumption calculated using the energy performance lines. The modular building, which had the highest levels of insulation and lowest rates of infiltration, had the lowest LTHW load followed by the Nightingale and nucleus buildings which were very similar. Operational measures to reduce the LTHW load were implemented using the performance lines to predict the energy which could be saved using set-back and zonal set-point temperature scenarios. Through these measures it was found that in realistic circumstances, the current LTHW loads could be reduced by nearly 25%.

In the summer, the temperatures in the nucleus and Nightingale buildings bed spaces met all of the overheating risk criteria. The modular building on the other hand failed to meet any of the summer comfort criteria except those which specified that minimal hours exceed 28°C. The modular building's mechanical ventilation exacerbated the temperatures causing serious overheating in the central areas. The nucleus building provided CO_2 levels and air flow rates suitable for the comfort of sick and recovering patients at the cost of a high air heating energy consumption. The Nightingale and modular buildings used natural ventilation to ventilate the bedroom areas of the ward, but the results for these showed that despite savings in energy, the CO_2 levels were over the recommended levels for in excess of 80% of their monitored hours. Conversely, when it came to infection control, the measured ventilation rates in the nucleus building were below the recommended 6ach^{-1} and the maximum estimated air

change rates for the naturally ventilated buildings suggested that they also failed to meet the same criteria, presenting higher risk for infection transmission.

Overall the nucleus building consumed the most energy, exceeding all benchmarks, the Nightingale was on the borderline of the new build and existing category and the modular building consumed the least, falling towards the bottom end of the new build category. The perception of each building's energy consumption and carbon emissions changed when energy demand was normalised according to the number of patients. On this energy use per patient basis, the nucleus building performed at a similar level to the modular building, and the Nightingale building was the best performing. This underscores that it is useful to consider energy per patient when assessing hospital energy and that efficient floor area use should be factored in when designing new hospital buildings.

The closing section of the work provides recommendations on improving monitoring in the NHS and how hospital designers can design the optimal low carbon hospital building. The recommendations focused specifically on, building form and layout, building fabric and the buildings LTHW and mechanical ventilation systems.

9 Conclusions

This thesis has provided insight into the monitoring practices at three hospital sites in the UK and has investigated the energy performance and internal environmental conditions in three case-study buildings at Bradford Royal Infirmary. The overarching purpose of this work was to contribute to assisting the NHS in their challenge of reducing the carbon emissions of their building stock through building energy demand reduction. It was desired that this would primarily be achieved through the development of a method for benchmarking and monitoring NHS hospital buildings and secondly by making observations on the design of more energy efficient and thermally comfortable healthcare buildings. This chapter closes the thesis by addressing how the project contributed to these two areas presenting the conclusions in the order in which they appeared throughout the thesis.

9.1 Case Studies

One of the first questions raised in this thesis was how can existing benchmarking and monitoring in the NHS be improved? The literature review and building surveys in chapters 2 and 4 helped to identify that current practice within the NHS is to compare the energy consumption taken from utility bills for an entire site to national benchmarks set by CIBSE or the Department of Health. A method for benchmarking was recently published in the US which emphasized that hospital buildings should be monitored and benchmarked at as small a resolution as possible. Through visiting the sites involved in the project it was identified that the majority of hospital buildings lacked monitoring equipment and the few that had monitoring capabilities, had systems which were incomplete and did not allow for close analysis of building energy data. Out of the seven buildings investigated on the three sites (chapter 4) only two buildings (at Cambridge) had the ability to monitor electricity and fossil fuels. Nevertheless, it was found that there were significant gaps in their recorded data which rendered many of the monitored periods useless. In addition to the buildings at Cambridge, wards within the Bradford modular building and the Glenfield nucleus building had updated distribution boards which contained digital meters, nevertheless these were not connected to a larger BMS system and lacked logging capability. Due to this lack of capability to monitor on an individual level, a central part of this thesis was to develop a method for quantifying the energy performance for individual hospital buildings.

The method described in chapter 3 involved breaking the energy consumption down into four areas; LTHW, mechanical ventilation, electrical ward and plant. The literature review identified that there was a gap in the knowledge of the development and implementation of simple empirical models for determining hospital building level energy consumption. Therefore, to make a contribution to the development of hospital energy monitoring, the main focus of the work was to develop a method to monitor the LTHW consumption based on the performance line methodology.

