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Building resilience to overheating into 1960’s UK hospital buildings within the constraint of the national carbon reduction target: Adaptive strategies

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ABSTRACT

The National Health Service (NHS) Estate in England includes 18.83 Mm^2 of acute hospital accommodation, distributed across 330 sites. Vulnerability to overheating is clear with 15,000 excess deaths occurring nationally during the July 2003 heatwave. The installation of mechanical cooling in existing hospitals appears to be the inevitable recommendation from NHS patient safety risk assessments but the carbon implications would undermine the NHS Carbon Reduction Strategy. NHS CO_2 emissions constitute 25% of all public sector emissions, equivalent to 3% of the UK total. In the post-2008 economic climate, the likelihood of wholesale replacement of the NHS Estate is significantly diminished; refurbishment is now of increasing interest to the Trusts that together make up the NHS. The research project ‘Design and Delivery of Robust Hospital Environments in a Changing Climate’ seeks to understand the environmental performance of the current NHS Estate and, from this, to establish its resilience. To this end, hospital buildings operated by four NHS Trusts are being monitored and simulated using dynamic thermal models calibrated against measured data. Adaptive refurbishment options are proposed and their relative performance predicted against the existing internal conditions, energy demands and CO_2 emissions. This paper presents findings relating to one representative type building, a medium-rise ward block dating from the late 1960s. It shows that this particular type may have more resilience in the current climate than might have been expected, that it will remain resilient into the 2030s, and that relatively non-invasive measures would extend and increase its resilience whilst saving energy.

1. Introduction

This paper investigates the resilience of various refurbishment schemes for a typical hospital tower building in the UK to climate change, focussing on summertime overheating. The National Health Service (NHS) Estate (England) comprises 28.38 Mm^2 of accommodation. In England, there are 330 acute hospital sites with a gross floor area of 18.83 Mm^2; 8.3 Mm^2 is occupied by patients [1]. The NHS is required by law to reduce its carbon emissions [2] and stringent targets for energy demand have been set. The NHS reports that it is currently responsible for 30% of UK total public sector carbon emissions, and 3% of all UK emissions [3]. Its annual carbon footprint, as of 2007, was 21 Mt pa (million tonnes of CO_2) of which 24% can be attributed to building energy [3]. Although energy is being used more efficiently, consumption has risen 40% since 1990 and increased by 2 Mt between 2008 and 2009 [3]. Attempts to reduce consumption in England by 0.15 MtC (million tonnes of carbon) between 2000 and 2010 appear to have failed [4]. According to the Department of Health’s ‘Health Technical Memorandum 07-02’, 44% of the energy used in a typical UK hospital is attributable to air and space heating [5]. ‘Health Technical Memorandum 07-07’ calls on NHS organisations to achieve targets for delivered energy of 35–55 GJ/100 m^3 for new buildings and major refurbishments, and 55–65 GJ/100 m^3 for less intensive refurbishments of existing facilities,[1] for all building uses including space heating, hot water, lights, appliances and catering [6]. Data shows that energy use in English hospitals is often far in excess of these levels [7].

The challenge of reducing CO_2 emissions and energy demand is amplified by the health implications of a changing climate.[2] The NHS is required to provide a safe and comfortable environment for patients and visitors (more than 1 million every 36 h) and staff (1.4

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[1] The use of GJ/100 m^3 relating energy use to volume is customary within the NHS.

[2] The CO_2 and energy reduction aims are often met simultaneously by reducing energy demand. However, since refurbishment may include changes to the method of supplying heat and electricity, meeting the CO_2 ambition may differ from meeting an energy target. For example the use of biomass from sustainable sources reduces emissions but the energy demand, in the form of wood or pellets, may increase as biomass boilers may be relatively inefficient compared to other conversion technology such as combined heat and power plant.

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million employees, 5% of the UK workforce [8]). The 2003 heatwave led to 15,000 excess deaths in Northern France, the UK heatwave of June/July 2006 is thought to have led to an increase in deaths over baseline mortality of 4%, and there were approximately 300 excess summer deaths after the 2009 heatwave between 30 June and 2 July [9]. Individuals sensitive to high temperatures are likely to be present at all times in hospitals, including those with compromised thermoregulatory systems (the elderly, the chronically and severely ill, those on certain medications that impair perspiration) as well as those who cannot take action in the face of high temperatures (small children, the bed-bound, patients with mental illnesses) [10]. However, very few existing buildings on the NHS Estate were designed to be air-conditioned; indeed, many are poorly insulated and often over-glazed, leading to increased risk of summertime overheating, even in recently completed buildings [11].

It is understandable that NHS hospital trusts may retrofit air conditioning to ensure patient safety. In fact, some commentators suggest that such a strategy would be sensible (London School of Hygiene and Tropical Medicine contribution to the EPSRC Adaptation and Resilience to Climate Change Coordination Network 'Overheating Seminar to address Policy Questions', at the Department of Communities and Local Government, 1 December 2010, attended by the author). While natural ventilation is promoted by the NHS for non-critical spaces such as wards and offices [6], there are perceived barriers: concerns about infection control, security and safety when using operable windows, and a risk-averse procurement environment [12]. There are few examples of innovative natural ventilation/passive cooling strategies being used in hospital buildings, although recent research suggests that 70% of an acute hospital could be naturally ventilated while notional propositions for such strategies have been made [10,12]. Thus although the NHS Heatwave Plan [9] advocates a 'passive approach' to combating heatwaves, including in the medium term (10–30 years outlook) a 'focus on building design of hospitals … to aid passive cooling where possible', it also suggests that the NHS should 'target vulnerable areas (patients, medications, IT) with air conditioning.' However, the take-up of air conditioning at the significant scale of the NHS Estate would clearly disadvantageously affect the national carbon reduction programme.

The DeDeRHECC project adopts the premise that by reducing the inherent overheating risk and energy demand of existing buildings through refurbishment, it is possible to reduce CO_2 emissions, achieve the energy targets, and improve resilience to climate change [13,14].[3] Energy demand reduction also provides NHS Trusts with added protection against fuel shortages and price rises. Within the context of mandatory carbon 'budgets', carbon savings through reduced energy use can be directed to patient care [15]. The focus on a particular building type, governed by specific criteria, can be justified by a.) the significant proportion of UK emissions generated by the NHS; b.) the scale of the NHS Estate and the recurrent types that comprise it; and c.) the role of the NHS in safely providing healthcare as a public service. It is also hypothesised that a building envelope that is well insulated, with measures to control solar gain and passively driven ventilation, will make buildings more resilient in the face of power loss and other natural and man-made catastrophes; i.e. a building with greater all round resilience. In this respect, many of the issues are applicable to other highly serviced building types.

The paper quantifies the impact of each proposed refurbishment option on the energy demand and CO_2 emissions of the building. The paper briefly reviews the current status of the NHS building stock and outlines the characteristics of the case study tower block. The current performance of selected spaces is reported. The paper presents the results from modelling the current and future performance of a key space, diagnoses the outcomes and proposes various refurbishment options to increase resilience. The performance evaluation criteria and model calibration are described. Lomas & Giridharan [16] explain the modelling exercise in greater detail in a related paper.

2. The case study building: the Addenbrooke's Ward tower

Addenbrooke's Hospital is located to the southeast of Cambridge (Fig. 1). The main ward tower, investigated here, was built between 1967 and 1972 comprising a ten-storey slab block. An initial survey of NHS hospital sites by the authors has identified 50 buildings of this basic type with an average of seven storeys, suggesting that an assessment of the inherent resilience of this type configuration for a hospital may have considerable potential impact. The research team's intent was to provide evidence to policymakers deciding whether to decommission these buildings, invest in relatively minor and less disruptive interventions, or contemplate more substantial interventions to realise long-term resilience.

Fig. 2a and b shows two floors, levels 8 and 6 of the Addenbrookes Ward Tower, comprising general and trauma wards. The figures indicate the spaces in which data have been collected. The tower is 120 m long on its SW/NE axis and variously 14.1 and 18.3 m deep. All floors have the same overall geometry consisting of a long central corridor to which rooms of 5.7 m depth are connected. On the north side, single patient rooms are found at the ends (5.7 m deep) with offices and utility space to the middle. On the south side, multi-bed wards (10.2 m deep from corridor to window wall) occupy the wider end parts of the building and have a projecting bay area; there are also some further single bedrooms. As Fig. 3 shows, there is a half-height service floor between the 8th and 9th floors (the latter designed as an isolation unit for infectious patients) and an air handling plant and tank room above floor 9. The main plant room is below in a basement. The occupied levels have a structural floor to ceiling height of 3.66 m with, as designed, a 0.90 m void above the suspended ceiling. Fig. 4, cross section through a typical floor, shows the relative proportions of the single and multi-bed spaces and also the relative height of the wards.

The windows run as a continuous ribbon at all levels on both facades incorporating opaque panels. Precast concrete panels form the spandrels. Figs. 3 and 5 show the original fenestration comprising centre pivot teak-framed windows, c. 2 m in height (U-value estimated as 5.6 W/m^2 K). The continuous glazing here yields a façade glazing ratio of 57%.

The commissioning clients and their designers were aware of the likelihood of unwelcome solar gains and glare arising from the southeasterly exposure because solar gain had already proved to be an issue in previous buildings on the site ([17, minute of 1 March 1963]. In the case of the ward tower, direct solar gain was to be mitigated by '*external blinds made of tygan which could be operated from inside the rooms*', to be fixed directly to the teak frames [17, minute of 23 August 1965]. 'Tygan' was the brand name of a type of polyvinylidene chloride plastic, in effect horticultural open woven shading cloth [18]. It is not known whether the clear variant was proposed (which could reduce light transmission by between 21% and 36%) or the green version (by 53–55%) [18]. However, in January 1969, it was reported that '*none of the blind manufacturers would guarantee an external fabric blind under the conditions prevailing on the elevations of the ward block and as a result of experience*

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[3] The project 'Design and Delivery of Robust Hospital Environments in a Changing Climate' ('DeDeRHECC') is funded by the UK Engineering and Physical Sciences Research Council (EPSRC) within the 'Adaptation and Resilience to Climate Change' (ARCC) programme, with additional contributions from the UK Department of Health.

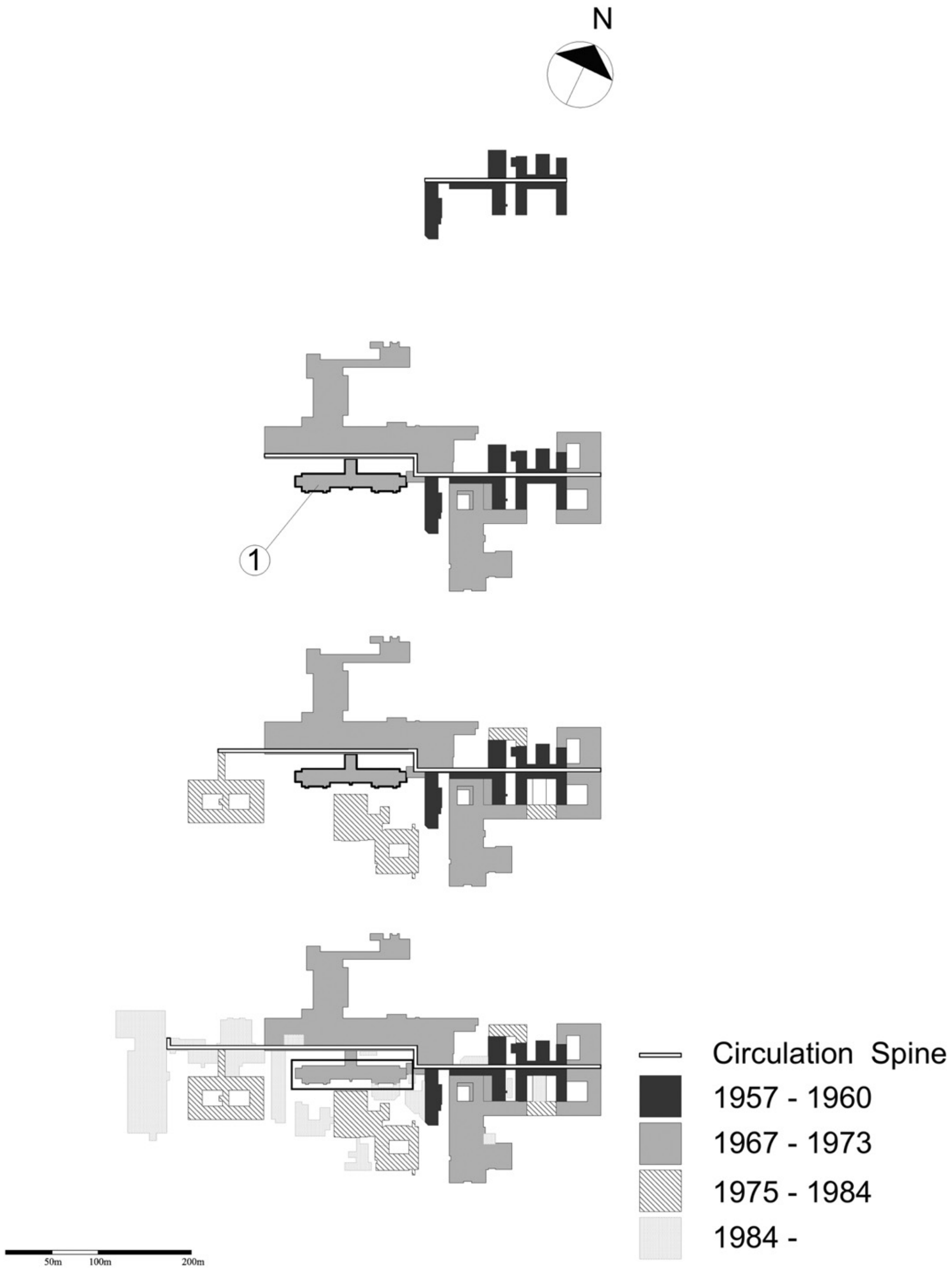

Fig. 1. Addenbrooke's Hospital, showing major construction phases. The Masterplan delivered an attenuated east-west spine, allowing the ward tower to enjoy southerly views over the countryside. Key Phase I, 1957–1962: pavilions orientated perpendicular to the spine, a conventional hospital arrangement with its roots in the nineteenth century Phase II, 1967–1972: notably, the main ward block is parallel with the spine in defiance of the traditional hospital arrangement and the recommendations of the Nuffield study 1973–1984 Post 1984 Spine on three levels: Level 1 services/supplies/waste; level 2 public/patients/staff; level 3 clinical/surgical.

gained in their use on other tall buildings, "Tygan" blinds were no longer manufactured' [19]. The proposed defensive measure was abandoned. Records show that there were complaints of excessive heat in the completed building [20].

