

This article was downloaded by: [University of Leeds]

On: 15 July 2014, At: 05:56

Publisher: Routledge

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Building Research & Information

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/rbri20>

Functional recovery of a resilient hospital type

C. Alan Short^a, Catherine J. Noakes^b, Carl A. Gilkeson^c & Alistair Fair^d

^a Department of Architecture, University of Cambridge, 1-5 Scroope Terrace, Cambridge CB2 1PX, UK

^b Pathogen Control Engineering Institute, School of Civil Engineering, University of Leeds, Leeds, LS2 9JT UK E-mail:

^c School of Mechanical Engineering, Institute of Thermofluids, University of Leeds, Leeds, LS2 9JT UK E-mail:

^d Edinburgh School of Architecture and Landscape Architecture, University of Edinburgh, 20 Chambers Street, Edinburgh EH1 1JZ, UK E-mail:

Published online: 08 Jul 2014.

To cite this article: C. Alan Short, Catherine J. Noakes, Carl A. Gilkeson & Alistair Fair (2014): Functional recovery of a resilient hospital type, Building Research & Information, DOI: [10.1080/09613218.2014.926605](https://doi.org/10.1080/09613218.2014.926605)

To link to this article: <http://dx.doi.org/10.1080/09613218.2014.926605>

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Versions of published Taylor & Francis and Routledge Open articles and Taylor & Francis and Routledge Open Select articles posted to institutional or subject repositories or any other third-party website are without warranty from Taylor & Francis of any kind, either expressed or implied, including, but not limited to, warranties of merchantability, fitness for a particular purpose, or non-infringement. Any opinions and views expressed in this article are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor & Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Terms & Conditions of access and use can be found at <http://www.tandfonline.com/page/terms-and-conditions>

It is essential that you check the license status of any given Open and Open Select article to confirm conditions of access and use.

RESEARCH PAPER

Functional recovery of a resilient hospital type

C. Alan Short¹, Catherine J. Noakes², Carl A. Gilkeson³ and Alistair Fair⁴

¹Department of Architecture, University of Cambridge, 1-5 Scroope Terrace, Cambridge CB2 1PX, UK
E-mail: cas64@cam.ac.uk

²Pathogen Control Engineering Institute, School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK
E-mail: c.j.noakes@leeds.ac.uk

³School of Mechanical Engineering, Institute of Thermofluids, University of Leeds, Leeds LS2 9JT, UK
E-mail: c.a.gilkeson@leeds.ac.uk

⁴Edinburgh School of Architecture and Landscape Architecture, University of Edinburgh, 20 Chambers Street, Edinburgh EH1 1JZ, UK
E-mail: alistair.fair@ed.ac.uk

Four adaptation options for ‘Nightingale’-type hospital ward buildings devised with practising clinicians are presented and evaluated. The adaptations recover functionality in an archaic ward configuration by delivering care to current UK National Health Service (NHS) models whilst preserving resilience to summer overheating. The investigation builds on recent work that demonstrates the significant resilience to heatwaves enjoyed by such traditionally constructed communal dormitories, the dominant UK hospital type between the late 1850s and 1939. Nightingale wards are potentially well-ventilated naturally, with good dilution of airborne pathogens. Although condemned as outdated by health ministers in recent years, many remain in use. As financial retrenchment suggests economical, creative refurbishment of hospitals will be required rather than new-build and replacement, the authors argue for health estates’ strategies that place value on resilience in a changing climate. Proposed adaptation options are investigated to assess resulting internal airflows and patient exposure to airborne pathogens. Options are costed and payback periods calculated to the standard public sector methodology. The proposed adaptations save time and cost over new-build equivalents. Selection of the most appropriate option is dependent on the characteristics of the patient cohort and care required.

Keywords: adaptation, airborne infection, climate change, hospitals, overheating, refurbishment, resilience, ventilation

Introduction

In 2001 the UK government demanded that the National Health Service (NHS) abandon the traditional healthcare model of a communal hospital ward and adopt the principle of single patient rooms, hitherto reserved for the very unwell and the privately insured. Although presented as a patient-facing ‘consumerist’ policy, part of a comprehensive NHS Modernization programme, more complex performance drivers preoccupying the UK Department of Health (DH) at the time determined the policy shift: increased space standards to facilitate inclusiveness in the

implementation of the consumerist agenda, in effect destabilizing existing ward geometries (Department of Health, 2008a); poor infection control statistics at a significant number of acute hospitals damaging public confidence and adding significantly to healthcare cost (Plowman et al., 2001); patient pressure to achieve universal single-sex accommodation across the NHS Estate (NHS, 2013a); achieving patient privacy and ‘Dignity on the ward’ (Department of Health, 2008a); and the policy for wholesale replacement of the retained NHS Estate through public-private partnerships (PPPs) (Pollock, Shaoul, &

Vickers, 2002). What came to be known as the Darzi Report, published in 2008 (Department of Health, 2008b), further stressed the empowerment of patients and the principle of dignity and respect towards patients, although it was curiously mute on policy directions for the physical environment for healthcare. Nonetheless, the 2008 Health Building Note 04-01 (Department of Health, 2008a) specifically recommended that 50% of beds should be in single rooms, reminding readers that this merely repeated the advice given in the original Health Building Note 4 published in 1997. (Department of Health, 2013)

The 2001 Labour Party manifesto, ‘Renewing Public Services: NHS Reform’, promised a re-elected Labour government would ‘create a new type of hospital – specially built surgical units, managed by the NHS or the private sector...’ (Labour Party, 2001). Pre-1949 inpatient wards built to Florence Nightingale’s original mid-19th-century specifications as open-plan dormitories for 24–30 patients (Nightingale, 1859) were specifically condemned. The DH put forward £120 million for their replacement, stating that:

Older hospitals may care for older people on Nightingale wards – wards where staff can find it difficult to provide an appropriate environment for older people. £120 million will be spent over three years, making many of these wards into wards particularly for the use of older people. This will bring in more four-bedded bays, with more privacy and peace; rooms available for private conversations; and single rooms for those who are most vulnerable. (Department of Health, 2001, p.56, para 4.23)

The then Parliamentary Under-Secretary of State at the DH, Hazel Blears, commented in 2002 that:

the Nightingale ward, though suited to the delivery of care in its day, is outmoded and cannot provide the sort of accommodation which patients want and need. (Department of Health, 2002)

Jill Maben, Deputy Director of the National Nursing Research Unit at King’s College London, reviewed the evidence base for and against the new policy:

the potential disadvantages of this form of accommodation (single bed wards) include: reduced social interaction with other patients leading to isolation, less surveillance by staff, an increased likelihood of rescue failure, and higher rates of slips, trips and falls. (Maben, 2009)

Maben referred to Mooney (2008) and Snow (2008) for concerns about impacts on nursing staff, who

argued that single rooms require greater nursing input. She also cited Roger Ulrich’s highly influential arguments for single-room hospital wards delivered as key findings of his group’s researches into ‘evidence-based design’ (EBD) in healthcare of which he was the originator. Ulrich *et al.*, reporting on a collective literature review carried out in 2004, advised:

The findings further support the importance of improving outcomes for a range of design characteristics or interventions, including single-bed rooms rather than multi-bed rooms, effective ventilation systems, a good acoustic environment, nature distractions and daylight, appropriate lighting, better ergonomic design, acuity-adaptable rooms, and improved floor layouts and work settings. (Ulrich *et al.*, 2008)

Sadler *et al.*, citing Ulrich, were explicit: ‘create 100% single-patient rooms’. In their summary of the cost of their recommended improvements they concluded: ‘Single-patient rooms are now the standard for new hospital construction and, therefore, no additional costs are assumed’ (Sadler, DuBose, Malone, & Zimring, 2008). Ulrich was invited to Britain to advise government; the single-room policy remains fundamentally unaltered (Department of Health, 2010). However, despite the very positive reception of this work across the NHS (NHS Scotland, 2011), the deteriorating financial situation implies that an assumed ‘nil cost’ is not applicable in the UK.

The intense resourcing challenge faced by all NHS Trusts militates against new buildings. Furthermore, Trusts also face the probability of an increasing frequency of extreme climate events, not least summer heatwaves, whilst being obligated to deliver energy and carbon reductions to ambitious NHS Carbon Reduction Strategy targets (NHS Sustainable Development Unit, 2010). Overheating in hospitals due to heatwaves is documented as impacting on the health and well-being of patients, staff and visitors (Carmichael *et al.*, 2012). National Statistics report a clear correlation between mortality in hospitals and heatwaves in England and Wales (Kovats, Johnson, & Griffiths, 2006, p. 8), concluding:

After accounting for the usual pattern of mortality by place of death, a larger than expected proportion of the excess deaths in the elderly occurred in hospitals and nursing homes;

and

In the non-elderly population, there was a large excess of mortality observed in nursing and residential homes, although the absolute numbers of deaths were small.

