

# A medium-rise 1970s maternity hospital in the east of England: Resilience and adaptation to climate change

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## Abstract

The late 1970s design for the Rosie Maternity Hospital on the Addenbrookes campus in Cambridge is a recurring type across the UK National Health Service, a framed three-storey courtyard configuration in brick masonry. It was selected as a case study project for the 'Design and Delivery of Robust Hospitals in a Changing Climate' project, pursuing the methodology developed for that research. Temperature data were collected in representative spaces within the hospital, over a two-year period. These revealed overheating in mild conditions relative to an observed 24°C threshold for sleep but concealed within the customary 28°C threshold marking the upper limit of acceptable conditions. The building was modelled using current climate data to predict 2010 conditions. The model was then calibrated against the observed 2010 data and used to predict the likely internal temperatures in current and 2030s. The results indicated an increase in peak temperatures. Four adaptive intervention schemes were subsequently developed: an 'enlightened' industry standard 'Passivhaus'-type option providing superinsulation, sealed glazing and heat recovery; a lower technology-based scheme promoting natural cross-ventilation by providing greater opening glazing area, opening up the plan, sunshading and additional insulation; an enhanced natural ventilation scheme glazing over the courtyards to provide supply air winter gardens, and an advanced natural ventilation option pursuing passive draught cooling. All four schemes were modelled using the projected current and 2030s weather data and their performance was compared. The schemes were fully costed to yield relative 'value for money' guidance to National Health Service Trusts. **Practical application:** The Heat wave Plan for England 2014 warns National Health Service (NHS) organisations of the risks to patients, particularly the very young, the elderly and the seriously ill, from extreme summer heat events.<sup>1</sup> The Chief Medical Officer in her introduction challenges each NHS locality to plan well in advance of hot spells, as appropriate. This paper describes the likely extent of overheating risk and a series of potential adaptation plans for a recurring NHS hospital building type. As a consequence, estates and facilities decision makers in NHS organisations and Public Health England officers

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charged with the mitigation of risk resulting from overheating of wards and clinical spaces will benefit directly in their necessary decision making from the findings. Policy makers in the Department of Health and policy advisors in the NHS Sustainable Development Unit and the Climate Change Committee Adaptation Sub-Committee will benefit from the evidence presented in advising the NHS and Department of Health.

### **Keywords**

Hospitals, resilience, adaptation, climate change, mixed mode

### **Introduction**

From 2009 until 2013, the Design and Delivery of Robust Hospital Environments in a Changing Climate (DeDeRHECC) research project investigated the impact of summer overheating in the built estates of four National Health Service (NHS) Acute Trusts: Addenbrookes Hospital within the Cambridge University Hospitals NHS Foundation Trust; Bradford Royal Infirmary within the Bradford Teaching Hospitals NHS Foundation Trust; St. Albans City Hospital within the West Hertfordshire NHS Trust and Glenfield Hospital, a Nucleus scheme within the University Hospitals of Leicester NHS Trust. In each of these hospitals, 125 spaces within three to four wards in two or more buildings were monitored from June 2010. In Cambridge, the Addenbrookes Hospital ward tower and the Rosie Maternity Hospital were analysed. The performance of Addenbrookes tower has been presented elsewhere.<sup>2</sup> This paper focuses on the Rosie Maternity Hospital, representative of a recurrent 1970s NHS hospital-type building.

The Rosie hospital accommodates the maternity and neonatal services offered by the Cambridge University Hospitals NHS Foundation Trust in the East of England.<sup>3</sup> It was funded by a single private donation, designed by the architects Yorke Rosenberg and Mardell (YRM) in the late 1970s and opened in 1983. It comprises a steel and concrete-framed, brick-clad, three-storey, double-loaded corridor, double courtyard building.<sup>4</sup> Recently, as yet

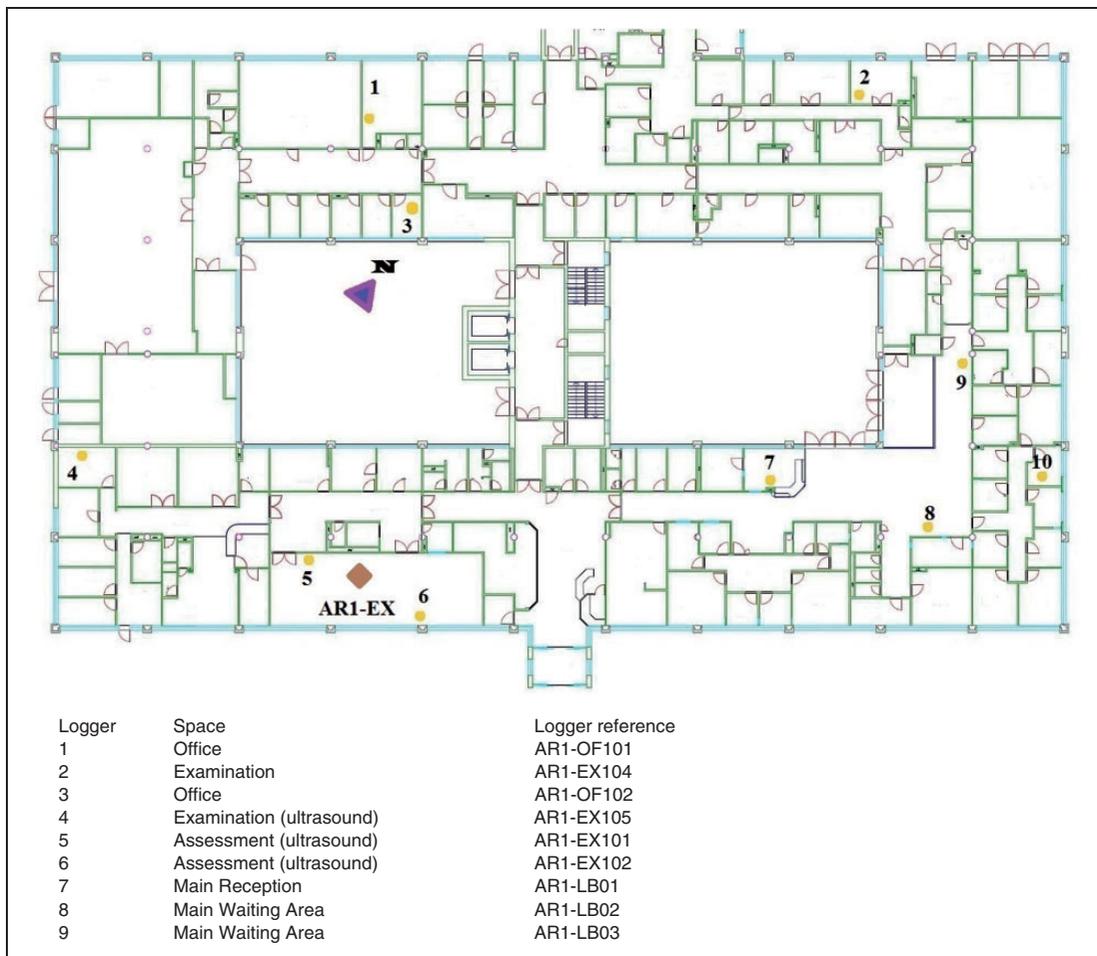
unpublished research, at Cambridge University for the Department of Health (DH) indicates the retention of some 117 postwar, three-storey, courtyard-type buildings across the NHS England Acute Estate, approximately 3 million m<sup>2</sup> alone. YRM delivered the St. Thomas's tower in Central London and the John Radcliffe Hospital in Oxford. The framed, repetitive bay, glazed treatment is consistent. Writing particularly of F. R. S. Yorke, YRM'S founder and an important publicist for modern architecture, Worsley wrote, 'it was the rise of the Welfare State that made his firm'.<sup>5</sup> The 'Rosie' is a recognizably YRM design in the rigorous expression of its frame, ultimately a building system and aesthetic derived from Mies van der Rohe's theoretical prewar schemes via Skidmore Owings and Merrill's extensive output in North America, within which wide structural bays are entirely filled with glazing to a rectilinear grid. YRM's tendency to clad their frames with ceramic tiles, as at St. Thomas's in London, was overruled by the donor who insisted on brick and possibly also on the generous provision of opening glazing, which was suppressed in the late 1990s when urgent reactive NHS guidance suggested window opening be restrained to 100 mm.<sup>6</sup>

The building is oriented approximately east-west so that the main entrance and many of the multibed wards face south. Clinical services for outpatients examination, imaging and consulting rooms, are located on the level 1 (ground floor), whilst inpatient wards occupy second and the third levels. Figures 1–3 show general plan layouts with the location of data loggers

installed by researchers. There are parallel academic and research functions, the Cambridge University Departments of Gynaecology and Obstetrics have accommodation in the north-west quadrant.

This paper investigates the performance of Rosie Maternity Hospital during summer 2010, and simulates the performance of adaptive interventions with a focus on summer time overheating. The study also costed all the schemes to yield relative 'value for money' guidance to NHS Trusts. The simulation weather files for the year

2010 (Bedford), current and future were created by the 'Prometheus' research team at Exeter University. The Bedford weather file was selected because the weather station at Cambridge does not measure all the necessary parameters to generate simulation weather files, especially the cloud cover and solar radiation intensity. The current Test Reference Year (TRY) and the Design Summer Year (DSY) were generated to the standard Chartered Institution of Building Services Engineers (CIBSE) methodology using weather data from the Bedford meteorological



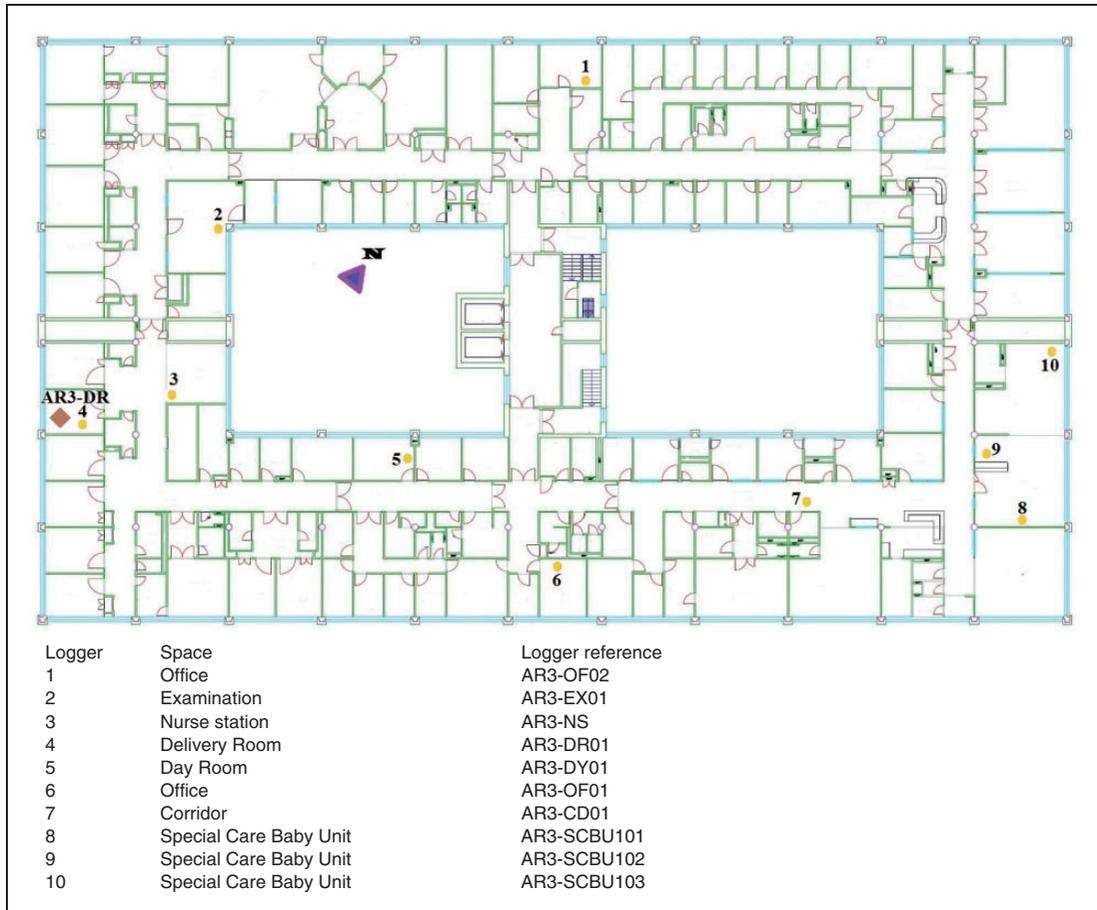
**Figure 1.** Monitored spaces and logger locations in Rosie level I. ARI-EX was considered for predicted performance analysis (space with logger 5 and 6).