The method involved locating the LTHW pipes supplying the building, fitting a portable flow meter and temperatures sensors to monitor the daily heating consumption for a number of days in each season of the year. The daily consumption was plotted against the daily average internal to external temperature difference to produce a performance line for each building. These lines were then used to predict the consumption for the year.

The energy for mechanical ventilation was monitored by spot measurements of the airflow into the individual wards and logging the AHU air temperature and ambient temperatures for a period of 8 days. Electrical energy consumption was monitored by placing current transformers on the distribution boards on the wards and in the plant rooms. The method was implemented in seven buildings on three sites. Through this, a number of limitations were uncovered: practical restrictions and reduced access from lack of drawings, asbestos and getting equipment into tight spaces. In addition to this, the method was dependent on numerous interdependent factors. This resulted in successful monitoring in three of the seven buildings.

The literature review identified a gap in knowledge regarding the monitored energy consumption of the various hospital building types in the NHS. Energy consumption of some building types had been modelled, but it is known that there are often disparities between the energy consumption predicted by the models and that based on monitored empirical data.

The literature review identified three factors that determined the buildings energy performance, these were, the building's form, services and occupant usage. Some buildings contained operating theatres and other medical areas, while others had only ward space. Therefore, to make the comparison fair, only the performance of the wards was studied.

The specific buildings were chosen for reasons of practicality and because they represented the wide variety of hospital buildings types in the UK: Nightingale, characterised by a narrow pavilion form, with a heavy structure and minimal services; nucleus embodying buildings with high levels of mechanical ventilation; and modular representing new hospital constructions with energy saving features.

The Bradford Royal Infirmary site had examples of each of these buildings in one location thus providing the perfect opportunity to monitor and compare their performance in the same climate. The conclusions from these three case-studies were as follows:

1920s Nightingale building:

- Annual energy consumption was 420.7kWh/m^2 or 56.1GJ/100m^3. This was exceptionally low energy consumption for a building of this age, and it is reasoned that it was due to the roof insulation being updated to modern standards and the lack of mechanical ventilation.
- The ward had only one thermostat to control the temperature across the entire ward. During the winter of 2012-13 the wards air temperature was higher than CIBSE recommendations for 30% of time. This could be reduced by increasing the zoning and thermostatic control.
- During winter, the natural ventilation failed to provide satisfactory levels of ventilation with CO_2 levels being above 750ppm for 85% of time. These corresponded with low estimated air change rates and thus increased risk of infection control.
- Overheating was not a problem in summer as all of the bed spaces met BS EN 15251, CIBSE and HTM-03-01 criteria during 2012. This finding supplements literature providing more evidence that Nightingale buildings can maintain an acceptable thermal environment in current summer months.

1986 nucleus building:

- Annual energy consumption was 808.7kWh/m^2 or 107.8GJ/100m^3. This was very high compared to the benchmarks, with the largest consumers being mechanical ventilation and DHW.
- A ventilation rate of 2.97ach^{-1} was supplied to rooms that were occupied by 6 patients. Spot measured CO_2 levels were below 750ppm suggesting rooms were comfortable and although the air change rate was below the

recommended 6ach^{-1}, this may still have been sufficient to reduce infection transmission.

- The inclusion of heat recovery would have reduced the energy consumption.
- The shaded supply duct for the mechanical ventilation allowed the supply air temperatures to remain cooler than ambient temperatures during warm periods. This resulted in mechanically ventilated multi-bed rooms being cooler than the naturally ventilated single bed rooms in summer.
- Overheating was not a problem in summer as all bed spaces met BS EN 15251, CIBSE and HTM-03-01 criteria during 2012.
- The main limitations with the monitoring of this building was that the electrical consumption could not be monitored, due restrictions in the distribution board. Furthermore the electrical energy for cooling supplied to the central areas of the building were omitted from the study.

2008 modular building:

- The building was very energy efficient for energy use with a total energy consumption of 289kWh/m^2 or 38.5GJ/100m^3, falling into the new build category. It had a low fossil fuel heating consumption due to its insulated and airtight fabric as well as its efficient AHU cross flow plate heat exchange system which did not have an air heater battery, but rather extracted more hot air than it supplied to the building.
- The AHU system provided comfortable air temperatures throughout the majority of the year except in summer when the bypass was not controlled properly.
- Ward electrical demand followed general ward occupancy patterns and increased in June compared to February.
- There was a positive correlation between window opening and ambient air temperatures in the first documented study of window opening patterns in a hospital ward.
- Over the winter period CO_2 levels were measured in the same space as the windows were monitored, it was found that the CO_2 levels exceeded the relevant BS EN 15251 overheating criterion for 88.5% of the time and varied according to occupancy. The regression between CO_2 and windows opened showed it was necessary for 3 windows to be open to maintain comfortable CO_2 levels.