The report attributes more than 2,000 deaths to the August 2003 heatwave in England and Wales.

Members of the nursing profession have consistently expressed reservations about this policy. For example, nursing staff reported in interviews with the authors (at Bradford Royal Infirmary (BRI) in 2011) and in published articles their belief that the communal Nightingale ward arrangement is actually beneficial in certain care settings, for older patients, for example, a rapidly increasing in-patient constituency. The *Nursing Times* reported in 2011:

We should not dismiss the value of Nightingale wards. [...] I would like the profession to take the positive aspects of the Nightingale wards and see them tailored to today's needs.

(David, 2011)

The article gained many positive comments from nurses, the majority anonymised, who deduced that the single-room agenda was driven by non-clinicians, policy-makers and the public specifically.

This article asks: could the general arrangement and shell of pre-1939 Nightingale ward buildings be recovered to provide viable environments for future patient care, delivering against new standards for the dignity and privacy of patients (NHS, 2013b) whilst achieving the mandatory carbon reduction target? Could the Nightingale ward type enable the NHS to navigate the hitherto intractable conundrum: what care and facilities strategies across the NHS Estate will enable it to deliver safe future environments in a changing climate meeting very ambitious yet mandatory carbon reduction targets? The paper considers Nightingale wards in terms of their design, energy performance, thermal comfort and infection control, and analyses a series of propositions that could achieve functional recovery of this frequently occurring hospital type.

The NHS Estate

Within the total NHS Estate in England of 28 Mm² (million m²), there are 330 acute hospital sites with a gross floor area of 18.83 Mm² on 6886 hectares of land of which at least 8.3 Mm² are occupied by patients (NHS, 2010). The research team's as-yet-unpublished analysis of aerial NHS hospital site images in England counts 219 pre-1939 Nightingale ward buildings on at least 72 sites, corroborated by the current DH 'ERIC' (estates returns information collection) database (NHS, 2013c).

The 2009 NHS Carbon Reduction Strategy reported that in 2004 the NHS generated 25% of public sector carbon emissions in England, some 18.6 MtCO₂e, of which 22% derived from building energy use, 4.1

MtCO₂e, rising to 24% in 2009 (NHS, 2009). By 2012 the proportion had dropped to 19%, some 3.8 MtCO₂e, as emissions derived from procurement and pharmaceuticals rose (NHS, 2012). Dr Dan Poulter, Under Secretary of State for Health (Department of Health, 2012), reported in the December 2012 announcement of the establishment of the NHS Energy Efficiency Fund that this energy consumption was costing almost £600 million a year. In a typical UK hospital, 44% of the energy used can be attributed to air and space heating (Department of Health, 2006).

The DH in its Health Technical Memorandum (HTM) 07-07 (Department of Health, 2009) set delivered energy targets of 35–55 GJ/100 m³ in new buildings and of 55–65 GJ/100 m³ for refurbished facilities, to include all building environmental uses (space heating, hot water, lights and appliances) but not the live loads of medical equipment. The reported building environmental energy use of the majority of NHS Trusts in England including Primary Care fell within the 44.8–98.0 GJ/100 m³ band for 2004/05 peaking at 125 GJ/100 m³ for teaching hospitals (Department of Health, 2008c).

Characteristics of the 'Nightingale' ward

The configuration of a Nightingale ward belongs to the genus of 'pavilion plan' hospitals. The 'pavilion plan' separates hospital wards into discrete, cross-ventilated buildings, connected by a circulation route across one end only. Although the nurse Florence Nightingale is the figure popularly associated with the introduction of this idea into British hospital design at the end of the 1850s, the so-called 'Nightingale' ward resulted from advocacy on the part not only of Nightingale but also of the Scottish surgeon John Robertson and the Editor of *The Builder*, George Godwin (King, 1966). In a paper of 1856 given in Manchester, Robertson criticized the poor ventilation of many British hospitals, suggesting that a better approach was found in the 'pavilion plans' of many continental European examples. He was especially positive about the hospital at Bordeaux, France. Robertson's paper, which was subsequently published with illustrations, informed a critical account by Godwin in *The Builder* of the recently completed Netley Military Hospital. Godwin continued to deploy and promote Robertson's ideas, with several further articles appearing in *The Builder* on the subject of hospital ventilation; some were written by Robertson himself (King, 1966; Godwin, 1858) (Figure 1).

During this period, Nightingale was preparing answers for the Royal Commission on Barracks and Hospitals, which began taking evidence in May 1857. Her ideas were published in her book *Notes on Hospitals* (Nightingale, 1859), which also included three papers from

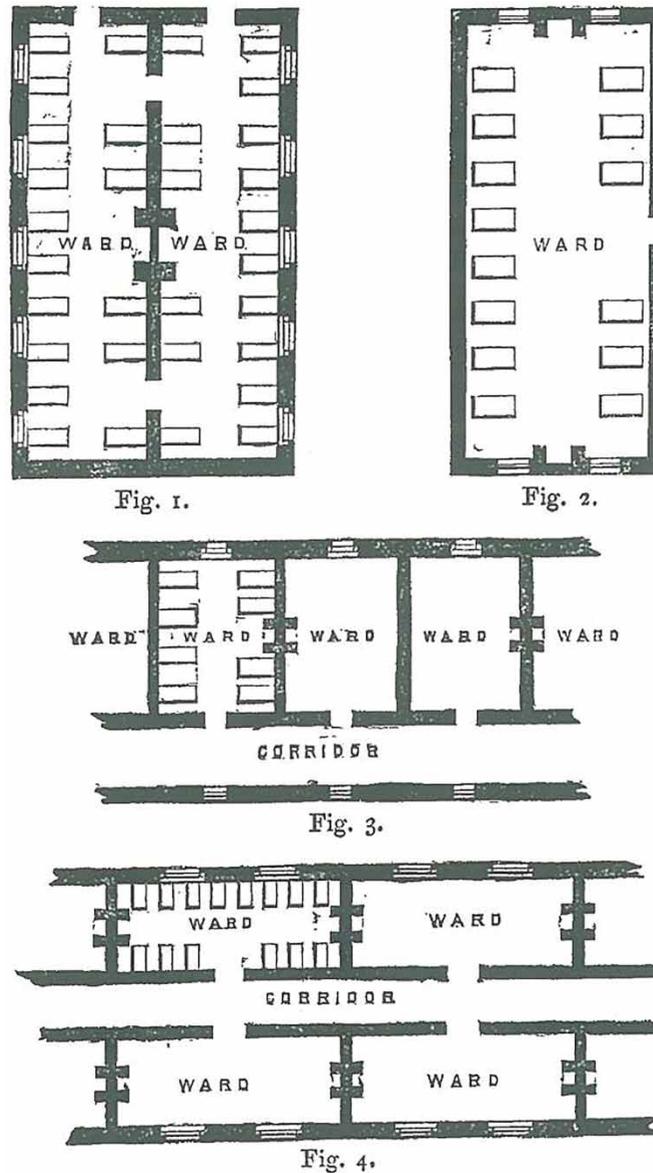


Figure 1 'These plans should be avoided for the future in hospital construction'
 Source: 'On Hospital Sites and Construction', an appendix to *Notes on Hospitals* (Nightingale, 1859)

The Builder likely to have been written by Robertson (King, 1966). Nightingale's interest in this subject stemmed from her experience of very high mortality rates in the two military hospitals at Scutari during the Crimean War of 1853–56. She deduced that patient recovery was linked to the opportunities to vent out 'bad air'. 'Good' ventilation, *i.e.* cross-ventilation in her model, would suppress the incidence of 'cross-infection', not understood as bacterial but derived from 'miasmas' (Thompson & Goldin, 1975). These 'miasmas' developed in part from the exhaled products of the human body, especially when sick, and were 'always highly morbid and dangerous' (Nightingale 1859). William Farr (1807–83) and

fellow sanitary reformers promoted belief in miasma, attributing to it the 1849 cholera epidemic (Halliday, 2001). Nightingale insisted that 'natural ventilation, or that by open windows and open fireplaces, is the only means for procuring the life-spring of the sick-fresh air', adding, 'no artificial ventilation will do this'. This comment may refer to recent attempts to ventilate hospitals mechanically, notably at the fully sealed York County Hospital of 1849, a bellows-driven forced ventilation experiment by Queen Victoria's 'Physician Extraordinary' in which air was driven into the wards and from which it was removed by an aspirator (Burdett, 1893). The failure of the system led to the installation of opening windows in 1859.