**Figure 2.** Monitored spaces and logger locations in Rosie level 2. AR2-MB2 was considered for predicted performance analysis.

station. The TRY was created using 1980–2004 hourly weather data. The DSY was the year that had the third hottest summer between 1980 and 2004. In this case, it was 1997. For the year 2010 as well as for the current TRY and DSY, the diffused solar radiation, direct solar radiation and global solar radiation were derived from Bedford cloud cover as directed by CIBSE TM48. The future probabilistic weather files

were derived using UKCP09 data for Cambridge under the A1B emission scenario.<sup>7</sup> The Prometheus team used a statistical technique to derive a single TRY and DSY for the future time slice. This work used 50 and 90 percentile weather files to generate the TRY and DSY, respectively. A detailed account of the weather file generation and selection process has been presented elsewhere.<sup>8</sup>



**Figure 3.** Monitored spaces and logger locations in Rosie level 3. AR3-DR was considered for predicted performance analysis (space with logger 4).

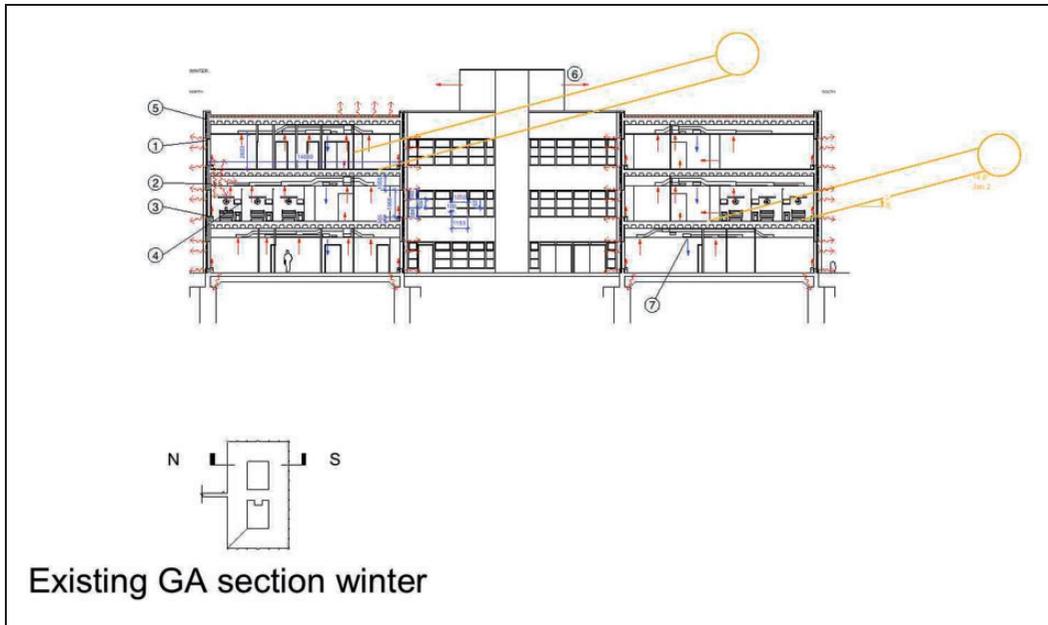
## Construction of the Rosie hospital

Figures 1–3 record the three floor plans of the hospital, Figures 4 and 5 show the frame structure. Table 1 summarises the use of materials.

Floor and roof slabs are coffered ‘waffle’ type reinforced concrete slabs of 150 mm continuous slab depth with two way beams adding 300 mm depth, 450 mm overall incorporating substantial thermal mass, spanning across a steel frame. Deep perimeter downstands to the floor and roof slabs form lintols to the wide bays. The

roof buildup comprises screed to falls, asphalt, 50 mm ‘Roofmate’ extruded polystyrene slabs, held below a 50 mm thick roof deck of pre-screeded woodwool slabs with reinforced edges and 50 mm thick layer of washed gravel (20–50 mm diameter).

Suspended ceilings conceal all spanning concrete from the occupied spaces, suppressing radiant exchange with the occupants. The conventional cavity external wall construction comprises: 100 mm brick; 50 mm thick polystyrene partial cavity fill; the inner leaf either 140 mm block or plaster board on timber (100 mm × 100 mm) studwork; the floors

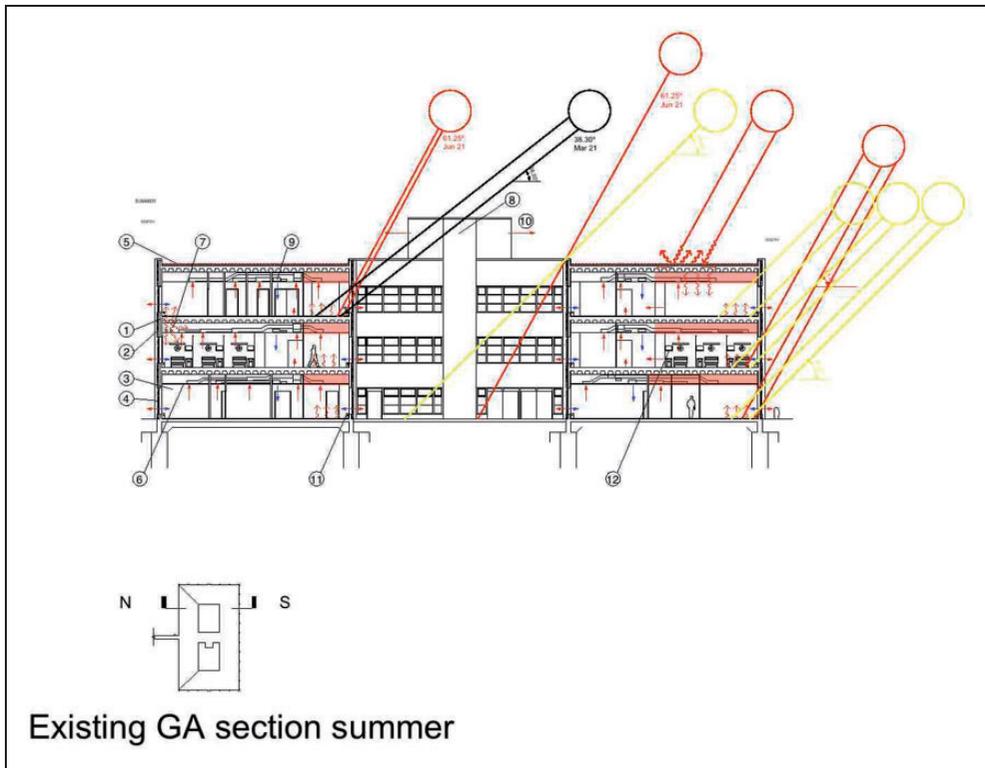


**Figure 4.** The Rosie Maternity Hospital, Addenbrookes, Cambridge. Existing Building, Summer Condition.

1. Reinforced concrete frame: waffle slab 150 mm with 300 mm downstands, from inner leaf to external cavity wall above glazing spanning full structural bay.
2. External leaf of 100 mm brick, 50 mm polyurethane insulation in cavity, inner leaf 140 mm concrete blockwork. Occasionally steel stud and two layers plasterboard.
3. Nonstructural internal partitions vary: plasterboard on 100 mm softwood studwork or 140 mm concrete blockwork plastered both sides.
4. External windows double glazed in hardwood frames, mullions and transoms (75 × 100 mm), opening lights restricted to 100 mm since late 1990s.
5. Roof: 150 mm RC slab, waffle 300 mm deep, 50 mm roof deck of prescreeded slabs with reinforced edges, asphalt, 50 mm extruded polystyrene 'Roofmate' held down by 50 mm of washed gravel.
6. Lightweight suspended gypsum ceiling tile grid.
7. Hot water (HW) pipes suspended within ceiling void, original insulation, some missing, water circulated at 55° or 60°C continuously to avoid bacterial growth.
8. Service riser to east and to west sides. Each connects to a plant room on ground floor (level 1) 3 AHU units in east, fresh air supply drawn down riser ducts from roof level.
9. Supply air, 2 AHU's heating, 1 AHU cooling per plant room. Unconditioned air supplied when external temperature below 22°C. Conditioned air delivered at 21°C through variable speed fan.
10. Exhaust air vented mechanically. No heat recovery.
11. Perimeter heating: thermostatic radiator valves recently installed (2011) supplied by HW at minimum 65°C. Target temperatures 24–25°C in all rooms–wards.
12. Internal gains: TV 2.2 w/m<sup>2</sup>; bed lamp 2.8 w/m<sup>2</sup>; general ceiling mounted lighting 3.3 w/m<sup>2</sup> as calculated for multi-bed ward.

screeded and finished with vinyl carpet. The rectilinear grid of windows in each structural bay is double glazed in hardwood frames (approximately 75 mm × 100 mm). Hot water and mains

steam pipelines are suspended below the floor slabs retaining their original insulation at the time of this study, some of which is missing. The steam pipe, the main ring supplying the whole site,



**Figure 5.** The Rosie Maternity Hospital, Addenbrookes, Cambridge Existing Building, Winter Condition.

1. Air leakage trough window frame.
2. Heat gains from uninsulated HW and particularly steam supply pipes.
3. Perimeter heating, HW supplied at 65°C.
4. Internal gains from lighting, bed lamp and TV.
5. Heat loss through poorly insulated fabric, essentially 50 mm polystyrene at wall and roof.
6. Warmed air exhausted at roof level.
7. Air supplied mechanically at 21°C+, mean target temperature 24–25°C.

**Table 1.** General construction information for the Rosie maternity ward complex.

Description	Material	Thickness (mm)	Thermal transmittance ( $\text{Wm}^{-2}\text{K}^{-1}$ )	Opening size (mm)	General information
External wall	Brick/cavity/50 mm insulation/plaster board	400	0.4	–	The floor to floor and floor to ceiling heights are 3.8 m and 2.5 m, respectively, in levels 1 and 2. In level 3, floor to floor and floor to ceiling heights are 3.9 m and 2.4 m, respectively. The window opening is restricted to 100 mm for patient safety
Roof	RC frame	250	0.5	–	
Floor	RC frame	Overall 450, slab 150	0.15	–	
Window	Timber-framed double glazing	–	1.9	675 × 1300 675 × 650	

Note: RC, reinforced concrete.

emitted heat continuously into the Level 2 ceiling void on the north side of the building. Recently the DH NHS Energy Efficiency Fund (EEF), administered by the lead author, has funded its reinsulation and the removal of asbestos lagging.<sup>9</sup>

### **Arrangement of existing services**

All spaces have perimeter heating elements without local thermostatic control, set within each bay below the extensive glazing, fed by supply and return pipes rising through the floor slab below, hot water reaching the perimeter radiators intended to be not less than 65°C, to maintain 24–25°C in occupied rooms year round. The building is currently operated at a set point temperature of 24.0°C. Mechanical ventilation heats supply air at temperatures below 22°C all year round. At the time of monitoring, there was no zone control. However, the Trust's Estate Management was planning to introduce Thermostatic Radiator Valve (TRVs). The researchers' expert panel observed that zone control employing wall-mounted thermostats would be more productive and efficient.<sup>10</sup> The Rosie hospital has its own plant room on level 1 of the west wing with four noncondensing dual fuel boilers, gas fired in normal mode. They supply hot water to the main header maintained at 60 and 70°C, respectively, in summer and winter temperature. The boilers come to operation in sequence during colder conditions to supplement heat provided by central steam plant supplying the whole site. The plant on site includes two shell–core heat exchangers to extract heat from the steam supplied from the central plant. The original exchangers are scheduled to be replaced by plate exchangers. Pumps work on constant volume and variable temperature.