- Low estimated ventilation rates in both multi and single bed spaces suggest there may be an increased risk of infection transmission, however Single bed isolation rooms might have been helpful to reduce transmission from infected patients.
- Summer temperature analysis revealed that the building did not perform well as it overheated for 100 days in 2012. Thermal comfort failed to meet BS EN 15251 criteria and portable cooling devices were installed in the months following the main analysis.

When the results for each case study were compared to each other, a number of key findings arose. The results showed that changing the energy source for the buildings, had an impact on the total energy consumption. In most cases the energy consumption was less for the hypothetical locally serviced building, but the carbon emissions were lower for the centrally located CHP system due to the reduced electrical consumption. This indicates that the CIBSE benchmark should only be used for assessing energy consumption on an entire site as it is not designed as an overall indicator of the efficiency for individual buildings. By normalising the carbon emissions according to the number of patients in the building it was found that the Nightingale building was the most effective with annual emissions of 2360 kgCO_2/patient while the modular and nucleus had similar emissions of 2950 and 3360 kgCO_2/patient respectively.

9.2 Recommendations

It is the desire of the NHS to develop a blueprint for the optimal low carbon hospital new build. Through the investigation of the various building types in this thesis a number of important lessons on hospital design have been gathered which can contribute to the design of this blueprint. This optimal building would be a combination of all the best design features from the individual buildings:

1. Layout – design the building to optimize the floor area per patient, minimising corridor areas and other circulation and ancillary spaces.
2. Building fabric – use a heavy weight structure to contribute thermal mass and stabilise summer temperatures. Use high levels of insulation outside the thermal mass to reduce the amount of heat escaping from the building during the winter months.

3. LTHW heating – implement a heating system controlled by a BMS which monitors and controls the temperatures in individual rooms and enables different set-points at specific times of day.
4. Ventilation – use a mechanical heat recovery ventilation system similar to the modular building to provide ventilation to the bed-spaces. Balancing the supply and extract to ensure the heat-recovery system could be used when the ambient temperature is low. The optimal ventilation system would be fitted with variable air volume control so that the flow rate supplied to the bed-spaces could change depending on the levels of CO_2 monitored in the space.
5. Monitoring – localised monitoring equipment such as heat flow and electricity meters should be installed and connected to main the BMS system at the conception stage of the building.

In addition to lessons that can be applied to future hospital design, the work has implications for the improvement of the current building stock. It demonstrates that it is beneficial for NHS estates teams to monitor buildings individually, as the process identifies the least efficient buildings, which might be improved first. The work also shows that although the Nightingale building was the oldest, it had a low energy consumption and when assessing carbon emissions per patient, it was the most effectively designed hospital. In addition, it was resilient to summer overheating in the current climate. Both findings suggest that rather than replacing these buildings, it may be worthwhile for the NHS to hold onto this traditional part of the stock, possibly retrofitting buildings with insulation in a similar manner to the building studied in Bradford.

The findings from the nucleus building suggest that, although mechanical ventilation is a viable method for meeting recommended indoor air quality levels, the NHS could focus on retrofitting these and other similar buildings with heat recovery systems to reduce the high energy load associated with mechanical ventilation. The feasibility of this depends on the layout of the existing ventilation system. In contrast, the indication that CO_2 levels were often higher than recommended in the naturally ventilated spaces, suggests that the NHS might wish to investigate the impacts of high CO_2 levels on patients recovery. In terms of the NHS' newly designed, well insulated air tight buildings, insight gained from the modular building at Bradford highlight that it will be useful for the NHS to pay close attention when choosing these buildings, as they have the potential to severely overheat in summer.

9.3 Further Work

Key contributions have been made to improve the monitoring and design of low carbon hospital buildings, however these recommendations have been made from the energy and internal environmental standpoint. Therefore it is important to mention that there are a myriad of other hospital design concerns pertinent to the NHS; costs, speed of erection, disruption to hospital activity, clinical functionality, etc. For the low carbon hospital design suggestions to be considered by the NHS, it would be essential to investigate them in the light of their other design needs. In addition to this point, there are four other areas of further research which would benefit this work: thermal energy modelling of the optimal hospital building design; a larger pilot study of the monitoring method with hospital estates teams across the UK; reviewing the internal environmental criteria; and developing a method for measuring natural ventilation and air quality in hospitals.