Nightingale, like Robertson, argued that each hospital ward should be located in a free-standing pavilion, connected to the rest of the hospital by a circulation route crossing one end only of the block. Her ideal was a single-storey pavilion containing just one ward, though she admitted that two-storey wards were acceptable. The pavilions were to be separated by a distance equal to twice the height of the buildings. Beds for 20–32 patients were to be located along each side of the ward perpendicular to the walls, with one window per bed and the windows located opposite each other. A ward for 20 patients would be 80 ft long, 25 ft wide and 16 ft high (Nightingale, 1859), the preferred axis being north–south, a window for every two beds, the windows consuming at least one-third of the wall surface area, located 2–3 ft off the floor and within 1 ft of the ceiling (Figure 2).

Nightingale suggested that the windows might be made of plate or double glass, but heating was seen as a trivial exercise relative to the challenge of ventilation. She derived the required supply of fresh air by calculating the ‘miasmatic’ emanations from a typical sick soldier: 370 ft³ per day from 16 soldiers and 123 ft³ a night, generating 16 pints of water, the fatal scenario being: ‘the consequent re-introduction of excrementitious matter into the blood through the function of respiration ...’ (Nightingale, 1859, p. 11). In fact, assuming the relative humidity to be 50%, to replace this quantity of vitiated air this yields a very low minimum air supply rate, some 0.167 litres/second/person, approximately 1/60th of the contemporary standard.

Her ideas were replicated nationally. The first completed ‘pavilion plan’ hospital was the Herbert Military Hospital in Woolwich (begun in 1863), though Blackburn Infirmary had been planned on these lines in early 1858; its completion was delayed and Woolwich was finished first (King, 1966). In fact Nightingale’s version of the continental pavilion hospital plan dominated hospital design in the UK into the 1930s (Thompson & Goldin, 1975) and also beyond, sometimes coupled to advanced ventilation strategies (Fair, 2014), though there was a parallel interest in circular ward planning during the 1880s (Taylor, 1988) while some hospitals, informed by examples such as the Rigs Hospital at Copenhagen of 1905, moved in the early 20th century from open dormitories to wards subdivided into smaller groups (e.g. Hertford County Hospital of 1934). BRI, the location of the wards discussed in this paper, was constructed as a ‘Nightingale’ hospital to the designs of Eric Morley from 1927. Only in the 1950s did an influential study by the Nuffield Provincial Hospitals Trust (1955) fundamentally break with the Nightingale approach in proposing four- and six-bed bays. In England, as of 2012, 22% of NHS acute hospital buildings predate 1948 (Department of Health 2008b).

Infection control and ward design

Whilst Nightingale did not fully understand the mechanisms of infection, she advocated good ventilation and adequate bed-spacing to reduce disease risk, a principle that still applies today. Although theories of ‘miasma’ had been disproved by the 1880s (Ayliffe & English, 2003), ventilation strategies intended to dilute and disperse ‘miasma’ are now known to be effective also in venting out airborne microorganisms emanating from patients, visitors and staff. Indeed, early advocates of germ theory effectively appropriated the language of the proponents of miasmas in advocating good ventilation and this move may have aided their success (Tomes, 1998).

Evaluating the relationships between design and infection risk requires consideration of transmission routes. The transmission of infection through direct contact and poor hand hygiene is predominantly a behaviour rather than a design issue, though it is likely that good practice is promoted by physical segregation of patients and proximity of hand basins as well as maintaining manageable bed occupancy rates and demands on healthcare staff (Kibbler, Quick, & O’Neill, 1998; Beggs et al., 2006). Indeed, poor management and overcrowding in large open wards has been associated with high rates of healthcare-associated infections (Commission for Healthcare Audit and Inspection, 2007).

Understanding of airborne transmission of infection stemmed from the pioneering work of Wells (1935). True airborne transmission is cited as when pathogen-carrying particles, typically < 5 µm in diameter, are released through actions such as coughing and sneezing, travel with the air in a space and then are inhaled by susceptible occupants. Tuberculosis, measles and chicken pox are all well-known airborne infections, and there is evidence that influenza (Tellier, 2009; Milton, Fabian, Cowling, Grantham, & McDevitt, 2013) and severe acute respiratory syndrome (SARS) (Yu et al., 2004; Qian, Li, Nielsen, & Huang, 2009) may be transmitted in this way too. Droplet transmission also involves airborne dispersion, but is often regarded as a form of indirect contact transmission as the mechanism involves deposition of particles onto surfaces leading to environmental contamination. Common infections such as influenza and rhinovirus are thought to be predominantly droplet-borne, however there is evidence that many hospital pathogens such as *C. difficile* (Roberts et al., 2008), methicillin-resistant *Staphylococcus aureus* (MRSA) (Kumari et al., 1998) and norovirus (Marks et al., 2003) may all be spread in this way. Regardless of the exact transmission mechanism, both airborne and droplet-borne transmission involves the release of particles into the air, and risk therefore depends on the fate of the particles.

DESIGN FOR A PAVILION HOSPITAL.

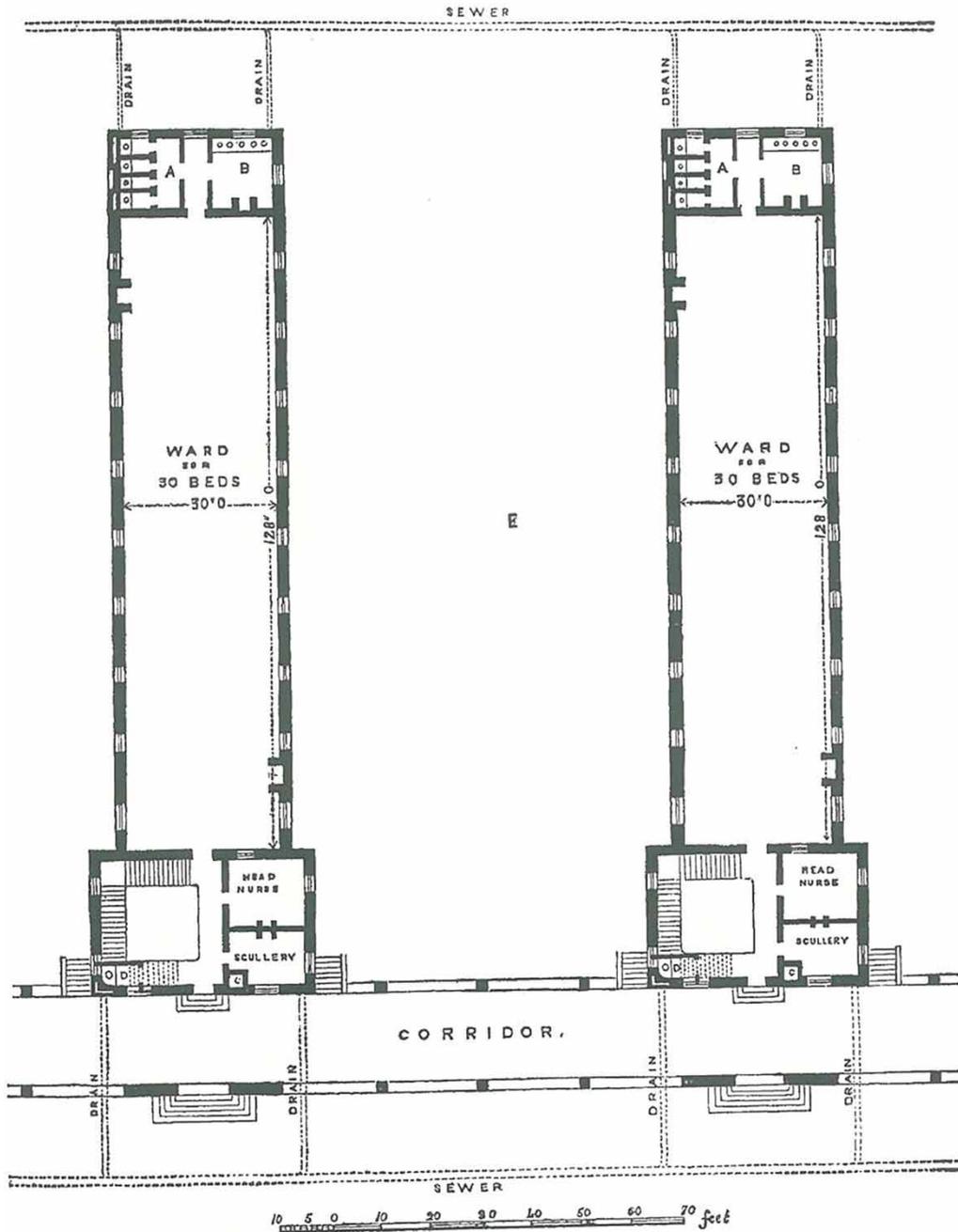


Fig. 5.

