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Hospital wards and modular construction: Summertime overheating and energy efficiency

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ABSTRACT

The UK National Health Service (NHS) is continually under pressure to provide more bed spaces and to do this within a tight budget. Therefore, NHS Trusts may turn to modular buildings, which promise faster construction and low energy demands helping the NHS meet its stringent energy targets. However, there is growing evidence that thermally lightweight, well insulated and naturally ventilated dwellings are at risk of overheating during warm UK summers.

This paper examines the energy demands and internal temperatures in two 16-bed hospital wards built in 2008 at Bradford Royal Infirmary in northern England using modular fast track methods. The two-storey building used ceiling-mounted radiant panels and a mix of natural and mechanical ventilation with heat recovery to condition patients' rooms. Monitoring showed that the annual energy demand was 289 kWh/m^2 ± 16%, which is below the NHS guidelines for new hospital buildings.

It was observed that the criterion given in Department of Health Technical Memorandum HTM03-01 can lead to the incorrect diagnosis of overheating risk in existing buildings. Assessment using other static and adaptive overheating criteria showed that patient rooms and the nurses' station overheated in summer. To maintain patient safety, temporary air conditioning units had to be installed during the warmest weather.

It is concluded that thermally lightweight, well insulated, naturally ventilated hospital wards can be low-energy but are at risk of overheating even in relatively cool UK summer conditions and that this needs to be addressed before such buildings can be recommended for wider adoption.

1. Introduction

The UK National Health Service (NHS) is responsible for around 4.5% of all UK emissions with annual carbon emissions in 2015 of 22.8MtCO_{2e} [1] compared to a UK total of 495.7 MtCO_{2e} [2]. The NHS is required by law to reduce its carbon emissions [3] and stringent targets for energy demand have been set. Around 20% of the NHS emissions were from buildings and whilst NHS emissions have fallen by 11% overall since 2007, building emissions have fallen by just 4% [1]. Around 44% of the energy used in a typical UK hospital is attributable to air and space heating [4].

The original NHS carbon reduction strategy, "saving carbon improving health" stated that the NHS aimed to reduce their carbon emissions by 10% by 2015 compared to 2007 levels [5]. This goal was met, with emissions reductions of 11% being achieved [1] despite activity levels within the organisation increasing by 18%. As the NHS continues to become more specialised [6], electrical energy consumption continues to rise, and now accounts for double the emissions of all other fuel types [4].

Although the NHS met their carbon reduction targets, the savings in building energy demand were just 4%, but there is considerable potential for savings. Refurbishing all NHS buildings using low carbon technology could reduce building energy consumption by 25%, and replacing all NHS buildings with a super-efficient stock could save another 25%. This would contribute up to 12% of the NHS's 2020 emissions reduction target of 34% [4,7]. Replacing the entire NHS stock is a huge task, and it is unlikely this will happen in the near future, however, increasing the efficiency of the existing stock, and ensuring that new buildings are as efficient as possible are realistic goals.

Climate change, whilst reducing wintertime heating demands, will increase the risk of summertime overheating. However, despite the diversity of UK healthcare buildings' constructional form, age and servicing strategy, very little of this stock is air-conditioned. In fact, Health Technical Memorandum HTM03-01 [8], which is concerned with 'specialist ventilation for healthcare premises', states that '*natural ventilation is always the preferred solution for a space, provided that the*

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quantity and quality of air required, and the consistency of control to suit the requirements of the space, are achievable'. This, combined with the pressure to reduce carbon emissions and initial and running costs, means that those commissioning health care facilities try to avoid air-conditioning. Thus health care spaces and wards in particular tend to use hot water heating systems, combined with natural, mechanical and/or hybrid ventilation to maintain air quality, for infection control and to prevent overheating in the summer '*wherever possible*' [4].

During periods of high ambient temperature, hospitals are expected to provide a safe haven for citizens who are suffering from the heat. It is recommended that they provide cool areas that remain below 26 °C for use during heatwaves [9]. They must also continue to provide comfortable conditions for existing patients, who may have compromised thermoregulatory systems (the elderly, the chronically and severely ill, those on certain medications that impair perspiration) or may not be able to take action in the face of high temperatures (small children, the bed-bound, patients with mental illnesses). Finally, hospitals must also provide a safe, healthy and productive working environment for clinical, nursing and other staff. Thus, hospitals must provide respite from summer heat for the most vulnerable people at precisely the times of the year when it is most difficult to do so.

The ability of hospital buildings to provide summertime thermal comfort is one of the most important considerations, but a consideration that often gets little attention when designing and commissioning new hospital buildings. The risk of overheating in hospital buildings has been highlighted by the Adaptation Sub-committee of the UK Committee on Climate Change [10,11].

New buildings are needed to meet the growing demand for NHS services. However, because the NHS is under continual financial pressure, it operates at near full capacity virtually all the time, e.g. over 87% of its 128,000 beds were occupied between July and September 2017 [12]. New buildings must therefore be extremely cost effective and delivered with minimum disruption to hospitals' services. Fast track, modular construction is one approach that promises shorter construction times and, importantly, less time on site, and less noise, dust and dirt, and so less disruption to the operation of the hospital site.

The modular construction of hospital wards is not new of course, the classical example being the Renkioi hospital, built in 1855, in the final months of the Crimean war for Florence Nightingale. It was assembled from prefabricated wooden huts designed by Isambard Kingdom Brunel, which were transported out from Britain by ship [13]. Currently called 'modern methods of construction' (sic), prefabrication has gained popularity for the construction of flats, student accommodation etc., but it is an approach that is also applicable to hospital wards. There is emerging evidence that thermally lightweight, well-insulated, airtight, single aspect, cellular residential spaces built using modern methods of construction are particularly susceptible to overheating [14,15] and that this is exacerbated by poorly designed and operated mechanical ventilation systems [16]. But will hospital wards built using similar techniques also overheat?

The primary purpose of this paper is to investigate the capability of modular methods of construction to produce hospital wards that remain thermally comfortable and safe for patients, staff and visitors during UK summers. It is important however, to determine if such buildings are capable of meeting the energy standards set by the NHS for new buildings. The new hospital wards built in 2008, using modular construction methods at Bradford Royal Infirmary (BRI) in the north of England acted as the case study. The internal temperatures in seven bedrooms in one of the two wards were recorded from 2010 to 2013 [17]. The values recorded in 2012, and during the 108-day period from 15th June to 30th September in particular, are reported and analysed using a range of overheating risk assessment criteria. The building's heat and electricity demands were monitored during 2012 and early 2013, and the demands for 2012 estimated.

The work was part of the EPSRC/ARCC-funded project '*Design and Delivery of Robust Hospital Environments in a Changing Climate*' (DeDeRHECC) in which, altogether, 111 spaces in nine hospital buildings across four hospital trust were monitored [18–23]. This paper adds to this body of knowledge, by specifically quantifying the energy demands of a well-insulated, thermally lightweight, pre-fabricated, modular healthcare building but also highlighting the serious risk of overheating intrinsic to this form of construction.

2. Energy demand and indoor environment: benchmarks and guidelines

Benchmarks for the energy demands and CO_2 emissions of healthcare buildings have been set out in the Chartered Institution of Building Services Engineers (CIBSE) Technical memorandum, TM46 [24]. For spaces providing long-term accommodation, such as hospital wards, which include sleeping, day-use spaces, some offices and domestic facilities, the benchmark is $124 kgCO_{2e}/m^2$ per annum, based on 65 kWh/m^2 for electricity and 420 kWh/m^2 for fossil thermal energy.[1] An analysis of all available UK display energy certificates between 2008 and 2012 (as reported in [4] indicated that the actual median consumption of 35 residential hospital buildings was 308 kWh/m^2 for fossil fuels and 93 kWh/m^2 for electricity; somewhat less overall than the TM46 benchmarks.

Importantly though, in 2006, targets were set for all healthcare trusts in Health Technical Memorandum HTM07-02, EnCO2de [25], requiring that the total energy uses of new buildings and major refurbishments should be less than 35–55GJ/100 m^3 and for less intensive refurbishments of existing facilities, less than 55–65GJ/100 m^3. These targets are reiterated more recently in HTM07-07 [26]. The figure of 55 GJ/m^3 is equivalent to about 413 kWh/m^2 for the BRI building, which is not, therefore, especially stringent.[2]

The target wintertime operative temperature to which general wards should be heated are given as 22–24 °C in CIBSE Guide A [27], whilst HTM03-01, Appx. 2, gives a surprisingly wide range, 18–28 °C, but 18–25 °C in critical areas, such as birthing rooms, operating theatres, etc. [8].

Natural ventilation is preferred in the general wards of UK hospitals [8]. Specified ventilation rates for occupied spaces vary from over $15 ls^{-1}$/person in a high quality environment, class IDA1 of BSEN13779 [28],[3] to less than $6 ls^{-1}$/person for low indoor quality, class IDA4. Minimum standards are largely set in within the IDA2, IDA3 range [27], which are, respectively, 10-15 ls^{-1}/person and 6-10 ls^{-1}/person. These values are very similar to the basic ventilation rates set in BSEN15251 for Cat I and Cat II buildings, 10 ls^{-1}/person and $7ls^{-1}$/person, respectively [29]. In occupied naturally ventilated buildings, the ventilation rate can be estimated from the measured increase in the indoor CO_2 level above ambient - the value of which in 2012/13 is memorable, as it was first time that 400 ppm was exceeded in the northern hemisphere. The indoor CO_2 levels corresponding to classes IDA2 and IDA3 during the monitoring period are thus 800–1000 ppm and 1000–1400 ppm respectively. Areas such as the bathrooms in the single and multi-bed rooms, the communal washrooms, and other area of foul waste need to have mechanical extract ventilation of at least $3ach^{-1}$ [8].[4]

[1] TM46 explains how these figures can be adjusted to account for differences between the ambient temperatures prevailing during a monitoring period and the standard year to which the TM46 benchmarks apply. In this work, no such adjustments were undertaken but comparisons made, between measurements and benchmarks, were cognisant of this approximation.

[2] The conversion uses a ceiling height of 2.7 m, as in the BRI modular wards.

[3] Standard applicable up to 2018 when replaced by BS EN 16798-3.

[4] Ventilation rates of 6 ach-1 are recommended if mechanical rather than natural ventilation is adopted, which is, of course, very high by the standards used in most other buildings.

3. Summertime thermal comfort in hospital wards

Hospitals must provide thermal comfort to a diverse range of occupants who have differing thermal comfort requirements, most important are the patients but others include clinicians and nursing staff, support staff (administrators, cleaners, etc.) and visitors. At times, any or all of these may occupy the same space whilst patients are awake or asleep. Whilst patients may be very sensitive to abnormally high or low temperatures (being old, or sick or having impaired thermoregulatory systems) other occupants will have more 'normal' thermal requirements and expectations, but they will inhabit the hospital for many more days (or years) than most of the patients.