The building has its own chiller providing chilled water to an air-handling unit (AHU) delivering comfort cooling to intensive care units and the operating theatres. The chiller set point temperature is 6°C. Standby mode set point is 9–10°C. When the chiller is not supplying chilled water to the cooling circuit, the temperature is set at 12°C.

The building is mechanically ventilated throughout the year. Figures 4 and 5 show the supply and exhaust points, corridor pressurized by supply, exhaust above patient beds. For ventilation, the building is zoned into east and west wings with an AHU room located on each side. Each plant room contains three AHU units and in each room only one unit has the provision to cool the air (the other two are only for heating). Fresh air to these AHUs is drawn from above roof level through ducts. Generally, when the outside air temperature is 22°C or above the fresh air is not conditioned (no heating) and it is directly supplied, but cooling is produced for special rooms such as the Special Care Baby Unit. The AHUs release the conditioned air at 21°C through variable speed fans. Fresh air is heated to 18°C and supplied to each zone via corridor ceiling supply grilles located. Anticipated maximum supplied air temperature is around 26°C in summer. In the winter, it could fall as low as 18°C. At night, level 1 has reduced air supply due to low occupancy.

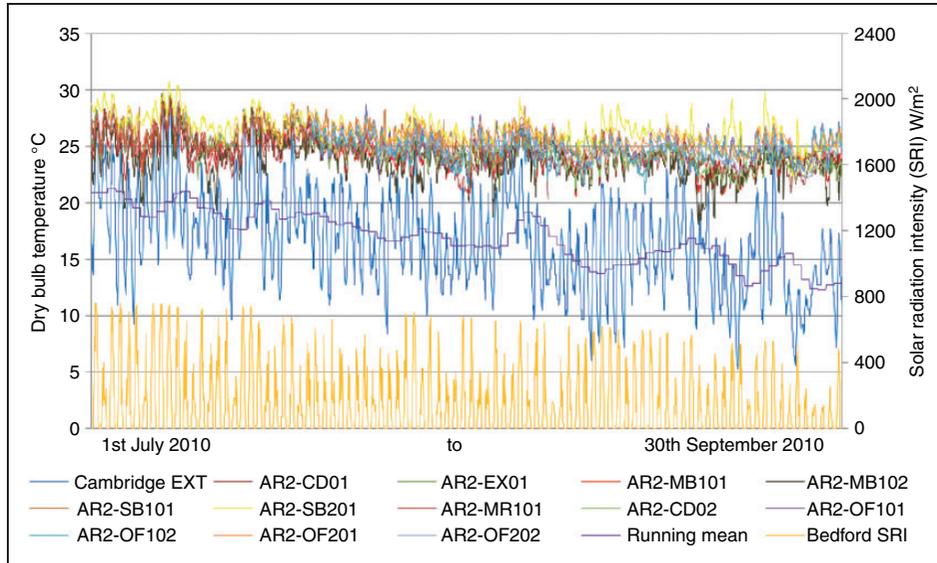
Extracts are located in service spaces, WCs, bathrooms and dirty utility rooms and in wards above beds. The centrally collected return air is released directly to the atmosphere above roof level with no heat recovery.

### **Performance of monitored spaces**

Twenty-six spaces on three levels were monitored at hourly intervals with Hobo U2 temperature loggers.<sup>11</sup> The larger spaces receive more than one logger (Figures 1–3). The logger positions were constrained as NHS infection control protocols resist foreign objects appearing in clinical spaces. Specific ventilation rates were recorded using a Balometer on a typical working weekday during January 2012.

The second level emerges as the hottest floor and AR2-SB2 (logger AR2-SB201) records the hottest space (Figure 6).<sup>12</sup>

Basic construction information and the mechanical servicing strategy are presented in Table 2.



**Figure 6.** Recorded Rosie level 2 internal and ambient dry-bulb temperature and solar radiation intensity.

**Table 2.** Multizone base model characteristics: selected spaces.

Description	AR1-EX	AR2-MB2	AR3-DR
External wall area (m <sup>2</sup> )	40.3	17.3	8.5
Floor area (m <sup>2</sup> )	96.1	50	16.3
Volume (m <sup>3</sup> )	231	120	39
Window area (m <sup>2</sup> )	23.4 glazed and 6.6 opaque	10.1 glazed and 2.5 opaque	NA
Internal heat gain (W/m <sup>2</sup> )	0–14.6	10.8–22	0.8–2.0
Perimeter heating	Yes	Yes	Yes
Mechanical ventilation rate	32 l/s (0.5 ach)	40 l/s (1.2 ach)	6 l/s (0.5 ach)
Window-opening strategy	The occupants were assumed to open the windows. The maximum opening is 100 mm. The opening area assumed to be 0% if the $T_{out} \leq 10^{\circ}\text{C}$ , and 50% if $T_{out} > 10^{\circ}\text{C}$ and $T_{in} \leq 24.5^{\circ}\text{C}$ , then ramps up to 100% at $T_{in} \geq 25.5^{\circ}\text{C}$		
Perimeter heating regime	Set point temperature is 24.5°C. Set point is 100% at $T_{out} \leq -3^{\circ}\text{C}$ and it ramps down to 75% at $T_{out} = 15^{\circ}\text{C}$ . It is off at $T_{out} = 18^{\circ}\text{C}$		
Ventilation heating regime	Supply air is heated to 18°C. Set point ramped down from 100% at $T_{out} \leq 16^{\circ}\text{C}$ to zero at $T_{out} \geq 18^{\circ}\text{C}$		
Extract regime	40–50% of the stale air is extracted through service areas and the balance escapes through window openings		
Occupancy	The occupancy levels in AR1-EX, AR2-MB, AR3-DR were 17 (5 staff, 6 patients and 6 visitors), 13 (3 staff, 6 patients and 4 visitors) and 4 (2 staff, 1 patient and 1 visitor), respectively. Between 7:00 and 9:00, and 18:00 and 20:00 at every hour there were two staff members at the multi bedroom for 5 min. The rest of the time at every hour, there was one staff member at the multi-bedrooms		

Note: AR2-MB2 was not monitored. However, it was selected in order to assess the performance of south facing multi-bedroom.

Discussion will be limited to the main lobby area (AR1-LB), the examination–consulting–meeting room (AR1-EX), the multi-bedroom ward (AR2-MB1), a single bedroom (AR2-SB2), a delivery room (AR3-DR) and a nurse station (AR3-NS), all as described in Tables 3 and 4. The spaces were selected to present a representative overview of all the critical types of space found in the Rosie hospital.

The spaces were monitored from July 2010 to October 2011. The focus of the DeDeRHECC research project is on resilience to summer overheating and so results for the consecutive summer periods 1st July to 30th September 2010 and 1st May to 30th September 2011 are presented (Tables 3 and 4). Analysis will focus on 2010 results insofar as calibration of the dynamic thermal model, the predictions it generated and the subsequent energy calculations are based on the 2010 Bedford weather file as described later in the paper.

To evaluate the monitored performance, the study used the ambient temperature from Cambridge University and solar radiation intensity from the Bedford meteorological station. The maximum ambient temperature during the summers of 2010 and 2011 were 29.6°C and 31.2°C respectively, 2010 was a relatively cool year, while the minimum temperatures for summer 2010 and 2011 were 5.2°C and 3.5°C, respectively. The peak solar radiation intensity for 2010 and 2011 was of the order of 750 W/m<sup>2</sup> and 950 W/m<sup>2</sup>, respectively, for the monitored periods.

During the period 1st July to 30th September 2010, the maximum temperature recorded in the building was 30.7°C observed in the single patient bedroom (AR2-SB2). This trend was also observed during summer 2011. During the 2010 monitored period, a minimum temperature of 20.3°C was found in the Lobby area and this trend repeated in 2011. For the 2010 monitored period, the mean daytime temperature varied between 23.9°C and 26.7°C, while mean nighttime temperatures varied between 23.4°C and 26.1°C. The single bedroom (AR-SB2)

experienced the maximum temperature conditions recorded. The lowest diurnal temperature range, 2.8 K, was recorded in the nurse station (AR3-NS) and the highest, 6.6 K, in the delivery room AR3-DR.

Thermal comfort was determined by comparing the measured temperatures with the criteria adopted in previous papers by the authors.<sup>13</sup> These included both the simple static guidelines and criteria described by the CIBSE and the adaptive thermal comfort thresholds described in BSEN15251. The appropriateness of these approaches and their relative credibility are discussed by Lomas and Giridharan.<sup>14</sup> The static criteria suggest that thermal discomfort will arise if there are more than 5% of the annual occupied hours over 25°C or more than 1% of annual occupied hours over 28°C in occupied spaces. The research team assumed throughout the DeDeRHECC project that hospital wards are occupied for 24 h a day every day of the year, with the exception of the lobby, consulting and examination rooms.

The latter criterion is given in Healthcare Technical Memorandum HTM03.<sup>15</sup> The CIBSE Guide also indicates that sleep will be impaired if temperatures exceed 24°C and that they should not exceed 26°C. However, the nighttime overheating risk criterion indicates that temperatures should not exceed 26°C for 1% of the occupied hours. Nighttime was taken as 21:00 to 06:00 throughout the DeDeRHECC project. The BSEN15251 thresholds increase as the ambient air temperature increases; a narrow band of acceptability, Category one (Cat.I) which is 5 K wide, and a wider band, Cat.II of 7 K, are of interest here.

In 2010, the single bedroom (AR2-SB2) and examination room (AR1-EX1) exceeded both BSEN15251 and HTM03 thresholds.<sup>16</sup>

The multi-bedroom ward and delivery room exceeded only the CIBSE criterion. None of the spaces met the adaptive comfort standard Cat.I.<sup>17</sup> However, the examination room (taking the average value of two loggers) and

**Table 3.** Comparison of internal temperatures measured between 1st July and 30th September, 2010, with BSEN1525 I, CIBSE and HTM03 overheating criteria: Representative spaces in Rosie maternity ward.

Space	Logger reference	Maximum temp °C (24h)	Minimum temp °C (24h)	Mean daytime temp °C (7:00 to 20:00)	Mean night time temp °C (21:00 to 6:00)	Maximum diurnal range (K)	HTM03:			BSEN1525 I:	
							Hours over 25°C (24h)	Hours over 28°C (24h)	Hours over 24°C	CIBSE: Hours over 26°C (21:00 to 6:00)	Hours over Cat I/ Cat II upper
<b>Level-1</b>											
Main lobby (AR1-LB)	AR1-LB01	28.8	20.3	24.5	24.0	4.8	525	9	NA	NA	255/53
	AR1-LB02	29.0	20.8	24.4	23.6	4.5	485	6	NA	NA	245/40
	AR1-LB03	26.5	20.5	23.9	23.4	4.3	63	0	NA	NA	65/2
Examination-meeting cum consultation (AR1-EX)	AR1-EX101	29.6	21.4	25.8	24.6	5.4	1174	94	NA	NA	977/454
	AR1-EX102	29.3	20.0	24.6	24.0	6.2	734	51	NA	NA	514/188
<b>Level-2</b>											
Multi bedroom (AR2-MB)	AR2-MB101	29.4	20.0	24.5	24.1	5.6	595	19	488	55	376/90
	AR2-MB102	29.4	18.1	24.1	23.5	6.5	466	23	302	46	293/74
Single bedroom (AR2-SB2)	AR2-SB201	30.7	22.3	26.7	26.1	4.9	1992	236	888	494	1972/168
<b>Level-3</b>											
Delivery room (AR3-DR)	AR3-DR01	29.9	18.2	24.8	24.7	6.6	661	3	512	81	598/114
Nurse station (AR3-NS)	AR3-NS	28.3	22.2	25.0	24.4	2.8	610	4	NA	NA	NA

Note: Total number of hours: 2208. Total number of night time (21:00 to 6:00) hours: 920. The loggers AR1-LB03, AR3-DR01 and AR3-NS were in operation between 27st July and 30th September. There were 1571 h. Nighttime hours: 653. The limiting overheating values for the monitored period are: HTM03, 30h over 28°C; BSEN1525 I, 110h above category upper threshold and CIBSE, 9 nighttime hours over 26°C. For the loggers AR1-LB03, AR3-DR01 and AR3-NS, the limiting overheating values are: HTM03, 21 h over 28°C; BSEN1525 I, 79 h above category upper threshold and CIBSE, 7 nighttime hours over 26°C. Nighttime sleeping criteria are not applicable to lobbies, examination rooms and nurse stations. Boldface and italic values with grey shade: criterion limit exceeded. AR2-MB2 was not monitored. However, it was selected in order to assess the performance of south facing multi-bedroom.