A. Ward Closets.
 B. Bath and Lavatory.
 C. Lift in Scullery.

D. Private Closet.
 E. Ornamental Ground.
 Ward Windows to be 4 ft. 8 in. in the clear.

Figure 2 Anonymous 'Design for a Pavilion Hospital', but likely to be the work of John Robertson under the editorial guidance of George Godwin
 Source: *The Builder* (August–September 1858)

Quantitative evidence directly relating ventilation to airborne infection risk originated in operating theatre studies (Lidwell et al., 1982) and early work on tuberculosis transmission (Riley et al., 1957). Together with a raft of experimental- and modelling-based studies this has led to consensus that infection does indeed transmit via airborne routes and that ventilation is an appropriate control measure (Li et al., 2007). This body of research has led to the guidance on healthcare ventilation used today (Department of Health, 2007; WHO, 2009; ASHRAE, 2003).

Resilience of the Nightingale ward building type

The basic resilience of the Nightingale ward pavilions at BRI was established as part of the 'DeDeRHECC' ('Design and Delivery of Robust Hospital Environments in a Changing Climate') project (Lomas, Giridharan, Short, & Fair, 2012). Temperature data were collected in two Nightingale Wards at the hospital between 2009 and 2011. Figure 3 depicts the current ward building. Aluminium thermal break windows with a central top-hung light limited to 100 mm maximum opening providing less than 0.09 m² were installed in the late 1990s to replace the original quadruple-banked steel hopper windows, alternately top- and bottom-hung, offering approximately 50% free area, some 1.35 m². The data collected indicate the temperatures in all spaces monitored fell comfortably within the recommendation for hospital wards recommended by HTM 03-01 of 18–28°C (Lomas et al., 2012), although peak external temperature was an undemanding 24.1°C in this period. Lomas et al. (2012) report that although night-time temperatures regularly exceeded 24°C, potentially affecting sleep, these occurred largely during the heating season, suggesting that a reduced set-point may reduce the incidence of higher night temperatures. A temperature of 26°C was exceeded for only 3 h in Ward 8 and for 1 h in Ward 9, with an absolute maximum of 27.4°C, despite the much-reduced opening window area. There was no evidence of overheating due to higher summer ambient temperatures or solar gain. The DeDeRHECC team adopted the adaptive thermal comfort standard BS EN 15251 for free-running naturally ventilated buildings as a more reliable indicator of comfort (British Standards Institution) than the current DH guidance. For health buildings it offers bands of tolerance related to vulnerability, Category 1 being most vulnerable. Lomas and Giridharan (2012) summarize the researchers' position. Fewer than 2% of the recorded temperatures exceed the Category I upper threshold, but the data yielded insufficient evidence of resilience to high ambient temperatures.



Figure 3 Digital reconstruction of the as-built Nightingale ward at Bradford Royal Infirmary, designed in 1927

Key: (1) solid masonry wall, 490–500 mm thick inner brick lead, about 75 mm rubble infill, 150 mm coursed ashlar; (2) airbricks to vents behind hot water radiators, blocked in the 1990s; (3) hot water 'hospital' radiators, replaced by convectors; (4) three-light aluminium-framed thermal-break windows installed in the 1990s, centre light opening restricted to 100 mm; (5) intermediate floors unusually thin slab; facilities staff report embedded timber beams and that the loading capacity is at a maximum; (6) 75 mm extruded polystyrene insulation; and (7) south-facing sun lounges in each floor

Source: freeze frame image from 'Robust Hospitals in a Changing Climate' (<http://www.sms.cam.ac.uk/media/1446036>)

A dynamic thermal model of the ward was developed using Integrated Environmental Solutions modelling software (IES, 2011) and was calibrated against observed data to investigate the wards' thermal performance and energy demands (Lomas et al., 2012). The model produced predictions of peak and mean temperatures closely aligned with the observed data, predicting 179 annual hours above the BS EN 15251 Category I upper temperature threshold, well within the BS EN 15251 allowable limit of 5% of hours above the Category I upper threshold (*i.e.* 438 h/year). The predicted environmental energy demand for 2010, a warm summer year, was 14 GJ/100 m³, with over 90% of this being for space heating. The researchers' analysis of DH 'ERIC' data indicates the non-building environment uses (hot water, catering, medical equipment, small power, retail space, pumps, controls, lifts, etc.) account for approximately 44% of the total energy demand of an acute hospital in England. Multiplying building environmental energy demand by 1.78 may then give some indication of overall use. Nonetheless, the adjusted energy demand¹ for the BRI Nightingale wards of approximately 25 GJ/100 m³ is significantly below the NHS target of 55–65 GJ/100 m³ for refurbished buildings and below even the target of 35–55 GJ/100 m³ for new-build hospitals.

By comparison with other standard NHS building types, a recent paper studying the demand of a 1960s' tower building with hybrid ventilation predicted an energy demand for space conditioning alone of 101 GJ/100 m³ (Short, Lomas, Renganathan, & Fair, 2012). Meanwhile CO₂ emissions for the BRI Nightingale wards are predicted to be about 30 kgCO₂/m² for environmental control purposes, which, using the crude adjustment noted above, would uplift to about 53 kgCO₂/m², very significantly less than the Chartered Institution of Building Services Engineers (CIBSE) TM46 benchmark for 'Hospitals; clinical and research' of 129.3 kgCO₂/m² (CIBSE, 2008). Here, then, is a hospital ward type that could deliver the NHS carbon reduction target, but which must be realigned with contemporary service models in order to become an operational solution to the NHS conundrum.

Adaptive options for the Nightingale building envelope

Though good, the performance of the Nightingales can be improved. Lomas et al. (2012) described three simple and incremental refurbishment options, summarized in Figure 4.

The first option adds 100 mm of insulation to the walls and 300 mm to the roof, opens up the triple light



Figure 4 Section showing the existing configuration and refurbishment options

Key: (1) remove stone, insulate (70 mm) and replace stone; (2) High level 100 mm air inlet ducts through solid wall; (3) radiant panel for hot and cold water; (4) opening lights in the existing windows with guards as needed externally; (5) introduce slow wide-span fans above the beds, an option not incorporated into the computational fluid dynamics (CFD) analysis; (6) shading and lightshelves of perforated white powder-coated aluminium to suppress glare and achieve a more even daylight distribution; and (7) seal vents and remove radiators/convectors as the changing climate requires some measure of radiant cooling about 2050

Source: freeze-frame image, same as Figure 3.

windows (ensuring safety with an external steel grille), and provides a sunshade at each opening. Trickle vents are recovered behind a new perimeter heating element, for winter ventilation. The second option adds to this strategy ceiling fans operated by patients; whilst the third option introduces 100 mm diameter high-level air inlets above each bed space, between each window, with a damper and a simple convective heating device fixed to the internal face to enable supply air to be pre-heated and/or recirculated within the space. Primary heating and cooling are delivered through the installation of radiant panels. The addition of radiant cooling eliminates entirely the risk of overheating.

The present paper assumes the second option as the base treatment of the envelope but without operating fans except during summer heatwaves. Prediction of the dispersal of pathogens considers wind effects but not the action of multiple ceiling fans. Annual energy demands and CO₂ emissions of the refurbished Nightingale ward were predicted using the dynamic thermal model and the Bradford 2010 weather file for the summer period, 1 May to 30 September, as recorded in Table 1.