The criteria by which the measured temperatures in spaces are assessed, must account for this diversity of occupation. Previous work [20] concluded that the adaptive standard BSEN15251 [29] was most appropriate but they also assessed hospital ward temperatures against static comfort criteria because, despite obvious weaknesses, static criteria are still widely used, not least in HTM03-01 [8].

3.1. Static overheating criteria

In the UK, the most often used static overheating criteria are those presented in CIBSE Guides and Technical Memoranda [27,30–32]; and [33]. For health care buildings specifically, HTM03-01 gives a static criterion, which is in line with the corresponding CIBSE criterion. All the firmly stated static criteria are actually intended for use in interpreting the predictions of models used to assist building design rather than for assessing the acceptability of temperatures measured in occupied buildings (Table 1).

The most recent CIBSE Guide A [27] states that "*during warm summer weather 25°C is an acceptable temperature*" and for offices, schools and the living areas of dwellings, the overheating criterion is "*1% annual occupied hours over operative temperature of 28°C*". The earlier CIBSE Guide J [30] and Technical Memorandum TM36 [31] suggested an overheating criterion of no more that 5% of hours over a dry-resultant temperature of 25 °C. None of these criteria are explicitly intended for evaluating buildings in use, but the CIBSE Guide A gives a brief summary of the limited available evidence, and for non-air conditioned offices and schools the 28 °C/1% criterion is restated.

The above CIBSE criteria relate to the hours when people are awake, but night time thermal comfort, and more generally comfort whilst sleeping, is especially important in a hospital context. For people at home, CIBSE Guide A [27] notes that "*thermal comfort and quality of sleep begins to decrease if bedroom temperatures rise much above 24°C*" (at these temperatures sleepers are likely to be covered by a single sheet) and that "*bedroom temperatures at night should not exceed 26°C unless ceiling fans are available*". An overheating risk criterion is given: there should be no more than "*1% of occupied hours over an operative temperature of 26°C*". This static criterion has been retained in the recently-published CIBSE TM59 [33].

In HTM03-01, it is recommended that '*during summertime, internal temperatures in patient areas do not exceed 28°C (dry-bulb) for more than 50 h per year*' [8]. This equates to about 0.6% of annual occupied hours as wards are virtually permanently occupied. The criterion makes no distinction between the needs of different occupants or whether people are awake or asleep.

In the work reported here, the temperatures in the monitored rooms were compared against all the relevant static criteria (Table 1). Because the sensors used measure an unknown mix of air, radiant and, perhaps, surface temperature, whether or not the criteria, and the measurements relate to true operative temperature or not was ignored.

3.2. Adaptive overheating criteria

Adaptive criteria account for individuals' physiological and behavioural adaptability to different temperatures and are gaining prominence. There are three adaptive comfort standards, [34]; the CIBSE TM52 [32], and the BSEN15251 [29]. The three standards plot envelopes of acceptable indoor temperature against a running mean of the ambient temperature (Fig. 1). Whilst the mechanism for calculating this running mean differs between the methods, all three offer very similar envelopes of thermal acceptability. However, as [20] note, BSEN15251 has advantages when trying to establish a framework for assessing the indoor temperatures of free-running buildings, and hospital buildings in particular: it discriminates between spaces used for different purposes; it provides different envelopes to account for the comfort needs of both sensitive and less sensitive individuals; and it provides the opportunity for the NHS, or others, to define the allowable deviations of temperature outside the envelope boundaries. Most importantly, the standard's scope explicitly includes '*hospitals*' and '*methods for long term evaluation of the indoor environment*', i.e. by measurement.

The BSEN15251 envelope width depends on the 'Category' of the space under consideration (Fig. 1). The most stringent is Cat I, which has the narrowest envelope: '*High level of expectation* [which] *is recommended for spaces occupied by very sensitive and fragile persons with special requirements like, handicapped, sick, very young children and elderly persons*'; whilst Cat II is the '*normal level of expectation and should be used for new buildings and renovations*'. Suggestions for the acceptable daily, weekly and annual deviations outside the chosen category limits are provided for measured temperatures. These equate to exceedances of

Table 1
Static overheating criteria, sources, applicable spaces and the intended application.

Source	Applicable space	Threshold	Overheating Criterion	Application
Static criteria				
CIBSE Guide J [30] and TM36 [31]	Office	25°C dry-resultant temperature[a]	Limit of 5% annual occupied hours threshold	Modelling
CIBSE Guide A [27]	Offices, schools and living spaces in dwellings.	25°C operative temperature 28°C operative temperature	Upper acceptable temperature limit[b] Limit of 1% annual occupied hours over threshold	Modelling and in-use monitoring
CIBSE Guide A [27] & TM59 [33]	Dwellings Bedrooms (night time)	24°C operative temperature 26°C operative temperature	Upper acceptable temperature limit for good quality sleep Limit of 1% annual occupied (night time) hours over threshold	Modelling
HTM03-01 [8]	Patient areas	28°C air temperature	Limit of 50 summertime hours over 28°C	Modelling
Adaptive criteria				
BSEN15251 [29]	Hospitals	Upper threshold of appropriate category	Limit set by regulatory body	Modelling and in-use monitoring
CIBSE TM52 [32]	Dwellings, all spaces		Less than 3% of annual occupied hours	Modelling

[a] Very similar to operative temperature.
[b] No firm criterion stated.

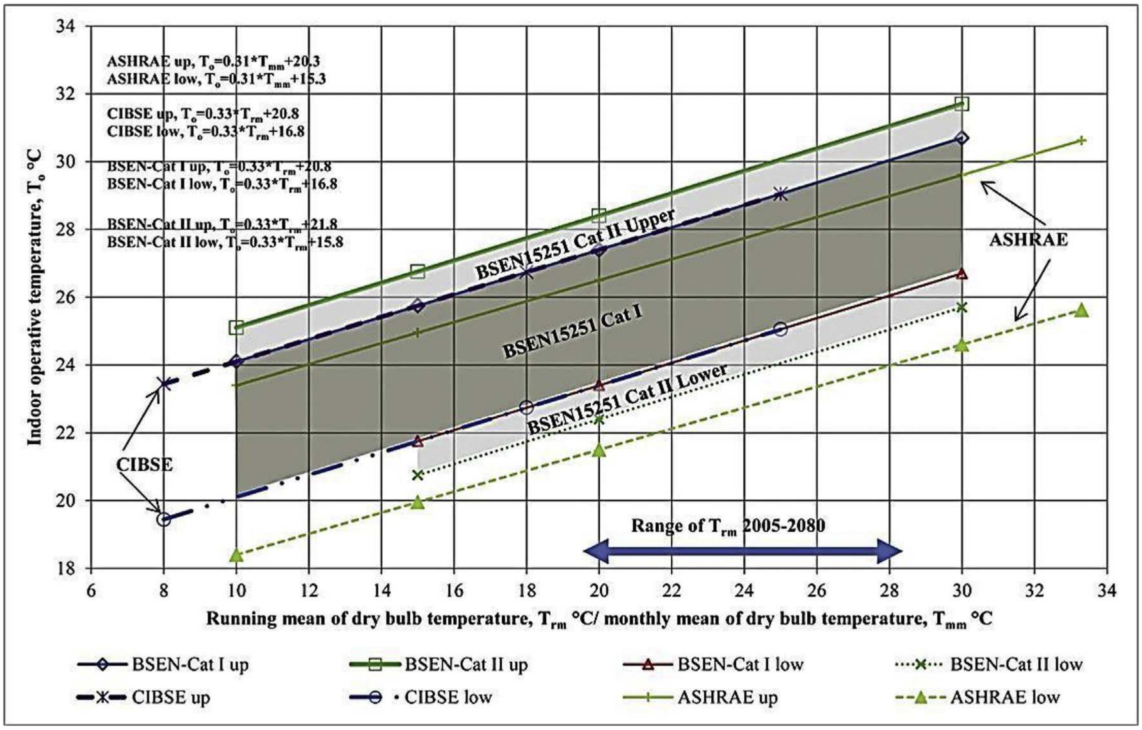

Fig. 1. Comparison of adaptive thermal comfort standards: equations, envelopes, boundaries, limits of applicability and range of predicted running mean temperature in the warmest month up to 2080 (after [20]).

either 3% or 5% of occupied hours (cf. CIBSE Guide A recommendation above).

The standard is specifically valid for spaces: "*where there is easy access to operable windows and occupants may freely adapt their clothing to the indoor and/or outdoor thermal conditions*" [authors' underlining]; and where '*there shall be no mechanical cooling*' but '*Mechanical ventilation with unconditioned air (in summer) may be utilized but opening and closing of windows shall be of primary importance as a means of regulating thermal conditions in the space'*. These are exactly the mechanisms by which the BRI hospital wards are conditioned and ventilated.

In this research, the upper temperature threshold of the Cat I envelope was used as the primary method for evaluating the measured temperatures in the patient rooms during both the day and the night with an allowable exceedance of less than 3% of monitored hours. This is in line with CIBSE TM52 (Table 1) and the newly published TM59 recommendation for '*Care homes and accommodation for vulnerable occupants, which are predominantly naturally ventilated*' [33]. A limit of 3% exceedance above the Cat II upper threshold was used for assessing the temperatures at the nurses' station. Secondary consideration was given to the static criteria, with the CIBSE 26 °C/1% criterion for night time comfort in patient rooms being given particular weight as this is retained in CIBSE TM59 [33].

4. The modular hospital wards

The modular building (Fig. 2) was constructed, in 2008, in response to an increased demand for bed spaces. The options were either a traditionally-constructed, three-floor extension to an existing building or a new modular extension. The modular option was slightly more expensive but promised the advantages of completion in just six months, compared to eighteen months for the traditionally construction building [35], and higher thermal standards, through both improved air tightness and higher levels of insulation [36].

The modular building is divided into two floors, each 62 m long on the N-S axis and 16 m wide on the E-W axis, with a floor to ceiling height of 2.7 m. It is seated on steel beams, which provided a level platform (Fig. 2).

The external fabric of the building is highly insulated throughout and, with the exception of the ground floor, the U-values for the building element are, in every aspect, lower than the requirements of the English Building Regulations of the time [37] (Table 2). Likewise the air tightness, $Q_{50} = 0.5\,m^3/h.m^2$, is much better than the Regulatory requirement ($Q_{50} = 10\,m^3/h.m^2$).

The bottom floor contains Ward 29 and the top floor Ward 30. In each ward there are four multi-bed rooms, each of 45.7 m^2 with 4 beds, as well as 12 single bedrooms, each of 15.6 m^2, to provide isolation care for infectious patients (Fig. 3). The beds were fully occupied virtually all the time. The bed rooms are double-banked either side of a 'blind' corridors. Having no windows, the only source of ventilation air for the corridors is from the mechanical system.

