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Low Energy Refurbishment Strategies for Health Buildings

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Low Energy Refurbishment Strategies for Health Buildings

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Public health buildings contribute significantly to UK carbon emissions. New build initiatives have received more attention than the considerable opportunities to reduce carbon emissions within the retained health estate. The research reported here has considered the environmental performance of a typical medium rise, medium depth, concrete-framed, late 1960s acute hospital following low energy environmental design interventions. The interventions are made to optimise daylighting and natural ventilation/cooling whilst reducing overheating caused by summertime solar gains. Three options are investigated: advanced natural ventilation using plena and exhaust stacks; fan-assisted natural ventilation, in which fans are used in the exhaust stacks; and mechanical ventilation/cooling with heat recovery. Computer simulations have been carried out to predict the influence on thermal performance (overheating risk) and energy consumption of each of these options on the original design. For each case, current weather data, and future weather data for years 2020, 2050 and 2080, have been used.

Keywords: hospital; refurbishment; natural ventilation; passive cooling; solar gain; simulation

1. Introduction

The Consultation Draft of the National Health Services (NHS) Carbon Reduction Strategy, drafted by the NHS Sustainable Development Unit (2008. pp.3-7) reveals that the “NHS in England is responsible for more than 18 million tonnes of carbon dioxide per annum”. This is about 3% of UK carbon dioxide emissions and 30% of public sector emissions, and costs approximately £429 million annually on heating and lighting alone. Mandatory climate change-related targets were introduced in 2001 by the Department of Health (Department of Health) for the NHS, as part of the response to the 2000 *Climate Change Programme* introduced in March 2000 wherein each Government department was required to identify targets to reduce carbon dioxide emissions (NHS Estate, 2004). As explained in *Health Technical Memorandum 07-02 EnCO₂de* (Department of Health, 2005.p. 3), NHS organizations in England are currently required to deliver efficiency savings of 15% energy or 0.15 MtC (million tonnes carbon) between March 2000 and March 2010. They are also committed to achieving a target of 35-55 GJ/100m³ energy performance for all new capital development and 55-65 GJ/100m³ for the refurbishment of existing facilities. The DH has reliable information (Estates Returns Information

Collection (ERIC), 2008a), on the energy performance of the Retained Estate recording a range of 70-125GJ/100m³, well above the current DH target. In 2004/05, the reported energy performance of the majority of NHS Trust acute hospitals in England was in the range of 44.8 to 98.0 GJ/100m³. The report “Statistics on energy performance and carbon and CO2 emissions” (Department of Health, 2006) estimates the lower and upper ranges of acute hospital energy consumption within the NHS Retained Estate in England in 2004/05 (Table 1). There is therefore an imperative to reduce energy use and, apparently, scope to do so. However, the Director of Estates and Facilities Management at the DH has commented

*‘no one knows how to achieve these targets in a health context, or if it is possible without compromising patient safety and well-being’.*¹

The NHS Trusts in England will now be required to further reduce their carbon footprint (NHS Sustainability Development Unit, 2008). It is proposed that “by 2009, all NHS organizations should set out ambitions, milestones and actions for carbon reduction across the areas of building energy use, travel, procurement, and waste in a Board approved Carbon Management Strategy”. An ambitious carbon reduction challenge set by this proposed strategy requires all new NHS facilities to be low carbon by 2015, and to meet the Government ambition for zero carbon, non- domestic buildings by 2018 (Ibid. pp.13, 16).

Around 44% of the energy used in a typical hospital is for air and space heating (Department of Health, 2005). Another 13% is consumed by fans. Thus superficial consideration suggests that climatic warming may reduce energy consumption. However, very little of the Retained Estate is air-conditioned, and in the poorly insulated, often over-glazed stock, an increased incidence of summer time overheating is a very real risk.

¹ Comment to Healthcare Sector Board, (01/05/2008) Modern Built Environment (MBE) Knowledge Transfer Network (KTN)

Such overheating can have serious consequences as healthcare buildings have a relatively high number of very heat-sensitive occupants unable to take adaptive action to keep cool. The Chief Medical Officer is clear in the Department of Health 2008 Heatwave Plan (Department of Health, 2008b): *‘During relatively mild heatwaves, excess death rates are significantly, but avoidably, higher in this country [UK]’*. The risk of future overheating is exacerbated by the increasing use of electrical equipment as a key component of care programmes, a trend that is likely to continue. Any move to use air-conditioning to combat these risks will add to the already high use of energy.

Although the NHS is attempting to meet its energy-related targets, recent evidence of NHS energy performance suggests that NHS organisations in *“both England and Wales are struggling to meet their energy-reduction targets and the 15 per cent emissions-reduction target is unlikely to be met”* (The NHS Confederation, 2007, p. 9). Statistics on NHS energy performance in England between 1999 and 2005 indicate that while energy is being used more efficiently within the NHS sector over this period, energy consumption has increased by 7 per cent to 44.8 million GJ (Department of Health, 2006). Over the same five year period, total carbon and CO2 emissions attributed to NHS Trusts in England also increased by 11%. The NHS had 14,040 sites in mid 2008 of which 21.7% of the buildings in use were constructed pre-1948, and 24.5% were built between 1948 and 1974. The ‘SHINE’ website (2009) reveals only 12 exemplar low energy NHS projects of which three are refurbishments. It has been suggested that, as a major contribution to achieving zero carbon regulated energy and occupant energy use by 2016, *“the refurbishment of the existing building stock is a further opportunity to improve the environmental sustainability of NHS buildings that should not be missed”* (Department of Health, 2008c).

Computer simulation programs are now used extensively to predict energy and thermal performance of building designs, especially in innovative designs for which the impact of design strategies such as solar shading, exposed thermal mass and night ventilation are difficult to quantify without the use of modelling. Previous applications of simulation to healthcare building design include the work of Narayan et al. (2006) who used Radiance and DOE2 to assess visual comfort, daylight penetration and the thermal comfort response to several design strategies for two healthcare projects. Miguet and Groleau (2002) used a newly developed simulation tool to investigate the daylight performance of a hospital near Paris. Their example illustrates the value of daylight modelling in providing “essential information to the architect”. Simulation has also been used to model the performance of individual spaces within a healthcare facility. For example, Melhado et al. (2005) used dynamic thermal simulation to compare the energy and thermal performance of three operating room layouts.