A number of recommendations have been suggested for low carbon hospital design. It would be useful to use these recommendations to produce plans for a prototype building and then use building energy modelling to build and simulate the prototype. A feasible and useful study would be to model each one of the buildings monitored in the study, calibrating the models internal environmental conditions and energy consumption to the monitored data. The prototype could be simulated in Bradford climatic conditions and its performance could be compared to the other buildings in the current climate as well as in future climates to investigate its resilience against overheating. The building would have high levels of insulation and a heat recovery system, therefore different methods of ventilating the building would need to be tested to identify the optimal ventilation system to provide acceptable temperatures throughout the year.

The energy monitoring method was only tested in a small number of individual hospital buildings. For this method to be widely accepted across the NHS, it would be necessary to formalise the methodology into a concise NHS guidance document for hospital estates teams. Then, the prescribed method could be piloted in a wide range of hospital buildings around the country together with surveys and interviews to gather feedback. A number of building types were omitted from this study, e.g. tower blocks. Carrying out nationwide pilots would not only provide essential information on the implementation of the method on a wider scale, but also provide a larger sample giving more information on the energy consumption of individual hospital building types which could be used to build a more detailed data-base of UK hospital energy consumption.

This would in turn be useful to investigate the variation between the energy consumption of the same building types in different UK locations.

The energy consumption of buildings is closely related to its environmental criteria. The literature review identified a gap in the research regarding the understanding behind environmental criteria chosen for hospitals. It would be useful to investigate the connection between the recovery rates of patients and levels of indoor air quality and temperatures. These studies will help to determine, minimum levels of internal conditioning, which would improve energy consumption. Furthermore, if the current levels are not optimal for patients, they could be improved to reduce recovery times. It is recognised however that linking recovery rates to environmental conditions might be very difficult.

The study of air quality in naturally ventilated rooms was limited in that it was not possible to measure the ventilation rates to the rooms. In addition, although CO_2 was used as an indictor of IAQ, the research discussed in the literature review suggests that CO_2 may only be useful for detecting levels of air freshness. It would be useful to conduct further research in two related key areas: the development of a simple non-intrusive method of measuring rates of ventilation into naturally ventilated hospital spaces, and the development of a simple and quick method to determine the air quality and level of air-borne pathogens in hospital spaces.

9.4 Summary

The overarching purpose of this thesis is to contribute to the NHS' work of lowering their building stock's carbon emissions. It has been identified that research is required in two main areas; the development of an optimal low carbon hospital building design resilient in future climate scenarios and the development of a monitoring and benchmarking method tailored to the energy consumption of the NHS' building stock. The thesis provides three main contributions to knowledge, which are founded on the understanding that UK hospital sites consist of individual buildings constructed over the past 100 years. The first contribution addresses the development and implementation of the monitoring method described in chapter 4. The method was implemented in seven buildings on three sites around the country and lessons were learned through the successes and failed attempts at monitoring. The second contribution covers the quantification of the energy consumption and internal environmental performance of three building types representing the wide range of hospital buildings throughout the NHS. The final contribution is in the lessons learned

from studying the buildings and the consequent recommendations that have been provided about hospital building design and servicing.

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Appendices

Appendix I: Flow Meter Pilot Study

A pilot study was undertaken in the early stages of the project to determine the characteristics of the LTHW pipes supplying the hospital wards. It was found that the pipes had diameters within the range of 13-75mm with the particular internal diameter of the pipe monitored being 50mm. It was also identified that when the pump was operating the flow rate of the water ranged from 3.06-23l/s (0.0036-0.023[m^3/s]), giving a velocity within the range of 1.83-11.73(m/s), which According to the equipment's data sheet, would enable the flow meter to produce a given accuracy of ±3% (Micronics, 2012).