**Table 4.** Comparison of internal temperatures measured between 1st May and 30th September, 2011, with BSENI5251, CIBSE and HTM03 overheating criteria: Representative spaces in Rosie maternity ward.

Space	Logger reference	Maximum temp °C (24h)	Minimum temp °C (24h)	Mean daytime temp °C (7:00 to 20:00)	Mean night time temp °C (21:00 to 6:00)	Maximum diurnal range (K)	HTM03: Hours over 28°C (24 hours)	Hours over 24°C (21:00 to 6:00)	CIBSE: hours over 26°C (21:00 to 6:00)	BSENI5251: hours over Cat I/ Cat II upper
<b>Level-1</b>										
Main lobby (ARI-LB)	ARI-LB01	28.9	19.9	23.7	22.7	5.0	223	6	NA	42/6
	ARI-LB02	28.1	18.7	23.8	23.1	5.0	201	1	NA	39/4
	ARI-LB03	28.2	18.8	23.7	23.0	4.7	177	2	NA	31/6
Examination-Meeting cum consultation (ARI-EX)	ARI-EX101	30.1	20.6	24.7	23.6	7.3	908	17	NA	<b>214/32</b>
	ARI-EX102	30.1	19.7	23.6	22.8	6.9	294	12	NA	39/10
<b>Level-2</b>										
Multi bedroom (AR2-MB)	AR2-MB101	29.7	20.2	24.5	24.0	6.0	966	21	65	<b>239/55</b>
	AR2-MB102	29.9	18.5	24.2	23.5	6.6	769	26	47	<b>210/67</b>
Single bedroom (AR2-SB2)	AR2-SB201	30.4	22.7	25.8	25.6	4.5	2703	<b>115</b>	491	<b>1292/347</b>
<b>Level-3</b>										
Delivery room (AR3-DR)	AR3-DR01	29.2	19.7	24.7	24.4	5.1	1169	26	81	<b>205/33</b>
Nurse station (AR3-NS)	AR3-NS	30.0	21.5	25.3	24.8	4.5	1778	33	NA	<b>489/59</b>

Note: Total number of hours: 3672. Total number of night time (21:00 to 6:00) hours: 1530. The limiting overheating values for the monitored period are: HTM03, 50 h over 28°C; BSENI5251, 184 h above category upper threshold and CIBSE, 15 nighttime hours over 26°C. Nighttime sleeping criteria are not applicable to lobbies, examination rooms and nurse stations. Boldface and italic values with grey shade: criterion limit exceeded.

the lobby met the Cat.I threshold during 2011. On the other hand, during 2011, only the single bedroom (AR2-SB2) exceeded the HTM03 threshold. In 2010, most of the spaces were monitored for 2208 h, however the number of hours crossing the threshold is close to, or higher than 2011 values, especially in terms of the BSEN15251 thresholds. On the other hand, the number of hours of ambient temperature over 24°C during 2010 (2028 h) and 2011 (3672 h) was 82 and 96, respectively. Therefore, better performance in 2011 can be attributed to milder summer conditions. However, in general, the 2010 summer has been considered as mild summer, not taxing conditions.<sup>18</sup> Therefore, these results indicate that summer overheating even in mild ‘normal’ conditions in the Rosie hospital is a major concern.

Overheating has been highlighted by hospital staff on many occasions during the researchers’ visits to Rosie Maternity Hospital. Excessive temperatures have been recorded by the DeDeRHECC team in the Bradford Royal Infirmary and the Edinburgh Evening News reported ‘Soaring heat at maternity ward “intolerable”’ in its 24th July 2014 issue.

Figure 4 depicts the winter mode in which unintended air infiltration through the envelope and fabric heat losses do not appear to dispel the significant internal heat gains. Mechanical ventilation delivers warmed air to achieve the set point temperature and perimeter skirting heating attempts to counter the prodigious cold down-draughting off the glazing.

The fundamental factors contributing to the poor summer time resilience are indicated in Figure 5. Hot water and steam pipes with intermittent insulation contribute to significant internal heat gains from lighting and equipment. The diagram reveals the extent of the exposure of direct solar gains through the liberal glazing area, which is largely fixed but with an intermediate band of lights opening to only 100 mm. This explains the marginal thermal comfort generated on even mild days in south and south westerly facing wards as shown in Figure 5.

## Predicted performance of the existing building: Modelling and calibration

To predict the annual frequency of overheating of the wards and the energy demands and CO<sub>2</sub> emissions in the current climate, the dynamic thermal model Integrated Environmental Solutions (IES) was used.<sup>19</sup> This software was chosen because 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 in the industry. Since measured temperatures were available, it was possible to calibrate the IES model prior to embarking on the assessment of the proposed refurbishment options.

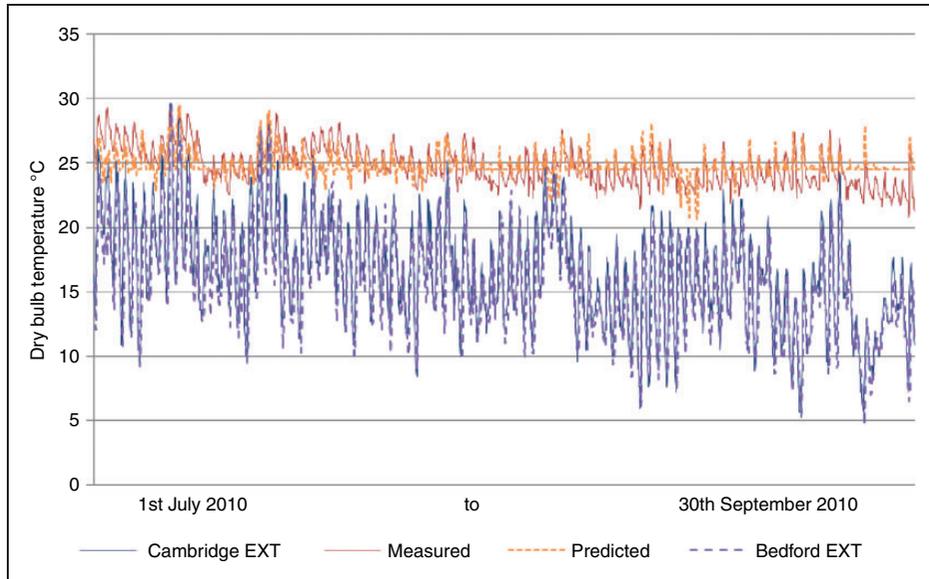
A multizone thermal dynamic model of the Western wing of the Rosie hospital was constructed to predict current and future performance. The measured hours over 28°C was taken as the primary criterion to be matched by the predictions. Table 2 records the construction information on which the model was run. The calibration was carried out by focusing on two spaces; AR1-EX and AR3-DR (Figures 7–9).

The weather file for Bedford in 2010 was used for the calibration, as described elsewhere.<sup>20</sup>

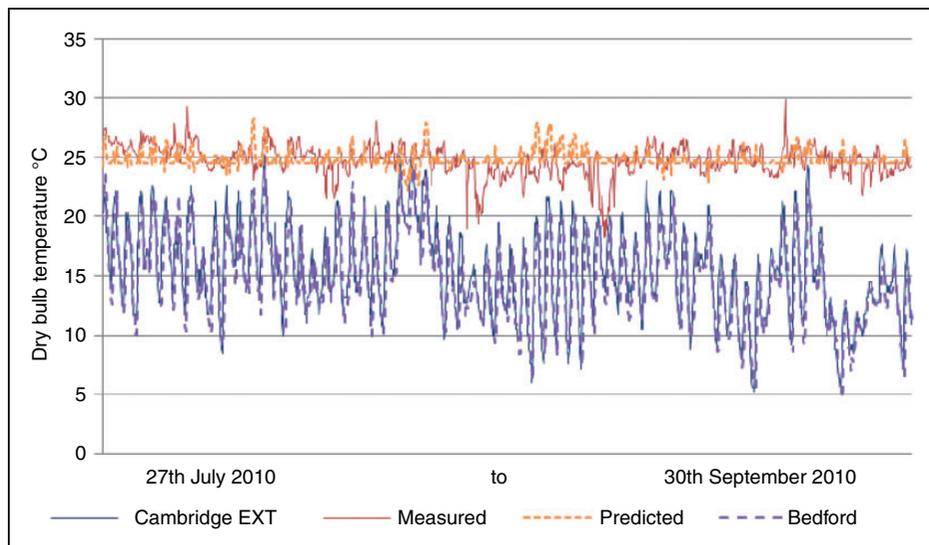
Sensitivity analysis was carried out to identify the critical variables necessary to tune the model. The model is sensitive to internal gains, especially heat gains from the equipment, the degree and duration of both window and door opening in all the rooms.

At night, the model assumes that in any 1 h, 50% of the doors were opened for 5 min in discussion with nursing staff. The window-opening regime (see Table 2) is one of the most uncertain assumptions but is very critical, especially in making nighttime predictions.

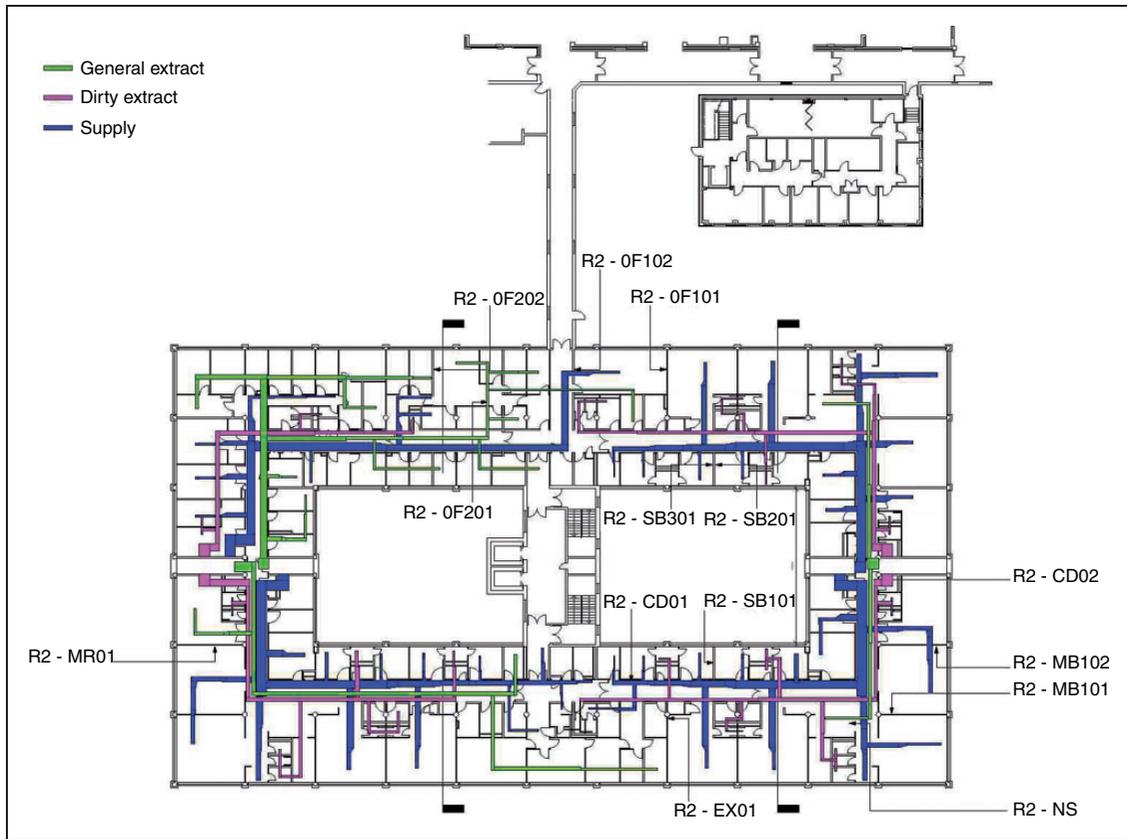
Entry onto wards for researchers was limited to brief forays to install or collect data loggers and on some days forbidden outright. The model cannot accurately reflect an individual’s preferences, i.e. the window-opening regime will not change in line with each and every occupant



**Figure 7.** Comparison of predicted and measured temperatures for AR1-EX, and ambient temperature, during the monitored period.