The work reported in this paper was part of a National Institute for Health Research (NIHR) funded project which investigated the opportunities for reducing NHS energy consumption apparently available in the refurbishment of the existing stock. This paper focuses on Northwick Park Hospital in west London, a representative concrete frame, lightweight clad, medium rise, medium depth hospital. The building lies within, but towards the perimeter of, the London heat island (Watkins *et al*, 2002) putting it at greater risk of overheating during summer periods due to the reduced cooling potential of night time ventilation. This paper shows how computer simulation was used to assess the relative impact on thermal, energy and daylight performance of three proposed refurbishment options.

2. The Maternity Wing at Northwick Park Hospital

Most (97%) of the buildings constructed on the Northwick Park site were constructed between 1965 and 1974². Data collected from all healthcare trusts in England show that 14% of the (whole) estate was constructed during the same period as Northwick Park (between 1965 -1974)². Northwick Park Hospital, designed in 1962/63 is therefore considered typical of highly glazed, concrete constructions of that era (figures 1 and 2). The concrete mullions visible in figure 2, were intended to control glare at critical points in the interior of the building by clustering them at some points more closely than at others but this was abandoned in favour of representing a vertical gathering of structural forces, floor by floor. The impact of these external concrete fins on solar gains is analysed in the paper. A band of clerestory windows, some opening, sit above sliding sash windows. Below the cill line are aluminium-faced spandrel panels. Over half the elevation is clear single glazing.

The work reported in this paper has focused on the maternity wing, located in the north-west corner of the site. The environmental characteristics of the maternity wing, in its as-built condition, are summarised in figures 3 and 4. The summer condition (Figure 3) shows the building to be subject to direct solar gain through single glazing, and by conduction through the fabric, the concrete is largely un-insulated. The potential to exploit the structural mass to achieve night ventilation cooling is reduced by the lack of a controlled ventilation strategy. Lightweight ceilings shield the slabs from occupants. Internal occupant and equipment gains are considerably higher than envisaged 40 years ago and lighting fixtures and hot water pipes contribute to internal gains.

The winter condition (Figure 4) reveals the likelihood of prodigious heat losses due to lack of insulation and infiltration losses through the ill-fitting glazing and cladding. Winter solar gains and glare are apparent on winter days behind south, west and east

² private correspondence S. Wright, Estates and Facilities Division, Department of Health

elevations. Internal blinds are in widespread use, reducing daylighting effectiveness and single glazing induces cold downdraughts.

3. As-built Performance

3.1 Daylight and Solar Modelling

An advanced simulation package TownScope (2004) was used to simulate the solar gain distribution for a simple flat facade model and a facade model which included the contribution of the existing external concrete framing. The development of this tool by the University of Liege under the sponsorship of the European Commission was part of a research programme on urban renewable (Azar, 2004; Teller and Azar, 2001).

TownScope is currently a well established software package in the research community and has already been used for many projects (e.g. Cremasco and Dupagne, 1999; Teller, 2002; Littlefair et al 2000, Al-Maiyah and Elkadi, 2007). The current version (TownScope v.3.0.1) can predict the three energy components of solar radiation as well as thermal comfort for any geographic location and sky conditions. In a recent study by Elkadi and Al-Maiyah (2007) the tool was also used to assess the impact of the change in the reflected energy of solar radiation on the visual experience of historic areas in both Edinburgh and Cairo. Validation exercises carried out using TownScope demonstrate its reliability in solar radiation assessment (Al-Maiyah, 2006).

In this study, to perform this first phase of simulation, appropriate photometric properties were assigned to the developed model(s) and detailed monthly climatic data for the cloud cover, diffused and direct solar energy and atmosphere turbidity. The three-dimensional models predicted the distribution of the direct, diffuse, reflected, and total solar radiation for all facades in mid June and December (e.g. Figure 5 shows results for the distribution of total solar radiation for the west facing elevation). The simple model

simulations show the full exposure of the largely glazed elevations. The projecting concrete frame and slabs form an egg-crate shading system, but the model reveals the interval between verticals and horizontals to be too great to protect the elevations adequately. For example, total incident energy at mid June on the west elevation, is reduced from 2,890 Wh/m² (simple model) to approximately 2,000 Wh/m² (as-built). The west-facing rooms are affected by reflected solar energy (approximately 320Wh/m²) in mid June due to the projecting wings either side. This is a function of the H plan geometry and is particularly significant on the first floor.

In temperate regions such as the UK, where overcast days occur for a significant proportion of the year, it is important to investigate the overcast sky luminance (Danny et al, 2004). However, in summer 2006 the UK has experienced noticeable changes in its climate with 12th July 06 being recorded the hottest day ever recorded in the UK and autumn 2006 was the hottest since 1659 (The Guardian, 2006). With the effects of climate change taking place, which is already having an influence on the global average surface temperature (IPCC, 2007), it was therefore appropriate to assess the daylighting performance of the existing envelope under clear sky as well as overcast conditions. Daylighting levels are therefore predicted under three sky conditions (CIE Sunny Sky, CIE Clear Sky without Sun and CIE Overcast Sky), for mid March, mid June and mid September at 9 am, 12 pm and 3 pm on each day. The daylighting performance behind the existing façade configuration for a south facing four-bed ward in March, June and September was investigated using a three-dimensional CAD model exported to the ADELIN (v.3) (Advanced Daylighting and Electric Lighting Integrated New Environment) simulation tool (2009). Selected results illustrating the daylighting performance are shown in Figure 6. Full results can be found in Table 2. In the case of the existing façade, the analysis shows that under the three sky conditions examined, south

facing wards tend to receive daylight levels significantly higher than the recommended illuminance levels (100 to 150 lux in bedded areas, CIBSE, 1989 and 100 lux general lighting in patient wards, CEN Standard, 2006). The analysis reveals that the building is highly over glazed, attracting prodigious solar gains in summer contributing to overheating. The result for the CIE Clear sky case, mid March at 3pm reveals illuminance levels of the order of 11,000 lux immediately behind the glazed elevation, whilst at the back of a four-bed ward of the order of 1,200 Lux, well above the recommended illuminance levels (CIBSE 1989 and CEN Standard 2006). This level of contrast is likely to induce the perception of gloominess within the ward and therefore the near-permanent use of artificial lighting which was observed by the authors on site visits.