Whereas contemporary guidance recommended natural ventilation for wards, at Addenbrooke's it was thought that a mechanical solution was required to achieve the then desired air change rate of 2.5 ach^{-1} [17, minute of 11 October 1963]. It was stated that air in winter would be heated to offset the air change heat loss only. Air was delivered to wards via ducts in the suspended ceiling of the corridor; bathrooms and utility rooms only were provided with extract ventilation. The defined temperature rise was 42 °F (23.3 K), thus with a 25 °F (−3.9 °C) outdoor temperature, an indoor temperature of 67 °F (19.4 °C) would be maintained indefinitely. Patent 'Frenger' radiant ceiling heating panels were installed, comprising perforated metal trays onto the top of which is clipped metal piping to take low-pressure hot water.

The designers' principal concern was to achieve comfortable temperatures in winter, rather than mitigate the summer overheating risk. Ministry of Health guidance, then just published, called for wards to be heated to 65 °F (18.3 °C) when the external temperature was 30 °F (−1 °C) [21]. The mid-1960s design team

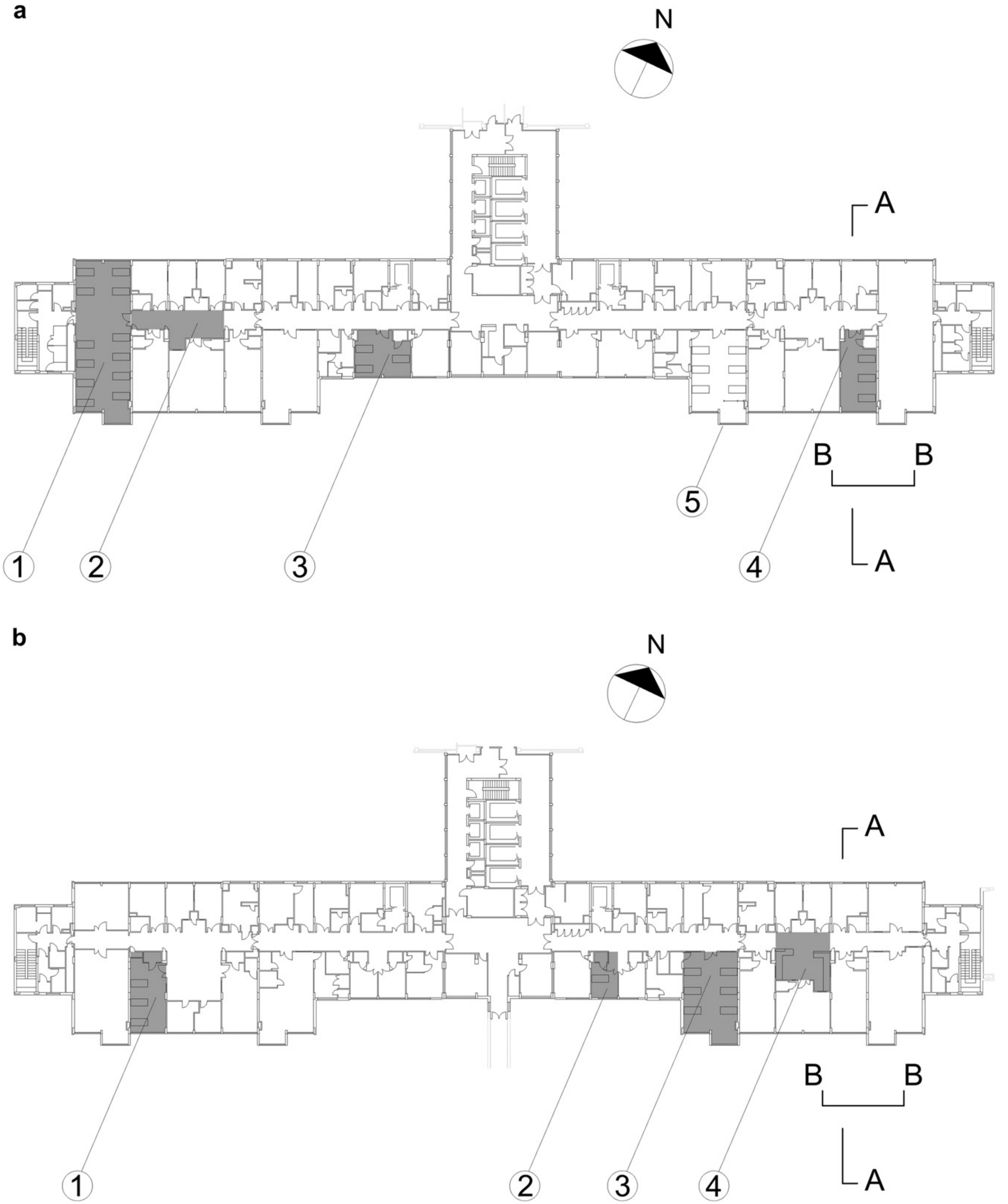

Fig. 2. a. Plan of Level 8 in the ward tower at Addenbrooke's Hospital. The most noticeable change to the original design comprises the removal of the enclosed day spaces in bays at the ends of the wards. . Key: Spaces being monitored; Two multi-bed wards (8MB4, 8MB10); A nurses' station (8NS). b. Plan of Level 6 in the ward tower at Addenbrooke's Hospital. The most noticeable change to the original design comprises the removal of the enclosed day spaces in bays at the ends of the wards. Key: Spaces being monitored; a seven-bed ward (6MB7); a nurses' station (6NS).

was aware that the heating of the earliest buildings at Addenbrooke's had been inadequate during the exceptionally cold winter of 1962–1963 [17]; the cold winter of 1947 may have also been on their mind.

2.1. Subsequent interventions and the building today

The hospital Estates staff report that there were no major changes to the external envelope until 2000 when the eastern

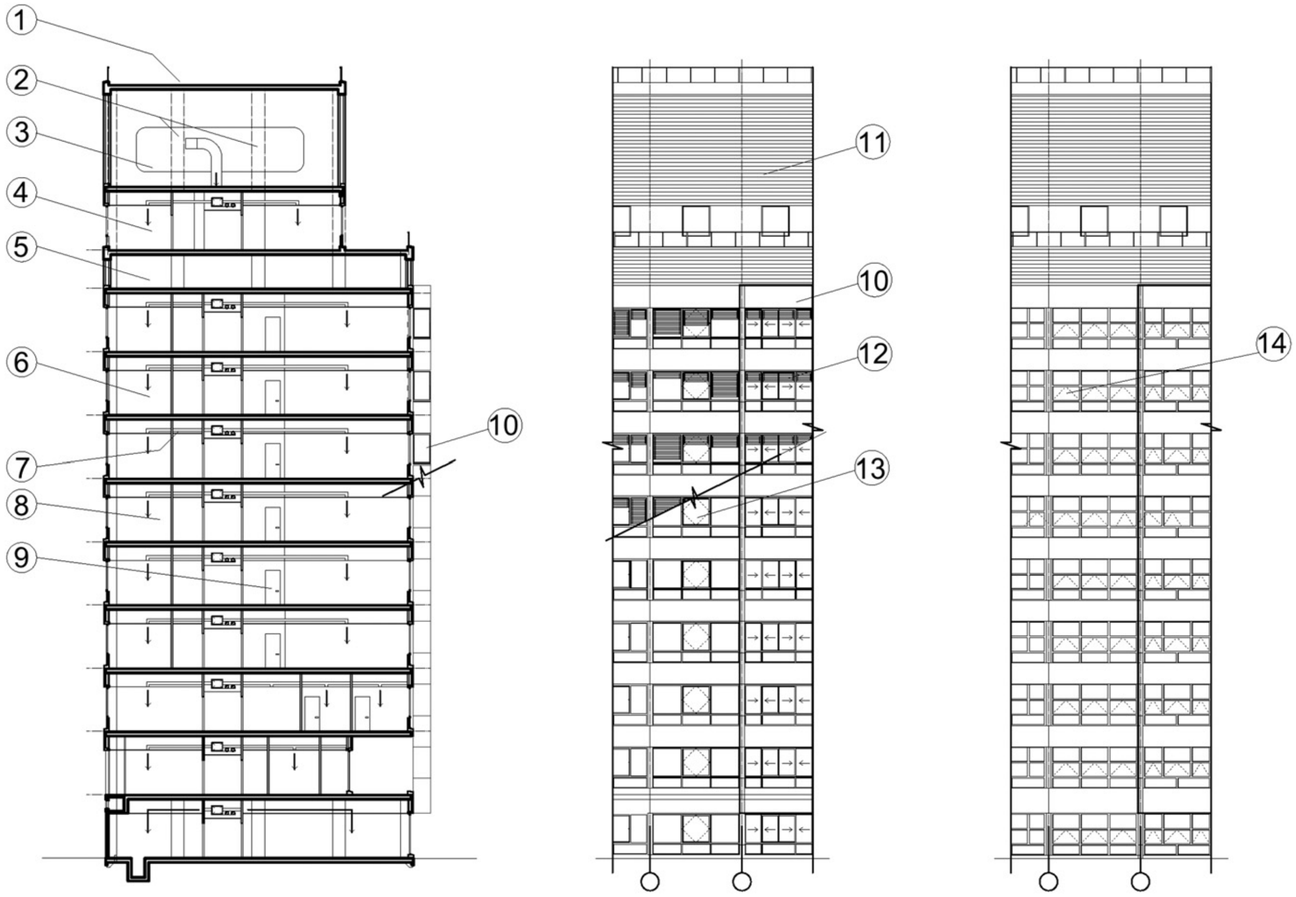

Fig. 3. The Ward Tower, Addenbrooke's Hospital, as originally built (showing also omitted shading), and as modified by 2011. Key: 1 Uninsulated roof deck; 2 Concrete piers in place of cross walls; 3 Plant room: air handling units delivering warmed air throughout the Tower; 4 Upper floor designed as isolation ward for infectious patients; 5 Services distribution plenum, half floor; 6 Typical ward floor: small rooms to N, 4–6 bed wards to S; 7 Wards designed with perforated metal ceiling panels connected to LPHW pipework to provide radiant heating; 8 Warmed air ducted to wards; 9 Bathrooms mechanically ventilated; 10 Fully glazed projecting bays to 6 bed wards. Originally enclosed and highly cross-ventilated. Possibly to accommodate smokers; 11 Facing brick in concrete frame; 12 Original horizontal centre pivot opening windows, 1.1 m square, operated by occupants; 13 Refurbishment in 2004 substituted double glazed windows in aluminium frames, lower casements only openable, top-hung.

half of the building was extended on levels 1–3 only (Table 1). In 2004, the windows were replaced with aluminium-framed SAPA Glostal low-emissivity double glazed windows ($U \approx 1.9$ W/m^2 K) with significantly reduced opening area (Fig. 5). The lower c.90 cm panes are top-hung and operable to provide a maximum opening of about 100 mm, restricted for patient safety, whilst the upper panes (also c. 90 cm tall) are fixed. The window-to-floor area ratio on the SE side, which of course is exposed to solar

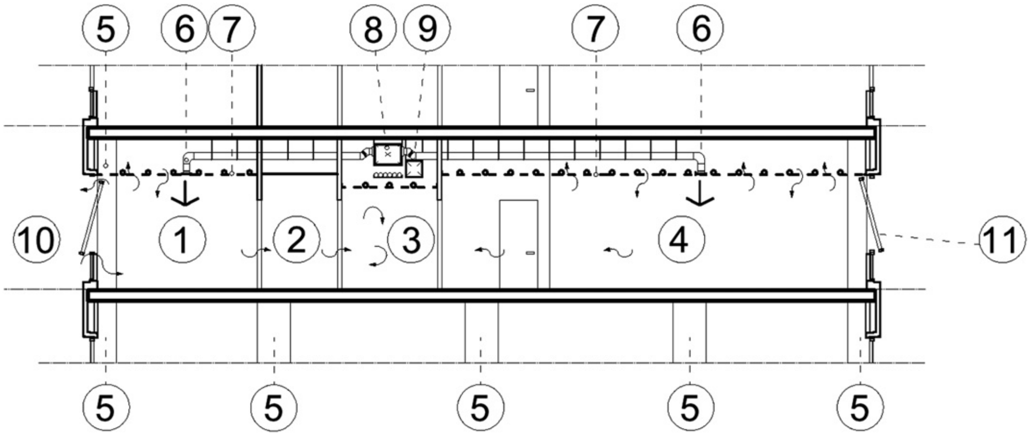

Fig. 4. Section through Level 8, as built, a typical ward floor, showing mechanical services and intended ventilation strategy (left-hand window: as built; right-hand, as existing). Key: 1 Single bedroom with centrally controlled mechanical supply and room user operated natural ventilation; 2 Internal storeroom: extract only with grille in doorway to draw in air from wards; 3 Corridor: no extract, warm air from wards dwells; 4 Six bed ward: centrally controlled mechanical supply and room user operated natural ventilation; 5 Concrete structure: piers enable flat slabs with no downstands; 6 Mechanical air supply; 7 Radiant ceiling: perforated metal trays with attached low pressure hot water heating pipes; 8 Main air supply duct; 9 Main services spine; 10 As built window arrangement; 11 Current window arrangement.