**Figure 8.** Comparison of predicted and measured temperatures for AR3-DR, and ambient temperature, during the monitored period.



**Figure 9.** Option 1 SMVHC.

1. Ventilation system delivers  $6 \text{ ach}^{-1}$  as required by HM 03-01.
2. Return air ducts in corridors and wc/bathrooms.
3. Windows are sealed shut.
4. South and west facing glazing shielded by interstitial blinds. Airtightness improved by continuous mastic seal.
5. Perimeter heating not utilised in this option.
6. Existing HW and steam supply pipes insulated to high standard.
7. Additional 100 mm insulation added to 50 m Roofmate extruded polystyrene slabs.
8. Walls receive 100 mm mineral fibre insulation and proprietary render treatment. Lower opaque-glazed panels to window frames receive additional 100 mm insulation.

decision, but it is not clear how autonomous inpatients and their visitors may be in practice. Therefore, the model used a generalised window-opening profile that researchers believe to reasonably reflect the overall trend in the ward from limited accounts by nurses and spot observations of the exterior elevations (see Table 2).

Experiments have shown that the largest difference between measured data and predictions

occur during periods of high solar radiation intensity (solar gain) and high airflow rate. The deviations during high solar radiation intensity could be attributed to the weather file used for the simulation i.e. in real situation; solar radiation intensity could have been less than that in the constructed Bedford simulation weather file. The model takes into account shading by the building to the west but not winter morning

**Table 5.** Comparison of measured and predicted results of three monitored spaces for the calibration period.

Space reference		Max. temp (°C)	Min. temp (°C)	Mean night time temp (°C)	HTM03:	CIBSE:	BSEN15251:	BSEN15251:
					total hours over 28°C	Nightt ime hours over 26°C	total hours above Cat I upper limit	total hours above Cat II upper limit
AR1-EX	Measured	29.3	20.8	24.3	60	NA	745	321
	Predicted	29.4	20.7	24.5	25	NA	535	165
AR3-DR	Measured	29.9	18.2	24.7	3	81	598	114
	Predicted	28.2	22.2	24.5	4	0	443	111

Note: Calibration period for AR1-EX and AR2-MB is 1st July to 30th September 2010. Calibration period for AR3-DR is 27th July to 30th September 2010. On most occasions predicted nighttime value for AR3-DR is marginally below 26°C.

shading from the east. Overall, the deviations of the predicted temperatures during high solar radiation intensity are not significant. The model-predicted temperatures were not very sensitive to the prevailing mechanical ventilation rate, but were sensitive to high natural ventilation rates via windows.

The predicted maximum temperatures of all the spaces were in reasonable agreement with the measured values (Table 5). In overheating studies, the reliable prediction of peak temperatures is important and any deviation should not exceed 2°C. In this context, the model could be considered reliable.<sup>21</sup>

The mean nighttime temperature shows a good agreement with the measured values for both the spaces (Table 5). The deviation in HTM03 value is slightly high in AR1-EX. This is largely due to limitations in the schedules.

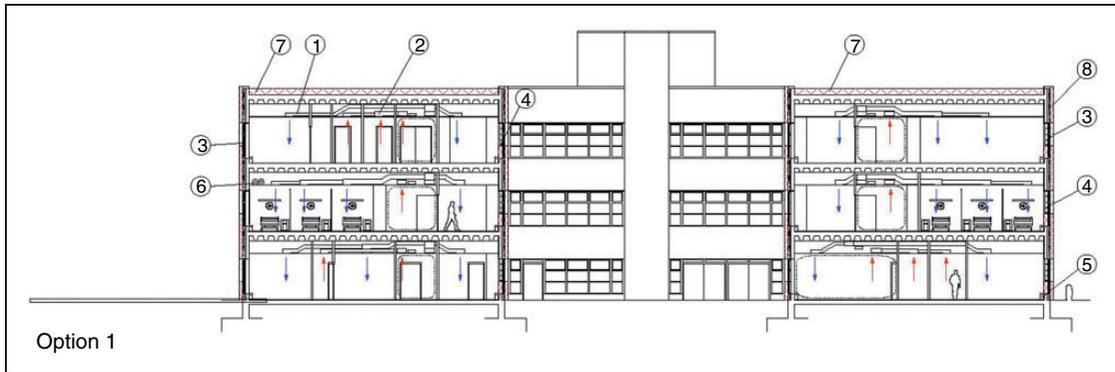
The NHS annual Heatwave Plan, released when DH determines external temperatures have reached a predetermined limit. The criterion for implementation varies across the country, being higher in the southeast to acknowledge adaptation to the prevailing heat island. The effectiveness of what are emergency short-term measures has been found to be affected by behaviours and understanding.<sup>22</sup> The building clearly requires longer term intervention to deliver greater resilience to current and future summertime overheating.

#### Four adaptation refurbishment options

Schemes to deliver greater resilience to hot summers were devised, commencing with what appears to have become the ‘enlightened’ industry standard ‘Passivhaus’ model adapted to the scale of the nondomestic building, a superinsulated envelope coupled with a rigorously controlled mechanical ventilation regime with efficient heat recovery, through lower technology, perhaps more conventional, cross-ventilated schemes to atrium-type solutions providing an air supply winter garden and in the final option, a relatively very low energy form of gravity-driven cooling.

Option 1, SMVHC: sealed mechanical ventilation heating and cooling (see Figures 9 and 10), proposes all glazing is sealed, airtightness improved as far as practicable, 100 mm insulation added to the roof and, through an overcladding insulation and render system, to the external walls. Mechanical ventilation is operated to achieve the unqualified DH recommendation of 6 ach with 60% heat recovery. Figure 10 shows the basic duct layout. Air cannot be recirculated within UK hospital wards.

Option 2, NCVPH: natural cross-ventilation retaining perimeter heating (Figures 11 and 12), reintroduces natural ventilation as the primary



**Figure 10.** Option 1 basic mechanical ventilation arrangement.

ventilation strategy. This follows DH best practice guidance:

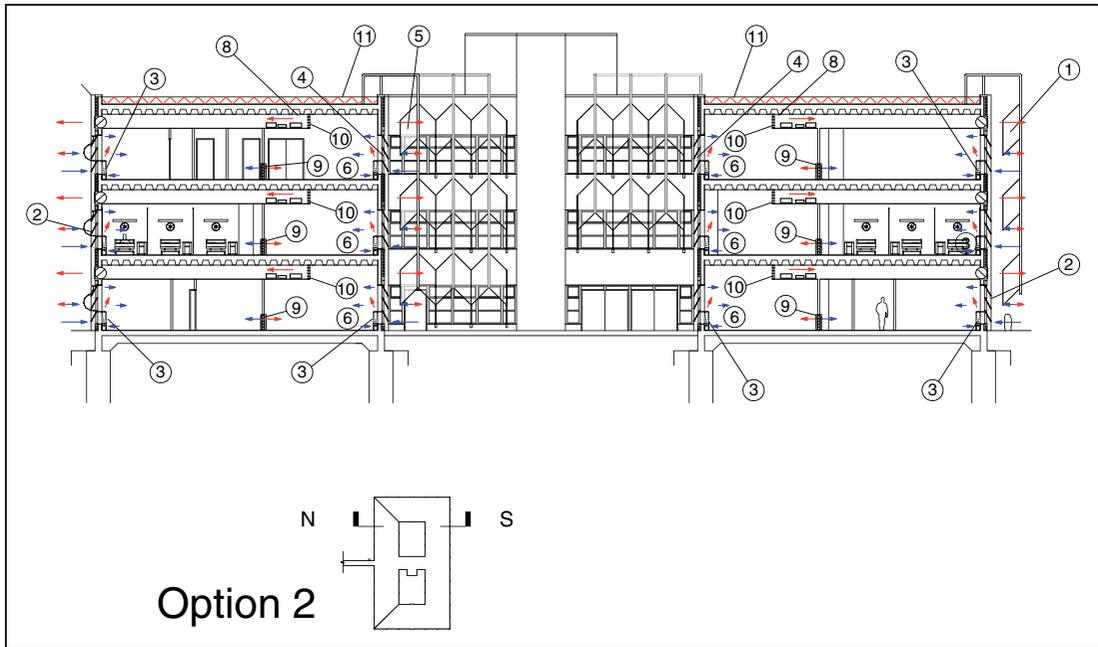
HTM 09-02 para 10.15 'Natural ventilation of rooms should be employed wherever possible and appropriate. Design should incorporate measures for minimizing solar heat gains, which, if controlled, will avoid the need for mechanical ventilation. Measures to minimize the need for cooling should include locating temperature-sensitive accommodation away from south-facing fascias, shading windows, and using reflecting glass where appropriate and cost-effective'.<sup>23</sup> Para 10.16 suggests, tentatively, the potential benefit of passive nighttime cooling.

This option proposes that the roof is insulated further, all glazing to South, Southwesterly and Southeasterly elevations are shaded externally to eliminate direct summer solar gains to reduce the scale of the cooling problem, but preserving bedhead level views out from the wards, all glazed panels to open to 45° with the addition of panels below existing cill lines, all applying to glazing to the courtyard elevations within. Again this is in line with current DH guidance. HTM 07-02 para 4.61 (p. 46) promotes 'passive solar design', to 'use the available daylight to its full extent' with provisos to avoid overheating and glare.<sup>24</sup> It cautions that in the modern

hospital setting, internal heat gains from activity and ever-increasing medical equipment may preclude passive solar design.

Spaces adjacent to the courtyards are opened out by the removal of cellular offices to become patient day-spaces and encourage distributed cross-ventilation (Figure 12). Suspended ceilings are removed in these areas to reveal concrete soffits to capture 'coolth' from cross-ventilation from the shaded courtyards, transfer grilles and ducts, as judged by cross-infection risk, connect these inboard spaces to the perimeter.

Option 3, ANCSVPH: Advanced Natural Cooling Summer Ventilation (see Figure 13) through glazed atria and retaining perimeter heating pursues a natural ventilation strategy and proposes the enclosure of both courtyards with glazed roofs. These become unheated atria with liberal opening areas above to dissipate summer solar gains and below slab air supply via concrete ducts offering a measure of ground cooling. All glazing to the atria becomes operable to 45°. In winter mode, air is admitted through damper-controlled perimeter heating units. Transfer ducts exhaust air from zones adjacent to the atria and again hung ceilings are cut back to expose thermal mass. External window guards deliver DH safety policy and all vulnerable glazing is shielded from direct summer solar gains. The option is capable of further refinement by incorporating winter heat recovery at the atrium head.