3.2 Dynamic Thermal Simulation

The IES VE software (version 5.9.0, 2008) was used to carry out dynamic thermal modelling. Within IES VE, ApacheSim coupled with a network airflow model was used for thermal simulation. This is an established tool for analysing the dynamic behaviour of single spaces and whole buildings including heating demands, cooling loads, casual and solar gains. ApacheSim provides comprehensive predictions of indoor air temperatures, dry resultant temperatures, CO₂ concentrations and ventilation rates. The model used for analysis comprised 30 spaces selected to represent the wide range of space types and conditions present in the maternity wing. These were arranged to form a block of largely thermally disconnected spaces distributed over four storeys. The locations of the rooms modelled are shown in Figures 7a, 7b, 7c and 7d. The constructions used are given in Table 3 and the heat gains assumed in the model, taken from the DH Activity Database (2008d), are given in Table 3. Infiltration levels of 0.45 ac/h were assumed.

Three types of room were modelled for this case: (i) those where mechanical ventilation is used at all times because rooms are in the core of the building with no

access to perimeter ventilation openings or windows; (ii) those on the perimeter of the building where single-sided ventilation is used in winter and mechanical ventilation in summer; and (iii) those with high heat gains where mechanical ventilation and cooling is used at all times. Where cooling is used, the cooling set point used was 25.5°C. Where mechanical ventilation is used, a flow rate of 4 ach⁻¹ was modelled. The ventilation schemes used are summarised in Table 5.

Each version of the computer model was simulated using the current CIBSE (2005) Test Reference Year (TRY) data for London. The simulations were repeated using future weather data synthesised using the morphing algorithm developed by Hacker *et al* (2005). This uses past weather data to produce TRYs for 2020, 2050 and 2080. The effects of this morphing algorithm are shown in Figure 8.

Table 6 shows the predicted number of occupied hours when the air temperature exceeds 28°C, for each space modelled using the current building construction. HTM03-01 (2007) states that the air temperature in patient areas should not exceed 28°C for more than 50 occupied hours per year. Figures shown in red indicate the number of hours during which it is predicted that this will be exceeded.

When exposed to the 2005 climate the as-built building appears to be relatively resilient. However, by 2020 the simulations predicted the majority of occupied spaces will exceed 50 hours above 28°C. By 2050 almost all spaces are seriously overheating and by 2080 all are. The results therefore suggest that the as-built building has no short or medium term resilience.

4. Refurbishment strategy

Figure 9 depicts the existing elevation overclad. The existing glazing is removed and a new deep elevation used which incorporates significant glazing to upper floors. Solar shading is provided to the new windows by deep, canted reveals. A network of

interlocking air supply and exhaust ducts is threaded between these glazed element. Figure 9 also shows a lateral section through the depth of the proposed new façade revealing, in passive mode, the pattern of fresh air supply ducts, receiving air from intakes configured to sustain a positive pressure (as employed by the authors in the refurbishment of the Poole Arts Centre (XXX), and the exhaust ducts above connecting to a wind-resisting termination (a design also employed by the authors at Poole Arts Centre and Contact Theatre (Ibid). A fan is indicated at the base of the termination operated by a flow sensor to counteract the periodic tendency to downdraught. Intakes into each room are shown at low level and exhausts at high level which exploits the upward buoyancy forces in the space (Figure 10).

The refurbishment in Figure 9 indicates the availability of a mechanical mode, potentially required in the south of England and certainly within the London heat island (Watkins *et al*, 2002). The stack termination is sealed by dampers and exhaust air is drawn out of the collection plenum into a return duct behind the parapet connecting to a centralised air-handling unit, in which heat is received, and cooling provided. Supply air is ducted to the base of the supply stacks along the elevation.

This hybrid arrangement theoretically enables the building, or separate compartments, to cycle between natural and mechanical modes. The controls will be more complex than a single mode system but energy savings will be maximised, and the building will acquire greater resilience to the warming climate.

4.1 Daylight and Solar Modelling of the refurbishment strategy

Figure 11 shows the effect on solar gain on the west façade in mid-June and mid-December due to the imposition of the double façade. Not all glazing is shielded, particularly in December, but peak incident total solar gain of approximately 1,700 Wh/m² in a limited area of glazing is predicted in mid-June, a considerable reduction on

the existing gains (approximately 32% reduction relative to the existing gain of 2,500 Wh/m²). The distribution of daylighting across a south facing ward is also improved (c.f. figures 6 and 12, and tables 2 and 7). For example, for the CIE clear sky mid March case without sun, a maximum total illuminance of 7,400 lux is predicted at the window and 340 lux at the innermost corner of the ward. The modelling of the CIE sunny sky in June reveals a significant difference in terms of daylight distribution when compared with the existing case. Despite the usefulness of this shading strategy in reducing the undesired solar gain in summer, it is evident from the simulation modelling that the imposition of the double facade has also led to about 29 % - 36% reduction of useful winter gain (e.g. on a large area of glazing of the west elevation, total incident energy at mid December is reduced from 276 Wh/m² (as-built) to around 195 - 171Wh/m² (refurbishment scheme)). This is a design compromise due to the imposition of the ventilation stacks.

4.2 Thermal Performance of the refurbishment strategy in various operating modes

Table 8 summarises the constructions used in modelling the refurbishment configuration and Table 9 shows the heat gain assumptions based on data from the DH Activity Database (2008d). A reduced infiltration of 0.25ach⁻¹ was assumed.

The proposed refurbishment scheme considers the following three modes of operation for ventilation and cooling. The rooms to which these changes were applied are identified by the shading in Table 10.