The patient rooms are naturally ventilated. Each single patient room has one, aluminium framed, three-pane window and a smaller single pane window (Fig. 4), giving a glazing to floor area ratio of 11.4%.[5] The single pane window and the top and bottom multi-pane windows are operable. Each multi-bed room has two of the three-pane windows and two double pane window,[6] giving a glazing to floor area ratio of about 7.3%. Like the single patient rooms, the top and bottom of the three pane windows and the top of the double pane windows are operable. The operable windows are top hung and outward opening. Either they can be closed or, due to the restraining mechanism, opened to provide a ventilation gap of just 100 mm; intermediate opening positions are not possible. The opening angle is thus 8°, and when all windows are fully open, the free-area for ventilation in the single patient rooms, is approximately 0.58 m^2, which is about 3.7% of the floor area. In the multi-bed rooms, the free-area is 1.17 m^2, which is just 2.6% of the floor area. There is very little site shading and no external solar shading on the building. Night time privacy, glare and solar gain control is provided by vertical strip blinds.

[5] Assumed framing approximately 15% of aperture area.

[6] An additional fixed pane immediately below the single pane shown for the single bed rooms (Fig. 2).

Fig. 2. The East facing façade of the 2008 modular building at Bradford Royal Infirmary.

Each room, in both wards, is heated by thermostatically controlled, radiant ceiling panels. The variable flowrate and variable temperature, low temperature hot water (LTHW) circuit runs through the corridor ceiling void. The LTHW is supplied from the constant flowrate primary heating circuit via a low loss header. A plate heat exchanger connected the primary heating circuit to BRI's central steam and condensate system [38]. The space heating set-point is approximately 23 °C, which is in the middle of the CIBSE recommended range (see above). The domestic hot water (DHW) for clinical sinks and for the sinks and showers in the rooms is supplied from outside the building through the site-wide distribution system. The DHW pipework also ran in the ceiling voids [38]. The mechanical ventilation system is designed to extract the foul air from toilets and other 'dirty areas' at a rate of 3ach^{-1}, in line with the HTM03-01 guidelines. Air-handling units (AHU) are located at the north east end of each ward; the louvered inlets and exhausts are visible in Fig. 2.

A cross-plate heat exchanger in each AHU pre-heats the fresh air but can be by-passed, in summer for example, to enable mechanical cooling using ambient air. There are no heating coils in the AHUs. The intention is that fresh air is sufficiently warmed simply by extracting heat from the out-going air. The arrangement is designed to deliver fresh air in winter at approximately 19 °C through supply and extract ducts that run down the full length of the corridor.

Because the building has a simple mixed-mode ventilation and heating strategy, with heat being taken from the site-wide heat network via a plate heat exchanger, it is possible to measure the whole-building heating energy demand. The modern electrical services facilitated interventions in the distribution boards to capture the electrical energy demands. The energy use for DHW cannot be readily measured and so has to be estimated.

Whilst measuring space temperatures and CO_2 levels is technically easy, gaining access to hospital wards, and individuals' bed rooms in particular, required careful diplomacy, discretion and patience on behalf of research teams.

5. Measurement and monitoring

5.1. Weather data

The weather at BRI was measured with a Delta T WS-GP1 weather station mounted on the roof of a near-by building. The station was battery powered and charged via a solar panel. It recorded hourly values of ambient air temperature, wind speed and direction, horizontal solar radiation and rainfall. The temperatures were recorded to an

Table 2
Summary of the modular building's design and construction.

General Information	Location	Bradford Royal Infirmary, UK (53° 48' N, 01° 47' W)
	Built	2008
	Occupancy	Wards 29 & 30: 28 beds in each
		Visiting 14:00-16:00 & 18:00-19:00
	Room types	Multi-bed rooms: 4x4 bed rooms (45.7m^2)
		Single bed: 12x1bed rooms (15.6m^2)
Geometry	Floor area	Level 1: Ward 29 (946m^2)
		Level 2: Wards 30 (946m^2)
	Ceiling height	2.70m
	Window orientation	East and West
	Window aperture	Multi-bed room: 2x1500x2100 + 2x750x1400
		Single bed room: 1x1500x2100 + 1x750x700
Services	Heating	Heated ceiling panels
	Ventilation	Bedrooms (natural)
		Corridors (mechanical with heat recovery)
Construction	Roof[a]	Flat roof with Kingspan Thermaproof TR31 & Isowool insulation: U = 0.13 W/m^{2}K
	Walls[a b]	Prefabricated Kingspan KS1000 Insulated wall with added insulation: U = 0.20 W/m^{2}K
	Glazing[a c]	Openable, double glazed, toughened glass, low-emissivity with argon filled cavity
		U = 1.5 W/m^{2}K, g ≈ 0.7
	Bottom floor[a]	Raised over under-croft: U = 0.31 W/m^{2}K
	Infiltration[a]	Air flow at 50pa, Q_{50} = 0.5 m^3/h.m^2

[a] For comparison, the Building Regulations Part [37] values are: 0.25 (W/m^{2}K); 0.35 (W/m^{2}K); 0.25 (W/m^{2}K); 2.2 (W/m^{2}K) and 10.0 (m^3/h.m^2) for roof, walls, floor, window and infiltration, respectively.
[b] From Bradford maintenance manuals [38]
[c] Window U-value and G-value estimated from CIBSE Guide A, Table 3.23 [39].

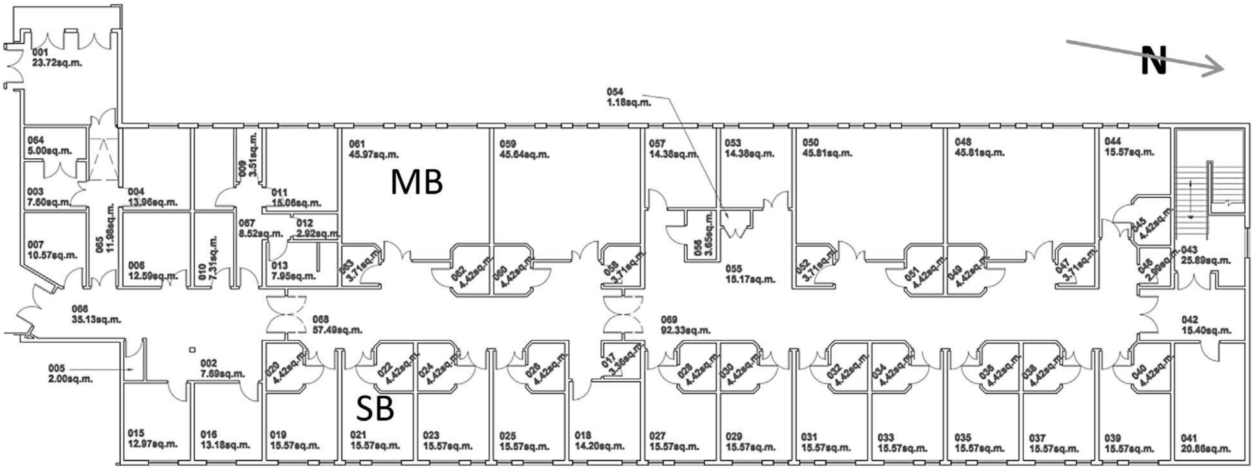

Fig. 3. Floor plan of the modular building. Single-bed (SB) rooms are along the east side and multi-bed (MB) rooms along the west side.

accuracy of ± 0.3 °C [41].

To verify the recorded air temperatures, and to provide data for periods prior to the installation of the weather station, data was sourced from the closest weather station operated by the British Atmospheric Data Centre [42], which was at Bingley about 2.9 miles west of BRI. During the monitoring period, the average temperature difference between the two sites was just 0.03 °C with a standard deviation of difference 0.74 °C.

Overall, 2012 was a cool year for Bradford. The annual temperatures that were substantially lower than those in the [43] Test reference Year (TRY) for the nearest available city, i.e. Leeds, and both the whole year, and the summer months, were cooler than in 2011 or 2013 at BRI. The peak temperature of 25.5 °C was lower than in either 2011 or 2013 and the frequency of occurrence of temperatures over thresholds from 24 °C to 28 °C were also lower (Table 3).

Table 3
Ambient temperature for each of the years monitored at BRI and the corresponding values in the nearest CIBSE Test Reference Year (TRY) for Leeds [43].

	Year				
	Leeds	Bradford Royal Infirmary			
	TRY	2010	2011	2012	2013
Temperatures					
Average °C	12.61	13.48	13.56	13.09	13.09
Maximum °C	31.6	24.9	27.6	25.5	27.9
Minimum °C	0.9	2.9	3.3	0.2	0.7
Annual hours above stated temperature					
24 °C	61	3	31	17	54
25 °C	38	0	19	5	31
26 °C	24	0	7	0	15
27 °C	18	0	1	0	4
28 °C	16	0	0	0	0

5.2. Monitoring energy demand

Electricity and heat energy demand were monitored on a number of separate occasions to understand seasonal variations. Electricity use was monitored for Ward 29 for a period of 15 days in February and 15 days in June 2012 using Hobo CTV-C current transformers on each phase of the two 415 V distribution boards [44,45]. It was assumed that electricity use would be approximately the same for both wards. Electricity was also monitored at the plant room distribution board which controlled the primary and secondary LTHW pumps as well as the fans for the mechanical ventilation units.

Heat demand was monitored using a portable, non-intrusive, ultrasonic flow meter [46] on the LTHW supply pipework, and surface mounted thermistors on the supply and return pipework that fed the ceiling panels in the wards. The thermistors were wrapped in insulation and calculated to measure within 0.1 °C of the water temperature. Heat monitoring took place on six separate occasions: February, May and July in 2012, and February, March and April in 2013. On each occasion, multiple measurements of the heat supplied to the building were made along with the contemporaneous indoor and outdoor temperature. This provided enough data to be able to produce a performance line characterising the heating energy consumption.

Fig. 4. Single bed room (left) and nurses' station and corridor (right), source DKP [40].

Fig. 5. Indoor temperature sensors (Hobo U-12 [Left], Hobo Pendant [Right]) [48].

The energy used for domestic hot water was not actually recorded. Instead, the use was calculated from standard equations [47].

Hobo pendant data loggers (Fig. 5), with a manufacturer's quoted accuracy ± 0.35 °C [48], were placed in the air supply duct to monitor the temperature of the air supplied to the building. An estimate of the heat reclaimed by the heat exchanger was obtained using the difference in temperature between the internal side of the heat exchanger (air extract side) and the external side (air exhaust) and the measured airflow flow rate, which was estimated from measurements of the air flow into the corridor and out of each WC using a hand held balometer.

5.3. Monitoring space temperatures

Temperatures in the wards were monitored using the Hobo pendant data loggers as well as Hobo U12 loggers, manufacturer's stated accuracies ± 0.53 °C (Fig. 5). All the temperature sensors were calibrated prior to use in the Loughborough University building physics laboratories. The indoor temperature sensors (and the weather station sensors) were set up to log the spot values on the hour. At this setting, the indoor sensors had enough memory to store data for three months. Regular site visits were undertaken to download the data, check for errors and analyse the data.