Before using the equipment for the rest of the project, its accuracy was validated under different flow rates. A testing rig was set up as shown in Figure A1. The maximum flow rate occurring when the valve was fully open was calculated using Bernoulli's equation:

$$\frac{u^2}{2g} + \frac{P}{\rho g} + h = \text{constant}$$

Equation A1

Where:

u=velocity of fluid (m/s)

g = gravity = 9.81 (m/s^2)

P = pressure cancels out as both at atmospheric pressure

h = height = 17(m)

Rearranging the equation leads to:

$$U = \sqrt{2gh} = \sqrt{2 \times 9.81 \times 17} = 18.26$$

$$\therefore V_m = aU = 1.96 \times 10^{-3} \times 18.26 = 0.035(m^3/s) = 35(l/s)$$

Where:

V_m= max volume flow rate (L/s)

A = Pipe area = 1.96x10^{-3} (m^2)

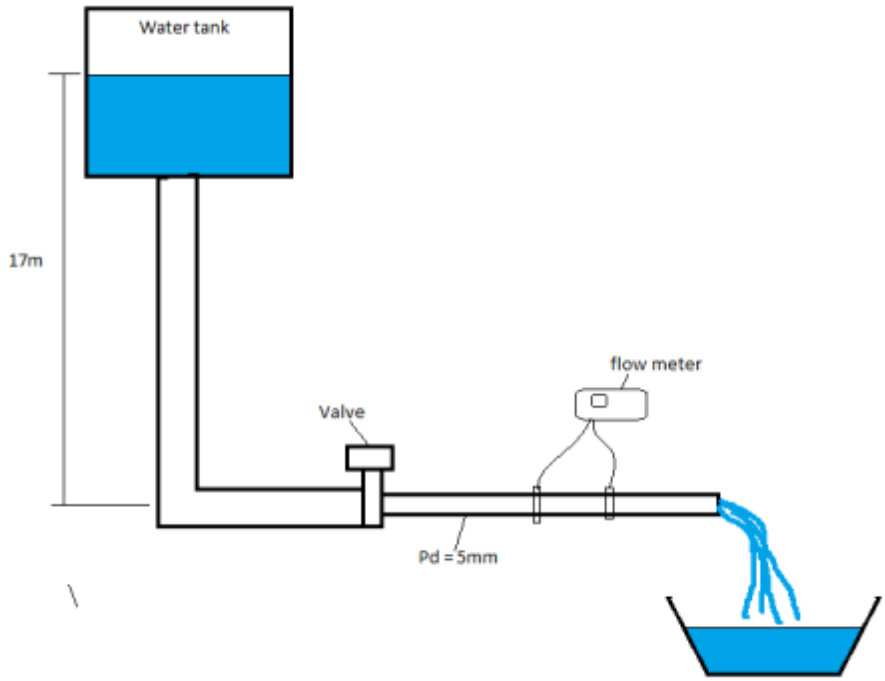

Figure A1 - Test rig set up

The rig was set up with a 150litre container placed at the bottom to collect the water. The calculations above show that the maximum flow rate that could be reached was 35L/s. However in real life it was found that this was far from possible due to restrictions in the circuit feeding the water.

In the experiment, the flow rate of the water was set to a constant by adjusting the flow valves. At this constant flow, water would come out of the pipe in a steady manner and steady readings would be seen on the flow meter. On Further increasing the flow rate, the flow would remain steady until a certain point, at which the flow would become turbulent leading to water being spurted out of the pipe at irregular intervals while the flow meter readings would be high and then drop down to zero or negative figures. It was clear that the water was not coming out of pipe at such high flow rates, therefore these extreme high and low errors were attributed to turbulence in the flow. The flow meter was tested over three stable flow rates, the results are found in Table A1.

Figure A2 - Pictures from Flow meter test (top left to bottom right) water temperature, flow meter, measuring equipment, pipe and container.

Time to fill container (Seconds)	*Volume of water measured in container (litres)*	*Measured Volume Flow (l/s)*	*Flow Meter reading (l/s)*	*Error*
38.27	123	3.21	3.122	2.95%
38.83	125	3.22	3.122	3.11%
39.6	127	3.21	3.122	2.72%
39.81	128.75	3.23	3.122	3.59%
26.87	140	5.21	5	4.21%
26.95	135	5.01	5	0.19%
26.93	140	5.2	5	3.97%
25.64	134	5.23	5	4.52%
31.49	132	4.19	4.071	2.97%
31.09	131	4.21	4.071	3.50%
30.68	128	4.17	4.071	2.48%

Table A1 - Results from the rig test

The average error of the validation experiment was found to be, 3.11%. This fits the instrumentations rated error (3l/s) for pipes with internal diameters of 13-75mm when the flow rate is larger than 0.2m/s (0.423l/s when internal diameter=51.92mm). The small difference is likely due to the error in the method of measuring the flow rate coming out of the pipe.