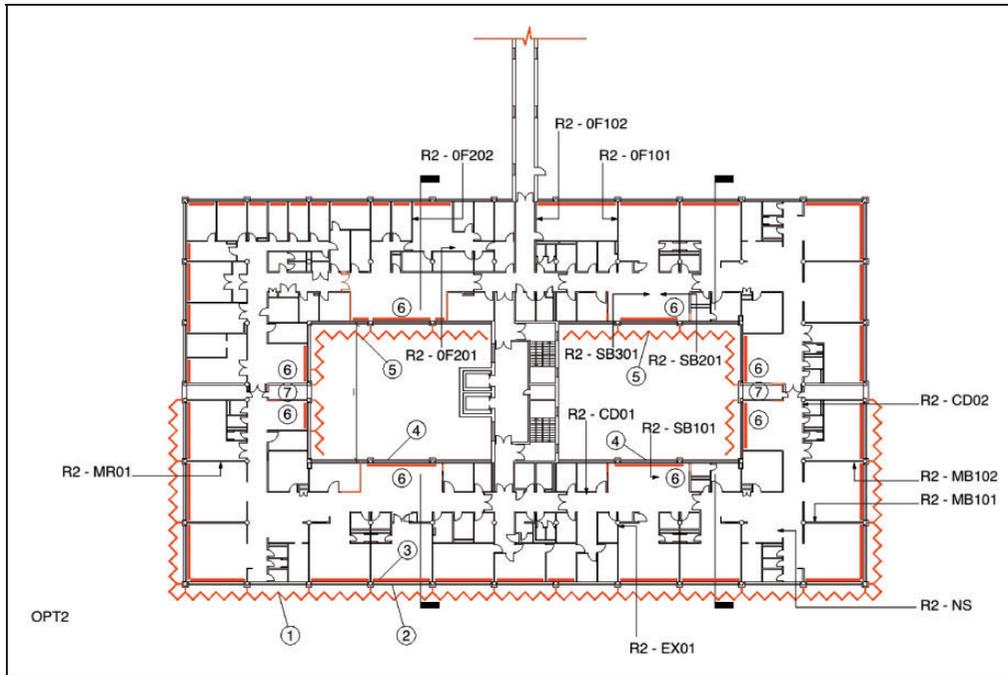


**Figure 11.** Natural cross-ventilation perimeter heating option 2 NCVH.

1. External sunshading applied to south, southeast, southwest elevations. Wing geometry of shade designed to maximise view to upper sky, in translucent coloured material.
2. Existing timber window units, currently four upper panels open, restricted to 100 mm. All eight glazed panels made openable to 45° with window guards to fulfill NHS safety regulations. Lower opaque elements to open to admit air across perimeter heating units.
3. Perimeter heating below glazing.
4. Courtyard glazing units: all glazed panels opening to 45° protected by window guards.
5. Sunshading as (1) applied to southwest and southeast elevations.
6. Cellular rooms to centre of each elevation to courtyards removed to open circulation areas directly to courtyard fresh air supply, become patient day areas.
7. Service risers maintained.
8. Suspended lightweight ceiling removed to expose concrete waffle slab.
9. Transfer grilles enable fresh air from courtyards to cross-sections.
10. Transfer ducts within suspended ceiling exhaust opened courtyard patient areas.
11. Additional 100 mm extruded polystyrene added to roof.

Option 4, NVPDCPH: natural ventilation incorporating passive draught cooling and perimeter heating (PDC) (see Figure 14) also proposes the enclosure of the courtyards but in a more active way, developing the low-energy cooling strategy of the UCL School of Slavonic and East European Studies SSEES building in Central London.<sup>25</sup> Cooled water

batteries at high-level openings induce a downward flow of precooled air which is contained by a lightweight, acoustically absorbent, fabric shroud. The cooled air is then drawn across surrounding occupied spaces. The diagram suggests ground-sourced cooling supplements the action of the PDC by utilising thermal storage, shown as readily available water



**Figure 12.** Opening up of plan areas adjacent to courtyards to enhance cross-ventilation.

tanks, crossing the seasons so that heat gained from summer hot spells is dissipated in winter and winter coolth utilised in summer. Banks of passive solar water heaters on the roof of each PDC rooflight supplement warming of winter supply tanks. Recovered heat from all sources is gathered in winter to supplement the supply to the perimeter heating system. Air is permitted to circulate within the twin summer and winter storage chambers to a predetermined regime.

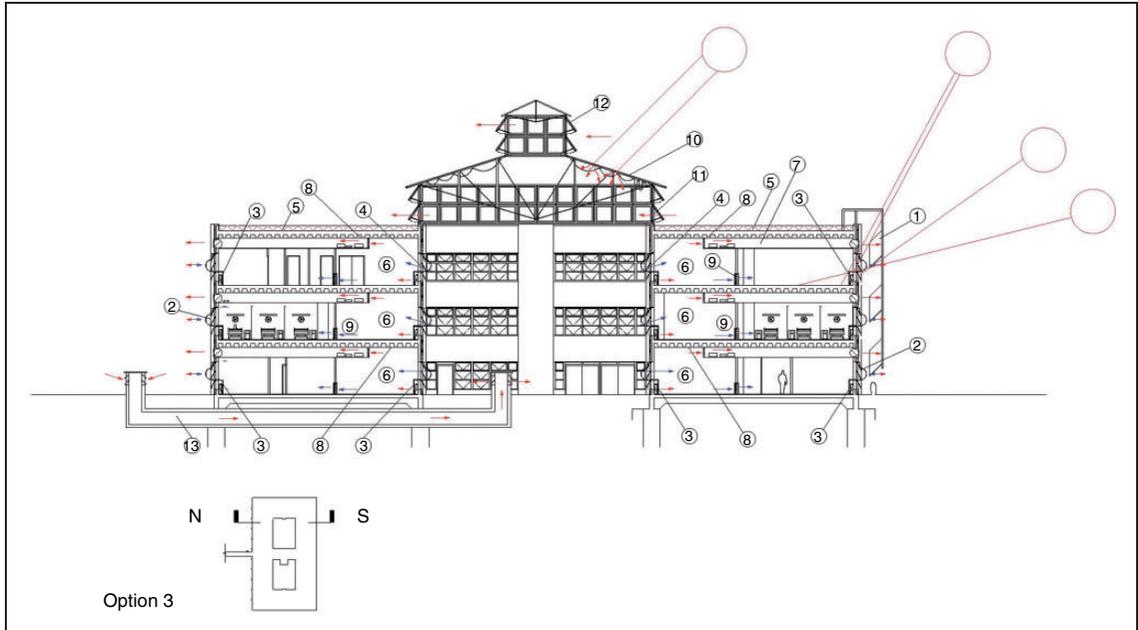
### **Predictions: Performance, energy consumptions and CO<sub>2</sub> emissions**

Predictions focus on AR1-EX, AR2-SB2 and AR3-DR for the building in its existing condition and the four adaptation scenarios. As per 2010 summer predictions, only AR3-DR exceeded the HTM03 1%/28°C threshold substantially, while all three spaces

exceeded BSEN15251 CAT 1 significantly (Table 6).

However, on most occasions AR3-DR only marginally crossed the 28°C threshold. During nighttime, both AR2-SB2 and AR3-DR exceeded the CIBSE criterion. Table 7, in summary, reveals that in typical years, both current and future TRYs, Option 1 generates the lowest 'overheating' performance in all three spaces, it incorporates mechanical cooling, while the existing building exhibited the worst performance.

In general, all three spaces under all four options met the HTM03 threshold for current as well as for future years except for AR3-DR under option-2. However, the deviation is only marginal. Further, three of the four spaces met BSEN15251 Cat I and II under all four options. Similarly, AR2-MB2 and AR3-DR met the CIBSE nighttime criterion as well.



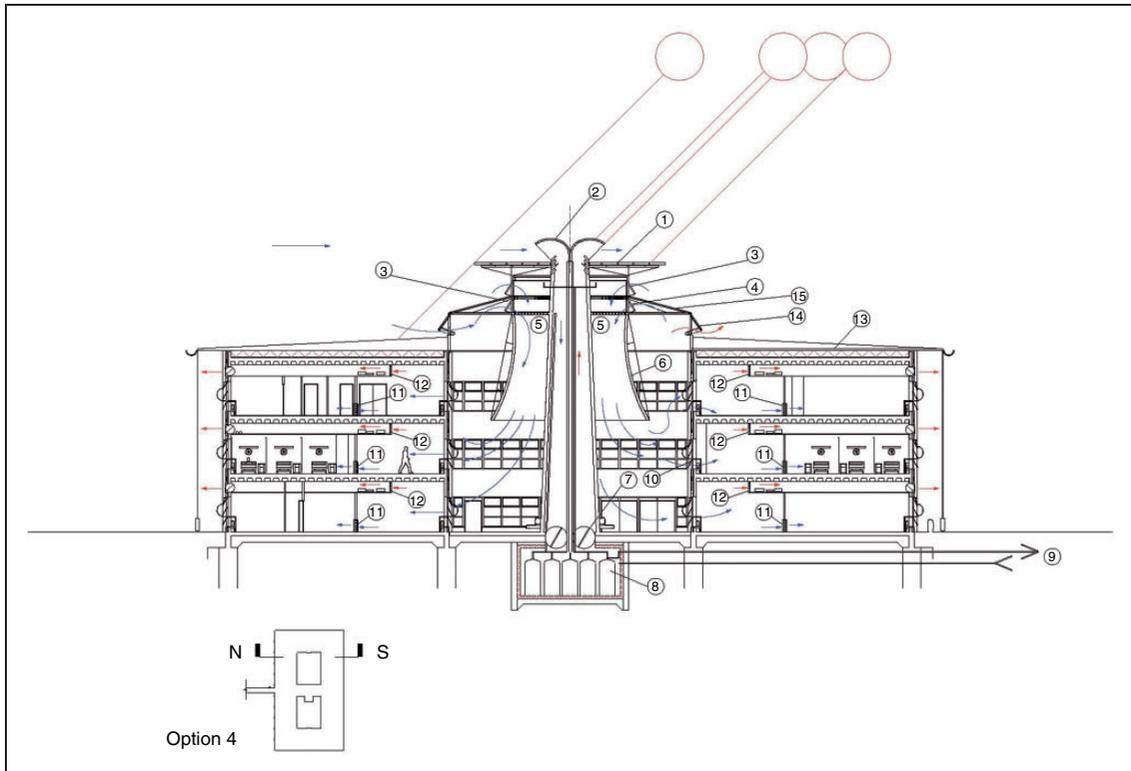
**Figure 13.** Option 3.

1. External sunshading applied to south, southeast, southwest elevations. Geometry of shade designed to maximise view to upper sky, in translucent coloured material.
2. Existing window units, currently four upper panels open, restricted to 100 mm. All eight glazed panels made openable to 45° with window guards to fulfill NHS safety regulations. Lower opaque elements to open to admit air across perimeter heating units.
3. Perimeter heating below glazing.
4. Courtyard glazing units: all glazed panels opening to 45° protected by window guards.
5. Additional 100 mm extruded polystyrene insulation added to roof.
6. Cellular rooms to centre of each elevation to courtyards removed to open circulation areas directly to courtyard fresh air supply, become patient day areas.
7. Transfer ducts exhaust inboard spaces (6) to exterior.
8. Suspended lightweight ceiling removed to expose concrete waffle slab.
9. Transfer grills admit supply air from enclosed courtyard to wards.
10. Lightweight steel framed double glazed roof across internal courtyards with actuated fabric awnings to exclude direct sunlight in overheating season.
11. Low-level actuated vents cross vent 'atrium', perform as smoke vents.
12. High-level lantern vents summer heat gains from upper part of atrium.
13. Low-level supply to atrium formed in spun concrete pipework.

During extreme years, DSY's Option 1 projected the best performance in all three spaces, while the existing building exhibits the worst performance (Table 7). For the current DSY extreme conditions, all four options broadly met the HTM03 1%/28°C while for the 2030's

Options 2–4 exceeded the HTM03 criterion. Further, during the nighttime options 2–4 room, AR2-MB2 only marginally exceeded the CIBSE criterion.

However, improved performance is achieved at a cost. Although the existing



**Figure 14.** Option 4 passive downdraught cooling PDC.

1. Solar water heating panels supply 'winter' tanks below courtyard.
2. Wind-catchers flush thermal storage chambers as required.
3. Opening glazed vents to exterior supply cooling batteries (5).
4. Internal opening glazed vents allow recirculation.
5. PDC cooling batteries.
6. Cone of acoustic absorbent material on light frame to direct PDC air flow.
7. Vent connects cooled water tanks chamber to external environment as required.
8. Cooled and warmed water tank enclosures formed below courtyard.
9. Flow and return to geothermal array via horizontal pipe to field or borehole.
10. Air admitted through opening vents in each bay of elevation.
11. Transfer ducts through outer corridor partitions.
12. Exhaust ducts connect courtyard-facing spaces to outer envelope.
13. Lightweight insulation on roof.
14. High-level vents to flush upper part of courtyard when PDC not engaged.
15. Glazed roof with retractable shading.

building, unaltered, has the worst thermal performance, it has the lowest energy consumption, see Figure 15, and the lowest CO<sub>2</sub> emissions, see Figure 16.