The first mode of operation (case 2 in Table 10), referred to as ‘Advanced Natural Ventilation’ (ANV), uses natural buoyancy forces to draw in ambient air through a shared low-level plenum to the spaces to be ventilated and to drive stale warm air through high-level terminals via individual exhaust stacks built into the façade of the building. No fans or cooling are used in the refurbished zone for this mode.

The second mode of operation (case 3 in Table 10), referred to as ‘Fan-Assisted Natural Ventilation’ (FANV), uses fans to draw air out through the high-level terminals which enables air to flow in at low-level naturally.

The third mode of operation (case 4 in Table 10), referred to as ‘Shared Mechanical Ventilation with Shared Mechanical Cooling’ M1(V+C) uses mechanical ventilation equipment to supply conditioned air to the shared low-level plenum and extract warm stale air from the high-level shared exhaust plenum. This system includes a heat recovery system. The heating and cooling set points, which are based on the air temperature in the inlet plenum, are 20°C and 26°C respectively.

In all three refurbishment cases, the opening sizes are determined by the air temperature and CO₂ concentration in the room being served. The opening size is varied linearly from fully closed to fully open as the air temperature rises from 23°C to 25°C or the CO₂ concentration rises from 800 ppm to 2000 ppm. For the FANV and M1(V+C) modes a variable air volume system was modelled which used the temperature in the exhaust plenum as the parameter for determining the required flow rate.

Table 11 summarises results for the predominantly ANV operation of the proposal (case 2). All the ANV spaces are robust to the 28°C limit in 2020, most maintain 100 hours or less by 2050, but half exceed 50 hours, and by 2080 all overheat for considerable periods. The addition of fan assistance (Table 12) begins to increase resilience, especially on the third floor where buoyancy forces are smallest, so that by 2050 all ANV spaces remain below 28°C for under 100 hours. For case 4 (hybrid mechanical/natural ventilation strategy) all spaces were controlled to remain below 28°C.

Figures 13 and 14 show the predicted annual energy consumption for each variation of the computer model using current CIBSE weather data (2005) and future weather data for the years 2020, 2050 and 2080. In general there is a reduction in the

heating energy (gas) consumption as the construction is improved due to better insulation and improved air-tightness. However, these savings may be over-predicted due to simplifications in the thermal model whereby distribution heat losses were ignored. Overall, there is a saving of approximately 22% between the as-built case and case 4 (the hybrid case which was able to deliver thermal comfort for all future weather data). The result is an energy consumption prediction which is below current DH targets. Figure 14 shows the energy consumption by usage. Although the equipment energy usage was assumed to remain constant, it is likely that equipment will become more efficient in the future and that this will yield further reductions in total energy consumption. The amount of cooling increases from the current weather data through to 2080, although the increase for case 1 (300%) is greater than case 4 (270%) due to the hybrid nature of the ventilation and cooling system and the solar protection afforded by the refurbishment design. The corresponding carbon emissions savings between case 1 and case 4 are approximately 10% (Figure 15). This is less than the energy savings due to the higher carbon emissions associated with electrical energy use relative to gas usage.

5. Conclusions

The Northwick Park Maternity Wing is not atypical of medium rise buildings of the relatively recent past, comprising a heavy concrete frame and severely compromised by an almost all glazed, very lightweight envelope. A holistic approach to refurbishment is the most fruitful in which excessive solar gain and highly non-uniform daylighting can be corrected whilst the performance of the envelope is enhanced to reduce heat losses and gains. Once a level of airtightness is achieved, a more controlled ventilation strategy can be developed and the inherent structural mass employed to assist passive cooling. Natural buoyancy forces will drive airflows most of the time but it would be judicious to provide

fan assistance to ensure consistency of flows not least to mitigate airborne spread of infection.

The modelling has shown that the building as currently constructed and operated is likely to suffer over-heating in about one-in-five of the spaces modelled. In future years this problem is likely to increase significantly unless changes to the ventilation and cooling strategy are made.

Use of an Advanced Natural Ventilation system in which buoyancy forces are used to draw in fresh air through a shared low-level plenum with cross venting to exhaust stacks, shows a marked improvement in the thermal performance, to the extent that the system is likely to deliver acceptable performance for the 2020 climate data. Fan-assisted natural ventilation improves on this further but full mechanical cooling is required in order to eliminate over-heating completely.

Energy consumption figures for the refurbishment cases show an improvement of about 22% compared with the current building construction with very considerably improved comfort. In general, heating energy consumption reduces as the climate warms and cooling energy increases. It is likely that the energy consumed by equipment may also decrease in time as more energy-efficient systems become available. However, it was not possible to accurately model this effect in this work. There is an urgent need for the collection and analysis of field data in this regard.

The modelling work has shown how low energy building design principles which consider the fabric and form of the building can be used in refurbishment projects to deliver significant savings in energy in line with current DH targets. Further work could be carried out to improve the assumptions made in the dynamic thermal simulation models, although the predictions so far are encouraging. This work has also highlighted to

value of recently generated future TRY weather data for use in 'future proofing' building designs.

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Table 1. Estimated acute hospital energy consumption within the NHS retained estate (Department of Health, 2006)

Hospital Type	Location	Energy Consumption (GJ/100m ³)
Small Acute	within London	55.98-84.29
	outside London	61.06-75.08
Medium Acute	within London	54.47-66.02
	outside London	61.36-74.33
Large Acute	outside London	62.92-80.26
	within London	65.95-79.77
Acute Teaching	outside London	56.90-81.18
	within London	77.99-98.02
Acute specialist		54.84-66.02

Table 2. Daylight Analysis of as-built scheme (south facing room)