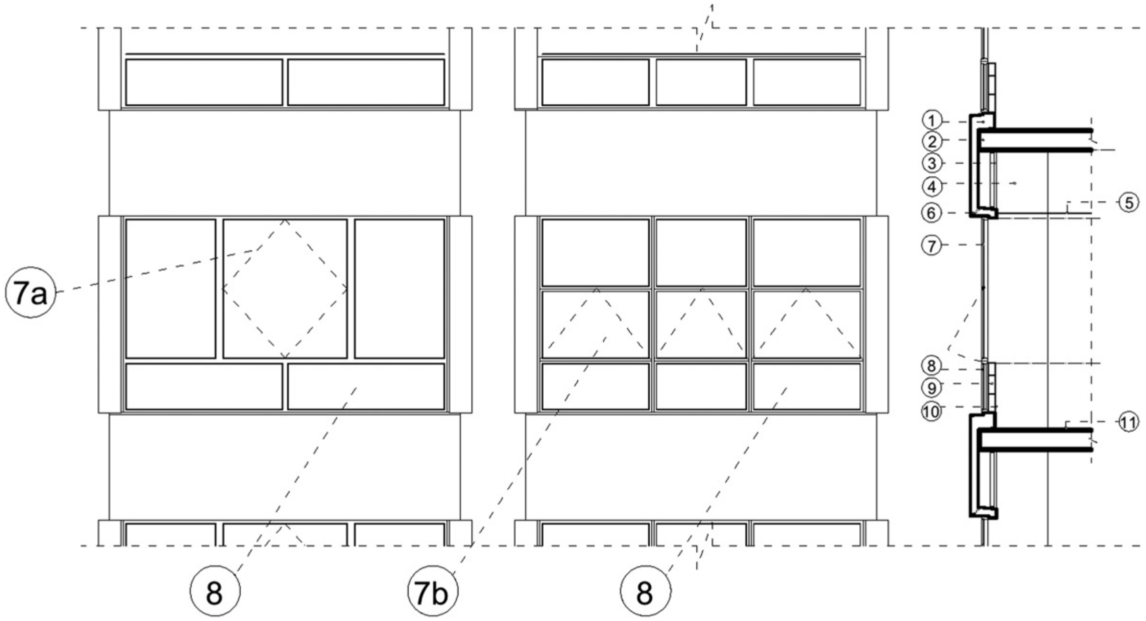

Fig. 5. Detail of one bay of original 1969 elevation (glazed area 57%) and subsequent re-glazing with thermal break aluminium frame. Key: 1 Precast aggregate concrete panels; 2 Floor slab (10 inches, 250 mm) with 3 inches (70 mm) cement sand screed; 3 Fibre board lining on timber battens; 4 Ceiling void (approx. 2 feet 11 inches, 900 mm deep); 5 Radiant ceiling: perforated metal trays with attached low pressure hot water heating pipes; 6 Drainage channel to divert away any infiltration by driving rain; 7a Original single-glazed centre pivot teak frame window; 7b Replacement 2004 aluminium frame thermal break double glazed units; 8 Fixed panel of opaque glass; 9 Blockwork behind fixed glazed panel; 10 Internal lining, assumed plasterboard on slabs; 11 Floor covering, linoleum in original, various vinyls subsequently.

gains, is thus about 35% in the deeper rooms and as much as 60% in the shallower spaces, although solid lightweight panels have been used in some panes to reduce the area of glass. The opaque panels below the windows remain as built and so are uninsulated ($U \approx 2.1$ W/m^2 K). The concrete spandrel above the window is insulated ($U \approx 0.5$ W/m^2 K). Even ignoring the heat bridging at the floor to outer wall junctions this yields an area-averaged U-value of about 1.2 W/m^2 K.

The heating and ventilation system today is little changed from the original. The radiant ceiling panels are said to operate at 30 °C–35 °C, switching off at ambient temperatures over 18 °C. Though ceilings in many wards have been replaced with gypsum tiles in a grid, radiant panels have been retained; fan coils have been added. Some floors have part perimeter heating. A small number of specialist rooms have their own dedicated supply and extract while local cooling has been added in certain areas. For all other spaces the central roof-located air-handling unit, which has a single inlet and supply fan, delivers air to the wards on the SE side and to treatment rooms on the NW side. The fan is twin speed but was observed to run at maximum speed over 1.5 years of data collection, 2010–2012. Insofar as the Trust Estate office did not have any information on the fan speed, current flow rate is taken as the maximum speed, i.e. 0.22 m^3/s. The air is heated to 18 °C prior to delivery to the building. There is no return air route and so all delivered air escapes from the building either through the designed toilet (and other) exhausts, through windows and doors or through other gaps in the fabric. The nurses' stations are thus vented inadequately by the air flowing back along the central spine to the extracts in the toilets and kitchens. This effectively offsets any risk of draughts from the ingress of cold air, but is, of course, extremely energy inefficient. The heat for the radiant panels and ventilation air originates from the central-site, gas-fired steam plant. The steam is delivered to plate heat exchangers in the base of the Tower that provide hot water at 80 °C in winter and 70 °C in summer.

3. Measured performance of existing wards

The internal temperatures in five spaces are currently being recorded at hourly intervals using Hobo pendant loggers.[4] The spaces are (Fig. 2a and b):

- ○ a seven bed ward on level 6 (6MB7)
- ○ a nurses' station on level 6 (6NS)
- ○ two multi-bed wards on level 8 (8MB4, 8MB10)
- ○ a nurses' station on level 8 (8NS)

Initial results from this work have been reported for a 46-day (1104 h) period, 1 July to 15 August 2010, by Lomas and Giridharan [16]. The temperatures in one ward, the 10-bed ward on Level 8 (8MB10), are illustrated in Fig. 6, alongside the Cambridge air temperature for the period and locally measured solar radiation intensity. During this period, the Level 8 ward temperatures were between 21.4 °C and 28.5 °C. 45% of the hours during the measurement period had internal temperatures over 25 °C, which for healthy people is seen as the value above which thermal dissatisfaction will occur, with 28 °C being the upper limit of thermal comfort acceptance. There were 38 night time hours (taken as 21:00 and 06:00) above 26 °C (i.e. 8% of the total).

Considering all the wards during the monitoring period, the temperatures ranged from 21.2 °C to 28.5 °C but with no more than 6 h (0.5% of the total) above 28 °C, which suggests the wards will operate for the whole year within NHS HTM03-01 [22] and CIBSE Guide A [23] guidelines (Table 2). During the night however, all three wards were warm with, depending on the ward, 4%–9% of

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[4] The temperature recorded approximates to air temperature, but must include an unknown radiant component. The loggers were positioned where permitted by the nurses and so cannot be taken as a true space-averaged temperature.

Table 1
Addenbrooke's Ward Tower: history of interventions from the opening in 1972 until February 2012.

	Glazing	External envelope	Ceilings	Heating	Mechanical ventilation	Central plant	Partitions
1972 as built	Centre pivot teak-framed windows, c. 2 m in height, *U*-value approx. equal 5.6 W/m^2 K. Façade glazing ratio 57%	Opaque panel below window, uninsulated. *U*-value 2.1 W/m^2 K. Concrete wall above window insulated, *U*-value 0.5 W/m^2 K	'Frenger' type patent radiant ceilings in wards, comprising perforated metal trays with hot water pipes clipped on top. Slab above suspended ceiling insulated.	Via 'Frenger' type patent radiant ceilings	Original design intent to deliver 2.5 ach^{-1}. Air delivered via corridors; bathrooms and utility rooms provided with extract. Maximum speed 0.22 m^3/s.	Air handling Unit (AHU) on Level 11. Filter, heating-coil and two speed pump. No pump at each floor to accelerate. Dedicated supply and extract to isolation wards on level 10.	Double-loaded with central corridor.
1972-	Observed deterioration		Insulation above suspended ceilings lost.	Perimeter heating installed in 6 bed bays on wards to counter heat loss from leaky windows (before 1985)			
1989 Ward D3 converted to Intensive Treatment Unit					Additional ventilation including cooling to this Ward only.		
1992 Ward D7 Minor layout alterations							Ward D7 conversion of largest 12-bed bay to a 7-bed bay and a treatment room
1995 Ward C9 Partial upgrade					Partial upgrade of two rooms to High Dependency Unit with AHU for 10 ach^{-1}		
1998 Wards C8 and D8 refurb		No fabric changes	Major internal refurbishment. New suspended ceilings with gypsum type ceiling tiles.	Changes maintain radiant panels to bed areas plus air handling unit/fan coil	Refurbishment excludes additional cooling and no AHU changes.		
2000 Wards C2 and C3 refurb as new Children's ward with day unit and intensive care		Extension to building (575 m^2 per floor on levels 1–3)	Major internal refurbishment: New suspended ceilings with gypsum type ceiling tiles.	Ward C3 is cooled; ward C2 extension has some comfort cooling in day spaces	2 no. side rooms have 20 ach^{-1}. Cooling to some new areas and additional AHU to new and refurbished areas only.		Some rearrangement of internal layout but essential of original remains
2001 Ward C4 refurb		No fabric changes	Major internal refurbishment: New suspended ceilings with gypsum type ceiling tiles.	Changes maintain radiant panels to bed areas plus air handling unit/fan coil	No additional AHU and no cooling included.		
2001 Ward C2					Additional cooling to ventilation plant for ward C2 only.		
2002 Ward D10 (Medium Secure Unit)		No fabric changes	Major internal refurbishment: New suspended ceilings with gypsum type ceiling tiles.	Perimeter heating retained plus air handling unit/fan coil	AHU upgrade to 20 ach^{-1} with cooling for this ward only.		Single room refurbishment

(*continued on next page*)

Table 1 (*continued*)

	Glazing	External envelope	Ceilings	Heating	Mechanical ventilation	Central plant	Partitions
2003 Ward D7 (Progressive Care)		No fabric changes	Major internal refurbishment: New suspended ceilings with gypsum type ceiling tiles.	Changes maintain radiant panels to bed areas plus air handling unit/fan coil	No additional cooling or AHU changes to this ward.		
2003 Ward D3 Creation of High Dependency Unit		No fabric changes	Major internal refurbishment: New suspended ceilings with gypsum type ceiling tiles.	Changes maintain radiant panels to bed areas plus air handling unit/fan coil	Additional cooling to new ward but no change to AHU.		
2004	Windows replaced with SAPA Glostal low-emissivity double glazed windows (*U*-value approx 1.9 $W/m^2 K$). Lower c. 900 mm panes top-hung, operable opening to 100 mm. Fixed top panes.	Opaque panels remain in situ, *U*-value unchanged.					
2004 Ward C6 refurb		No fabric changes	Major internal refurbishment: New suspended ceilings with gypsum type ceiling tiles.	Changes maintain radiant panels to bed areas plus air handling unit/fan coil			
2008 Ward D2 Minimal refurb		No fabric changes	Cosmetic upgrades	Radiant panels	No major alterations to ventilation and no cooling.		
2009 Ward D5 Minimal refurb		No fabric changes	Cosmetic upgrades	Radiant panels	No major alterations to ventilation no cooling.		
2010 Ward D3 and D4 major refurb to provide Intensive Care Facility		No fabric changes	Major internal refurbishment: New suspended ceilings with gypsum type ceiling tiles.	Changes maintain radiant panels to bed areas plus air handling unit/fan coil	Refurbishment of existing AHU serving ward D3; new ventilation plant serving D3 and D4 with AHU cooling and some standalone air conditioning systems.		Some minor alterations to layout
2011 Ward C9 Conversion to Teenage Cancer Facility		No fabric changes	Major internal refurbishment: New suspended ceilings with gypsum type ceiling tiles.	Changes maintain radiant panels to bed areas plus air handling unit/fan coil	Additional ventilation and cooling provision to this ward only.		

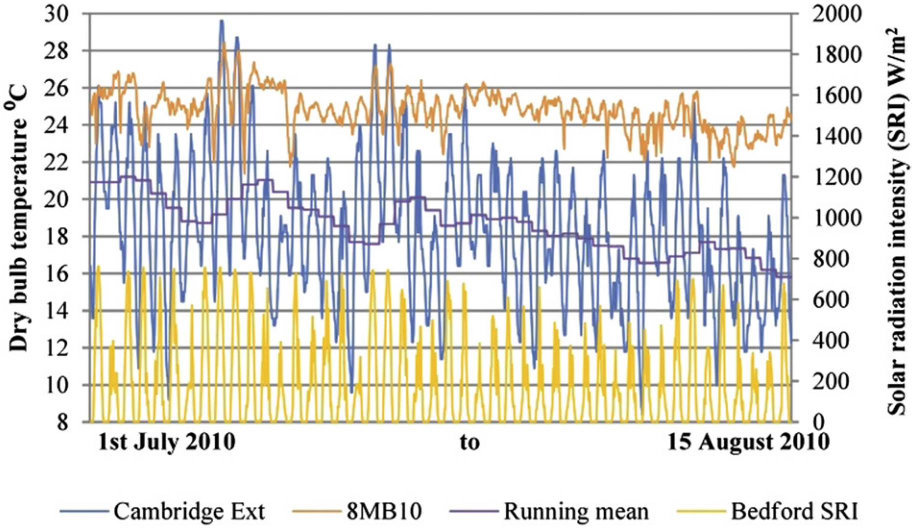

Fig. 6. Measured temperature, ambient temperature and its running mean for a seven-bed room on Level 6 (6MB7).

night time hours over 26 °C, above which temperature healthy people experience poor quality sleep [23].

The recent thermal comfort standard BSEN15251 takes account of human adaptation to recent ambient temperatures and thus occupants' preference for higher temperatures inside naturally ventilated buildings during warm summer spells [24]. Thus the envelope of acceptable temperatures has upper and lower limits that increase with the running mean of the ambient temperature and are applicable to different categories of persons; Cat I being applicable to *very sensitive and fragile persons with special needs* and thus seems appropriate to hospital wards (Fig. 7). Spaces of '*normal occupancy*' (Cat II) might include administrative offices, consulting rooms, and perhaps nurse stations, whilst Cat III might be relevant to public arrival and waiting areas etc.

During the recording period, none of the monitored wards experienced more than 26 h when the measured temperature was above the BSEN15251 Cat I limit (see e.g. Fig. 7); 55 h, i.e. 5% of the total, might be seen as unacceptable (Table 2).[5] Although window opening frequency was not recorded, site visits revealed that windows were open to their maximum limit (100 mm) during warmer weather from early in the morning until late evening. Temperature records in the larger deep-plan wards indicated a gradient from the warmer core to the cooler perimeter.

4. Modelling the existing building – current climate

To predict the annual frequency of overheating of the wards and the energy demands and CO_2 emissions in the current climate, the dynamic thermal model IES was used [26]. This software was chosen as it is widely used by UK building engineering consultancy firms including partners in the 'DeDeRHECC' project. Its application to the refurbishment of hospitals would thus meet with general understanding and interest. Dynamic thermal models are routinely used by practitioners and academics to predict the future performance of existing buildings, or the current and future performance of refurbished (or new) buildings. Since measured temperatures were available, it was possible to calibrate the IES model prior to embarking on the assessment of the proposed refurbishment options.

Contemporary building energy models, with their powerful graphical interfaces, enable large models of whole buildings to be created relatively easily and it is tempting to capitalise on this capability. When comparing multiple refurbishment options for large, complex multi-cellular buildings, as here, it was clear that it would be prohibitively time consuming to model the entire Tower. In any case, because big models require users to make many more assumptions, it may be debatable whether the insights relating to overhearing risk that might be gained would be any more reliable, not least because calibration is only possible for the few spaces for which temperature data is likely to be available. In this respect, the work is intended to demonstrate a methodology that NHS Trusts could adopt for their own Estates.

The work concentrated on creating a well-calibrated model for a space with reliable measured temperatures. The focus is the southeast-facing seven-bed ward, 6MB7 (Fig. 2b), which is typical of the wards of similar orientation in the Tower building. The choice of a southeast-facing room, without shading from surrounding buildings, was driven by the central interest of this project, summertime overheating risk. The modelled ward had a floor area of 70 m^2, a volume of 190 m^3, and there were two double glazed window systems with four and six components (Fig. 5). The perforated metal radiant ceiling warmed the space which was mechanically ventilated. Details of the model and the sources of the data are in the Appendix and the environmental control strategy is also included in Table 3.