The highest energy consumption and CO<sub>2</sub> emissions are found in options 1 and 4, respectively. Options 1–3 were within the NHS refurbishment energy benchmark, while

**Table 6.** Summary of predicted performance during the summer of 2010: Three selected spaces.

Space reference	Max. temp (°C)	Min. temp (°C)	Mean night time temp (°C)	HTM03: total hours over 28°C	CIBSE: nighttime hours over 26°C	BSEN15251: Total hours above Cat I upper limit	BSEN15251: Total hours above Cat II upper limit
AR1-EX	29.6	21.5	24.3	39	NA	980	342
AR2-MB2	28.9	23.2	24.8	48	81	1324	548
AR3-DR	31.6	22.4	24.7	174	52	1159	541

Note: The HTM03 threshold is based on dry bulb temperature and rest are based on dry resultant temperature. CIBSE nighttime condition is not applicable to nurse station and corridors since there is no provision for sleeping. BSEN15251 conditions are applicable only to spaces with operable windows. It is assumed that during the period of October to April the spaces will not overheat due to elevated ambient temperature and solar gains. Therefore, the limiting overheating values are: HTM03, 50 h over 28°C; BSEN15251, 438 h above category upper threshold and CIBSE, 37 nighttime hours over 26°C.

option 4 marginally exceeded. However, all four options were within the CIBSE threshold of 28°C.

### Costs of implementing the four options

Davis Langdon AECOM ('AECOM' is the registered company name of this international multi-disciplinary practice) undertook detailed elemental costings from drawings and specifications produced by Short and Associates Ltd. Architects. Table 8 shows that Options 1 and 2 do not add floor area to the existing building, but Options 3 and 4 do by enclosing the courtyards, albeit as unheated spaces. Option 2, embodying established sustainable refurbishment practice, is marginally more costly than the first sealed building/heat recovery option but value engineering may align these options more closely to approximate £1000/m<sup>2</sup>, at the lower end of current NHS refurbishment cost as experienced by DeDerHECC researchers and the extensive Davis Langdon database. In fact options 3 and 4, although of an order of magnitude greater initial capital cost, at £1500–1800/m<sup>2</sup> are also within the realm of current investment.

Table 9 explores particular elemental costs and assumptions by the cost consultant. Design risk and fee elements affect the end cost significantly. Design fees and design risk, a

contingency against late resolution of detail, for the as yet uncharted PDC option are double those for the familiar sealed building/heat recovery option. Demolition costs incurred in opening out the plan around the courtyards to promote through ventilation also slew the figures. Transfer ducts and grilles would be a considerably cheaper option. Ceiling costs also reflect the relative scale of internal rearrangement. Space heating and air treatment capital costs are judged to be broadly similar for options 1–3 and of an order of magnitude greater for the PDC scheme. However, running costs to deliver acceptable conditions will be very different as Figure 15 suggests, considerably higher than current cost for all four options, option 2 NCVPH being relatively the lowest at some twice the energy demand of the building as it exists.

### Discussion and conclusions

The existing building enjoys a relatively low energy and low carbon performance against the DH guidance benchmarks but at the cost of comfort, it is unable to shed heat so that internal temperatures reach 28°C in relatively mild external conditions. Night temperatures are consistently uncomfortable, 23.5–26°C, suggesting that simple measures against the recommended threshold may give an inadequate account, for example, one bedroom records 1992 h above

**Table 7.** Summary of predicted performance for current and future, test reference (TRY) and design summer (DSY) years: Three selected spaces.

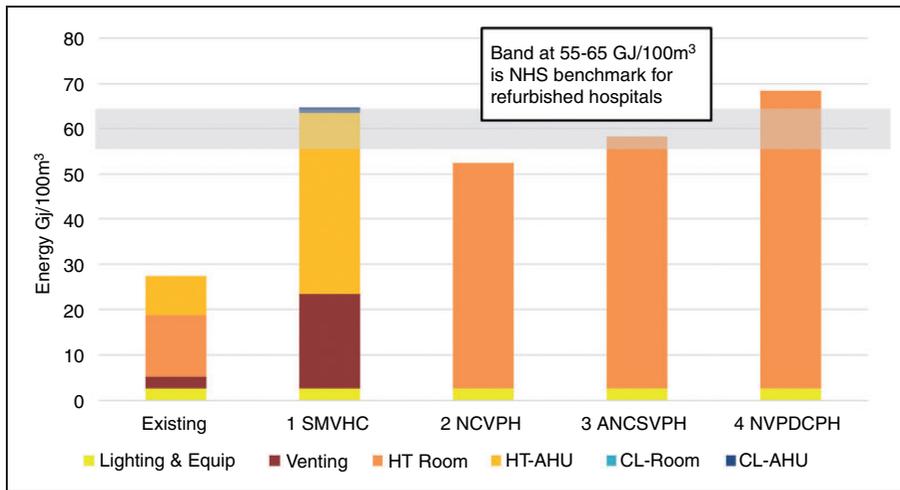
Scenario	Space reference	Year	Max. temp (°C)		Min. temp (°C)		Mean night time temp (°C)		HTM03: Total hours over 28°C		CIBSE: Night time hours over 26°C		BSENI5251: Total hours above Cat I upper limit		BSENI5251: Total hours above Cat II upper limit	
			TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY
Existing	ARI-EX	05	29.4	31.2	21.8	22.2	24.4	24.5	37	164	NA	NA	1117	1212	393	489
		30s	31.2	34.1	21.6	21.7	24.5	24.9	120	468	NA	NA	808	827	313	403
	AR2-MB2	05	28.9	31.1	23.2	23.2	24.8	25.1	34	225	60	186	1492	1614	620	726
		30s	31.4	22.5	34.0	22.8	25.1	25.9	195	706	219	555	1158	1209	447	589
	AR3-DR	05	32.5	32.6	23.5	23.6	24.7	24.9	198	315	49	130	1329	1438	611	670
30s		33.3	36.4	23.0	22.5	24.9	25.5	392	732	122	361	1082	1088	583	691	
Option 1: SMVHC	ARI-EX	05	28.1	28.2	20.4	20.4	22.2	22.3	0	0	NA	NA	NA	NA	NA	NA
		30s	27.8	27.9	20.3	21.4	22.3	22.5	0	0	NA	NA	NA	NA	NA	NA
	AR2-MB2	05	29.3	29.2	23.1	23.1	24.5	24.5	23	33	1	1	NA	NA	NA	NA
		30s	29.0	28.9	23.3	23.4	24.4	24.4	12	6	0	0	NA	NA	NA	NA
	AR3-DR	05	28.3	28.4	21.4	21.4	23.3	23.3	0	0	0	0	NA	NA	NA	NA
30s		28.2	28.3	21.6	22.0	23.3	23.3	0	0	0	0	NA	NA	NA	NA	
Option 2: NCVPH	ARI-EX	05	28.0	30.5	20.0	20.3	22.2	22.4	1	48	NA	NA	89	127	8	31
		30s	30.9	33.9	20.1	20.1	22.3	22.8	33	220	NA	NA	114	272	44	161
	AR2-MB2	05	27.9	30.5	20.6	20.6	22.8	23.0	1	55	0	15	117	164	8	33
		30s	31.0	33.5	20.5	20.6	23.1	23.8	40	245	5	54	128	304	49	183
	AR3-DR	05	28.4	30.4	20.6	20.6	22.6	22.8	4	67	0	7	128	197	36	71
30s		31.7	34.9	20.6	21.1	22.7	23.3	56	274	3	32	202	337	82	204	
Option 3: ANCSVPH	ARI-EX	05	28.3	30.8	19.7	20.0	22.1	22.3	2	37	NA	NA	61	118	4	29
		30s	28.5	33.1	19.8	19.7	22.2	22.6	11	112	NA	NA	63	185	22	78
	AR2-MB2	05	27.8	30.4	20.8	20.7	22.7	22.9	1	43	0	13	33	69	0	25
		30s	29.0	32.7	20.7	20.5	23.0	23.6	19	160	4	42	85	228	19	110
	AR3-DR	05	28.3	30.3	20.9	20.7	22.6	22.9	1	62	0	8	119	193	30	64
30s		31.4	34.3	20.6	21.0	22.8	23.4	42	250	3	36	188	317	68	180	
ARI-EX	05	05	28.1	30.5	21.3	20.9	22.9	23.0	1	20	NA	NA	191	205	43	56

(continued)

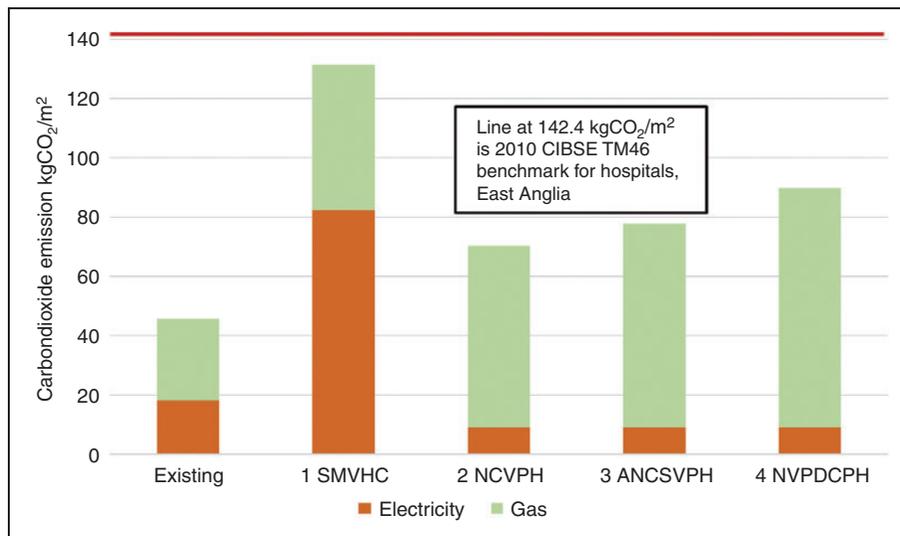
Table 7. Continued.

Scenario	Space reference	Year	Max. temp (°C)		Min. temp (°C)		Mean night time temp (°C)		HTM03: Total hours over 28°C		CIBSE: Night time hours over 26°C		BSEN15251: Total hours above Cat I upper limit		BSEN15251: Total hours above Cat II upper limit	
			TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY	TRY	DSY
Option 4: NVPDCPH	AR2-MB2	30s	28.2	31.0	21.0	21.1	22.9	23.1	3	29	NA	NA	100	51	28	14
		05	28.0	30.4	22.0	22.0	23.4	23.5	1	29	0	17	110	130	4	20
		30s	27.9	31.9	21.8	21.6	23.7	24.2	5	55	4	57	49	76	7	25
Option 4: NVPDCPH	AR3-DR	05	28.4	30.4	21.0	21.4	23.0	23.1	4	64	0	7	135	203	32	65
		30s	31.6	34.6	21.4	21.7	23.1	23.5	48	261	3	30	201	317	78	191

Note: SMVHC: heating and cooling through ventilation (6ach) with 60% heat recovery. NCVPH, natural cross-ventilation with perimeter heating; ANCSVPH, advanced natural ventilation through atrium with perimeter heating; NVPDCPH, natural ventilation with passive down draught cooling and perimeter heating. 05 and 30s represent 2005 (current) and 2030s, respectively. The HTM03 threshold is based on dry bulb temperature and rest are based on dry resultant temperature. CIBSE nighttime condition is not applicable to nurse station and examination room since there is no provision for sleeping in these spaces. BSEN15251 conditions are applicable only to spaces with operable windows. HTM03 standard not applicable for fans. Nighttime hours are 21:00 to 6:00. Simulated hours (3672) are for May to September. It is assumed that during the period of October to April, the spaces will not overheat due to elevated ambient temperature and solar gains. Therefore, the limiting overheating values are: HTM03, 50 h over 28°C; BSEN15251, 438 h above category upper threshold and CIBSE, 37 nighttime hours over 26°C. Unshaded values indicate that they are within the threshold limit, dark grey shade indicate that the exceedance is substantial and light grey shade indicates exceedance is minor.