1		Sky model: CIE Clear Sky with Sun		
		Daylight distribution on the examined bed surface [klux]		
Simulation date/ time		Max daylight illuminance (direct + diffuse)	Min daylight illuminance (direct + diffuse)	Mean daylight illuminance (direct + diffuse)
March	9:00 AM	32.91	1.45	9.02
March	12:00 PM	53.47	3.02	21.88
March	3:00 PM	53.47	3.02	21.88
June	9:00 AM	34.74	1.69	6.1
June	12:00 PM	63.27	2.57	13.84
June	3:00 PM	35.74	1.64	6.11
September	9:00 AM	34.78	1.75	9.33
September	12:00 PM	53.47	3.28	18.78
September	3:00 PM	33.4	1.7	8.95
2		Sky model: CIE Clear Sky without Sun		
		Max daylight illuminance (diffuse)	Min daylight illuminance (diffuse)	Mean daylight illuminance (diffuse)
March	9:00 AM	7.65	0.75	2.67
March	12:00 PM	11.66	1.37	4.08
March	3:00 PM	8.55	0.81	2.94
June	9:00 AM	11.78	1.22	3.92
June	12:00 PM	16.56	1.7	5.4
June	3:00 PM	11.93	1.23	3.97
September	9:00 AM	12.87	1.24	4.41
September	12:00 PM	17.67	2.13	6.44
September	3:00 PM	12.56	1.21	4.3
3		Sky model: CIE Overcast Sky		
		Max daylight illuminance (diffuse)	Min daylight illuminance (diffuse)	Mean daylight illuminance (diffuse)
March	9:00 AM	2.61	0.23	0.81
March	12:00 PM	3.93	0.34	1.22
March	3:00 PM	2.88	0.25	0.89
June	9:00 AM	4.72	0.41	1.47
June	12:00 PM	5.84	0.51	1.81
June	3:00 PM	4.77	0.41	1.48
September	9:00 AM	3.29	0.28	1.02
September	12:00 PM	4.42	0.38	1.38
September	3:00 PM	3.22	0.28	1

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Table 3 Constructions used in the as-built dynamic thermal simulation

Element	Construction	U-value (W/m ² K)
External Walls	Cast Concrete 350mm Plaster 13mm	2.19
External Glazing	Clear Float Glass 4mm	5.53
Spandrel Panels	Aluminium 2mm Plywood 25mm	2.9
Internal Walls	Plaster 13mm Concrete Block 105mm Plaster 13mm	2.04
Internal Floor/Ceiling	Cast Concrete 400mm Cavity 340mm Ceiling Tiles 10mm	1.95
Flat Roof	Stone Chippings 10mm Felt/Bitumen Layers 5mm Cast Concrete 100mm Cavity 340mm Ceiling Tiles 10mm	1.63

Table 4 Heat gains used in the as-built dynamic thermal simulation

Space Name	Equip ment (W)	Day-time 08:00 to 20:00			Night-time 20:00 to 08:00		
		Lighting (W)	Occupancy (W)	Density (W/m ²)	Lighting (W)	Occupancy (W)	Density (W/m ²)
GF Consulting Room 1a	230	273	146	29	0	0	0
GF Consulting Room 1b	230	273	146	29	0	0	0
GF Consulting Room 2a	230	184	98	33	0	0	0
GF Consulting Room 2b	230	184	98	33	0	0	0
GF Consulting Room 3a	230	167	90	35	0	0	0
GF Consulting Room 3b	230	167	90	35	0	0	0
GF Corridor 1a	0	979	0	12	685	0	8
GF Corridor 1b	0	979	0	12	685	0	8
GF Toilets 1a	0	367	0	12	257	0	8
GF Toilets 1b	0	367	0	12	257	0	8
GF Treatment Room 1a	700	324	174	44	227	122	39
GF Treatment Room 1b	700	324	174	44	227	122	39
GF Ultrasound Room 1a	600	210	113	53	147	79	47
GF Ultrasound Room 1b	600	210	113	53	147	79	47
FF Four Bed Ward 1a	400	620	332	26	434	233	21
FF Four Bed Ward 1b	400	620	332	26	434	233	21
FF Four Bed Ward 2a	400	620	332	26	434	233	21
FF Four Bed Ward 2b	400	620	332	26	434	233	21
FF Four Bed Ward 3a	400	620	332	26	434	233	21
FF Four Bed Ward 3b	400	620	332	26	434	233	21
SF Delivery Room 1a	330	414	222	28	290	155	22
SF Delivery Room 1b	330	447	239	27	313	168	22
SF Four Bed Ward 1a	400	620	332	26	434	233	21
SF Four Bed Ward 1b	400	620	332	26	434	233	21
TF Four Bed Ward 1a	400	588	315	27	411	220	21
TF Four Bed Ward 1b	400	588	315	27	411	220	21
TF Four Bed Ward 2a	400	588	315	27	411	220	21
TF Four Bed Ward 2b	400	588	315	27	411	220	21
FF High Dependency 1a	5800	677	363	121	474	254	116
FF High Dependency 1b	5800	677	363	121	474	254	116

Table 5 Ventilation modes used in as-built dynamic thermal simulation model

Room	May to Sept	Oct to April
GF Consulting Room 1a	MV	SSV
GF Consulting Room 1b	MV	SSV
FF Four Bed Ward 1a	MV	SSV
FF Four Bed Ward 1b	MV	SSV
FF Four Bed Ward 2a	MV	SSV
FF Four Bed Ward 2b	MV	SSV
FF Four Bed Ward 3a	MV	SSV
FF Four Bed Ward 3b	MV	SSV
SF Delivery Room 1a	MV	MV
SF Delivery Room 1b	MV	MV
SF Four Bed Ward 1a	MV	SSV
SF Four Bed Ward 1b	MV	SSV
TF Four Bed Ward 1a	MV	SSV
TF Four Bed Ward 1b	MV	SSV
TF Four Bed Ward 2a	MV	SSV
TF Four Bed Ward 2b	MV	SSV
GF Consulting Room 2a	MV	SSV
GF Consulting Room 2b	MV	SSV
GF Consulting Room 3a	MV	SSV
GF Consulting Room 3b	MV	SSV
GF Corridor 1a	MV	MV
GF Corridor 1b	MV	MV
GF Toilets 1a	MV	MV
GF Toilets 1b	MV	MV
GF Treatment Room 1a	MV	MV
GF Treatment Room 1b	MV	MV
GF Ultrasound Room 1a	MV	MV
GF Ultrasound Room 1b	MV	MV
FF High Dependency 1a	M2(V+C)	M2(V+C)
FF High Dependency 1b	M2(V+C)	M2(V+C)