Although many of the parameters fed into the model were known from the plans and sections and through site visits, some were uncertain. Sensitivity analysis revealed that the summertime temperature predictions were especially sensitive to the uncertainties in the mechanical ventilation rate, the window opening strategy and the inter-zonal flow between the room and the void above the suspended ceiling. Temperature predictions were however less sensitive to uncertainty in the background infiltration rate and the window and wall *U*-values. As is normal when modelling, many thermal factors were ignored, such as heat bridging and inter-room heat exchange (surrounding spaces were assumed to be the same as the modelled space and doors closed). The adjustments to the three most sensitive input parameters is, therefore, also compensating for the uncertainty in many other features.

It proved rather difficult to devise values for the three parameters that simultaneously produced good predictions for exceedences of the HTM03 criterion and both the lower and upper

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[5] BSEN15251 is applicable to temperatures monitored during occupancy and, strictly, these should be operative temperatures.

Table 2
Criteria for assessing internal temperatures in naturally ventilated spaces and energy demands and CO$_2$ emissions.

	Source	Assessment metric	Criterion	Applicability	Comment
Internal temperatures[a]	HTM03[b]	Total hours, dry-bulb temperature over 28 °C.	Limiting value 50 h.	All spaces and buildings.	Weather year to be used in simulations not stated.
	CIBSE Guide A	Night time hours operative temperature over 26 °C.	No more than 1% of hours above value.	Sleeping spaces only.	Value based on homes and not healthcare facilities.
	BSEN15251	Adaptive comfort Cat. I and Cat II envelopes. Thresholds of operative temperature vary with running mean of ambient temperature.	No more than 5% of hours outside envelope, in any day, week, month or year.[c]	Naturally ventilated buildings with operable windows.	Cat I is applicable to spaces with vulnerable individuals, such as wards, Cat II for 'normally' occupied spaces, such as offices, consulting rooms, etc.
Carbon dioxide emissions	CIBSE TM46	Total emission due to all end uses in hospitals[d]	131 kgCO$_2$/m^2 (see note[e])	All hospitals, clinical and research.	Benchmark for generating the display energy certificate's operational rating. Value is typical of existing hospitals.
Energy demand	HTM07-07	Total energy demand for all end uses in hospitals.[d]	55–65GJ/100 m[c] (see note[f])	Hospital refurbishment schemes	Target for refurbished NHS buildings in Health Technical Memorandum

[a] The HTM03 and CIBSE criteria are, strictly speaking, intended for use at the design stage, rather than for evaluating performance in use – though they are frequently used for this purpose. The BSEN15251 is explicitly intended for both purposes.

[b] Also restated in BREEAM Healthcare 2008 (BRE, 2010).

[c] The method actually suggests limits of 3% or 5% applied to each day, week, month and year. Here, for assessing the relative performance of the refurbishment options with operable windows. Only the total figure for the summer months is considered.

[d] The energy and CO$_2$ benchmarks relate to the totals for hospital buildings, space conditioning, which is the focus of the work here, is just under half the total for the entire NHS, with equipment, catering, etc accounting for the rest.

[e] The given value in TM46 is 129.3 kgCO$_2$/m^2, which has been adjusted by +4%, as per the CIBSE Guide method, to account for the weather in the East Anglia Region in which Cambridge is located. The resulting figure is 131 kgCO$_2$/m^2. Using the TM46 carbon intensity conversion factors, this would equate to 530 kWh/m^2.

[f] This can be readily converted to the customary units of kWh/m^2, from the units of GJ/100 m^2 used by the NHS, In this work the conversion used throughout is: GJ/100 m^{2}x $[(H \times 10^6)/(3600 \times 100)] =$ kWh with H being 3.5 m, an assumed average floor to ceiling height. Thus 55 GJ/100 m^3 equates to 535 kWh/m^2, which is close to the tabulated benchmark value in TM46 (see note[e]).

BSEN15251 Cat I boundaries (see Fig. 7). Therefore, priority was given to predicting reasonable HTM03 exceedences. The final model predicted maximum, mean and minimum temperatures between 1st July and 15th August of 28.6, 23.9 and 20.9 °C respectively, with 12 h above the HTM03 threshold of 28 °C. The corresponding measured values were 28.4, 25.0 and 21.0 °C and there were actually 6 measured hours above 28 °C (see Appendix A). Part of the difference is due to the small difference in the weather between Cambridge and Bedford from where the data used in the simulations was obtained.[6] Hourly differences between measurements and predictions are largely due to the impossibility of replicating the pattern of the actual manual operation of windows. Spot checks were undertaken during hot spells.

5. Predicted performance of existing building – current climate

The model devised was used in conjunction with weather data for 2010 taken at Bedford [16] to predict the annual overheating risk and the annual energy demands for the existing ward. For the period May–September 2010, the model predicted that there would be 16 h for which the internal air temperature exceeded 28 °C (Table 4) and 789 annual hours over the BSEN15251 Cat I upper temperature threshold, which, assuming occupancy for all hours in the year, exceeds the 5% acceptable threshold (i.e. 438 h). Although the ward space temperatures exceeded the BSEN15251 Cat I upper threshold, these results are better than might be expected for a building of this era. However, this robustness is an accidental by-product of the building's air leakiness and considerable mass, and comes with an energy penalty.

The predicted environmental energy demand for Cambridge in 2010 was 101GJ/100 m^3, with the bulk of the energy being used to heat the fresh air (46%), to warm spaces via the ceiling (38%), and for driving the fan that delivers the air (14%). This substantially exceeds the NHS gross target for refurbishments of 55–65 GJ/100 m^3 (Table 2). The uncontrolled loss of heat by leakage of air from the building leads to this high energy demand.

Concerning CO$_2$ emissions, CIBSE provides in Technical Memorandum TM46 benchmarks that are used for determining the operational rating of buildings [26].[7] The whether adjusted benchmark for 'Hospitals; clinical and research' in the Cambridge (East Anglia) region is 142.4 kgCO$_2$/m^2 (Table 2). The predicted energy demand equates to 179 kgCO$_2$/m^2, which exceeds the TM46 benchmark by some 26%.

It is worth noting that the NHS and CIBSE benchmarks include all energy use, for space heating and ventilation, and also for hot water, medical equipment, small power, pumps, controls, lifts etc, which on average, across all NHS buildings, are responsible for approximately 44% of the emissions. Thus, in spaces like wards, which use energy for heat, ventilation, lighting and small power only, the energy and CO$_2$ emissions ought to be around half of the benchmark values if, overall, NHS Trusts are to meet their targets.

It is evident that, whilst the wards in the Addenbrooke's Tower provide satisfactory comfort levels, this is achieved at the cost of excessive energy demands. The researchers investigated whether refurbishment could curb the heat lost through uncontrolled leakage of ventilation air from the building, whilst also reducing

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[6] The Meteorological Office station at Bedford was the closest one to Cambridge for which all the parameters necessary to construct an hourly simulation weather file were available.

[7] These are the mandatory 'energy ratings' shown on the Display Energy Certificates that must be displayed in all UK public buildings over 1000 m^2. The certificates rate buildings on an A to G scale using the TM46 values as the benchmark.

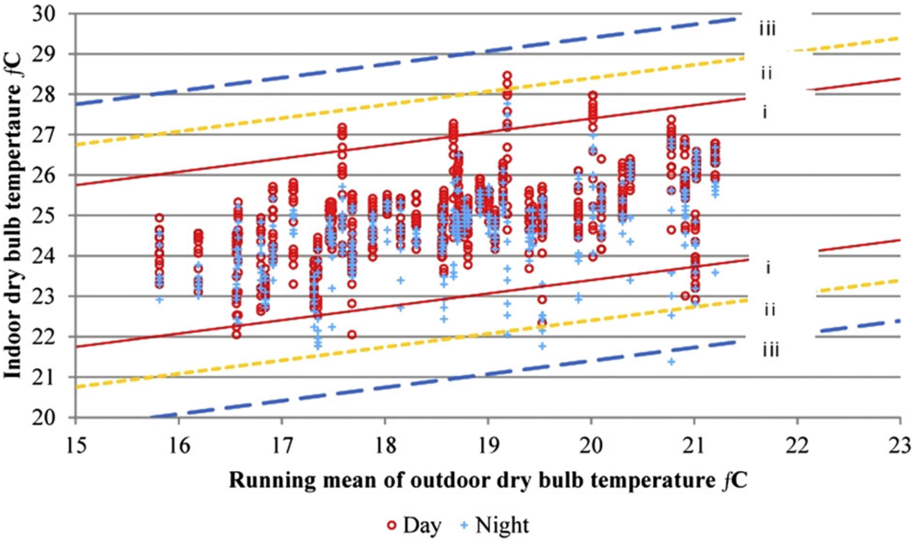

Fig. 7. Thermal model wireline of simulated ward room.

energy demand, and maintaining or even improving the internal environment.[8]

6. The refurbishment strategies: approaches to adaptive intervention and predicted performance in the current climate

There is a particular premium on rapidly executed, light-touch interventions in NHS buildings, the product of economic circumstances as well as a justifiable focus on improving the patient experience and infection control.[9] Table 1 records that the majority of interventions in the Addenbrooke's Tower have been largely cosmetic. NHS Trusts' decision-making with respect to their estates is driven by capacity control and so the long or medium term loss of a significant portion of the available space is disruptive (Jan Filochowski, West Hertfordshire Hospitals NHS Trust to authors, Project Sounding Panel meeting, March 2011). There are patient safety issues in the large-scale temporary dislocation of clinical activities (Patricia Young, National Patient Safety Agency, to authors, 2010) while project Partner NHS Trust Chief Executives have commented on the harmful effects on patients of dust arising from construction work, especially the difficulties in cocooning neighbouring spaces, denying them natural ventilation and potentially exacerbating summertime overheating risk (Filochowski to authors).

Five refurbishment options were considered by the authors, ranging from light-touch options to more invasive measures that implement innovative passive strategies. Each option exploited the inherent characteristics, mechanical installations and capacity in the existing building. The strategies sought also to improve the internal environment in the wards and other spaces,[10] and in this regard the features that are considered in the BREEAM Healthcare 2008 scheme [27] are pertinent, not least because Trusts are increasingly interested in the BREEAM rating that their buildings might achieve. The scheme gives the Energy section the highest weighting of all the nine BREEAM sections (19%)[11] but the second highest weighting is given for the 'Health and Wellbeing' section (15%).[12] This includes provision of: daylight, adequate view out; glare control; natural ventilation; thermal zoning; and thermal comfort.

Each of the options is described and illustrated (Figs. 8–12) with the key features and environmental control strategies (heat loss and solar control, ventilation, heating and cooling) being summarized in Table 3. For each option the predicted annual energy demands and CO_2 emissions of one ward, the refurbished multi-bed ward 6MB7, were predicted using IES and the Bedford 2010 weather [28] and compared with the NHS and TM46 benchmarks (Figs. 13 and 14). The internal temperatures predicted for the summer period May–September (153 days, 3672 h) were assessed using the HTM03-01 and CIBSE overheating criteria (virtually all annual overheating hours will occur during the May–September period). For the three refurbishment options incorporating operable windows, the BSEN15251 approach was also used to assess the internal temperatures; the two refurbishment options, in which the building is sealed, mechanically ventilated, heated and cooled, were not assessed using the BSEN15251 approach. By way of context there were just 4 h in Cambridge in 2010 when the ambient temperature exceeded 28 °C [16].

It is important to note that in all the simulations, the ventilation, heating and cooling control strategies (Table 3) were devised with the provision of overall summertime thermal comfort (as defined by the guidance) as the priority. Less attention was given to the

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[8] Lomas and Giridharan [16] examined the potential for patient operated internal ceiling fans to improve summertime temperature conditions, but this measure would not impact on the energy use and CO_2 emissions.

[9] A parallel study of recent NHS refurbishment and construction projects forms part of the 'DeDeRHECC' project; the authors are working with researchers from the Engineering Design Centre at the University of Cambridge and the Design Group at the Open University to assemble detailed case histories.

[10] For example [16], shows that the nurses' stations in the core of the Tower substantially overheat.

[11] The lower the predicted emissions the greater the number of BREEAM credits that are awarded and additional credits can be earned by meeting the demand from renewable energy sources (BREEAM Issue Ene5). Further, a high credit score for 'Reduction of CO_2 Emissions' (Issue Ene 1) is mandatory if an Excellent or Outstanding rating is to be achieved. Innovation credits can be earned through exemplary levels of CO_2 reduction and daylight provision.

[12] To elaborate the BREEAM issues: daylight - daylight factor, $DF > 3\%$ over 80% of floor space of wards (Issue Hea 1); provision of adequate view out – most easily fulfilled by wards less than 7 m deep (Hea 2); glare control – especially through occupant-controlled blinds (Hea 3); provision of natural ventilation – operable window area to 5% of floor area or, in deep-plan rooms, provision of cross ventilation (Hea 7); and Thermal Comfort – meeting the HTM03-01 overheating criterion (Hea 10); and Thermal Zoning – to enable occupant control of heating and cooling systems (Hea 11).

Table 3
Refurbishment options and environmental control strategies.

Options[a]	Mechanical ventilation Strategy[b]	Natural ventilation strategy		Space heating strategy		Passive environmental features	
		Windows[c]	Other	Radiant ceiling	Perim. heat.	Solar shading	Exposed ceiling slab
0 NVMVRH: Current building, natural and mechanical ventilation, radiant ceiling heating.	Central AHU 4 ach^{-1} Heating only $VH_{spt} = 18\ ^\circ C$[d] See Appx A for details.	Manually Operable See Appx A for details.	–	Radiant heating $RH_{spt} = 30/32.5\ ^\circ C$ See Appx. A for details.	No	None	No
1 SMVHC: Sealed building, mechanical vent. with heating and cooling.	Central AHU 6 ach^{-1} Air heating and cooling $VH_{spt} = 22\ ^\circ C$[d] $VC_{spt} = 24\ ^\circ C$[e]	Sealed	–	Inactive	No	Blinds within window system	No
2 SMVRHC: Sealed building, mechanical vent. but radiant ceiling heating and cooling.	Central AHU 4 ach^{-1} Heating only $VH_{spt} = 18\ ^\circ C$[d]	Sealed	–	Radiant heating and cooling.[f] $RH_{spt} = 26\ ^\circ C$[g] $RC_{spt} = 22\ ^\circ C$[h]	No	Fixed external shading to south elevation	No
3 NVMVPH: Natural ventilation, mechanical ventilation, with perimeter heating.	Central AHU 4 ach^{-1} Heating only $VH_{spt} = 18\ ^\circ C$[d]	Manually operable[i]	–	Inactive	Yes $PH_{sp} = 21\ ^\circ C, 22\ ^\circ C$[j]	Fixed external shading to south elevation	Part exposed, existing ceilings cut back from perimeter
4 CVPH Natural cross ventilation, perimeter heating.	None	Manually operable	Cross ventilation ducts. Perimeter dampers actuated by BMS.	Inactive	Yes $PH_{sp} = 21\ ^\circ C, 22\ ^\circ C$[j]	Fixed external shading to south elevation	Substantially exposed.
5 SVPH Natural stack ventilation, perimeter heating.	None	Manually operable and BMS control	Stacks. Cross vent. ducts. Perimeter dampers actuated by BMS.	Inactive	Yes $PH_{sp} = 21\ ^\circ C, 22\ ^\circ C$[j]	Deep facade	Substantially exposed.