The performance of the Nightingale wards in a future climate has been predicted for current and future typical and extreme temperature years, the 2005 test reference year (TRY), containing monthly data typifying Bradford chaining the most typical January to the most typical February, etc., and the 2004 design summer year (DSY) depicting the third hottest year in the 22-year string based on the mean temperature recorded between April and September, the 90th percentile. Future weather years were created from the UKCP09 future climate projections by the University of Exeter assuming an A1B global emissions development scenario producing TRYs and DSYs for the 30-year periods centred around 2030, 2050 and 2080 for the 5 km grid square covering Bradford. The method used has been fully described by Eames, Kershaw, and Coley (2011), and is summarized in Lomas and Giridharan (2012). Higher temperatures increase gradually in the TRYs but quite rapidly in the DSYs; the difference between the temperatures in typical and extreme years becomes more pronounced so that risk-based decisions on the incorporation of mechanical cooling become more complex. The dynamic thermal model was used to predict temperatures in the Nightingale ward as currently exists and in the refurbished ward as option 2, as appropriate. The internal heat gains, window-opening strategy and control strategies (e.g. for the cooling option) were maintained as for the 2010 analyses described above. Neither the existing nor the refurbished building will overheat in typical years, as judged by the HTM 03 and BS EN 15251 criteria, but in the 2050s warmer night-time temperatures may be experienced

Table 1 Bradford Royal Infirmary: predicted summer internal temperatures for 2010, 2030, 2050 and 2080 in test resultant years (TRY) and design summer years (DSY)

	TRY				DSY			
	Maximum temperature (°C)	Mean night-time temperature (°C)	BS EN 15251: Total hours above Category I upper limit	BS EN 15251: Total hours above Category II upper limit	Maximum temperature (°C)	Mean night-time temperature (°C)	BS EN 15251: Total hours above Category I upper limit	BS EN 15251: Total hours above Category II upper limit
<i>2005</i>								
Existing	33.2	22.8	301	142	29.1	22.7	137	30
Refurbishment	30.0	23.0	243	56	26.6	23.0	200	37
<i>2030</i>								
Existing	30.6	23.3	283	83	32.5	23.9	421	228
Refurbishment	27.2	23.2	173	46	29.3	23.4	83	29
<i>2050</i>								
Existing	30.7	23.5	370	140	33.0	24.6	648	333
Refurbishment	27.7	23.2	84	11	29.0	23.7	46	5
<i>2080</i>								
Existing	30.8	23.8	320	104	36.1	25.4	974	619
Refurbishment	27.3	23.3	22	0	32.6	24.1	182	73

Notes: Night-time hours are 21:00–06:00.

Highlighted results show that the exceedance is deemed important in that it could not be easily corrected by refining the control strategy.

It is assumed that during the winter (October–April) the space will not overheat due to elevated ambient temperatures and solar gains, so the exceedance limit for BS EN 15251 is > 438 h above upper category threshold.

(although these might be ameliorated easily with a refined window-opening regimen if the windows are openable to a useful degree in sufficient numbers). However, although HTM 03 shows overheating occurs in the existing building and with refurbishment option 1 in the DSYs as early as the 2030s, the BS EN 15251 approach indicates that the refurbishment options that do not incorporate cooling will remain comfortable in both typical and extreme years right up to the 2080s. The existing building is predicted to overheat based on the Category I thresholds during the 2050s. The addition of mechanical cooling (*i.e.* the radiant ceiling innovation in option 3) would ensure there is no overheating in either typical or extreme temperature years right up to the 2080s.

The analysis summarized here indicates that the inherent resilience of the Nightingale wards, together with the northerly location of Bradford (and thus modest summertime temperatures even in the 2080s), would enable passive retrofit to succeed in producing a building that is comfortable until towards the end of this century. However, it would be essential also to offer a reconfiguration of the open wards to align the spaces more closely with the NHS Modernization policy objectives. The rest of the paper presents and tests options for such reconfiguration.

Infection control analysis of Nightingale wards

Studies assessing airflows and infection risk in naturally ventilated wards are few, not least because of the challenges involved in measuring airflows. Escombe et al. (2007) showed that in some cases ventilation rates in naturally ventilated spaces could be much higher than those achievable by mechanical ventilation, while Qian et al. (2010) conducted a detailed study in a naturally ventilated ward in Hong Kong and showed the dependency of the ventilation rate on the external wind conditions. Of relevance to the current paper is a recent study conducted in a Nightingale ward at St Luke's Hospital, also in Bradford (Gilkeson, Camargo-Valero, Pickin, & Noakes, 2013). This is an older ward than those considered in Lomas et al. (2012), but the construction, orientation and ventilation strategies are similar. Using CO₂ as a tracer gas, this study showed that with external wind speeds of 1.0–4.0 m/s ventilation rates of 3.4–6.5 air changes per hour (ACH) were achieved in the ward with only 60% of the windows open. Moreover, the study explored the influence of partitions between beds on the distribution of a tracer released at a representative patient location on the leeward or windward side of the building. Results considered the total exposure to the tracer over 25 min at different patient locations. In an open ward this was seen to be relatively uniform, suggesting a reasonable degree of mixing.

With partitions in place the results showed a redistribution of the tracer, with higher exposure close to the source and in the bed immediately opposite, but lower exposure in neighbouring beds. However, the overall exposure in the ward was comparable in both cases. If exposure can be considered analogous to infection risk, then these results suggest that the cross-ventilated Nightingale ward, with the right wind conditions, is capable of achieving ventilation rates comparable with the six ACHs recommended by the Department of Health (2007) and that partitioning the ward may be feasible without substantial impact on infection risk.

Adaptive reconfiguration options

Figure 5 shows (a) the Nightingale layout as originally built, along with several notional new layouts developed by the authors: (b) 'partitions' – the plan subdivided into one-bed cubicles, the full 16 ft in height, and adds external bathroom towers; (c) 'Pullman' – adopting the arrangement of a compartmented railway carriage with an internal corridor and subdivision into six two-bed rooms served by split bathroom towers; (d) 'zigzag' – preserves the full open volume but configures the beds either side of a wardrobe-high central partition set out in a zigzag plan, offering visual if not acoustic privacy with five external bathroom towers; and (e) 'external corridor' – allowing the recovery of usable floor space by adding an external corridor to each floor, creating ward rooms of three to five beds within the full width of the original pavilion.

These basic options were initially outlined in schematic form and then developed in consultation with staff at BRI, examining patient safety, supervision, the cycle of inspection, the dispensing of medicines and treatments, the distribution and collection of food, and the night-time care model with reduced staff. It emerged that a key factor in considering the future of the Nightingale wards as functioning clinical spaces was the perceived risk of airborne cross-infection both in the open ward and in variants offering some subdivision. The relative safety of the propositions was evaluated using a computational approach to predict dwell times for air in the region of patients and their neighbours giving some insight into infection control implications.

Airflow simulation approach

While ventilation and infection risk are clearly related, assessing the ventilation performance of a hospital ward, particularly a naturally ventilated one, is not straightforward. Tracer gas experiments offer a possible approach to assessment, however they cannot be carried out in occupied spaces and the methodology is not straightforward (Escombe et al., 2007; Gilkeson,