MV mechanical ventilation

SSV single-sided natural ventilation

M2(V+C) dedicated mechanical ventilation with mechanical cooling

Table 6 Thermal performance predictions for the as-built dynamic thermal simulation (without cooling)

Room	Hours over 28°C			
	2005	2020	2050	2080
GF Consulting Room 2a	11	48	186	344
GF Consulting Room 2b	14	54	193	348
GF Consulting Room 3a	15	48	155	262
GF Consulting Room 3b	14	73	211	344
GF Corridor 1a	0	0	19	120
GF Corridor 1b	0	0	19	120
GF Toilets 1a	0	0	23	129
GF Toilets 1b	2	3	33	178
GF Treatment Room 1a	32	69	212	562
GF Treatment Room 1b	32	72	224	584
GF Ultrasound Room 1a	54	107	311	812
GF Ultrasound Room 1b	54	107	311	812
GF Consulting Room 1a	48	188	350	588
GF Consulting Room 1b	13	79	247	420
FF Four Bed Ward 1a	104	291	502	927
FF Four Bed Ward 1b	39	150	313	710
FF Four Bed Ward 2a	93	278	482	890
FF Four Bed Ward 2b	38	141	300	689
FF Four Bed Ward 3a	37	108	235	470
FF Four Bed Ward 3b	30	80	181	381
SF Delivery Room 1a	52	149	310	689
SF Delivery Room 1b	24	71	207	525
SF Four Bed Ward 1a	89	270	471	877
SF Four Bed Ward 1b	38	142	300	685
TF Four Bed Ward 1a	38	120	247	477
TF Four Bed Ward 1b	38	115	231	480
TF Four Bed Ward 2a	49	151	255	472
TF Four Bed Ward 2b	32	94	202	400
FF High Dependency 1a	0	0	0	0
FF High Dependency 1b	0	0	0	0

Table 7. Daylight Analysis of refurbishment scheme (south facing room)

1	Sky model: CIE Clear Sky with Sun			
		Daylight distribution on the examined bed surface [klux]		
Simulation date/ time		Max daylight illuminance (direct + diffuse)	Min daylight illuminance (direct + diffuse)	Mean daylight illuminance (direct + diffuse)
March	9:00 AM	22.68	0.48	2.2
March	12:00 PM	50.53	1.07	7.06
March	3:00 PM	37.11	0.54	2.74
June	9:00 AM	7.15	0.49	1.54
June	12:00 PM	57.01	0.68	3.84
June	3:00 PM	8.49	0.48	1.52
September	9:00 AM	24.02	0.62	2.3
September	12:00 PM	48.54	1.15	7.55
September	3:00 PM	29.62	0.52	1.97
2	Sky model: CIE Clear Sky without Sun			
		Max daylight illuminance (diffuse)	Min daylight illuminance (diffuse)	Mean daylight illuminance (diffuse)
March	9:00 AM	4.5	0.26	0.96
March	12:00 PM	7.39	0.34	1.49
March	3:00 PM	6.62	0.25	0.99
June	9:00 AM	6.74	0.38	1.36
June	12:00 PM	10.38	0.47	1.83
June	3:00 PM	8.03	0.36	1.32
September	9:00 AM	7.62	0.42	1.56
September	12:00 PM	12.23	0.54	2.34
September	3:00 PM	9.72	0.38	1.44
3	Sky model: CIE Overcast Sky			
		Max daylight illuminance (diffuse)	Min daylight illuminance (diffuse)	Mean daylight illuminance (diffuse)
March	9:00 AM	1.53	0.08	0.27
March	12:00 PM	2.31	0.11	0.4
March	3:00 PM	1.69	0.08	0.3
June	9:00 AM	2.77	0.14	0.48
June	12:00 PM	3.43	0.17	0.6
June	3:00 PM	2.8	0.14	0.49
September	9:00 AM	1.93	0.1	0.34
September	12:00 PM	2.61	0.13	0.45
September	3:00 PM	1.89	0.09	0.33

Table 8 Constructions used in the refurbishment dynamic thermal simulation

Element	Construction	U-value (W/m ² K)
External Walls	Steel 3mm Polyurethane Board 75mm Plaster 13mm	0.31
External Glazing	Pilkington K Glass 6mm Cavity Clear Float Glass 6mm	1.95
Internal Walls	Plaster 13mm Concrete Block 105mm Plaster 13mm	2.04
Internal Floor/Ceiling	Cast Concrete 400mm	1.92
Flat Roof	Stone Chippings 10mm Felt/Bitumen Layers 5mm Fibreboard Insulation 150mm Cast Concrete 100mm	0.22

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Table 9 Heat gains used in the refurbishment dynamic thermal simulation

Space Name	Equip ment (W)	Day-time 08:00 To 20:00			Night-time 20:00 To 08:00		
		Lighting (W)	Occupancy (W)	Density (W/m ²)	Lighting (W)	Occupancy (W)	Density (W/m ²)
GF Consulting Room 2a	230	107	98	28	0	0	0
GF Consulting Room 2b	230	107	98	28	0	0	0
GF Consulting Room 3a	230	98	90	30	0	0	0
GF Consulting Room 3b	230	98	90	30	0	0	0
GF Corridor 1a	0	571	0	7	400	0	5
GF Corridor 1b	0	571	0	7	400	0	5
GF Toilets 1a	0	214	0	7	150	0	5
GF Toilets 1b	0	214	0	7	150	0	5
GF Treatment Room 1a	700	189	174	39	132	122	35
GF Treatment Room 1b	700	189	174	39	132	122	35
GF Ultrasound Room 1a	600	123	113	48	86	79	44
GF Ultrasound Room 1b	600	123	113	48	86	79	44
GF Consulting Room 1a	230	159	146	24	0	0	0
GF Consulting Room 1b	230	159	146	24	0	0	0
FF Four Bed Ward 1a	400	362	332	21	253	233	17
FF Four Bed Ward 1b	400	362	332	21	253	233	17
FF Four Bed Ward 2a	400	362	332	21	253	233	17
FF Four Bed Ward 2b	400	362	332	21	253	233	17
FF Four Bed Ward 3a	400	362	332	21	253	233	17
FF Four Bed Ward 3b	400	362	332	21	253	233	17
SF Delivery Room 1a	330	242	222	23	169	155	19
SF Delivery Room 1b	330	261	239	22	182	168	18
SF Four Bed Ward 1a	400	362	332	21	253	233	17
SF Four Bed Ward 1b	400	362	332	21	253	233	17
TF Four Bed Ward 1a	400	343	315	22	240	220	18
TF Four Bed Ward 1b	400	343	315	22	240	220	18
TF Four Bed Ward 2a	400	343	315	22	240	220	18
TF Four Bed Ward 2b	400	343	315	22	240	220	18
FF High Dependency 1a	5800	395	363	116	277	254	112
FF High Dependency 1b	5800	395	363	116	277	254	112