NV – natural ventilation; MV – mechanical ventilation; RH – radiant ceiling heating; MVHC – mechanical ventilation heating and cooling; RHC – radiant heating and cooling; PH – perimeter heating; CV – cross ventilation; SV – stack ventilation.

[a] In all cases: floor area, 70.3 m^2, surrounding five spaces all assumed to be at same temperature as modelled space except in Option 5 in which the space below, the void, was exposed to external conditions. In all options the internal doors closed. Vertical elevations have 100 mm insulation and roof 300 mm insulation $k = 0.025$ W/m K; window area, 12.2 m^2, i.e.17% window-to-floor area ratio. Volumes vary - with existing ceiling at 2.7 m height, 190 m^3; with exposed concrete ceiling at 3.9 m height, c270 m^3; and with part exposed ceiling height 3.3 m on average, Option 3, 227 m^3.

[b] All mechanically ventilated strategies have heat recovery at 60% efficiency, with summer by-pass function.

[c] Option1 – existing windows with additional single pane protecting interstitial blinds in ventilated cavity, $U = 1.8$ W/m^2 K. –5 – double glazing, no blinds, $U = 1.9$ W/m^2 K.

[d] VH_{spt} – ventilation heating set-point, heat output ramped down from 100% when ambient temperature, $T_a \le 16\ ^\circ C$ to zero at $T_a \ge 18\ ^\circ C$.

[e] VC_{spt} – ventilation cooling set-point, heat output ramped up from zero when $T_a \le 18\ ^\circ C$ to 100% at $T_a \ge 20\ ^\circ C$.

[f] Insulation above panels and existing pipework and connections repaired as necessary.

[g] RH_{spt} – radiant heating set-point, output ramped down from 100% when, $T_a \le -3\ ^\circ C$ to 60% at $T_a = 15\ ^\circ C$, and off at $T_a = 16\ ^\circ C$.

[h] RC_{spt} – radiant cooling set-point, output ramped up from zero when $T_a \le 18\ ^\circ C$ to 100% at $T_a \ge 20\ ^\circ C$.

[i] Occupants assumed to open windows if wind speed below 7.5 m^2. Maximum opening, 100 mm, giving an area of 1.0 m^2 for Existing option, 2.4 m^2 for 3 NVMVPH, 1.2 m^2 for 4 CVPH and 1.7 m^2 for 5 SVPH. Openings of top and bottom windows by 0% if $T_a \le 15\ ^\circ C$ ramping open to 100% at $20\ ^\circ C \le T_a \le 21\ ^\circ C$, then closing to 25% at $T_a \ge 23\ ^\circ C$.

[j] PH_{spt} – perimeter heating set-point is 21 °C summer and 22 °C winter. Heat output ramps down from 100% when, $T_a \le 16\ ^\circ C$ to 0% at $T_a = 18\ ^\circ C$.

Table 4
Predicted dry resultant temperatures in the refurbished wards during May–September, 2010 Cambridge weather.

	Predicted			HTM03:	CIBSE:	BSEN15251:	
	Max. temp. (°C)	Min. temp. (°C)	Mean night time[a] temp. (°C)	Total hours[b] over 28 °C	Night time[c] hours over 26 °C	Total hours over Cat I upper limit[d]	Total hours over Cat II upper limit
Existing	28.6	21.3	24.0	16	21	789	300
1 SMVHC: Sealed building, mechanical vent. With heating and cooling.	27.3	21.5	23.1	0	1	na	na
2 SMVRHC: Sealed building, mechanical vent. But radiant ceiling heating and cooling.	25.2	21.6	22.8	0	0	na	na
3 NVMVPH: Natural ventilation, mechanical ventilation, perimeter heating.	25.7	20.9	21.5	0	0	0	0
4 CVPH: Natural cross ventilation, perimeter heating.	26.8	20.4	21.6	0	1	0	0
5 SVPH: Natural stack ventilation, perimeter heating.	25.6	21.0	21.8	0	0	0	0

It is assumed that during the winter half of the year (October to April) the space will not overheat due to elevated ambient temperatures and solar gains. The limiting overheating values are therefore: HTM03, >50 h over 28 °C; BSEN15251, >438 h above category upper thresholds and CIBSE, >37 night time hours (1%) over 26 °C).

[a] Night time hours are 21:00–06:00.

[b] Simulated hours are for May–September (153 days, 3672 h).

[c] The grey shows where limiting criteria are exceeded.

[d] The HTM03 threshold is based on air temperature and rest are based on dry resultant temperature.

impact of the chosen control strategies on the night time temperatures or the annual energy demand and CO_2 emissions. Thus there were times when the night time temperatures dropped below the BSEN15251 Cat I and Cat II envelope. By micro-adjustment of the heating set-point it was possible to avoid this, however, such refinements were not generally pursued in this work.[13] Similarly, changes to the control strategy might reduce the energy demands and CO_2 emissions slightly and in practice facilities managers manually adjust control settings in response to weather changes and other events, but in a thermal simulation model this is not easily done. Thus in interpreting the refurbishment options' performance, the night time temperatures are afforded little weight and the energy demand figures may not be optimally low. Nevertheless the results give a valid strategic impression of the relative performance of the existing building and refurbishment options.

Option 1: SMVHC: Sealed building, Mechanical Ventilation with Heating and Cooling, Fig. 8.

The application of 'PassivHaus' principles to a substantial public building. The external envelope is overclad to improve substantially air-tightness and *U*-values. The relatively recent high-performing thermal break aluminium-framed double glazing is retained. The ventilation system operates at 6 ach^{-1}, as required by HTM03-01, windows are sealed and a third layer of glazing added internally. The glazing is shielded by new interstitial blinds. (This arrangement, which contrasts with the usual location of the interstitial blind in a vented cavity on the external side of the double glazing, was adopted in an attempt to retain the existing windows and thus to minimize disruption). The radiant ceilings are retained but are not active; perimeter heating is not employed in this first option. Resilience to overheating is provided by increased mechanical ventilation with some mechanical cooling for peak lopping when required.

The peak lopping strategy ensured that there were few summertime hours above each of the HTM03-01 and CIBSE thresholds (Table 4). The annual predicted energy demands and emissions were 59 GJ/100 m^3 and 137 $kgCO_2/m^2$ respectively (Figs. 13 and 14), which is within the NHS target for refurbished buildings (but of course excludes delivered energy, which would add to this figure). Very little energy was used for cooling but the ventilation energy demand to deliver the high airflows was significant. Overall the design achieved substantial improvement over the performance of the existing building.

Option 2: ***SMVRHC***, Sealed Mechanically Ventilated environment, Radiant ceilings active in winter (Heating) and summer (Cold water for cooling), heat recovery, Fig. 9.

The envelope is thermally upgraded as option 1. The 2004 double glazing is retained but solar shading is provided by fixed external shades tailored to shield all southerly glazing through the potential overheating season. The mechanical supply delivers the fresh air requirement only, i.e. below 6 ach^{-1}, and heat recovery is provided. The original radiant ceiling installation is refurbished and employed in winter to provide additional radiant heating (boosting the ducted warm air supply as required). In summer, cooler water (at 22 °C) is pumped through the system. Almost all the insulation originally provided to the soffit above the radiant ceilings is presently missing; in this scenario it is essential to replace it.

The simulations indicated an insignificant number of summertime hours above each of the HTM03 and CIBSE thresholds (Table 4). The annual predicted energy demands and emissions were 46 GJ/100 m^3 and 102 $kgCO_2/m^2$ respectively (Figs. 13 and 14). This represents a further improvement: reduced energy demand, especially for the fans, which are delivering 4 ach^{-1} as in the existing building; reduced heating energy demand, as the heat is delivered directly to the space; and yet the space offers the potential for individual control of heating and cooling via the radiant ceiling.

Option 3: ***NVMVPH,*** a hybrid option, with Natural Ventilation and concurrent Mechanical Ventilation supply, heat recovery, opening windows and Perimeter Heating (Fig. 10).

Option 3 adopts similar thermal upgrading to the envelope, retains current double glazing units, and enables all of the glazing to be opened by occupants in peak summer periods. A high degree of occupant control contributes to the overheating defence strategy of this option. In addition, the suspended ceilings are cut back as far as the supply ductwork allows, in order to expose the concrete slabs inboard from the window walls. Perimeter heating is introduced. In some ways the services strategy is similar to that in the existing building, but with perimeter heating rather than a radiant ceiling, and much improved fabric, shading and also heat recovery.

There were no predicted summertime hours above the CIBSE, HTM03-01 or indeed the BSEN15215 thresholds (Table 4). The annual predicted energy demands and emissions were 40 GJ/100 m^3 and 111 $kgCO_2/m^2$ respectively (Figs. 13 and 14), with ventilation

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[13] Such fine-tuned adjustment is time consuming and was impractical given all the simulations undertaken. Models do not permit the sort of reactive continuous refinement that is done by facilities managers.

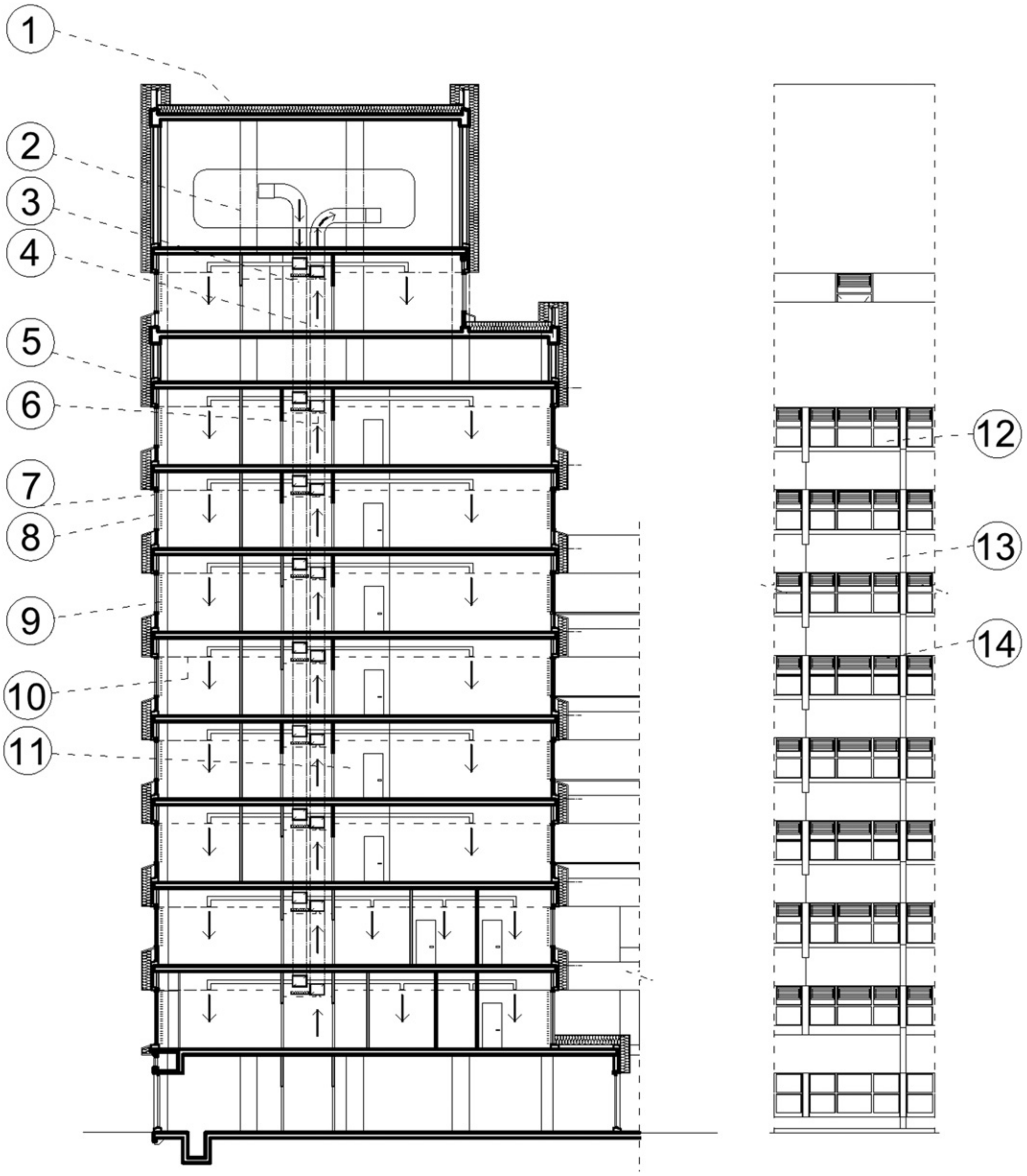

Fig. 8. Option 1: SMVHC, sealed building, mechanical ventilation with heat and cooling. Key: 1 Insulation on roof (100 mm); 2 Air handling unit with supply and extract; 3 Supply duct; air supplied to wards via ceiling, 6 ach; 4 Return duct; 5 100 mm insulation to external elevations; 6 Air extracted through corridors; 7 Seal windows; 8 Triple glazed windows; 9 Add blinds between original double glazed unit and new single-glazed panel; 10 Radiant ceilings inactive; 11 Mechanical ventilation to bathrooms maintained; 12 Triple glaze and seal windows; 13 100 mm external render; 14 Blinds added between original double glazed window and new glazed panel.

energy (to deliver 4 ach^{-1}) being about 40% of the whole. The operable windows and perimeter heating provide occupant control.

Option 4: CVPH, natural Cross Ventilation, Perimeter Heating (Fig. 11).

This option dispenses with the mechanical ventilation system. It upgrades the external envelope to the standard of Options 2 and 3 and provides perimeter heating with actuated trickle vents below fully operable occupant-controlled windows, adapting the existing installation. Furthermore, each floor can be cross-ventilated by threading crossover ducts in alternating directions across the width of the floor plate. The option envisages active use of night ventilation and removes all suspended ceilings to expose the full flat concrete soffit above all patients. The aim is that vigorous night ventilation will cool the soffits.