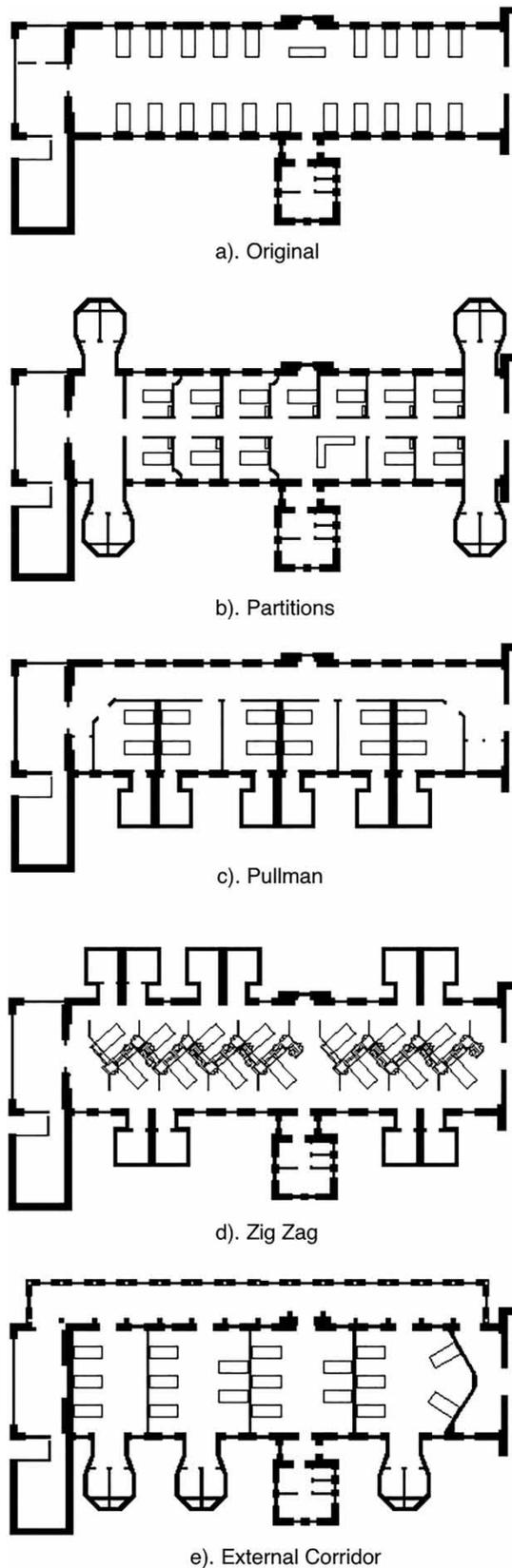


Figure 5 Nightingale ward: overview sketches of the reconfiguration options

Camargo-Valero, Pickin, & Noakes, 2013). Moreover it is not generally feasible to use such an approach to explore design changes. Computational fluid dynamics (CFD) is a numerical simulation approach that can be used quickly to explore building airflows and ventilation effectiveness under a range of different circumstances. By discretizing mass, momentum and energy equations that govern fluid flow across a mesh of elements representing the room geometry, it is possible to evaluate spatial distribution of parameters such as velocity, pressure and temperature within a building. While computational resources often limit simulations to idealized steady-state scenarios, the approach is widely used in building airflow assessment, including hospital-based studies (Tang et al., 2011). Here a series of CFD simulations were carried out to investigate the impact of the various ward internal redesigns on both ventilation characteristics and thermal comfort.

Model geometry and mesh

For consistency, each ward configuration is based on the same plan area of 10×8 m and the height remains constant at 3.7 m, leading to a ward air volume of approximately 300 m^3 . Figure 6 illustrates the simplified ward layouts considered in the study, derived from those proposed in Figure 5.

The traditional Nightingale ward model, Figure 6(a), is a section of the full ward consisting of six beds (three per side), each measuring $2.0 \times 1.0 \times 0.7$ m. Figure 6(b) shows the second configuration with full-height partitions between beds; previous studies have underlined the potential for these as an infection-control measure (Noakes, Sleigh, Escombe, & Beggs, 2006; Gilkeson et al., 2013). In the Pullman-style layout, Figure 6(c), the beds are arranged into three pairs and the doors to each compartment are assumed to be open allowing for cross-ventilation via the corridor. Figure 6(d) shows the zigzag scheme comprising an island of skewed beds together with 2.1 m-high partitions segregating the immediate vicinity of each bed. Although not shown in Figure 6(d), a slight variation of the skewed island design is also considered with both the partitions and beds raised above the ground by 0.15 m. The final configuration, Figure 6(e), is similar in layout to the traditional ward, subdivided to achieve gender separation but with the beds positioned on the end walls (as opposed to the side walls) with the addition of an external access corridor. A notable feature of this layout is the asymmetric distribution of windows; only two are present on the windward side of the ward (the central one is missing to cater for a toilet/shower room), whereas a total of six are present on the leeward side, *i.e.* three on the corridor and three supplementary windows positioned above it.

Computer-aided design (CAD) models were developed using Ansys Workbench, version 13.0.0 SP2 (Ansys

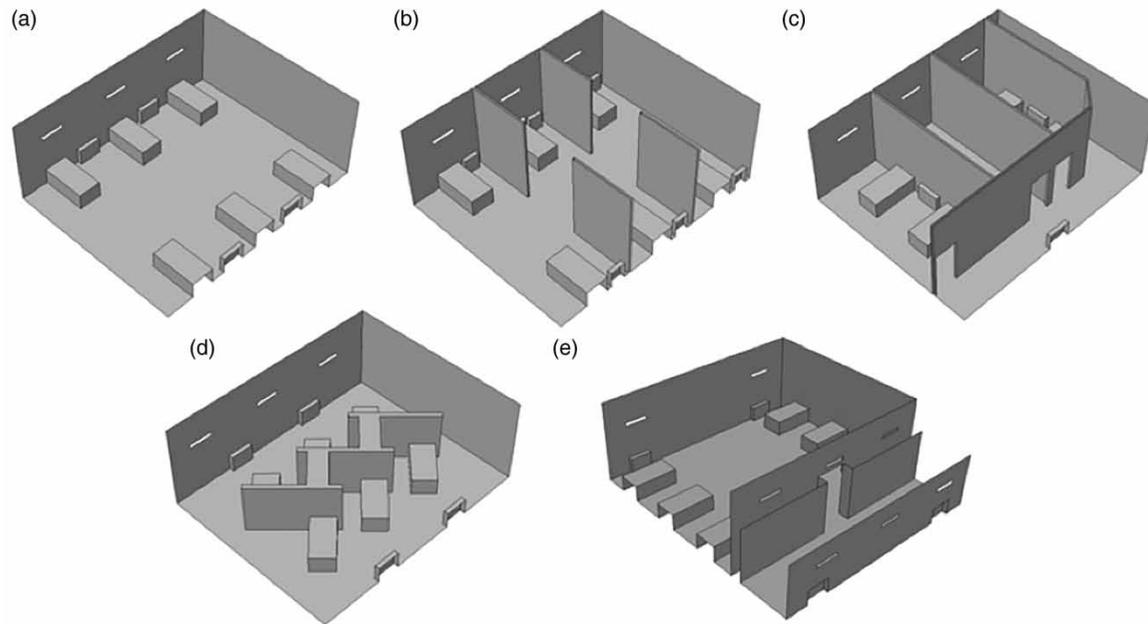


Figure 6 The hospital ward layouts studied: (a) traditional, (b) partitioned, (c) Pullman, (d) skewed island and (e) external corridor configurations

Inc., 2013, <http://ansys.com/products/fluid-dynamics>). In each case the air volume was discretized into a grid of hexahedral cells with cell refinement applied to all surfaces. The coarsest cells have an individual edge spacing of 0.12 m with finer cells, 0.06 m, applied to the walls and an extra-fine cell size of 0.03 m adjacent to the window openings, radiator surfaces and the upper surface of each bed. Figure 7 shows this grid structure for the ‘Pullman’ ward layout. The global cell count ranged from 0.8 to 1.5 million cells depending on the ward layout.

Boundary conditions

Cross-ventilation is modelled by treating the open windows as rectangular inlets, each measuring 0.15 × 1.00 m. On the windward side an inlet velocity,

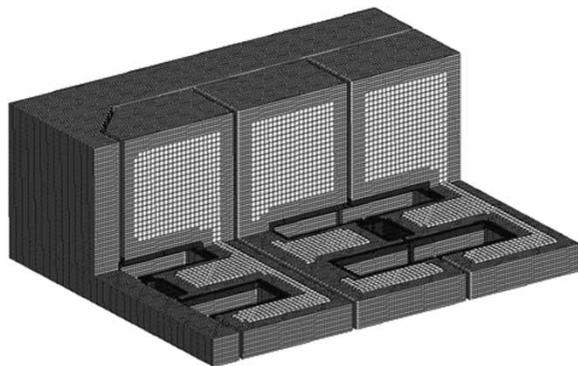


Figure 7 Sections of the computational grid structure for the Pullman-style hospital ward

U_{IN} , was imposed with a magnitude of 0.5 or 1.5 m/s. For the traditional ward these inlet velocities correspond to ventilation rates of two and six ACHs, respectively. Air was assumed to enter at an angle of 45° to the horizontal axis. This methodology has been shown to replicate experimentally determined flow patterns through casement windows in a Nightingale hospital ward (Gilkeson et al., 2011). All ward configurations were assumed to contain similar small radiators. With the focus of this study being on the relative performance of ventilation and thermal comfort between wards, small geometrical details (e.g. lighting and equipment) are neglected. For the same reason patient geometry is omitted, however typical thermal output (per patient) is accounted for using an appropriate temperature applied to the upper surface of each bed. Thermal boundary conditions for summer and winter cases are given in Table 2.