One sensor was placed in single bedrooms and at the nurses' station and two sensors were placed in multi-bed spaces and corridors to identify the variations in temperature across these larger spaces (Fig. 6). They were strategically positioned at head height away from the influence of solar gains. The particular rooms were chosen to give a fair representation of the temperatures around the building. Only temperatures from Ward 30 are reported as results from an earlier study, which monitored both wards, showed that Ward 30 was consistently warmer than Ward 29.

5.4. Monitoring ventilation rates and window opening

The mechanical ventilation rates were estimated from measurements made using a handheld balometer. The flow into the corridor from the accessible air supply outlets and the flow out of the WCs, and other foul areas, from the accessible extract vents were recorded on a number of occasions [17].

The CO_2 levels in multi-bed room MB2 were recorded during the winter of 2012/13 (at location MB2a in Fig. 6) using Telaire 7001 CO_2 sensors connected to a Hobo U12 for data logging. The manufacturers stated accuracy was ± 50 ppm or 5% of the reading, whichever is greater [49]. Over the same period the status of the six operable windows, either closed or open by 100 mm, was recorded using Hobo Pendant G acceleration data loggers, manufacturers stated accuracy ± 0.075 g [44,45].

6. Energy demands and comparisons with benchmarks

6.1. Calculating annual energy demands

Although there were seasonal and temporal variations in electricity demand, there were strong similarities in the mean minutely power demands in the summer and winter (Fig. 7). The power demands gradually increase during the early morning, peaking between 09:00 and 10:00 when activity on the ward was high. Peaks occur later in the day during visiting times (14:00–16:00 and 18:00–19:00) and, between these, at teatime. The mean energy demand measured in June was 10.38 W/m^2 (i.e. normalised by the floor area of Ward 29), and is about 15% higher than in February, 9.06 W/m^2. This could be partly because of the use of portable fans to cool the bedrooms in summer (see below). From these figures, an estimate of the annual electrical energy demand of the wards of 57.1 kWh/m^2 was obtained. The energy demand of the constantly running fans and pumps, 33.3 kWh/m^2, was readily estimated by short term monitoring of their fixed power demand.

To calculate the annual space heating energy demand, the measured daily average heat demand was plotted against the daily average difference in temperature between the ward (T_{ar}) and ambient (T_{ao}) and the regression line determined (Fig. 8). The temperature difference at which the ward required no space heating, sometimes called the balance point temperature, was about 9 °C ± 3 K. This is much less than the base temperature used for degree-day energy demand calculations for hospitals of 18.5 °C, confirming that the building was well insulated

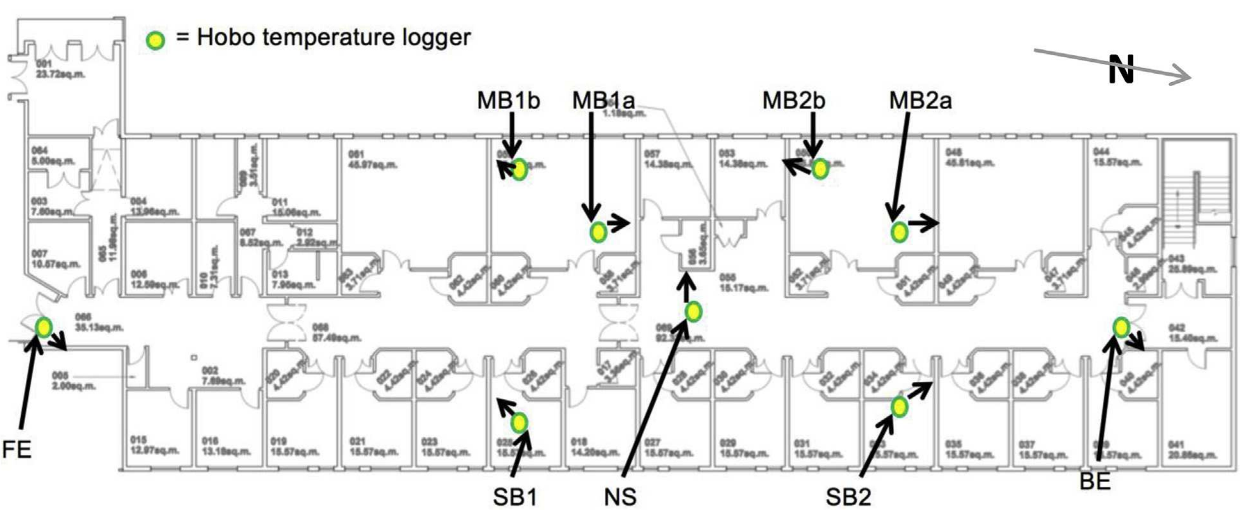

Fig. 6. Modular building Ward 30 floor plan demonstrating placement of temperature sensors (MB = Multi-bed, SB = Single bed, FE/BE = front/back entrance, NS = nurse station).

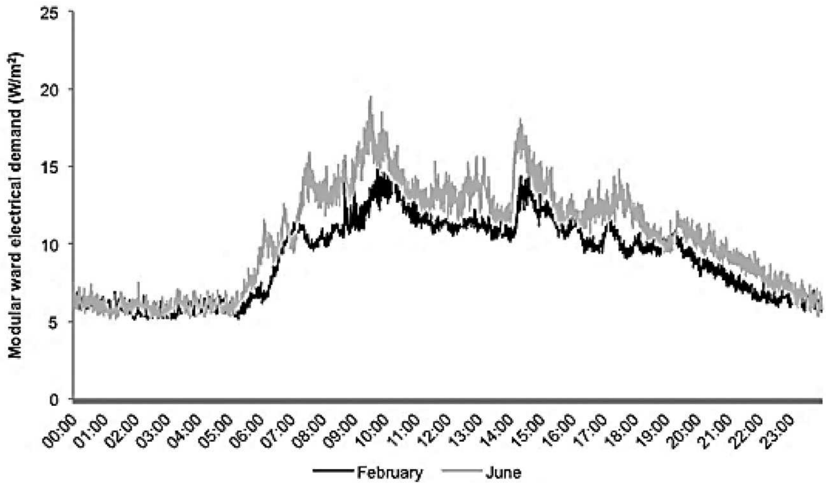

Fig. 7. Averaged minutely power demands of Ward 29 of the BRI modular building, from data monitored over 15 days in February and 15 days in June 2013.

and airtight.

By taking the average daily difference in temperature between the measured ward temperatures (see below) and the temperature measured at the weather station, the annual space heating demand, for the period from 1st April 2012 to 31st March 3013, was calculated. This was then normalised by the ratio of the degree-days measured on site, to base 18.5 °C, 3770 K.days, to the degree-days in a typical year in the East Pennines region, 4061 K.days [50]. This yielded a value of 46.8 kWh/m^2. Taking into consideration the uncertainty in the measurements (± 16%) and the efficiency of the centralized system (estimated to be 53% based on measurements of plant efficiency and estimated distribution losses from the site-wide heat network), it was estimated that the modular building used 88.3 ± 14.2 kWh/m^2 of fossil fuels per year for space heating. The demand for DHW was not monitored directly and so had to be estimated using equation in CIBSE Guide F [47] together with an estimate of the a daily usage of DHW of 105 L/person/day, which is an average of [51] figures for hospitals (80–130 l/p/d). The estimated total annual DHW fossil fuel use assuming, as for the space heating, an efficiency of 53%, was 110.4 kWh/m^2 ± 16%.

6.2. Comparison with energy benchmarks

The calculated total energy demand, 289 kWh/m^2 per annum, was about 31% less than the average for the BRI site as a whole (Fig. 9), the CO_2 emissions were about 21% less (Fig. 10). The electrical energy demand, 90.4 kWh/m^2, is similar to the median of the 35 other residential hospital buildings reported in [4]; 93 kWh/m^2, but the fossil fuel demand, 199 kWh/m^2, is 35% less than the median.

Although the electrical energy demand was marginally above the CIBSE TM46 benchmark, the heating and total energy demand was much lower. The total energy demand of 38.5GJ/100 m^3, even accepting a 16% measurement uncertainty, easily meets the energy demand target of 55GJ/100 m^3 that has been set for new buildings [25] and [26] (Fig. 9).

These comparisons, with both other relevant hospital buildings, and the other buildings on the BRI site, indicate that the intention of providing a new building for BRI that had low space heating energy demands had been successful. The electrical consumption was comparable to the other buildings and with benchmarks. More generally, however, as the NHS continues to become more specialised, electricity demands are likely to increase [6].

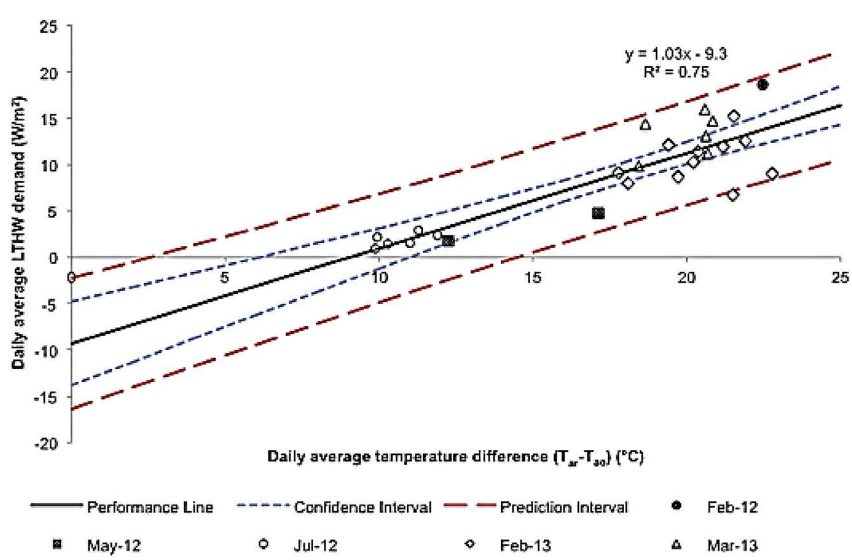

Fig. 8. Performance line for Ward 29 of the BRI modular building based on average daily measurements taken between February 2012 and March 2013.