There were no predicted summertime hours above each of the thresholds (Table 4) and the annual predicted energy demands and emissions were just 20 GJ/100 m^3 and 44 kgCO$_2$/m^2 respectively; the omission of fans being the key to such low energy demand.

Option 5: SVPH, natural Stack Ventilation with Perimeter Heating (Fig. 12).

The principle of natural ventilation explored in Option 4 is reinforced with stacks to develop greater pressure differences and hence flows as required. Stack ventilation of high rise buildings has been the subject of some speculative work [29] which introduced the idea of segmenting a building into bundles of floors that could be more easily served by shorter stacks. A potential difficulty is the effectiveness of stub stacks on the windward face in which the flows may reverse with a reversing flow regime set up on each floor. In a hospital where the avoidance of the risk of airborne infection spread is clearly important, reversing flow regimes are unacceptable. This option removes the envelope of a floor at mid-height to provide a free air environment in which the stacks to the lower four floors can terminate. The stacks are strictly dedicated to one space per cell, as the part elevation/section reveals. The occupation of the elevation by deep stacks reduces the glazed area beneficially and

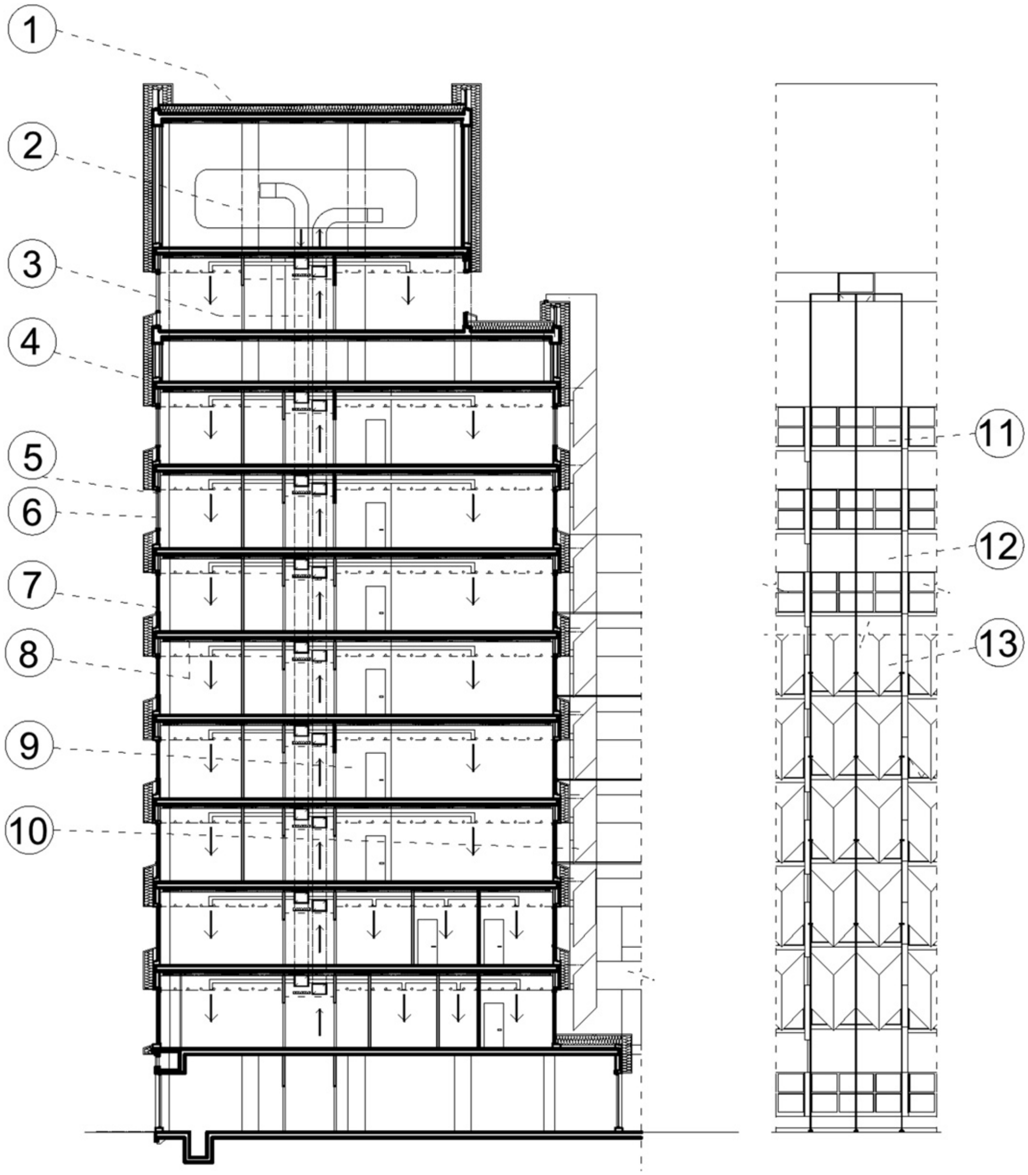

Fig. 9. Option 2: SMVRHC, sealed building, mechanical ventilation, radiant ceiling for heating and cooling. Key: 1 Insulation on roof (100 mm); 2 Air handling unit with supply only; 3 Supply duct; air supplied to wards via ceilings, fresh air only; 4 100 mm insulation to external elevations; 5 Seal windows; 6 Triple glaze windows; 7 Radiant ceiling active; 8 Insulation to slab above radiant ceiling; 9 Extract via bathrooms; 10 External shading, perforated aluminium panels; 11 Triple glaze and seal windows; 12 100 mm external render; 13 External shading.

the depth also beneficially shades the glazing through the critical summer overheating period. All windows are rendered operable and the cross-ducts of Option 4 are introduced below a fully exposed flat concrete soffit. The intention would be to night-ventilate vigorously within the comfort parameters of sleeping patients and patrolling medical staff.

For this final and more elaborate option, there were no predicted summertime hours above each of the comfort thresholds (Table 4) and the annual predicted energy demands and emissions were just 32 GJ/100 m^3 and 67 $kgCO_2/m^2$ respectively (Figs. 13 and 14). This option was modelled with not only the façade exposed to external conditions but also the floor (below which is the void, i.e. the open area intended to provide greater exposure to the mid-height stack terminations). Thus the heat loss is greater than for Option 4, which has only the façade exposed to external conditions (Fig. 12). The additional energy, compared to Option 4, may be avoided by more refinement to the ventilation control strategy. The other floors would have a better performance.

In summary therefore, considering the performance of all the options, it would seem possible for all five of them to yield internal thermal comfort conditions that are an improvement on the existing building. Furthermore, with appropriate control of the mechanical systems, BMS controlled openings, manually operated windows, perimeter heating, or radiant ceilings, improved occupant control is possible. The energy demands and CO_2 emissions of all the options are lower than for the existing building but the ability to achieve this performance over the entire building implies reliable room-by-room temperature control, either occupant or BMS controlled, which is something that is entirely absent in the current building.

It is nonetheless important to note that these predictions do not include energy use for matters unconnected with space conditioning (small power, medical equipment, restaurants etc), which

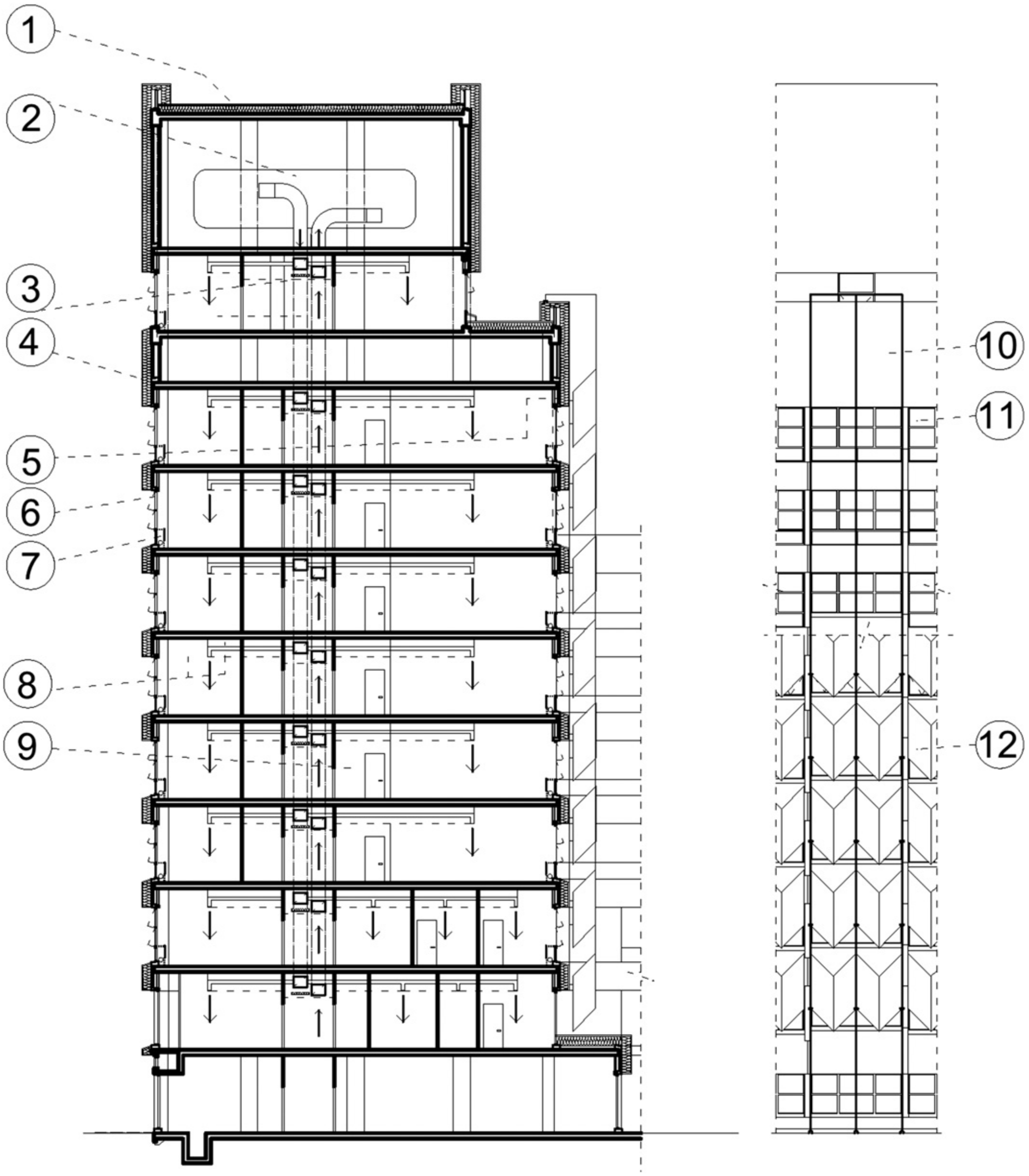

Fig. 10. Option 3: NVMVPH, natural and mechanical ventilation, perimeter heating. Key: 1 Insulation on roof; 2 Air handling unit; 3 Supply duct; air supplied to wards via ceiling, fresh air only; 4 100 mm insulation to external elevations; 5 External shading; 6 Opening windows; 7 Perimeter heating with low-level air supply via windows; 8 Ceiling exposed save for ventilation duct; 9 Mechanical extract via bathrooms; 10 100 mm external insulation; 11 Opening windows; 12 External shading.

can be 44% of the total. Given this, it is likely that only Options 2–5 could plausibly meet the NHS energy target and CO_2 emissions benchmark of 55–65 GJ/100 m^3. Importantly this excludes the option which has a mechanical supply of 6 ach^{-1} as stated in HTM03-01. We observe therefore that unless highly efficient heat recovery with a summer by-pass is used, the HTM03-01 mechanical ventilation requirement and NHS energy demand targets may be mutually incompatible; efficient fans are essential.

7. Modelling the refurbishment options – future climate

To assess the performance of the wards under the Cambridge climate of the future typical and extreme weather, as represented by Test Reference Years (TRYs) and Design Summer Years (DSYs)[14] were created for the 2030's the 2050's and the 2080's. Also, to provide a compatible benchmark against which to compare these predictions data was generated in a similar way for the current climate of the 2000's. The procedure for creating the weather data has been described in detail elsewhere [16] so is described in brief here.

The TRYs and DSYs for the current climate were created by the Prometheus project research team at Exeter University from the 25 years of hourly data that was available from the Bedford station (1980–2004) using the standard CIBSE method as described in Levermore and Parkinson [30]. The 2005TRY is built by chaining the most average January to the most average February etc and then smoothing the joins. The 2005DSY is simply the third hottest of the 20 years based on the average dry-bulb temperature form April and September; for the Bedford data set this was 1997. The 2005TRY has a broadly similar number of hours above 25 °C and 28 °C to the 2010 year; a similarity that extended across all hours from 20 °C to 28 °C. Thus the year of monitoring would seem, quite fortuitously, to be rather typical of the current climatic conditions in Cambridge.

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[14] The DSY is a year such that summers are only on summer in 20 is warmer.