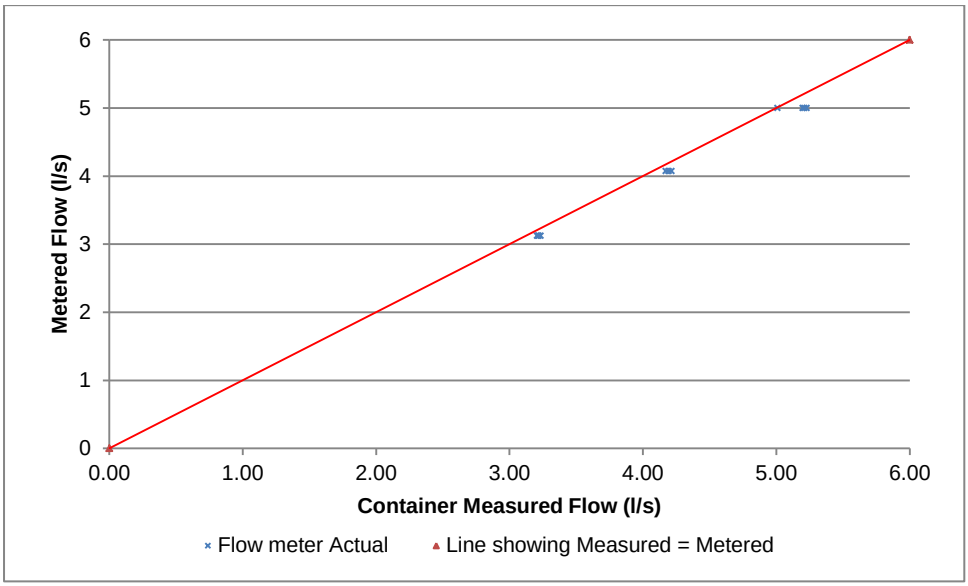

Figure A3 - Comparison between measured and metered flow rates

	Testing Meter					*CTV-A Current (A)*		*SPC Mini Current (A)*		
Load	Current (A)	Voltage (V)	Power Factor	Watts (W)	Frequency (Hz)	Logger 1(69)	Logger 2 (68)	Logger 1 (2259)	Logger 2 (2220)	Logger 3 (2255)
Off	0	237	0	0	49.95	0.037	0.037	0.01	0.01	0.03
Fan Only	0.11	237	0.65	17	49.95	0.037	0.037	0.08	0.1	0.08
40W	0.17	237	0.97	40	49.95	0.05	0.05	0.14	0.15	0.14
60W	0.25	237	0.98	58	49.95	0.05	0.05	0.21	0.22	0.2
Low Heat	5.74	235	1	1347	49.95	5.7	5.71	5.55	5.6	5.4
High Heat	11.39	232	1	2646	49.95	11.45	11.5	11.21	11.28	10.96

Table A2 - Results from Testing the Electrical Monitoring Equipment

It was necessary to monitor the temperature of the water in the supply and return pipes to calculate the temperature difference between the fluids in the pipes. It was therefore essential to find out the difference in temperature differences between the water and pipe surface, i.e. T_{a1} and T_2 for each pipe. Ideally the temperature difference should be the same for each pipe. However, this may not be the case as the rate of heat transfer will vary depending on the temperature of the water, the pipe material and the external air temperature. In this circumstance, the pipe material and external air temperature are the same, but the supply temperature tended to be 55˚C and the return temperature tended to be 35˚C.

To work this out, the heat transfer principles have been used:

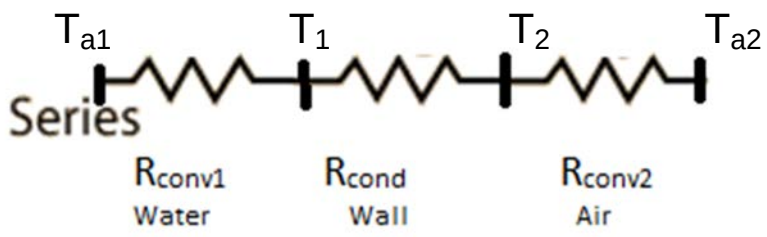

Figure A4 - heat transfer diagram demonstrating resistances and temperatures through pipe wall