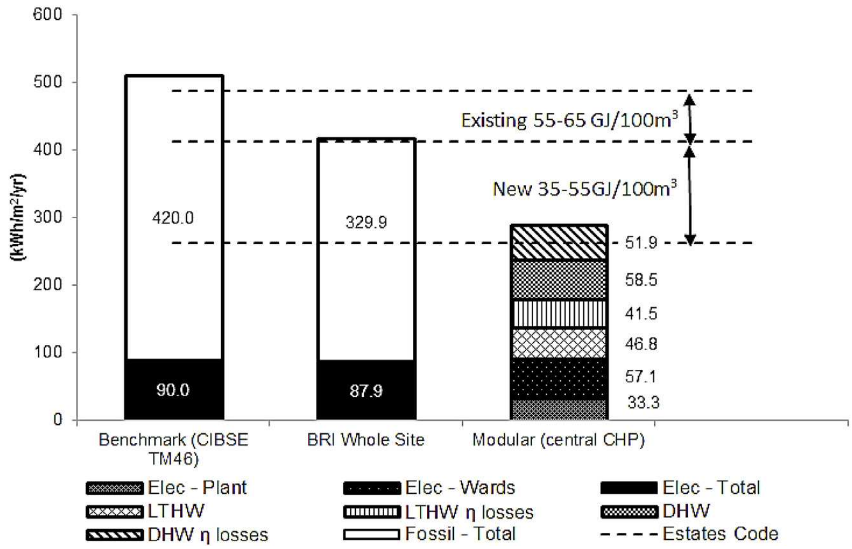

Fig. 9. The estimated annual energy demands of Ward 29 of the BRI modular building, the BRI site as a whole, and the CIBSE TM46 [24] and HTM07-02: EnCO2de [25] benchmarks.

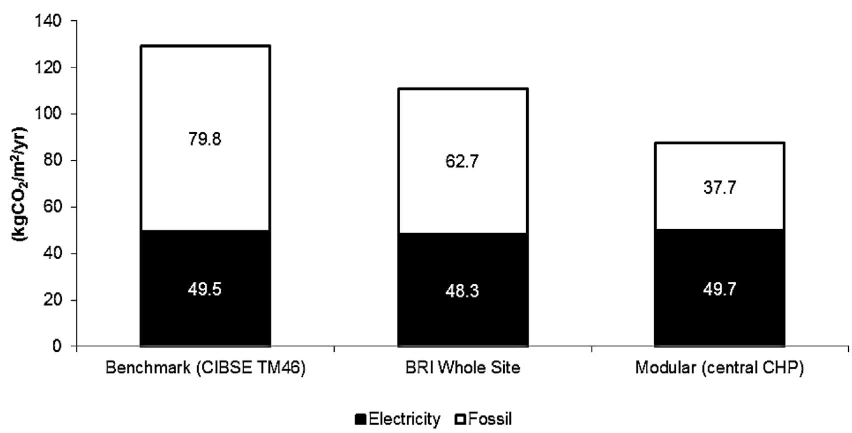

Fig. 10. Total carbon emissions for Ward 29 of the BRI modular building compared with the BRI site. As a whole, and the CIBSE TM46 [24] benchmark.

7. Winter time temperatures and air quality

During the winter of 2012/13, the ambient temperature at Bradford dropped to almost -5 °C (Fig. 11). Nevertheless, the heating and ventilation system maintained space-averaged temperature in Ward 30 to within the CIBSE Guide A range of 22–24 °C [27] for 91% of the time, with a mean temperature of 23.2 °C and a standard deviation of 0.6 °C. The individual room temperatures were within this range for 67%–93% of the time, depending on the room. There were occasional deviations in temperature outside the CIBSE range, possibly due to window opening (Fig. 11), but temperatures were never, except for 9 h in SB1, below the lower limit of 18 °C as recommended by HTM03-01 [8].

The ventilation rate measurements indicated that the AHU supplied air to the wards at a fixed rate of 0.575 m^3/s and extracted air at a rate of 0.775 m^3/s. These values equated to a corridor supply rate equivalent to 3ach^{-1} and a bed room WC extract rate of 3ach^{-1}; which conforms to the guidance in HTM03-01. Because the building is negatively pressurised, airflow through open doors and windows is always into the wards and towards the bathrooms and toilets. This helps to reduce the risk of airborne contaminants spreading through the wards, or from the ward into other spaces when connecting door are open. The arrangement would also encourage external air to flow into the bedrooms when the windows are opened.

The monitored wintertime temperatures suggested that the heating and mechanical ventilation system provided comfortable conditions, despite there being no heating coil in the AHU. The temperatures measured in the AHU indicted however, that the supply temperature was below 16 °C, i.e. 7 K below the heating set point, which is the HTM03-01 allowable limit, for 870 h during the winter period, i.e. more than 50% of the time. That the monitored corridor and space temperatures were nevertheless comfortable, suggest that the supply air was rapidly heated by the ceiling panels and that there was probably heat pick-up to the supply air duct as it passed down the central corridor. The southern (FE) end of the corridor was, in fact, generally warmer than the rest of the ward, with temperatures exceeding 24 °C for 46% of the time.

The averaged CO_2 levels at each hour in the monitored room (MB2) were calculated by averaging the 1680 values recorded at each hour (01:00, 02:00 … 24:00) between 23rd November 2012 and 31st January 2013. Similarly, the average free area of ventilation provided by opened windows was calculated for each hour (Fig. 12).

It is apparent that the time-averaged CO_2 emissions are below 1000 ppm, the upper threshold for class IDA2 spaces, for much of the time. There are notable increases in the CO_2 levels during the morning activity period, when the nursing staff and others attend to the patients, and greater increases during the two visiting periods, 14:00–16:00 and 18:00–19:00. During the visiting periods, the occupancy of the rooms could more than double and so it is not surprising that the CO_2 levels rise, but the average value remains within the IDA3 class (upper limit, 1400 ppm). Windows tend to be closed at night, but begin to be opened

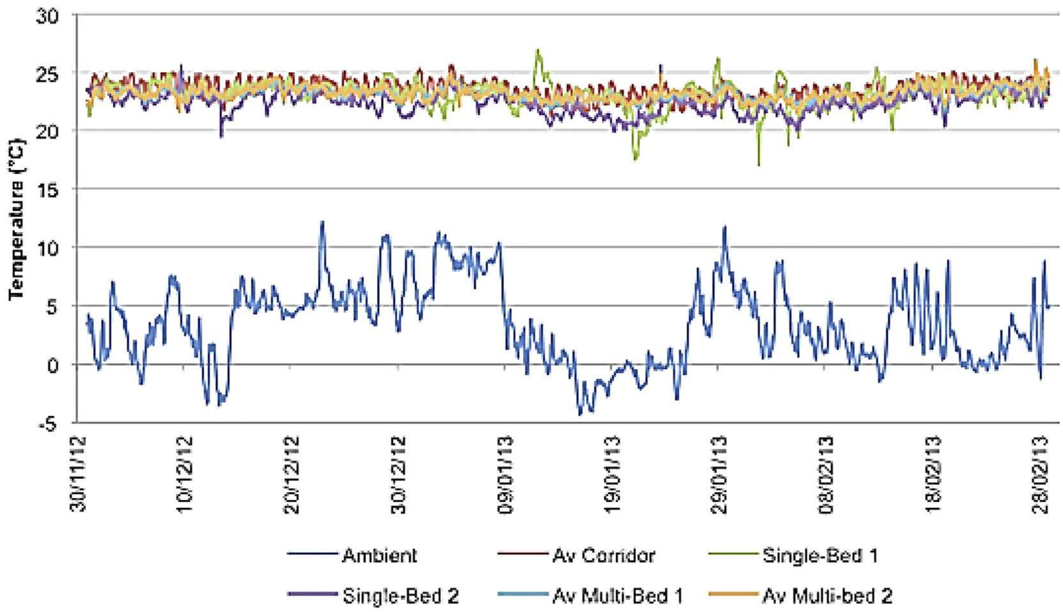

Fig. 11. Measured ward and ambient winter temperatures in Ward 30 of the BRI Modular building (Dec 2012–Feb 2013).

in the morning. More windows are opened during the afternoon visiting period, perhaps in response to a perceived deterioration in air quality or because of elevated temperatures. This has the effect of reducing the CO_2 levels. Fewer windows were opened during the evening visiting period, perhaps because it was night time and also because the ambient temperatures were dropping.

Because the data is for the average CO_2 levels at each hour, 50% of the time the CO_2 levels will be higher (and 50% of the time lower). It would seem though, that the levels are broadly consistent with the provision of British Standard ventilation requirements for IDA2 class spaces and IDA class 3 spaces during visiting times. What is clear is that with appropriate use of the windows, air quality can be maintained and the required ventilation rates achieved.

8. Summertime temperatures in the ward

8.1. Monitored hourly temperatures

During the summer, the east-facing single bed rooms had similar temperatures and were the coolest of the monitored spaces. The temperature never dropped below 19.7 °C in either room but the peak reached 28 °C on 24th June, the warmest day (Fig. 13, Table 4).

The peak temperatures in the multi-bed rooms were similar to those in the single bed rooms, both reached 29 °C on July 24th (Fig. 14). However, MB1 was on average warmer than MB2 and the single bed rooms.

The multi-bed rooms may be warmer than the single bed rooms because they face west which, because of solar gain, makes them more susceptible to overheating than similarly-glazed hospital rooms facing other directions [19]. However, given that MB1 is warmer than MB2, it is more likely that the higher temperatures are because the southern end of the corridor (FE) is particularly warm (Fig. 15), and because the

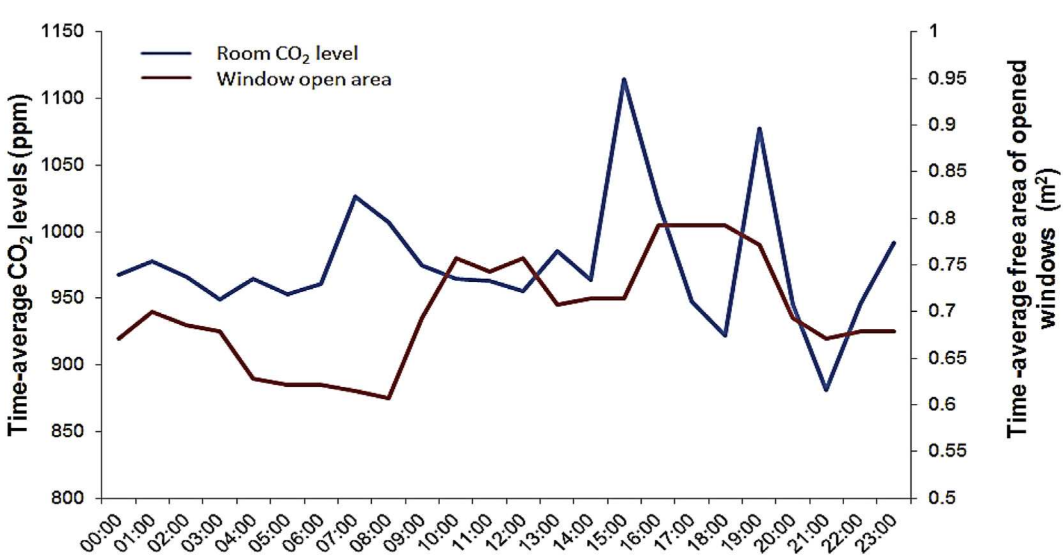

Fig. 12. The average CO_2 level recorded at each hour of the day over the period from 23rd November 2012 to 31st January 2013 and the corresponding average free area of window ventilation opening.