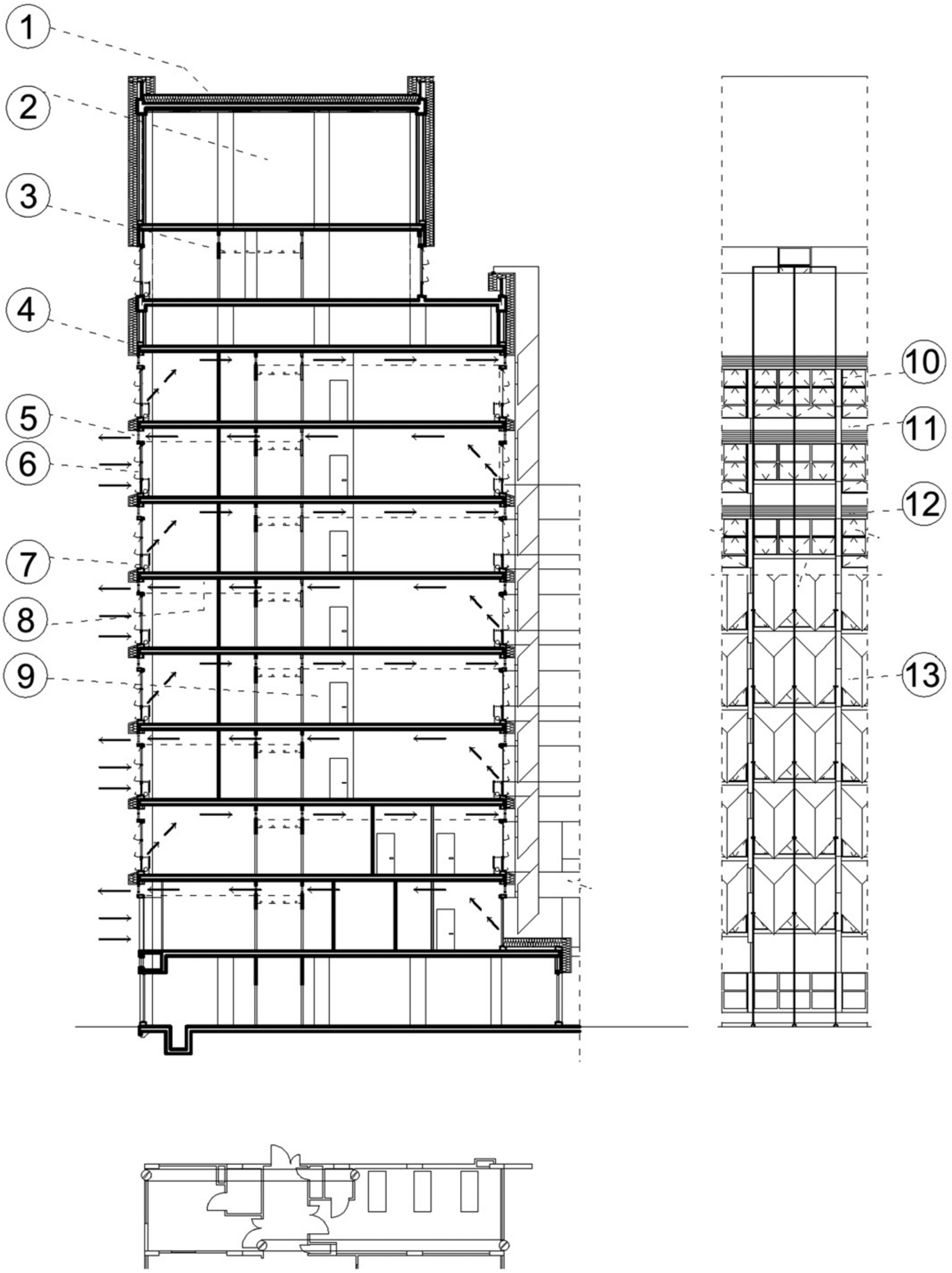

Fig. 11. Option 4: CVPH, natural cross ventilation, perimeter heating. Key:1 Insulation on roof; 2 Air handling unit for bathroom extract only; 3 Suspended ceiling in corridor only; 4 100 mm external insulation; 5 High level air outlet route and grille to achieve cross ventilation (shown alternately on each floor); 6 Opening windows; 7 Low-level air supply via opening window behind perimeter heating; 8 Ceiling slab exposed; 9 Extract via bathrooms (not shown); 10 Opening windows; 11 100 mm external render; 12 Grilles for air outlet; 13 External shading.

The weather for the future years was also created by the Exeter team by the method described by Eames et al. [28] using the UKCP09 weather generator [31] assuming the global A1B emissions scenario as described in the IPCC Special report on Emissions Scenarios (i.e. a globally technologically advanced world in which energy production includes a broad portfolio of fossil-fuel and non-fossil-fuel sources) [32].[15] Annual hourly TRY and DSY weather files were created for the 2030s, 2050's and 2080's for the 5 km grid square covering Cambridge.

The temperatures in ward 6MB7 were predicted using IES and compared using the CIBSE, HTM03 and BSEN15251 overheating criteria; the existing building and all five refurbishment options were modelled with all eight weather years (Table 5). The BSEN15251 assessment method is particularly relevant in the context of climate change, as it takes account of occupants' adaption and thus preference for warmer conditions in naturally conditioned spaces, as the external environment warms. Indeed, one must question the

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[15] This is the emissions trajectory the world is currently following.

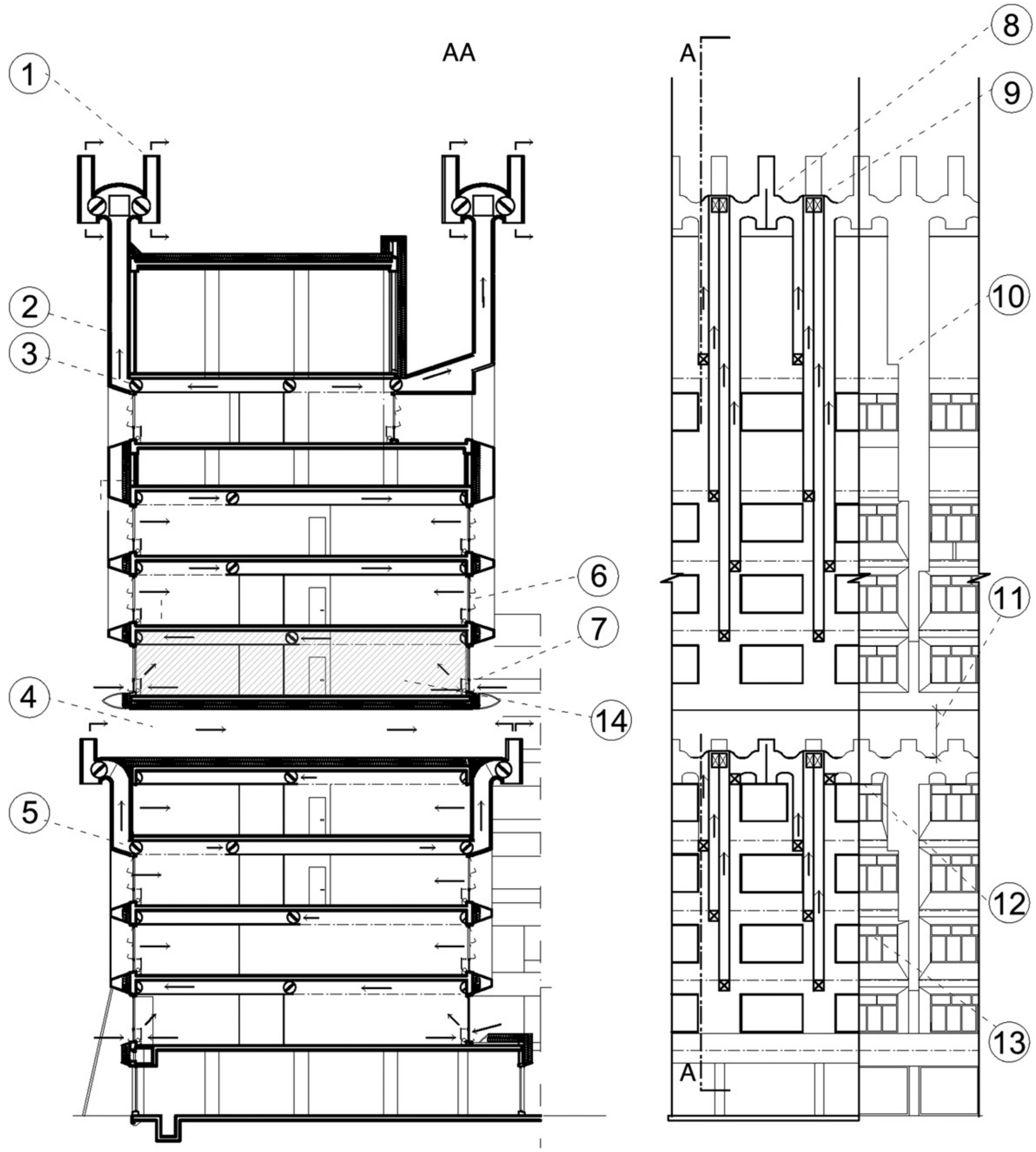

Fig. 12. Option 5: SVPH, natural stack ventilation, perimeter heating Option 5: 1 H-pot stack termination, robust to wind turbulence; 2 Insulated perimeter stacks external to existing elevation; 3 BMS controlled damper at entrance to stack, manual over-ride; 4 Level 6 envelope removed to create free space connecting north and south sides; 5 Lower bank of five floors connected to stacks; 6 All glazing openings under user control; 7 Perimeter heating connected to actuated vents; 8 Terminations connect to form full cross H-pot arrays, dividers guard against cross flows and risk of airborne cross infection; 9 Each stack comprises four discrete cells isolated from point of entry to cross pot; 10 Actuated points of entry into stacks; 11 Void through tower; 12 Lower ranges of stacks terminate in plane of void to enable 360° access to stack termination; 13 Glazing reduced in size and shaded within thickness of superimposed 'double façade'; 14 Highlighted floor modelled, slightly a typical as above void. *U*-value for floor 0.07 W/m^2 K.

relevance of comfort standards intended for free-running buildings that are based on fixed temperature criteria when comfort in future warmer weather conditions is being assessed.

8. Future performance of the existing and refurbished building

The predicted future performance of the existing buildings and the refurbishment options is shown in Table 5. It has been noted [16] that the existing building would be deemed too hot by 2030s, as indicated by the HTM03-01 criterion, especially in an extreme year. However, using the BSEN15251 method the overheating in 2030s appears less serious in both typical and extreme years, especially in the spaces intended for normal, non-clinical, occupancy (as judged by the hours above BSEN15251 Cat II limits).[16] Beyond the 2030s the existing ward displays a marked increase in the frequency of overheating in extreme years.

The two refurbishment options in which the building is sealed and mechanically cooled (Options 1 and 2, SMVHC and SMVRHC) remained comfortable in both typical and extreme years to 2080s, in

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[16] The similar performance in the TMY and DSY years is because the BSEN15251 method accounts for occupants' adaptation to the warmer conditions of the hotter year.

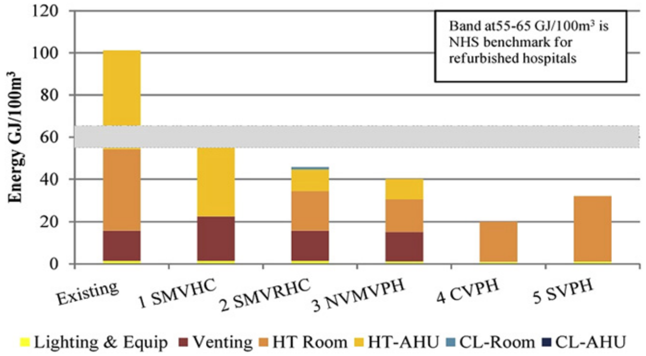

Fig. 13. Predicted energy demand for existing buildings and refurbishment options for the year 2010, Cambridge.

that the internal temperatures remained below 28 °C for all but a few hours.[17] Option 2, which has the external solar shading, rather than the internal inter-pane shading, and local cooling provision via the radiant ceiling, performs better than Option 1. The external shading improves resilience at little maintenance overhead by reducing the reliance on the mechanical cooling systems. Thus comfortable conditions are maintained through to 2080s but with a much lower energy penalty. The cooling strategy offered by incorporating large areas of radiant ceiling panels invites the use of low-carbon cooling systems, such as ground (or air) source heat pumps.

In typical years, the hybrid Option 3 (NVMVPH) and naturally ventilated Options 4 and 5 (CVPH and SVPH) remain comfortable until the 2080s. The improved façade insulation and solar shading, with a contribution from the internally exposed thermal mass, enable this performance. These results concur with those reported earlier for stack ventilated buildings outside the London environs [10]. All three refurbishment options produced spaces that have fewer hours with air temperature over 28 °C than there are ambient hours over 28 °C in the 2030s, 2050s and 2080s (see footnote to Table 5).

In extreme years, using the BSEN15251 method for appraisal, the hybrid Option 3 (NVMVPH), clinical spaces (Cat I) are comfortable until the 2050s, but non-clinical spaces remain comfortable even in the 2080s. Clinical spaces become unacceptably warm by the 2080s. The presence of a mechanical ventilation system with a return air route enables retrofitting as the climate warms, for example by the addition of a cooling coil in the air handling units (AHUs). In fact, by the 2080s, AHUs will have been through several refurbishment and replacement cycles. This option is only viable from an energy demand perspective if the airflow rates are as low as possible and very efficient heat recovery system and fans are used. The design outperforms the existing hybrid building because of the substantially improved fabric and external shading.

In extreme years, the natural ventilation options, either cross ventilation (CVPH) or stack ventilation (SVPH) performed well, as judged by the BSEN15251 method, in the 2030s. However, by the 2050s performance is unacceptable in Cat I spaces and by the 2080s also in Cat II spaces. In these extreme years the number of hours internal temperatures exceeded 28 °C was greater than exceeded externally, suggesting that passive night time cooling is less effective in extreme years. The stack-vented option performed marginally better in environmental terms than the cross-vented option, though there is an energy penalty on the floor with the exposed slab (as is illustrated in the bar chart, Fig. 13).

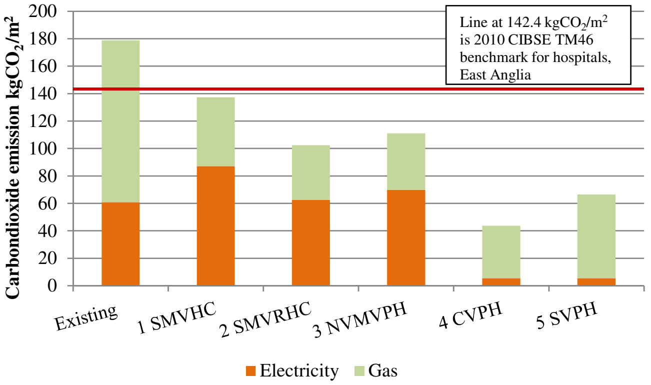

Fig. 14. Predicted CO_2 emissions for existing buildings and refurbishment options for year 2010, Cambridge.

Table 6 sketches out the likely operational implications of the options for the hospital campuses, assembled in consultation with staff from Partner NHS Trust estates management teams. There is a clear premium on avoiding the wholesale closure of patient-occupied space to achieve these ends.

In summary it would seem that, even in extreme years, all five refurbishment proposals are resilient to climate change up until the 2030s. Thereafter, designs that incorporate mechanical cooling, probably in association with mechanical ventilation, remain comfortable in extreme years. Refurbishments offering the potential for the future addition of cooling would seem prudent. They would reduce current energy demands, CO_2 emissions and initial cost, whilst providing a degree of future-proofing.