Table 10 Ventilation modes used in the refurbishment dynamic thermal simulation model

Room	Ventilation Scheme							
	As-built (Case 1)		Case 2		Case 3		Case 4	
	May to Sept	Oct to April	May to Sept	Oct to April	May to Sept	Oct to April	May to Sept	Oct to April
GF Consulting Room 1a	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
GF Consulting Room 1b	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
FF Four Bed Ward 1a	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
FF Four Bed Ward 1b	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
FF Four Bed Ward 2a	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
FF Four Bed Ward 2b	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
FF Four Bed Ward 3a	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
FF Four Bed Ward 3b	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
SF Delivery Room 1a	MV	MV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
SF Delivery Room 1b	MV	MV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
SF Four Bed Ward 1a	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
SF Four Bed Ward 1b	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
TF Four Bed Ward 1a	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
TF Four Bed Ward 1b	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
TF Four Bed Ward 2a	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
TF Four Bed Ward 2b	MV	SSV	ANV	ANV	FANV	FANV	M1(V+C)	M1(V+C)
GF Consulting Room 2a	MV	SSV	M2(V+C)	SSV	M2(V+C)	SSV	M2(V+C)	SSV
GF Consulting Room 2b	MV	SSV	M2(V+C)	SSV	M2(V+C)	SSV	M2(V+C)	SSV
GF Consulting Room 3a	MV	SSV	M2(V+C)	SSV	M2(V+C)	SSV	M2(V+C)	SSV
GF Consulting Room 3b	MV	SSV	M2(V+C)	SSV	M2(V+C)	SSV	M2(V+C)	SSV
GF Corridor 1a	MV	MV	M2(V+C)	MV	M2(V+C)	MV	M2(V+C)	MV
GF Corridor 1b	MV	MV	M2(V+C)	MV	M2(V+C)	MV	M2(V+C)	MV
GF Toilets 1a	MV	MV	M2(V+C)	MV	M2(V+C)	MV	M2(V+C)	MV
GF Toilets 1b	MV	MV	M2(V+C)	MV	M2(V+C)	MV	M2(V+C)	MV
GF Treatment Room 1a	MV	MV	M2(V+C)	MV	M2(V+C)	MV	M2(V+C)	MV
GF Treatment Room 1b	MV	MV	M2(V+C)	MV	M2(V+C)	MV	M2(V+C)	MV
GF Ultrasound Room 1a	MV	MV	M2(V+C)	MV	M2(V+C)	MV	M2(V+C)	MV
GF Ultrasound Room 1b	MV	MV	M2(V+C)	MV	M2(V+C)	MV	M2(V+C)	MV
FF High Dependency 1a	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)
FF High Dependency 1b	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)	M2(V+C)

MV mechanical ventilation

SSV single-sided natural ventilation

M2(V+C) dedicated mechanical ventilation with mechanical cooling

ANV advanced natural ventilation

FANV fan-assisted natural ventilation

M1(V+C) shared mechanical ventilation with shared mechanical cooling

Table 11 Thermal performance predictions for case 2 (ANV refurbishment)

Room	Hours over 28°C			
	2005	2020	2050	2080
GF Consulting Room 1a	6	2	28	109
GF Consulting Room 1b	4	2	27	100
FF Four Bed Ward 1a	35	13	43	284
FF Four Bed Ward 1b	31	12	40	258
FF Four Bed Ward 2a	36	13	47	293
FF Four Bed Ward 2b	32	12	40	267
FF Four Bed Ward 3a	39	19	60	312
FF Four Bed Ward 3b	37	14	55	285
SF Delivery Room 1a	45	17	83	444
SF Delivery Room 1b	40	12	72	421
SF Four Bed Ward 1a	37	13	52	314
SF Four Bed Ward 1b	34	12	46	291
TF Four Bed Ward 1a	46	24	117	458
TF Four Bed Ward 1b	44	23	108	449
TF Four Bed Ward 2a	45	24	117	454
TF Four Bed Ward 2b	43	23	105	437
GF Consulting Room 2a	0	0	0	0
GF Consulting Room 2b	0	0	0	0
GF Consulting Room 3a	4	0	0	0
GF Consulting Room 3b	15	0	0	0
GF Corridor 1a	0	0	0	0
GF Corridor 1b	0	0	0	0
GF Toilets 1a	0	0	0	0
GF Toilets 1b	0	0	0	0
GF Treatment Room 1a	0	0	0	0
GF Treatment Room 1b	0	0	0	0
GF Ultrasound Room 1a	0	0	0	0
GF Ultrasound Room 1b	0	0	0	0
FF High Dependency 1a	0	0	0	0
FF High Dependency 1b	0	0	0	0

Table 12 Thermal performance predictions for case 3 (FANV refurbishment)