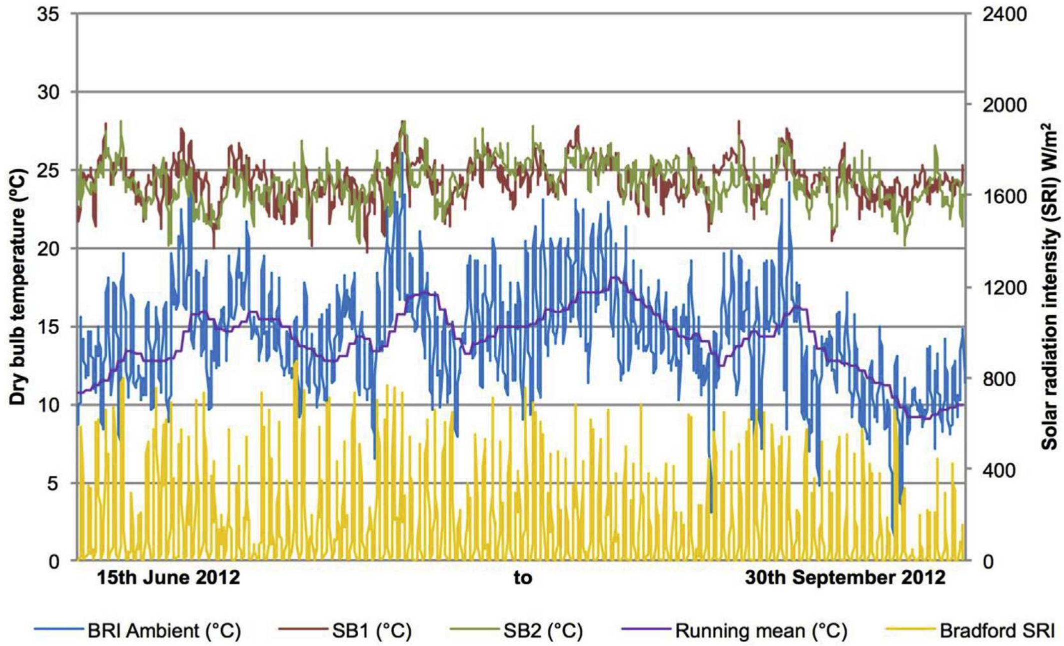

Fig. 13. Average internal temperature for modular single bed spaces.

doors to the MB rooms were opened much more than in the single bed rooms. This could be because they house less infectious patients, or simply that there is four times more movement between the corridor and the room.

Either way, this allows the mixing of air between the multi-bed rooms and the warm corridor. The southerly, front end (FE), of the corridor reached 30 °C on 15th August and was much warmer than the northerly, back end (BE). The nurses' station, which is located in the middle of the corridor, was also warm, mean temperature 25.5 °C with a peak of 29 °C (Fig. 15, Table 4).

Considering the warmest day, July 24th, in more detail (Fig. 16), the elevated temperatures in the corridor, especially at the front end are clear. The blind corridor has no windows to enable natural cooling with night time air, and the increasing temperatures at night suggest that the mechanically supplied air may actually be warmer than ambient.

Inspection of the temperatures measured in the AHU and the corridors, suggested that the by-pass damper was indeed closed between 19:00 and 07:00 each night from 24th July onwards (Fig. 17), thereby causing fresh incoming air to be pre-warmed by heat from the outgoing air. Over the whole summer period, the air supplied from the AHU was always much warmer than the ambient air, varying in temperature from 20 °C to 26 °C.

The damper is operated by simple time-based control and may have been set to close at night because of concerns that the cold night air might chill the ward. There was additional heat pick-up to the supply duct causing a further temperature increase of c3K in the air supplied to the southern (FE) end of the corridor. Mechanical ventilation systems that introduce an overheating risk have been reported for domestic flats by [16].

8.2. Overheating assessment

Whilst none of the monitored wards exceeded the 28 °C/50hr threshold of HTM03-01, the southern (FE) end of the corridor substantially exceeded the 50hr threshold. The nurses' station and MB1 exceed the CIBSE 28 °C/1% criterion and all the spaces exceeded the CIBSE Guide A and TM59 criterion of 26 °C/1% during the night (Table 4).

Table 4
Monitoring summer temperatures in Ward 30 from June 15th 2012 to Sept 30th 2012 and assessment against static overheating criteria.

Room	Max temp (24hrs) (°C)	Min temp (24hrs) (°C)	Mean temp (7:00-20:00) (°C)	Mean temp (21:00-6:00) (°C)	Max diurnal range (K)	Hours over 25°C (00:00-24:00)[a]		Hours over 28°C (00:00-24:00)[b,c]		Hours over 24°C (21:00-6:00)		Hoursover 26°C (21:00-6:00)[d]	
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%**
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%**
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%**

Static criteria thresholds (see Table 1) – **Bold underlined** indicates values that fail the relevant criterion.
[a] CIBSE Guide J and TM36, 25°C/5%.
[b] HTMO3-01, 28°C/50hrs.
[c] CIBSE Guide A, 28°C/1%.
[d] CIBSE Guide A and TM59, 26°C/1%.

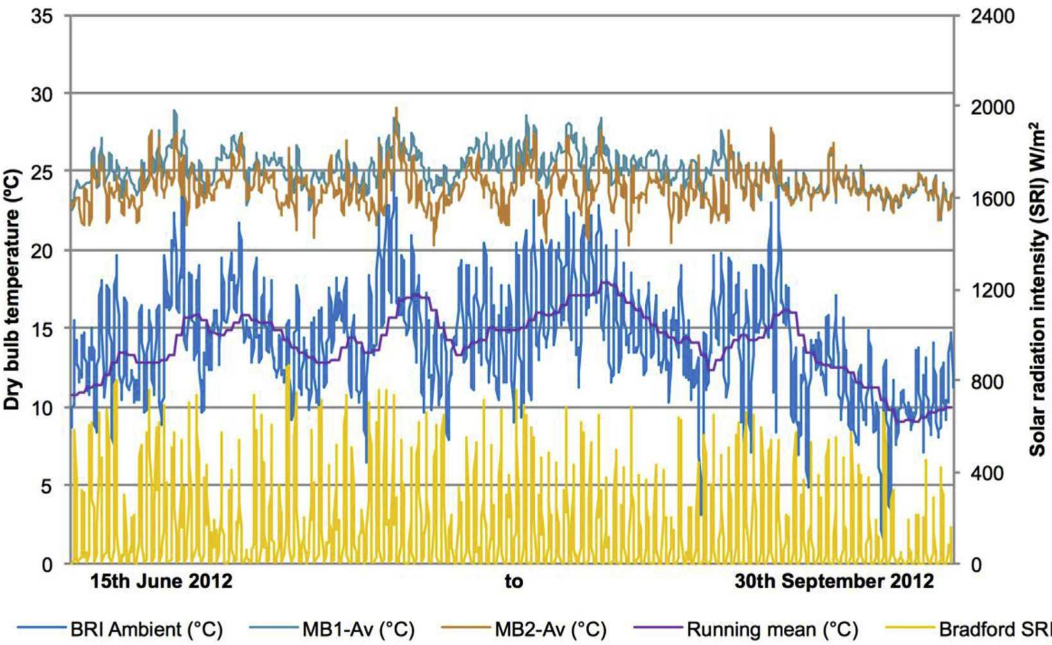

Fig. 14. Average internal temperature for modular multi-bed rooms.

The results from the CIBSE criteria, rather than the HTM03-01 criterion, are considered a much better indicator of the conditions in the spaces because they are based on percentage exceedance rather than a fixed value, e.g. 50hrs as in HTM03-01. Whether or not this fixed criterion is exceeded heavily depends on the duration of the monitoring, for the monitoring period used here, 50hrs is approximately 2% of the time.

Comparing the measured temperatures with the adaptive thermal comfort thresholds, reveals exceedance of both the Cat I and Cat II upper thresholds during both the day and night in both single, and multi-bed rooms (e.g. Figs. 18 and 19). Sometimes the temperatures even exceeded the Cat III upper threshold, even during the night in the multi-bed room (Fig. 19).

Overall, the patient rooms exceeded the Cat I BSEN15251 upper threshold temperature for between 7% and 35% of the time, which is clearly more than the established limit of 3% exceedance (see section 3.2). The nurses' station exceeded the Cat II upper threshold for 11% of the time; again well in excess of the 3% limit (Fig. 20). The high temperature at the southerly end of the corridor (FE) is clear.

Observations made while visiting the BRI wards substantiated the quantitative assessment provided by the CIBSE and, more especially, the BSEN15251 criteria, and illustrated the inappropriateness of the HTM03-01 analysis that suggested there was not an overheating problem. For example, it was noted that the summer the modular building always felt warmer than other wards in other buildings on the BRI site, and there were frequent complaints about the heat from clinical staff,

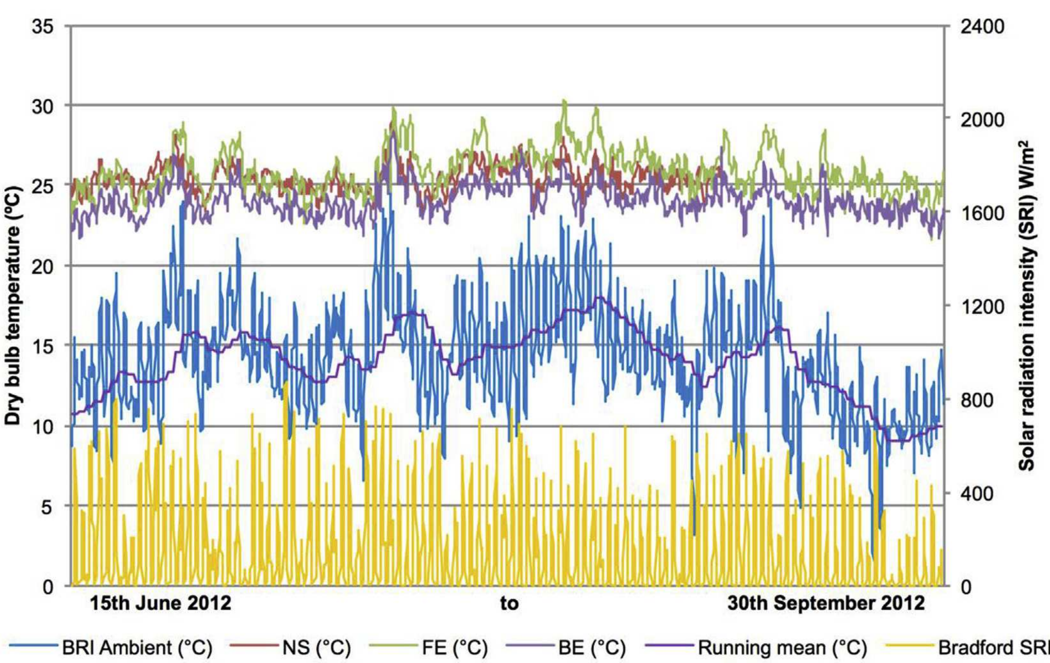

Fig. 15. Average internal temperature for modular corridor and nurses' station.