Table 2 Thermal boundary conditions

Boundary	Temperature (C)	
	Summer	Winter
Inlet	22	12
Wall	22	22
Bed top	30	30
Radiator	22	45

Solution process

Steady-state airflow simulations were run in parallel on a high performance computing cluster with 16 processors ($2 \times$ dual-quad core 2.26 GHz Nahalem processors and 24 Gb of SDD RAM) using Fluent, version 13.0 (Ansys Inc., 2013, <http://ansys.com/products/fluid-dynamics>). Solutions for the governing fluid flow equations (continuity, momentum and turbulence) were computed using second-order discretization and the standard $k-\epsilon$ turbulence model in conjunction with standard wall functions and the SIMPLE algorithm. Simulations ran for 10 000 iterations during which the absolute residual levels had dropped between four and six orders of magnitude ensuring good convergence. Although the simulations were steady-state, it is possible to exploit the resulting velocity field and determine the residence time in each region of the air volume being studied. In order to achieve this, a passive scalar equation was solved in conjunction with domain-wide source terms which enabled the distribution of the local ventilation rate, V_L , to be found.

Airflow simulation results

Altogether eight different ward-ventilation configurations are considered and they are summarized as follows:

- a: Traditional – windward ventilation
- b: Partitioned – windward ventilation
- c1: Pullman style – windward ventilation
- c2: Pullman style – leeward ventilation
- d1: Skewed island – windward ventilation
- d2: Raised skewed island – windward ventilation
- e1: External corridor – windward ventilation
- e2: External corridor – leeward ventilation

The rationale for simulating leeward ventilation exclusively for the Pullman (c) and external corridor wards (e) is that these are the only asymmetric ward configurations, therefore it is important to consider both potential wind directions. In the analysis of ward airflows three ventilation parameters are considered, namely: (1) V_G , the global ventilation rate through each ward, (2) V_B , the ventilation rate local to each bed, calculated in a spherical volumes, 1.0 m diameter in the breathing zone of a laying patient, and (3) V_L , the local ventilation rate measured in each individual cell of the grid.

Airflow patterns

Figure 8 shows the observed airflow patterns in the form of path lines released from the inlet windows which are coloured by relative ventilation rate. These reveal the complexity of indoor airflow even for relatively simple cross-ventilation. The traditional (a),

partitioned (b) and skewed island (d1, d2) flow fields are all very similar. They are dominated by the inlet flows which are guided cross-ward by the ceiling. A small proportion of this fresh air directly bypasses the ward and exits through the outlet windows, whereas the remainder mixes in the patient zone before exiting. The asymmetry present in the Pullman (c1, c2) and external corridor ward (e1, e2) geometries leads to differing flow fields depending on the flow direction. For both of these wards, leeward ventilation leads to substantial mixing regions in each respective corridor with significantly reduced air movement in the vicinity of the hospital beds. Therefore, the asymmetry and greater geometric complexity present in these particular designs do not lend themselves to stable and uniform ventilation characteristics. In contrast, the simpler designs appear to be very effective solutions and they are more suited to natural cross-ventilation.

Bed-level ventilation rates

Figure 9 shows the distribution of bed-specific ventilation rates for all ward configurations under the influence of low wind speeds (*i.e.* 0.5 and 1.5 m/s, respectively).

For proposals (a) to (d) the two imposed wind speeds lead to global ventilation rates of two and six ACHs, respectively; the inclusion of partitions does slightly reduce the air volume in some cases but the overall effect on V_G is minimal. The addition of the corridor to the extended ward (cases (e1) and (e2)) increases the overall volume from 300 to 346 m³, which reduces V_G accordingly (constant wind speeds are assumed in all cases). Considering the results for the traditional ward (Figure 9(a)), beds A, B and C experience uniform ventilation rates, which correspond to the ventilation supplied by the adjacent inlet windows. On the opposite side of the ward the central bed (E) experiences an increase in ventilation for $V_G = 2$ ACH, which is notably higher than that experienced by beds D and F at either side. This is attributable to the airflow at either end of the ward being slowed down by a boundary layer attaching itself to the end walls. In contrast, the higher wind speed ($V_G = 6$ ACH) leads to proportionately higher ventilation rates for beds D and F, which suggest that the distribution of ventilation rates at this side of the ward is sensitive to the wind speed. In the partitioned ward case (Figure 9(b)) there is a distinction present in the observed ventilation rates at either side of the ward but with little variation across the inlet and outlet walls. The presence of the partitions serves to stagnate the airflow as it progresses cross-ward, leading to noticeable reductions in V_B on the leeward side.

For the Pullman-style hospital ward (Figure 9(c)) there is a clear variation in ventilation rate throughout the

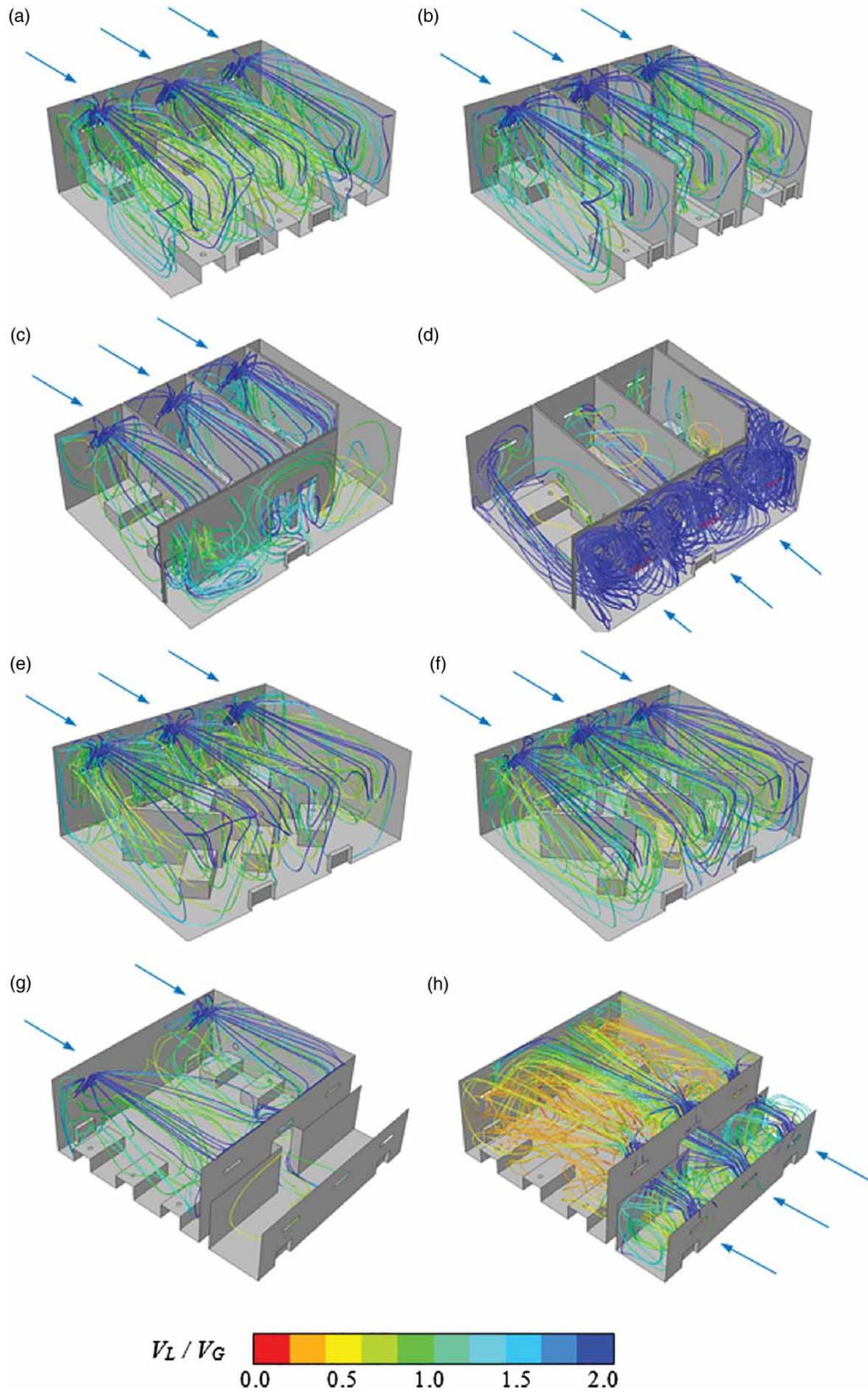


Figure 8 Airflow path lines coloured by the relative ventilation rate, V_L / V_G for high wind speed (1.5 m/s)
 Key: (a) traditional, (b) partitioned, (c) Pullman (windward ventilation), (d) Pullman (leeward ventilation), (e) skewed island, (f) skewed island (raised partitions), (g) external corridor (windward ventilation), and (h) external corridor (leeward ventilation) hospital wards