Steady State Heat Conduction – Using Thermal Resistance Network

$$Q = \frac{T_{a1} - T_{a2}}{R_{Conv1} + R_{Cond} + R_{Conv2}}$$

Assume the water is in perfect contact with the inside surface of the pipe, hence:

$$R_{Conv1}=0$$

Therefore $T_{a1} = T_1$

Conduction

$$R_{cond} = L/KA$$

A=area (let A=1)

K = thermal conductivity (W/mK) = 60.5 (W/mK) @ 300K (Cengel, 2003)

L = pipe thickness = 5mm =0.005m

$$\therefore R_{cond} = 0.005/60.5 = 8.265\text{x}10^{-5} \text{ (K/W)}$$

Convection

$$R_{conv2}=1/hA$$

h=convection heat transfer coefficient (W/m^2K)

Free convection of gases, h = 2-25 (W/m^2K) [(Cengel, 2003)pg26]

For assume free convection of air = 13.5 (W/m^2K)

$$\therefore R_{conv2}=1/13.5 = 0.074 \text{ (K/W)}$$

$$Q = \frac{55 - 18}{8.265x10^{-5} + 0.074} = \frac{37}{0.0741} = 499.442W$$

Supply = Finding T_2, When T_1=55˚C:

$$Q = \frac{T_1 - T_2}{R_{Cond}}$$

$$T_2 = T_1 - QR = 55 - (499.442 \times 8.265x10^{-5}) = 54.9587^{\circ}C$$

$$\therefore T_1 - T_2 = 55\text{-}54.959 = 0.041^{\circ}C$$

Return = Finding T_2, When T_1 = 35˚C:

$$Q = \frac{35 - 18}{8.265x10^{-5} + 0.074} = 17 = 229.473W$$

$$T_2 = T_1 - QR = 50 - (229.473 \times 8.265x10^{-5}) = 34.981^{\circ}C$$

$$\therefore T_1 - T_2 = 35\text{-}34.981 = 0.019^{\circ}C$$

There is 0.022˚C difference between the temperature differences for the supply and return pipe temperatures, which will make not make any significant difference to the measurements as the accuracy of the sensors is 0.04°C.

Appendix II: Building U-Value Calculations

Bradford Modular

Layer (Out-In)	*Name*	*Thickness (mm)*	*Thermal Conductivity (K)*	*Thermal Transmittance (W/m^2K)*	*Thermal Resistance (R)*	
se	External Surface (Upwards)				0.04	
1	CR32 Steel Sheet	3	45		0.000	
2	Plywood	9	0.14		0.064	
3	Kingspan Thermaproof TR31	80		0.275	3.636	
4	Air (flowing Up)	35			0.160	
5	Plasterboard	15	0.17		0.088	
6	Isowool Insulation	185	0.04		4.625	
si	Internal Surface (Upwards)				0.1	*U-Value (W/m^2K)*
Total					8.714	0.11

Table A3 - Modular roof U-value calculations

Layer (Out-In)	*Name*	*Thickness (mm)*	*Thermal Conductivity (K)*	*Thermal Transmittance (W/m^2K)*	*Thermal Resistance (R)*	
se	External Surface (Downwards)	n			0.04	
1	Rockwool	150	0.037		4.054	
2	Floortherm board	60	0.022		2.727	
3	Plywood	9	0.14		0.064	
4	Carpet	5	0.06		0.083	
si	Internal Surface (Downwards)	n			0.170	*U-Value (W/m^2K)*
Total					7.139	0.14

Table A4 - Modular ground floor U-value calculations

Layer (Out-In)	*Name*	*Thickness (mm)*	*Thermal Conductivity (K)*	*Thermal Transmittance (W/m^2K)*	*Thermal Resistance (R)*	
se	External Surface (Downwards)	n			0.04	
1	Kingspan KS1000 MR insulated wall	80		0.3	3.33	
2	plywood sheathing	12	0.14		0.09	
3	Isowool	90		0.35	2.86	
4	plywood	12	0.14		0.09	
5	plasterboard.	15	0.17		0.09	
si	Internal Surface (Downwards)	n			0.13	*U-Value (W/m^2K)*
Total					6.62	0.15