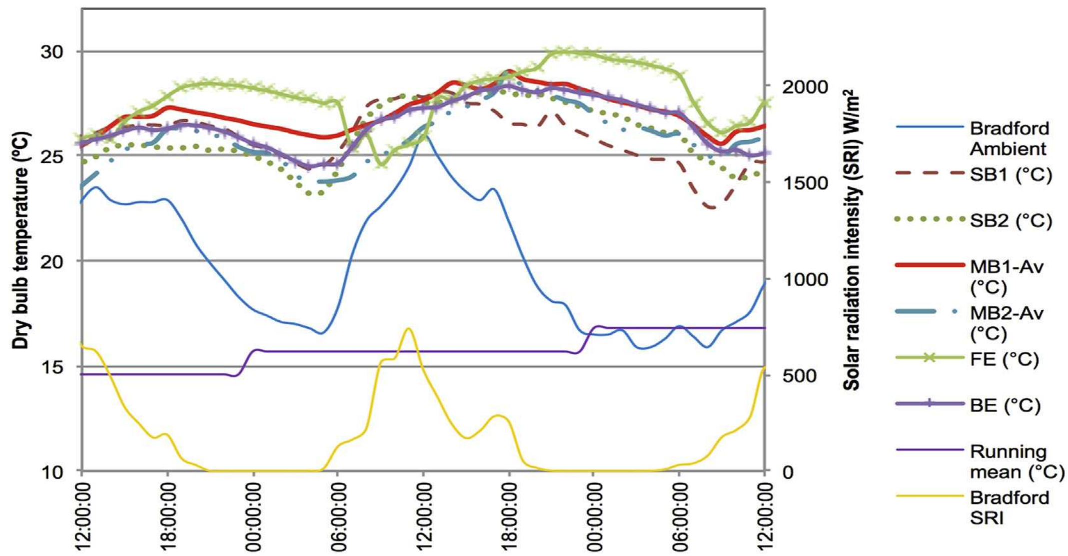

Fig. 16. Temperatures recorded during the warmest day, 24th July 2012, and the 12 h either side.

doctors and nurses, as well as from the estates department staff.

The overheating had operational consequences. For example, during visits to the building in 2011 and 2012, it was observed that the staff had placed fans in bedrooms and corridors to provide cooling. The use, and perceived benefit of fans in this hospital building supports the proposition about their usefulness made in [20].

In 2013, which was a much warmer year than 2012 (Table 3), and included a July heat wave, not only were fans used in the wards but portable air conditioning units were also installed. These were placed in all four of the multi-bed rooms in both Ward 29, ground floor, and in Ward 30, first floor (Fig. 21). These were the only wards on the Bradford site known to the researchers where this had taken place, suggesting that the building was, uniquely, unable to provide an acceptably cool summer time environment. The risks inherent in such remedial measures are discussed below.

9. Discussion

The well-insulated, air tight design of the modular building at BRI, which incorporates radiant heating and mechanical ventilation with heat recovery, suggested that it should enable energy efficient space heating, and this proved to be so. With a total annual energy demand of 289 kWh/m^2 (38.5GJ/100 m^3), it was well within the CIBSE TM46 benchmark [24] and the NHS benchmark of 35–55 GJ/100 m^3 [25] & 2013).

The building lacked any form of direct measure of heat and power consumption. This is regrettable given that monitoring is now an established practice and that this was a new building. An error in the calculated energy demands of 16% was calculated directly from the 95% confidence interval of the regression line through the 27 daily measurements that were made over a one-year period. Sub-metering would have enabled a more accurate measure and it would assist in the effective management of energy, and help the NHS meet its energy reduction targets.

The combination of natural ventilation in the bed rooms and mechanical extract ventilation from the WCs, with make-up air supplied to the corridors from an AHU with heat, provided the required ventilation rates and acceptable air quality. During periods of activity in the ward, the windows were opened and this restored acceptable air quality. During the wintertime, the combination of mechanical ventilation with

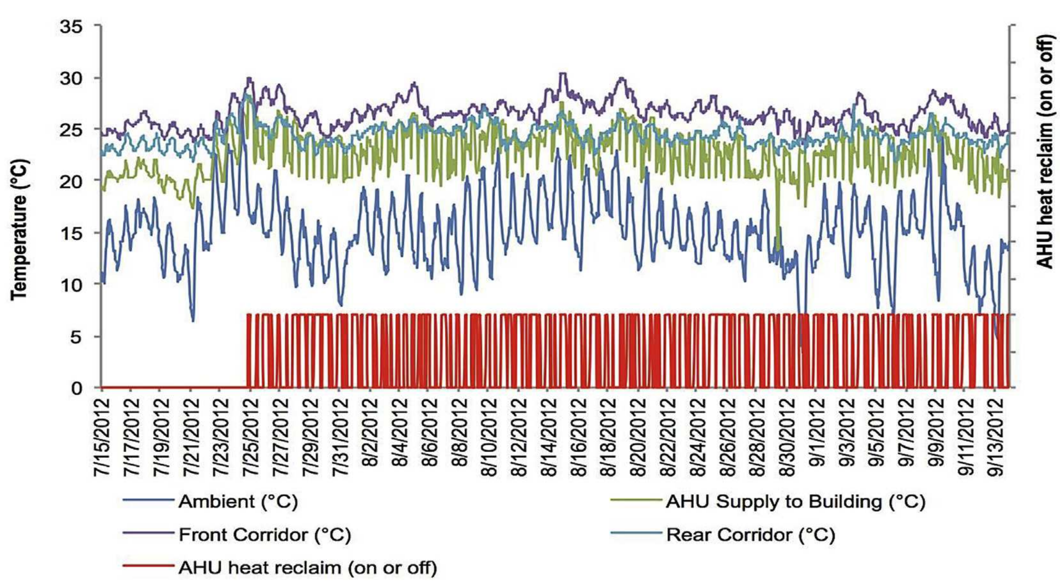

Fig. 17. The AHU supply and corridor temperatures and indicating the operations of the by-pass, heat reclaim damper in the air-handling unit.

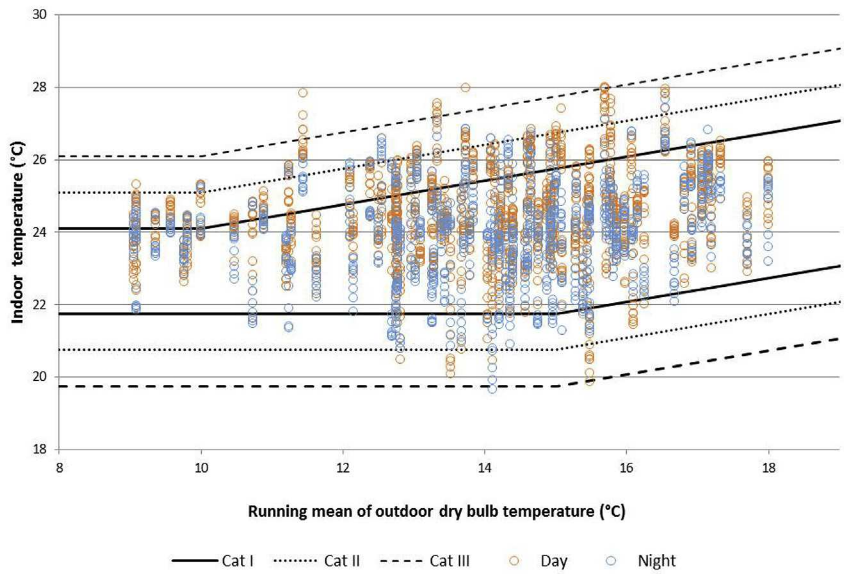

Fig. 18. Comparison of the temperatures in single-bed room SB1, with BSEN15251 temperature thresholds.

heat-recovery and ceiling-mounted heating panels maintained temperatures within the range of 18–28 °C given in HTM03-01 [8] and for many spaces for most of the time within the narrower CIBSE Guide A range of 22–24 °C. Overall, therefore the building can be considered to perform well in winter, even during cold periods such as those experienced at Bradford in 2012/13.

The attempts to assess the incidence of overheating revealed that the HTM03-01 28 °C/50hr criterion was inherently unsuitable for assessing monitored in-situ performance. This is because whether or not a space is, or is not, deemed to be overheated heavily depends on the period of monitoring; 50hrs represent 2% of the time for monitoring period of 108 days used in this work, but it is just 0.6% for a year-long monitoring campaign. The static CIBSE criteria were more appropriate, but the BSEN15251 adaptive approach, as noted by [20]; is the most appropriate. The method accounts for the different sensitivities of the nursing staff, visitors and patients, enables any length of monitoring period and accounts for the changes in sensitivity of people as ambient temperatures change either over time or with geographic location. More research work is needed however, to establish the allowable frequency of threshold exceedance; herein 3% of hours was used. More fundamentally, research is needed to understand fully the adaptive potential of people in beds, especially those that are ill, elderly or otherwise vulnerable.

The summertime performance of the building was unsatisfactory. Despite the north of England location and the relatively cool summer conditions in 2012, the monitored ward building seriously overheated as measured by the two criteria recommended in the recently published CIBSE Technical Memorandum TM59 [33]: the BSEN15251 adaptive comfort criteria for daytime temperatures and the static 26 °C/1% criterion of CIBSE Guide A for night time. None of the spaces met the BSEN15251 Cat I criterion and the overheating in the corridor and at the nurses' station was chronic and sustained. In these areas, and in one of the multi-bed rooms, the temperatures even exceeded the thresholds applicable to Cat II occupants, such as clinical staff and visitors.