Room	Hours over 28°C			
	2005	2020	2050	2080
GF Consulting Room 1a	0	2	38	142
GF Consulting Room 1b	0	0	25	123
FF Four Bed Ward 1a	0	9	44	282
FF Four Bed Ward 1b	0	9	46	287
FF Four Bed Ward 2a	0	9	46	286
FF Four Bed Ward 2b	0	9	48	290
FF Four Bed Ward 3a	5	14	61	313
FF Four Bed Ward 3b	4	19	93	490
SF Delivery Room 1a	0	11	60	415
SF Delivery Room 1b	0	13	67	439
SF Four Bed Ward 1a	0	9	46	301
SF Four Bed Ward 1b	0	9	52	305
TF Four Bed Ward 1a	8	19	81	406
TF Four Bed Ward 1b	8	20	84	447
TF Four Bed Ward 2a	8	19	75	404
TF Four Bed Ward 2b	8	22	87	438
GF Consulting Room 2a	0	0	0	0
GF Consulting Room 2b	0	0	0	0
GF Consulting Room 3a	0	0	0	0
GF Consulting Room 3b	0	0	0	0
GF Corridor 1a	0	0	0	0
GF Corridor 1b	0	0	0	0
GF Toilets 1a	0	0	0	0
GF Toilets 1b	0	0	0	0
GF Treatment Room 1a	0	0	0	0
GF Treatment Room 1b	0	0	0	0
GF Ultrasound Room 1a	0	0	0	0
GF Ultrasound Room 1b	0	0	0	0
FF High Dependency 1a	0	0	0	0
FF High Dependency 1b	0	0	0	0

Figure Captions

Figure 1. Maternity wing viewed from south-west showing entrance lobby and plant space on roof

Figure 2. Photograph showing main entrance and highly glazed elevation with concrete mullions

Figure 3. Section through maternity wing (as-built) showing environmental characteristics during summer time operation.

- (1) fabric heat losses/gains
- (2) lightweight surfaces
- (3) uncontrolled infiltration
- (4) direct solar gain through large areas of unshaded glazing
- (5) and (6) internal heat gains from patients, staff, equipment and lighting

Figure 4. Section through maternity wing (as-built) showing environmental characteristics during winter time operation.

- (1) poorly insulated roof slab radiates heat to night sky
- (2) heat loss through poorly insulated solid envelope, glazing and non-airtight construction
- (3) dry resultant temperature (operative temperature) is lower than air temperature due to cold surfaces
- (4) ill-fitting single glazing causes uncontrollable infiltration and cold downdraughts for patients
- (5) conductive heat losses through uninsulated ground floor slab
- (6) wind effects increase heat loss from building
- (7) glare from low-level sun results in use of blinds which reduces daylight resulting in greater use of artificial lighting
- (8) and (9) internal heat gains from patients, staff, equipment and lighting

Figure 5. Distribution of total solar irradiation on west facing elevation for mid June (top – simple model, bottom – building as-built).

Figure 6. Daylight model predictions for as-built construction (top left: model geometry, top right: mid March using CIE clear sky without sun, bottom left: mid June using CIE sunny sky, bottom right: mid December using CIE overcast sky).

Figure 7a. Ground floor plan showing rooms modelled in dynamic thermal simulation

Figure 7b. First floor plan showing rooms modelled in dynamic thermal simulation

Figure 7c. Second floor plan showing rooms modelled in dynamic thermal simulation

Figure 7d. Third floor plan showing rooms modelled in dynamic thermal simulation

Figure 8. Future temperatures predicted by morphing algorithm

Figure 9. Refurbishment proposal showing replacement of existing elevations.

- (1) H-pot terminal

- (2) Exhaust plenum
- (3) Windows shaded by being recessed in thick wall
- (4) Air inlet “ring” duct and mechanical supply
- (5) Passive air inlets
- (6) Air supply “drop” to ground floor
- (7) Control dampers
- (8) Mechanical extract fan with recirculation to central AHU
- (9) Vitiated air gathered in return air shaft and exhausted through heat exchanger
- (10) AHU with heat recovery
- (11) Mechanical supply of fresh air
- (12) Air exhausted through fan-assisted terminals in passive mode
- (13) Return shaft
- (14) Dedicated exhaust shaft
- (15) Supply shaft
- (16) Primary supply shaft
- (17) Air enters through control dampers in soffit

Figure 10. Refurbishment proposal showing ventilation strategy for a 4-bed ward

- (1) Modular low-level inlets
 - (2) Air exhaust bulkheads could be extended to provide separate exhaust openings closer to outer and inner beds
 - (3) Suspended ceiling removed in wards
- ME Mechanical extract
MS Balanced mechanical supply with heat recovery

Figure 11. Distribution of total solar irradiation on west facing elevation for refurbishment design (top – mid June, bottom – mid December).

Figure 12. Daylight model predictions for refurbishment construction (top left: model geometry, top right: mid March using CIE clear sky without sun, bottom left: mid June using CIE sunny sky, bottom right: mid December using CIE overcast sky).

Figure 13. Predicted total annual energy consumption (GJ/100m³ heated volume)

Figure 14. Predicted total annual energy consumption by usage (MWh)

Figure 15. Predicted carbon generated (tonnes CO₂)

Figure 1
209x297mm (600 x 600 DPI)

Figure 2
601x801mm (72 x 72 DPI)

Figure 3
209x297mm (600 x 600 DPI)

Figure 4
209x297mm (600 x 600 DPI)

Figure 5
146x182mm (300 x 300 DPI)

a. March / CIE Clear Sky without Sun

b. June / CIE Sunny Sky

c. December / CIE Overcast Sky

Figure 6
182x142mm (300 x 300 DPI)

Figure 7a
148x117mm (200 x 200 DPI)

Figure 7b
151x117mm (200 x 200 DPI)

Figure 7c
147x119mm (200 x 200 DPI)

Figure 7d
146x117mm (200 x 200 DPI)

Figure 8
249x151mm (600 x 600 DPI)

Figure 9
145x243mm (200 x 200 DPI)

Figure 10
209x297mm (600 x 600 DPI)

Figure 11
147x185mm (300 x 300 DPI)

Figure 12
182x145mm (300 x 300 DPI)

Figure 13
258x158mm (600 x 600 DPI)

Figure 14
258x158mm (600 x 600 DPI)

Figure 15
258x158mm (600 x 600 DPI)