**Figure 15.** Predicted energy demand for existing and refurbishment options for the year 2010, Cambridge (Bedford weather file). The energy values are average of AR1-EX, AR2-MB2 and AR3-DR.



**Figure 16.** Predicted CO<sub>2</sub> emissions for existing and refurbishment options for year 2010, Cambridge (Bedford weather file). The CO<sub>2</sub> values are average of AR1-EX, AR2-MB2 and AR3-DR.

25°C, 888 of which occur at night. In the 2030 DSY, the existing building has a nighttime mean temperature in excess of 25°C. The mechanical ventilation rate is too low. In most of the

bedrooms it does not even reach a minimum value of 10 litres per second per person (l/s/p).

Option 1 predicted that DSY peak temperatures oscillate around 28°C, additional cooling

**Table 8.** Comparative cost estimates overview as of July 2012, Davis Langdon AECOM Cost Report Rev. A.

Option	Area in m <sup>2</sup>	Cost £/m <sup>2</sup>	Total £sterling
1. SMVHC	8536	953.38	8,138,016
2. NCVPH	8536	1152.40	9,836,855
3. ANCSVPH	9324	1568.85	14,627,985
4. NVPDCPH	9324	1776.59	16,564,897

Note: SMVHC, sealed mechanical ventilation heating and cooling; NCVPH, natural cross-ventilation with perimeter heating; ANCSVPH, advanced natural ventilation through atrium with perimeter heating; NVPDCPH, natural ventilation with passive down drought cooling and perimeter heating.

**Table 9.** Comparative elemental cost breakdown by selected elements derived from Davis Langdon AECOM Cost Report Rev. A July 2012.

Option	Demolitions	Works to external envelope including roof	Space heating and air treatment	Works to ceilings	Allowance for design risk	Allowance for design fees
1. SMVHC	0	3.6 M	610 K	128 K	280 K	884.5 K
2. NCVPH	1.19 M	2.044 M	545 K	272 K	339 K	1.069 M
3. ANCSVPH	1.194 M	4.38 M	571 K	412 K	504 K	1.56 M
4. NVPDCPH	1.59 M	4.72 M	1.526	412 K	572 K	1.8 M

Note: SMVHC, sealed mechanical ventilation heating and cooling; NCVPH, natural cross-ventilation with perimeter heating; ANCSVPH, advanced natural ventilation through atrium with perimeter heating; NVPDCPH, natural ventilation with passive down drought cooling and perimeter heating.

capacity will be required, and will be increasingly necessary. Does the building have the capacity to accommodate it? Predicted energy demand is high and associated CO<sub>2</sub> emissions very high, 130 kgCO<sub>2</sub>/m<sup>2</sup> almost two-third resulting from its electrical demand which will, of course, rise as cooling capacity is increased, the 'worm in the bud' of this approach, it has no other means of defence. Option 2 peak DSY temperatures hover between 33.5 and 34.9°C, additional cooling will be required but night ventilation cooling, an obvious response, is wholly excluded by current practice. A peak of 31°C is predicted in TRY summer conditions. More research is required into the clinically safe night conditions in maternity wards. Could cooler temperatures be contemplated? Incubators in ICUs provide close environmental control for vulnerable infants. However, option

2 has the lowest energy penalty and markedly lower CO<sub>2</sub> emissions than option 1. Option 3 offers similar DSY peak conditions, but TRY peaks in line with current guidance. Predicted energy demand and CO<sub>2</sub> emissions are only marginally higher than option 2. Option 4 offers lower TRY and DSY peaks than options 2 and 3. In the natural and hybrid schemes, the unblocking of key plan areas to reduce resistance and enhance cross ventilation, especially adjacent to the courtyards, has the potential to reduce overheating substantially, but at an appreciable construction cost.

Avoiding the sealing of the building, the key characteristic of options 2–4, emerges as an important element in evolving a 'least regret' adaptation strategy for this building type. Option 1 emerges as requiring the lowest immediate capital investment but the additional

increment for option 2 may be delivered in cash releasing and other quantifiable savings. The carbon reduction commitment payment alone will contribute significantly as will a more rapid throughput of patients. However, even the almost wholly passive adaptation option is predicted to double existing energy consumption. The current DH EEF Scheme would not fund any of the options, the Treasury requires a return on investment of 2.4 within five years of implementation. This is potentially a huge barrier to achieving adaptation of the public non-domestic building stock, which is unfortunate given that the NHS Retained Estate would seem to be a particularly promising place to implement a public sector adaptation scheme.

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### Conflict of interests

None declared.

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11. *Note*: The recorded value approximates to air temperature, but must include an unknown radiant component. They were placed where permitted and so do not necessarily a spatial average temperature. The accuracy is  $\pm 0.35^\circ\text{C}$  from  $0^\circ$  to  $50^\circ\text{C}$ .
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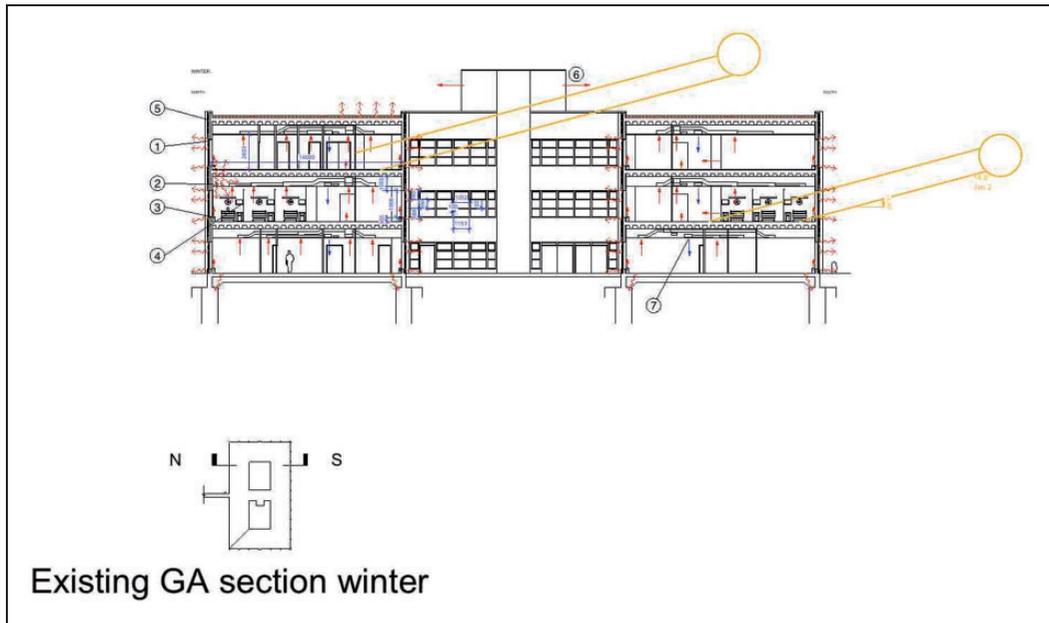
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## Corrigendum

Corrigendum for ‘A medium-rise 1970s maternity hospital in the east of England: Resilience and adaptation to climate change’ by C Alan Short, Giridharan Renganathan and Kevin J Lomas. *Building Services Engineering Research*

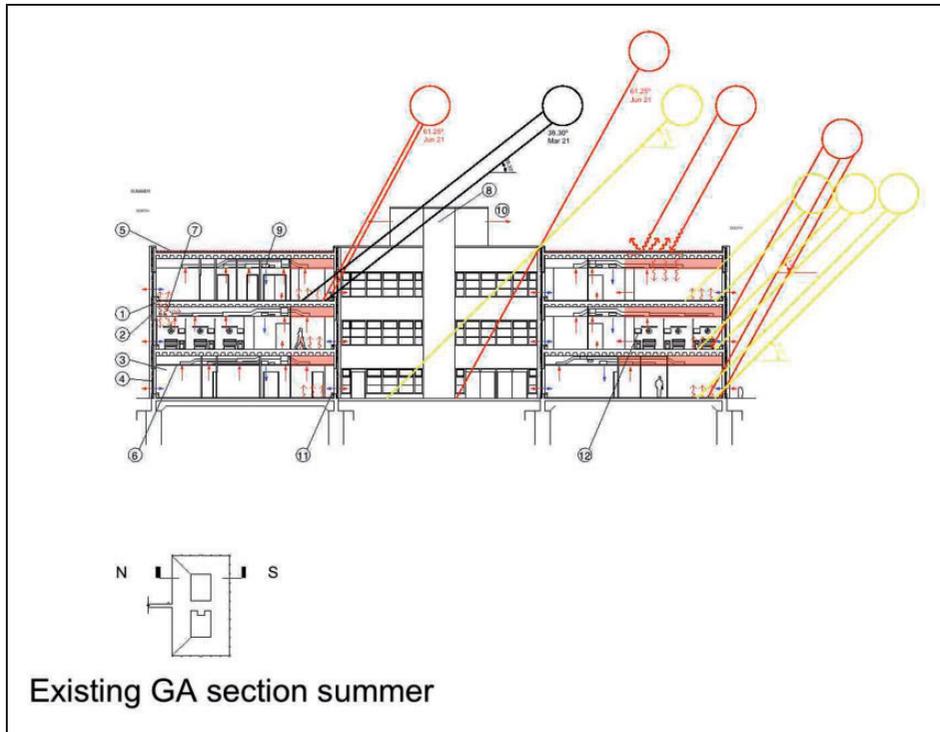
& *Technology* 36(2): 247–274. DOI: 10.1177/0143624414567544

In the above article, the Figure 4 and Figure 5 legends were printed incorrectly. The correct versions are printed below. The authors apologize for this error.



**Figure 4.** The Rosie Maternity Hospital, Addenbrookes, Cambridge Existing Building, Winter Condition.

1. Air leakage trough window frame.
2. Heat gains from uninsulated HW and particularly steam supply pipes.
3. Perimeter heating, HW supplied at 65 C.
4. Internal gains from lighting, bed lamp and TV.
5. Heat loss through poorly insulated fabric, essentially 50 mm polystyrene at wall and roof.
6. Warmed air exhausted at roof level.
7. Air supplied mechanically at 21 C+, mean target temperature 24–25° C.



**Figure 5.** The Rosie Maternity Hospital, Addenbrookes, Cambridge. Existing Building, Summer Condition.

1. Reinforced concrete frame: waffle slab 150 mm with 300 mm downstands, from inner leaf to external cavity wall above glazing spanning full structural bay.
2. External leaf of 100 mm brick, 50 mm polyurethane insulation in cavity, inner leaf 140 mm concrete blockwork. Occasionally steel stud and two layers plasterboard.
3. Nonstructural internal partitions vary: plasterboard on 100 mm softwood studwork or 140 mm concrete blockwork plastered both sides.
4. External windows double glazed in hardwood frames, mullions and transoms (75100 mm), opening lights restricted to 100 mm since late 1990s.
5. Roof: 150 mm RC slab, waffle 300 mm deep, 50 mm roof deck of prescreeded slabs with reinforced edges, asphalt, 50 mm extruded polystyrene 'Roofmate' held down by 50 mm of washed gravel.
6. Lightweight suspended gypsum ceiling tile grid.
7. Hot water (HW) pipes suspended within ceiling void, original insulation, some missing, water circulated at 55 or 60 C continuously to avoid bacterial growth.
8. Service riser to east and to west sides. Each connects to a plant room on ground floor (level 1) 3 AHU units in east, fresh air supply drawn down riser ducts from roof level.
9. Supply air, 2 AHU's heating, 1 AHU cooling per plant room. Unconditioned air supplied when external temperature below 22 C. Conditioned air delivered at 21 C through variable speed fan.
10. Exhaust air vented mechanically. No heat recovery.
11. Perimeter heating: thermostatic radiator valves recently installed (2011) supplied by HW at minimum 65 C. Target temperatures 24–25 C in all rooms–wards.
12. Internal gains: TV 2.2 w/m<sup>2</sup>; bed lamp 2.8 w/m<sup>2</sup>; general ceiling mounted lighting 3.3 w/m<sup>2</sup> as calculated for multibed ward.