The overheating appears to be a consequence of uncontrolled internal heat gain and the lack of any obvious design measures to combat

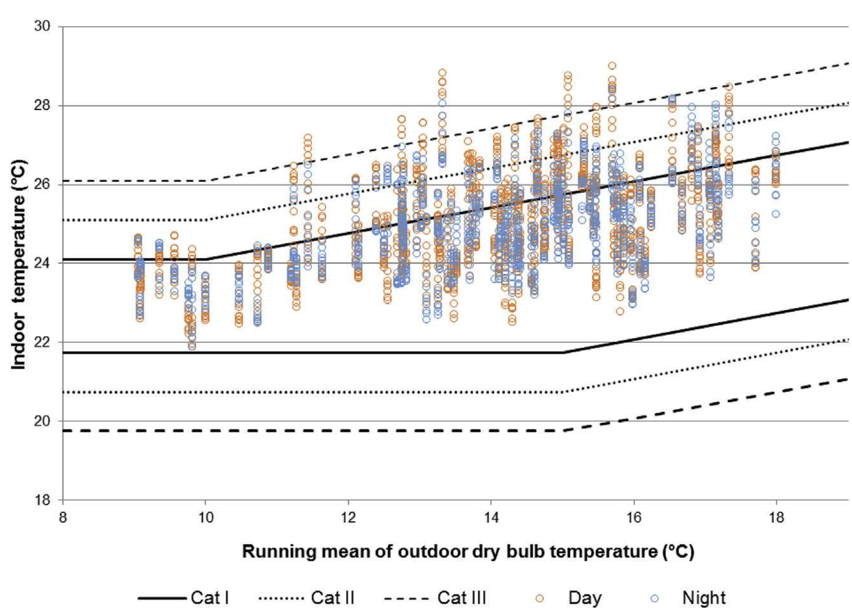

Fig. 19. Comparison of the temperatures in multi-bed room MB1, with BSEN15251 temperature thresholds.

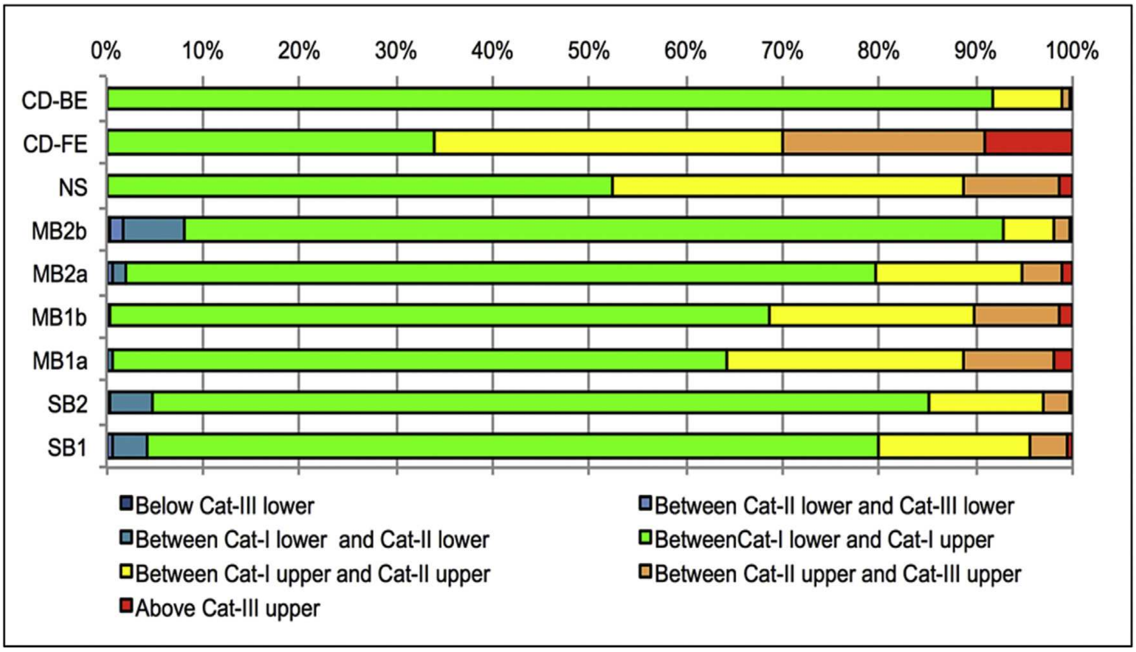

Fig. 20. Percentage of all measured summer time hours within each BSEN15251 comfort band. The green bands show the period of time within the Cat I thermal comfort limits that are applicable to hospital patients (MB = Mixed bed, SB = Single bed, FE/BE = Corridor front/back, NS = Nurse station).

Fig. 21. Portable air conditioning unit, with makeshift safety barriers in a multi-bed room MB2 of Ward 30 during the summer of 2013.

summertime heat gain, no matter from what source. Furthermore, because the building is thermally light weight, well insulated and air tight, any heat that accumulates doesn't easily dissipate by conduction or through background infiltration.

The building has double banked, blind corridors, which provide the route for hot water pipes, the mechanical ventilation supply and extract ducts, as well as other services. The measurements suggested that the air supply duct picked up heat as it passed down the c60 m corridor. Heat pick-up in ventilation systems as a contributor to chronic overheating in homes has been noted by others [16]. An associated problem is that in health care buildings, unlike, for example dwellings, indoor night time temperatures cannot fall below the lower limit of thermal comfort. This may be why the by-pass in the AHU was closed at night so pre-warming the supply air. The combined effects of heat pick-up and bypass operation means that the mechanical system delivers hot air into the building throughout the summer, rather than being a system that can help to night time ventilation cooling.

The problem of how to operate the by-pass damper is not easily solved. If the damper is closed at night then there is no prospect of night time cooling, if it is open then occupants may be chilled. What is needed is a more intelligent operating strategy, one that opens the damper to enable night time cooling when the wards are warm and the night air is cool, but which closes the damper when the ward temperatures are acceptable. This is conventional feed-back control, with all the attendant problems, what indoor temperatures to monitor and when to switch the status of the damper?

Because the corridors are blind, the heat that accumulates in them cannot be ventilated away, for example by using operable windows or some other occupant-controlled means of ventilation. (Secure multi-pane operable windows suitable for ward and corridor ventilation are readily available, e.g. Fig. 22). Many others have noted the problems associated with blind corridors (e.g. see [52] and [53]. The tendency to locate nurses' stations in the middle of wards, often off corridors, means they are particularly prone to overheating, and the nurses themselves can do nothing about it.

In the BRI building, the accumulated heat appears to enter the multi-bed rooms under the positive air pressure. Unlike the single bed rooms, these rooms did not house particularly infectious patients and the doors were often left open. In any case there would be frequent movement into and out of the rooms. Further, as they have multiple occupants any one patient may not feel empowered to open windows (or close the door) in an attempt to control the room temperature.

Although there was no external shading to the bed room windows, the glazed area was modest. However, the window opening was restricted to just 100 mm, which is common in hospitals, care homes, multi-storey housing and other buildings where security and the safety of occupants is a concern. This restriction, together with the number and design of the operable windows, meant they provided only a small free-area for ventilation (in the multi-bed rooms equivalent to c2.6% of the floor area) and opened to an angle of just 8°, which may well not satisfy the requirements (of 15°) for purge ventilation given in the

Fig. 22. A secure, safe, well-insulating window ventilation system located at the end of an otherwise blind corridor.

Building Regulations [54]. Thus even if patients and nurses wished to intervene to cool the rooms in summer, the ventilation opportunity provided is inadequate.

Because of the overheating, fans were used throughout the building in summer and, on the hottest days, portable air-conditioning units (Fig. 21). Air conditioning units have inaccessible, large-area heat exchange surfaces, possibly covered with a film of moisture, and trays of warm condensate water. These can act as a perfect breeding ground for bacteria. The portability of the units provides a route by which any infectious agents can be spread around the hospital.

The inherent dangers of overheating in thermally lightweight designs of the type seen at Bradford, may well be ameliorated by the use of passive means such as natural ventilation inlets that are secure but of sufficient free-area and designed specifically to enable summertime temperature control. In cooler UK locations like Bradford, such measures are especially likely to provide satisfactory thermal control. The problem is that there is no regulatory requirement to provide adequate means for controlling summertime temperatures. The evidence from this monitoring study suggests that perhaps such regulations should be considered.

The obvious alternative to passive control measures, which may be the only reliable solution in some parts of England, is to use air conditioning. However, this is likely to be incompatible with the need to cut energy use and reduce CO_2 emissions. It also places a higher ongoing maintenance and cost burden on hospital estates teams. Both passive and active solutions imply costs, and so are unpalatable given the tight financial constraints under which the UK health service operates.

It might be that with much better design and operation, new well-insulated, thermally lightweight and naturally ventilated buildings, built using modular off-site methods, could provide safe, energy efficient, environmentally friendly and low cost hospital wards in the UK. Whether the construction industry is capable of delivering such designs, and doing so within the cost constraints imposed on them, is also uncertain.

10. Conclusions

A hospital building at Bradford Royal Infirmary in the north of England has been monitored to determine the energy demands, internal temperatures and ventilation performance. The two-storey building which, housed two, 28-bed wards, was built using fast-track, modular construction techniques. It was well-insulated, air tight, thermally lightweight, and unshaded. The naturally ventilated single and multi-bed bed rooms were heated with radiant ceiling panels. There was mechanical extract ventilation from WCs and other ‘dirty’ areas with makeup air supplied to the corridors by an air-handling unit with heat recovery.

The measured annual total energy demand of 289 $kWh/m^2 \pm 16\%$, equivalent to 38.5 GJ/m^3, was well within the CIBSE benchmark and the target of 35–55 GJ/m^3 set for new hospital buildings. The fossil fuel energy demand was estimated as 199 $kWh/m^2 \pm 16\%$, confirming that the well-insulated building together with the efficient heating and ventilation systems performed well.

The building maintained thermally comfortable wintertime conditions despite there being no heating coil in the AHU. The extract ventilation rates in the bathrooms and other dirty areas complied with relevant Standards' requirements. The ventilation rates for fresh air provision in one multi-bed space, as inferred from measured CO_2 level, were within the requirements of the relevant British Standard. By using the available operable windows, acceptable air quality could be maintained, even during the afternoon and evening visiting times.

The measured summertime temperatures revealed that overheating, as indicated by the BSEN15251 adaptive thermal comfort criteria, occurred in all the patient rooms (Cat I) and at the nursing station (Cat II). Night time overheating, as indicated by the CIBSE 26 °C/1% static criterion occurred in all the monitored spaces. The west-facing, multi-bed rooms severely overheated, precipitating the use of fans and, during the hot summer of 2013, portable air-conditioning units.

The analysis of overheating revealed that the Department of Health's overheating criterion, as stated in HTM03-01 (2007), is inappropriate for assessing the risk, or incidence of overheating in existing hospital buildings, and may even lead to an incorrect overheating diagnosis. Given the likelihood of increasing summertime overheating, especially if buildings like the one at Bradford proliferate, this deficiency needs to be addressed.

The design and operation of the mechanical ventilating system, compounded by the blind corridors, the restricted window opening, and perhaps the lack of external shading, in a well-insulated, thermally lightweight building, created a combination of factors that led to the summertime overheating.

Modular construction may provide an energy efficient and convenient solution to the pressing need for additional hospital bed spaces in the UK. However, the evidence from this study is that better design of the fabric and mechanical systems is needed if such buildings are to provide a safe and comfortable summertime environment for patients and clinical staff.

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