However, caution is required in the interpretation of the predicted performance. The configuration of the wards may change, the lighting systems, heating arrangements, density of occupation and installed and portable equipment loads are likely to change through the period considered. Table 1 gives a detailed account of planned interventions since completion, none for 17 years, refurbishment of several wards at 28–30 years, largely cosmetic, and a sequence of more fundamental interventions in years 37–40. Addenbrooke's Estates staff advise that there is a planned maintenance/refurbishment cycle of 15 years for wards and so two cycles may be anticipated by 2050. The control strategies for Options 4 and 5 would ideally be 'remembered and retained' within subsequent work; the required 'as built' manuals may help preserve the principles but after the second cycle the memory can be expected to lapse with a subsequent effect on performance and patient discomfort, which could provoke intervention. Changes in lighting systems and medical technology would influence internal heat gains. The pressure is towards ever more energy efficient equipment but a significant increase in the amount of equipment, likely as hospitals become ever more specialised, may have an impact. Predicted internal temperatures are most heavily influenced by the climate, the shading, the assumed ventilation strategy and the heating and cooling technique and for each refurbishment strategy these have been fully defined (Table 3). Predictions of future energy demands and CO_2 emissions are avoided because the primary thrust of this paper is overheating assessment, and because these will be heavily influenced by the efficiency of the building and hospital campus plant and changes in the carbon intensity of the fuels used; especially electricity.

In response to short term changes in the weather or the longer term drift of the climate, some adjustments to the control regimes would certainly be made by occupants and more importantly by the facilities managers. Rather than speculate about these possibilities, the control regimen for each refurbishment option was held constant for all the years studied. Thus the predictions show the relative

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[17] Although the night time temperatures exceed 26 °C on many occasions, and the day time hours exceeded 28 °C occasionally, optimisation of the control strategy could avoid this if needed.

Table 5
Summary of predicted internal air and dry resultant temperatures for May–September, future Cambridge climate.

Refurbishment option	TRY							DSY						
	Max. temp. (°C)	Min. temp. (°C)	Mean night time[a] temp. (°C)	Total hours[b] over 28 °C	Night time[a] hours over 26 °C	Total hours above Cat I Upper limit	Total hours above Cat II Upper limit	Max. temp. (°C)	Min. temp. (°C)	Mean night time[a] temp. (°C)	Total hours[b] over 28°C	Night time[a] hours over 26 °C	Total hours above Cat I Upper limit	Total hours above Cat II Upper limit
2005														
Existing	28.6	21.3	24.2	10	10	1041	399	30.1	21.3	24.3	115	60	1198	497
1 SMVHC	27.2	21.8	23.2	0	5	na	na	28.8	21.9	23.5	13	78	na	na
2 SMVRHC	24.9	21.6	23.0	0	0	na	na	25.8	21.6	23.0	0	0	na	na
3 NVMVPH	24.9	20.8	21.4	0	0	0	0	27.8	20.7	21.7	0	30	0	0
4 CVPH	24.9	19.7	21.5	0	0	0	0	28.2	20.0	21.7	5	17	16	2
5 SVPH	24.9	20.8	21.7	0	0	0	0	27.6	22.3	22.0	0	20	0	0
2030s														
Existing	30.6	21.6	24.3	93	59	859	395	33.0	21.2	24.7	383	231	711	341
1 SMVHC	28.3	22.0	23.7	0	36	na	na	29.2	22.4	24.4	14	210	na	na
2 SMVRHC	26.1	21.8	23.1	0	0	na	na	27.1	22.2	23.5	0	5	na	na
3 NVMVPH	27.2	20.8	22.1	0	6	4	0	30.4	20.9	23.4	98	185	58	18
4 CVPH	28.2	20.3	22.3	3	32	21	3	32.3	20.6	23.4	199	208	166	70
5 SVPH	26.7	21.0	22.3	0	13	0	0	30.1	20.9	23.3	102	141	60	22
2050s														
Existing	31.0	21.2	24.3	163	87	866	351	34.8	21.8	25.2	620	388	938	445
1 SMVHC	28.6	22.0	24.0	0	64	na	na	29.5	22.5	24.9	59	396	na	na
2 SMVRHC	26.2	21.9	23.2	0	0	na	na	27.8	22.3	23.8	2	23	na	na
3 NVMVPH	27.3	20.9	22.4	0	11	2	0	31.9	21.0	24.4	395	451	240	72
4 CVPH	28.9	20.3	22.5	18	41	22	4	33.9	20.8	24.5	582	435	462	203
5 SVPH	27.9	20.9	22.5	2	12	4	0	31.6	21.2	24.5	491	416	345	117
2080s														
Existing	31.7	20.7	24.5	232	152	806	396	36.5	20.9	26.0	1035	609	1132	645
1 SMVHC	28.6	22.3	24.2	0	151	na	na	29.7	22.6	25.5	145	610	na	na
2 SMVRHC	26.5	22.1	23.4	0	1	na	na	28.4	22.3	24.2	20	84	na	na
3 NVMVPH	28.1	21.0	23.0	15	110	23	0	33.8	21.0	25.8	990	654	693	324
4 CVPH	29.7	23.3	23.0	96	136	136	46	35.7	20.8	25.9	1060	638	870	577
5 SVPH	28.3	21.1	23.0	11	87	10	0	34.1	21.3	25.7	1014	636	758	418

The HTM03 threshold is based on air temperature and rest are based on dry resultant temperature.
The grey shows where limiting criteria are exceeded.
The darker grey indicates where the exceedence is deemed important in that it could not be easily corrected by refining the control strategy.
It is assumed that during the winter half of the year (October to April) the space will not overheat due to elevated ambient temperatures and solar gains. The limiting overheating values are therefore: HTM03, >50 h over 28 °C; BSEN15251, >438 h above category upper thresholds and CIBSE, >37 night time hours (1%) over 26 °C).
The ambient temperature exceeds 28 °C in the current and future TRYs/DSYs by 2/44, 37/219, 62/341 and 126/566 h in 2005, 2030, 2050 and 2080 respectively.

[a] Night time hours are 21:00 to 06:00.

[b] Simulated hours are for May–September (153 days, 3672 h).

Table 6
Operational impact of each refurbishment option, energy demand, internal temperatures.

Options	Operational impact: phased/incremental	Operational impact: full closure	Internal disruption	External work	Relative cost
1 SMVHC: Sealed building, mechanical vent. With heating and cooling.	External overclad independent of internal use Mechanical systems overhaul floor by floor	Unnecessary	Mechanical systems above ceilings, controls, plant rooms, triple glaze	Yes	Conventional refit and new controls
2 SMVRHC: Sealed building, mechanical vent. But radiant ceiling heating and cooling.	Floor by floor, works to ceilings	Unnecessary	As (1) plus remedial work to Frenger ceilings	Yes – as (1) plus sun shading	Conventional refit and new controls plus renovation of Frenger ceilings
3 NVMVPH: Natural ventilation, mechanical ventilation, with perimeter heating.	Floor by floor, work to perimeter heating, additional openings made in below-cill panels	Unnecessary	As (1) plus installation of perimeter heating, cut back ceilings§	Yes, as (2) plus additional opening lights in windows	Conventional refit, simpler controls
4 CVPH: Natural cross ventilation, perimeter heating.	Floor by floor, but more intensive	An option, to accelerate completion	Remove all ceilings, install cross flow ducts and perimetr heating	Yes, as (3)	Less conventional refit, making good exposed concrete
5 SVPH: Natural stack ventilation, perimeter heating.	Floor by floor internal works, removal of ceilings, cross flow ducts, new windows	An option, as (4). Work to external elevations is more comprehensive and across several levels	As (4) and strip out level 6	Yes, as (3), plus perimeter stacks and deep reveals. Remove level 6	Not unconventional: strip back to frame, and reclad with stacks

performance of the different options and give a very good indication of their inherent resilience untainted by unsynchronised tuning of the model.

9. Conclusions

This paper has reported on the current performance, refurbishment potential and modelled future performance of a representative 1960s UK hospital ward tower. The original designers of the Addenbrooke's building were not oblivious to environmental concerns and considered the use of shading on the glazed south-facing elevation, but this measure was omitted.

The existing wards in the Addenbrooke's Tower provide satisfactory comfort levels in the climate of Cambridge c. 2010 but this is achieved at the cost of excessive energy demands and CO_2 emissions, largely due to loss of heat through uncontrolled air leakage. The building remains resilient until the 2030s but becomes problematic thereafter. The current performance of the building is the result of its control strategy (which lacks exhaust) and the extent of the glazing. The results confirm that BSEN15251, which takes human adaptation to ambient temperature into account and provides comfort criteria appropriate to both clinical and non-clinical spaces gives a more favourable reflection of the resilience of spaces with natural ventilation and operable windows, than assessment methods such as HTM03-01 that use a fixed criterion. Fixed comfort limits, such as HTM03-01 look increasingly inappropriate in times of weather that is more variable and that will gradually warm over time.

Refurbishment, in particular to curb the heat lost through uncontrolled leakage of ventilation air from the building, could reduce energy demands and maintain or even improve the internal environment in the current climate. Space by space control and monitoring potential to enable optimised control is essential. The five refurbishment options also offer the opportunity to increase the resilience of the building in a warming climate whilst saving energy. Relatively modest interventions could achieve substantial savings whilst achieving future resilience in at least typical years. Beyond the 2030s, a degree of mechanical intervention will be required in extreme years and provision should be made for its eventual installation. Current work by the authors is exploring the 'whole life' financial costs of the options. Unless highly efficient heat recovery with a summer by-pass is used, with efficient fans, the HTM03-01 mechanical ventilation requirement of 6 ach^{-1} and NHS energy demand targets of 55–65 GJ/100 m^3 may be mutually incompatible, suggesting that further research in this area could be useful to the Department of Health.

Although focussed on a hospital building, the adaptive strategies explored in this paper could be applied to other non-domestic building types in temperate climates, for example office towers, in that they offer options for refurbishment incorporating the potential for upgrading in response to climate. The case study suggests that wholesale air conditioning is not necessary now, nor in the immediate future, and is indeed undesirable in financial as well as in energy use terms.

Acknowledgements

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The work reported here would not have been possible without the assistance of Cambridge University Hospitals NHS Foundation Trust, which provided access for data collection and other information about the Tower Block services strategy, and most particularly Ian Jackson and the Archivist, Hilary Ritchie.

The authors are most grateful to the ARCC 'Prometheus' project team at the University of Exeter who provided the future climate data sets and to the British Atmospheric Data Centre (BADC) for providing access to weather data.

The authors are also extremely grateful to Peter Kelly, Longmei Dai and Patrick Fleming at Cambridge for producing drawings of the building as it is and as it could be refurbished and to Dr.Stamatina Rassia for recovering construction information from the Trust.

Appendix A. : A note on the Addenbrooke's Ward 6MB7 model.

The ward was modelled using the IES software [25]. For the current building and the five refurbishment options ward 6MB7 was simulated. Its energy use and internal temperatures was taken as being indicative of the relative performance of the current building and the various refurbishment options. The model was calibrated as outlined in Section 4 and as described more fully by Lomas and Giridharan [16].

This Appendix describes the model of the current Addenbrooke's Tower building. The variations to simulate each refurbishment option are given in Table 2 and its footnotes. The model is illustrated in Fig. A1 and the key parameters listed in Table A1. The architectural elevations and plans, Figs. 2b, 3 and 5, give further insight.

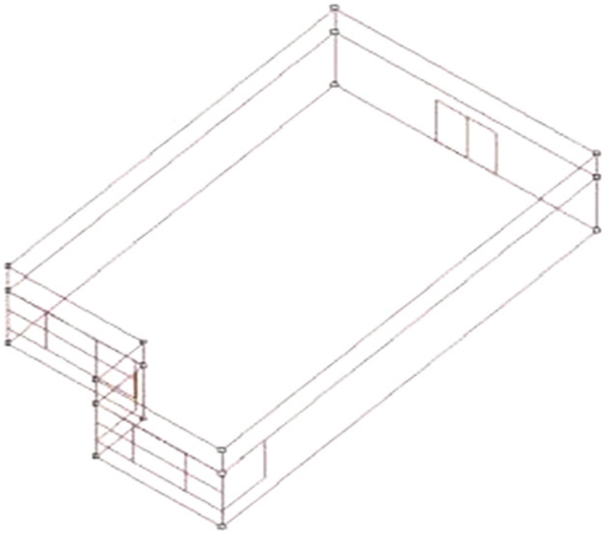

Fig. A1. Diagrammatic representation of model for ward 6MB7.

Appendix

Table A1
Characteristics of ward 6MB7 model.

Feature	Description	Notes
Zone	Floor area, 70.3 m^2, volume 190 m^3. Maximum depth 10.2 m.	See Fig. A1 for shape
Height	2.7 m to radiant ceiling and 0.9 m above to concrete soffit.	
External areas	Wall, 36.7 m^2; transparent glazing, 10.4 m^2.	
Windows	Lower 0.95 m height operable to 100 mm gap, upper 0.95 m high window fixed.	See Fig. 5 for detail
Internal walls	Assumed to be concrete, with five adjacent spaces all at same temperature as modelled space. Internal door assumed closed.	
U-values	Windows, double low-emissivity, $U = 1.9$ W/m^2 K; uninsulated lightweight panel below windows and to sides of projecting bay, $U = 2.1$ W/m^2 K; wall above window, insulated concrete, $U = 0.5$ W/m^2 K.	
Ventilation rate	Mechanical supply 4 ach^{-1}. Exchange from room into ceiling void and back, 2.5 ach^{-1} (based on ceiling void volume). Infiltration 0.25 ach-1. No exchange with surrounding spaces.	Determined from facilities managers and by calibration of model. Building has no dedicated air extract model implicitly assumes 4 ach^{-1} extract.
Window opening strategy	Occupants assumed to open the windows if wind speed below 7.5 m^2. The maximum opening 100 mm. The opening area was assumed to be 0% if $T_a \leq 15$ °C ramping up to 100% (100 mm) at 20 °C $\leq T_a \leq$ 21 °C, then closing to 25% at $T_a \geq 23$ °C.	IES calculates air exchange based on wind speed and direction. Actual window opening varies with occupant behaviour.
Ventilation air heating regimen.	Supply air heated to set-point of 18 °C. Set-point ramped down from 100% (18 °C), at ambient temperatures $T_a \leq 16$ °C, to zero at $T_a \geq 18$ °C.	Determined from facilities managers, but they adjust the set points throughout the year in response to occupant requests.
Radiant heating regimen	Punched metal panels heated to a set-point of 30 °C in summer and 32.5 °C in winter. Set-point ramped down from 100% when $T_a \leq -3$ °C to 60% at $T_a = 15$ °C and off at $T_a = 16$ °C.	Thus, when ambient temperature reached 18 °C, the building is in free-running mode. In practice facilities managers adjust the set points throughout the year in response to occupant requests.
Internal heat gains	Daily gains from reading lamp, lights and TV fluctuates from 0 to 6.7 W/m^2. Additional gains of 6 to 11 W/m^2 due to occupants and staff movement.	

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