Table A5 - Modular wall U-value calculations

Bradford Nightingale

Layer (Out-In)	*Name*	*Thickness (mm)*	*Thermal Conductivity (K)*	*Thermal Transmittance (W/m^2K)*	*Thermal Resistance (R)*	
se	External Surface (Horizontal)				0.04	
1	Yorkstone Outer Skin	150	0.7		0.214	
2	Rubble (sandstone)	25	1.3		0.019	
3	Air	25			0.180	
4	Inner Skin	350	0.7		0.500	
si	Internal Surface (Horizontal)				0.13	*U-Value (W/m^2K)*
Total					1.084	0.92

Table A6 – Nightingale building wall U-value calculations

Layer (Out-In)	*Name*	*Thickness (mm)*	*Thermal Conductivity (K)*	*Thermal Transmittance (W/m^2K)*	*Thermal Resistance (R)*	
se	External Surface (Upwards)				0.04	
1	Insulation Retrofit	120	0.04		3.000	
2	Original Insulation	75	0.04		1.875	
3	Roof lined with Boards and felt				0.300	
si	Internal Surface (Upwards)				0.1	*U-Value (W/m^2K)*
Total					5.315	0.19

Table A7 – Nightingale building roof U-value calculations

Bradford Nucleus

Layer (Out-In)	*Name*	*Thickness (mm)*	*Thermal Conductivity (K)*	*Thermal Transmittance (W/m^2K)*	*Thermal Resistance (R)*	
se	External Surface (Downwards)				0.04	
1	Pandel handmade bricks	102.5	0.4		0.256	
2	Drytherm	50	0.037		1.351	
3	Celcon Blocks	140	0.15		0.933	
si	Internal Surface (Downwards)				0.13	*U-Value (W/m^2K)*
Total					2.711	0.37

Table A8 – Bradford nucleus wall U-value calculations

Appendix III: Bradford Royal Infirmary's Weather related load

BRI's weather related energy use was used in the normalisation of the fossil fuel energy data. Monthly energy data was requested from BRI's estates team for the purpose of calculating the baseline gas consumption for the site. Data from 2009 and 2010 was provided (Figure A5) which showed that the lowest energy consumption took place in July and August and that 2010 had a slightly higher consumption than 2009. The average energy consumption over these two months in both 2009 and 2010 was 732MWh. This value was assumed to be the non-weather related load or baseline gas consumption for the site, accounting for domestic hot water, and boiler and pipe losses. The figure of 732 MWh was multiplied by 12 to find the gas consumption for the year, and then divided by the floor area of the hospital site, which is 81,226m^2, to give gas heated DHW and efficiency losses of 108 kWh/m^2/yr non weather related load.

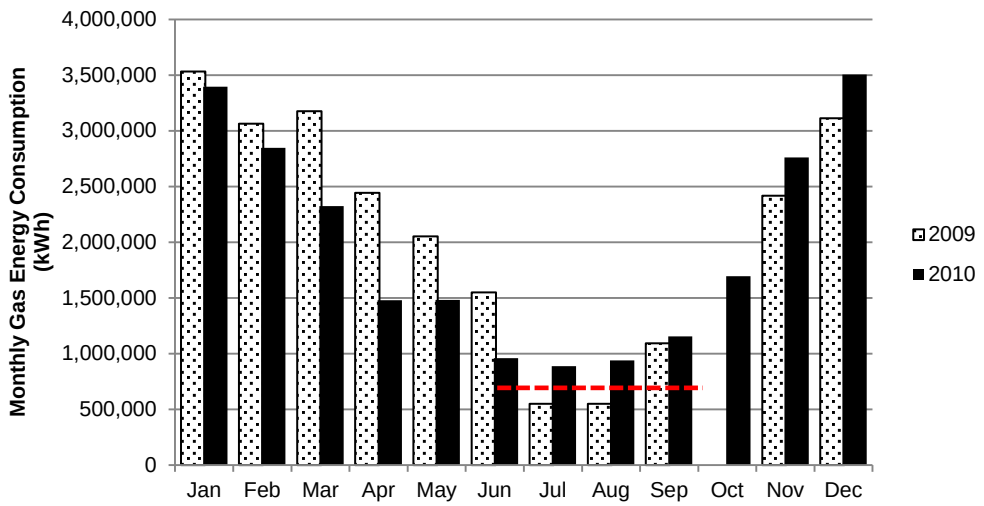

Figure A5 – Bradford Royal Infirmary, whole site monthly gas consumption for 2009 and 2010, [red line represents the average monthly non-weather related demand]