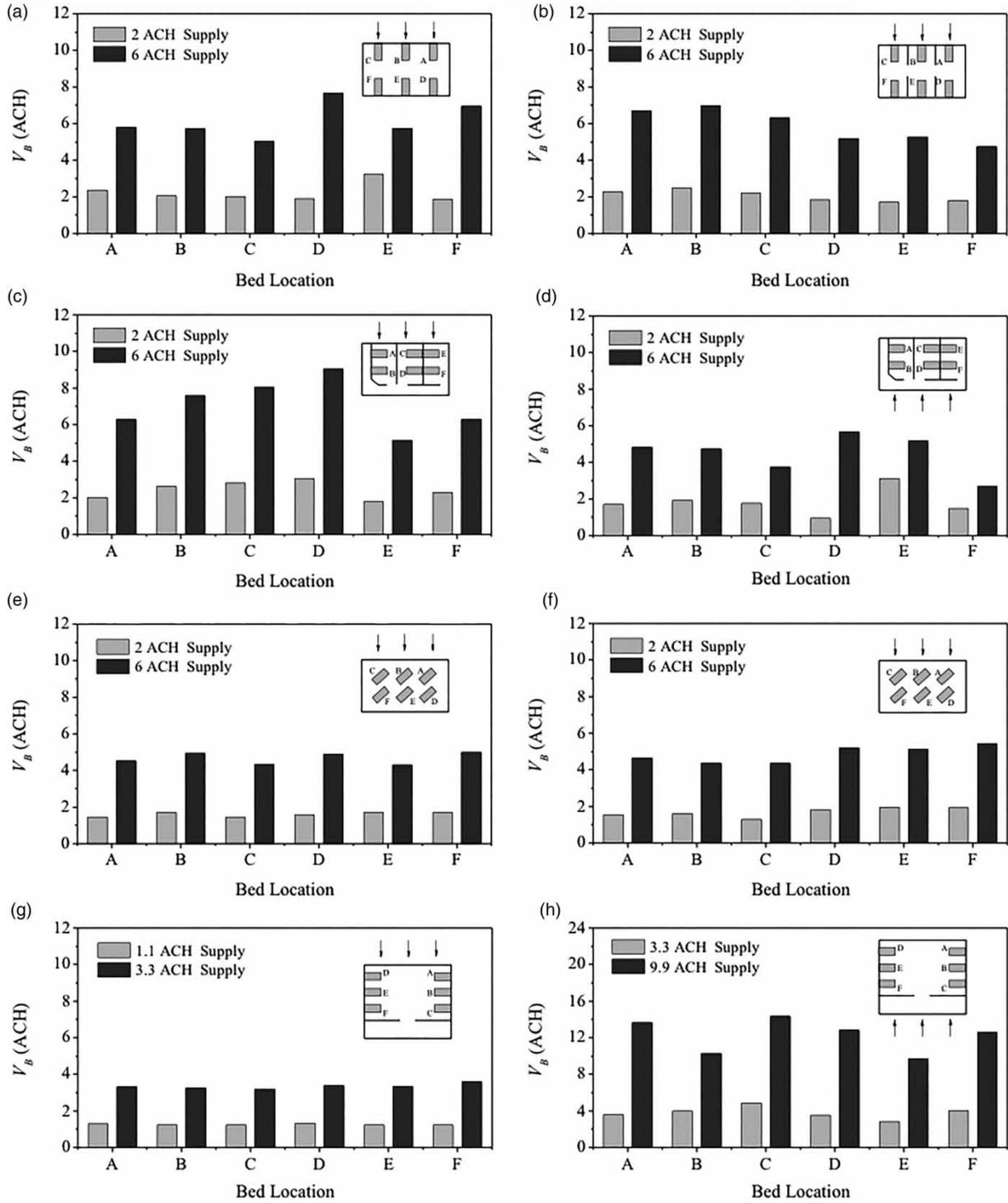


Figure 9 Distribution of bed-level ventilation rates, V_B , for high wind speed (1.5 m/s)
 Key: (a) traditional, (b) partitioned, (c) Pullman (windward ventilation), (d) Pullman (leeward ventilation), (e) skewed island, (f) skewed island (raised partitions), (g) external corridor (windward ventilation), and (h) external corridor (leeward ventilation) hospital wards

space with differences of up to 40% between beds. Here, the maximum local ventilation rate observed for the high wind speed is almost nine ACHs, which is 50% higher than the supply rate. This occurs

above bed D which is directly opposite the central inlet window and adjacent to the door opening. It follows that as the airflow passes this central bay, it rushes through the door opening thereby increasing

the ventilation rate local to bed D. In contrast, the leeward ventilation regimes show that when the air enters the opposing side of the building, the route of entry to each bay is poorly defined and this leads to reduced air movement and thus lower ventilation (Figure 9(d)).

Results from both skewed island cases (Figure 9(e, f)) show that the raised partitions have very little impact on the observed ventilation rates. The differences in V_B from bed to bed are minimal which underlines the uniformity of the airflow in the centre of the ward. This characteristic can be expected because the beds are clustered centrally which is away from the regions experiencing high flow gradients, *i.e.* near inlets, outlets and perimeter walls. Overall, the ventilation rates are slightly lower than those observed in the traditional ward, however the uniformity of flow suggests improved stability in the ventilation conditions (assuming straight cross-ward ventilation).

The observed ventilation rates seen in the external corridor ward are fairly constant under the influence of windward ventilation (Figure 9(g)). This is explained by the fact that the beds adorn both end walls of the ward, each of which is supplied with fresh air from the same window. A point of note is that the absolute ventilation rates are significantly lower for this case because, as described above, the central window on the windward side of the building is omitted due to a toilet/shower room being present. There are six windows present on the opposing side of the building, which explains the dramatically higher ventilation rates seen for the leeward case (Figure 9(h)). The peak ventilation rate is approximately 14 ACHs occurring by bed C, which is just behind the doorway connecting the corridor to the ward. As with the Pullman layout, leeward ventilation for the external corridor case leads to a significant variation in ventilation from bed to bed, however in this case the variability stems from the interaction between the three high-mounted inlets and the inflow through the corridor opening.

Local ventilation rates

Whilst the bed-specific ventilation rates give a clear indication of the air exchange rates, which can be expected by patients, analysing the distribution of local ventilation rates throughout each ward is a convenient way of comparing them. This was achieved using a horizontal plane spanning each ward with 7700 analysis points situated at a height of 1.2 m above the ground.

Figures 10 and 11 present histograms of the distribution of V_L in this plane for low and high wind speeds, respectively. For the low wind speed cases, the most striking feature is the range of V_L observed, which is particularly broad for the Pullman ward (Figure 10(c) and (d)) and the extended ward with

leeward ventilation (Figure 10(h)). These wider ranges are indicative of poorer mixing which leads to a greater spectrum of data. In contrast, the markedly narrower spectrum observed for the traditional ward (Figure 10(a), skewed-island designs (Figure 10(e) and (f)) and the external corridor ward with windward ventilation (Figure 10(g)) indicate greater mixing levels with a more even distribution. It is also noticeable that the peak of the distribution is below two ACHs, the supply ventilation rate for the ward, in the skewed island design, compared with slightly above in the traditional open layout. The same overall trends are seen in the histograms for the high wind speed of 1.5 m/s in Figure 11, which shows that the distribution of ventilation rates is insensitive to wind speed.

Although the histograms provide a wealth of absolute ventilation rate data, Figure 12 shows contour plots of the relative ventilation rate, V_L/V_G , which is a measure of how well the inlet flows reach various parts the wards. For $V_L/V_G = 1.0$ the ventilation rate at any given point is equal to the global value, V_G ; when $V_L/V_G < 1.0$ the local ventilation rate is below V_G ; and for $V_L/V_G > 1.0$ the ventilation is greater than V_G . As would be expected, the contour plots clearly show a high relative ventilation rate near the inlets and in most cases this extends along the roof where the inlet flows are entrained. The range of relative ventilation rates is relatively small for the traditional, partitioned and skewed island designs (Figures 12(a), (b), (c) and (d)), whereas great variability is present in the remaining cases. In particular, the Pullman ward (leeward ventilation) exhibits very high air exchange rates in the corridor adjacent to the inlets and the bay walls restrict airflow, thereby slowing the flow rates through the actual bays.

Thermal characteristics

In analysing the temperatures in the ward two parameters were of interest, namely: (1) the mean average of the local bed-level temperatures (*i.e.* the average of all six beds), T_{B-AVE} ($^{\circ}\text{C}$) and (2) the difference between the minimum and maximum bed-level temperatures, ΔT ($^{\circ}\text{C}$). Tables 3 and 4 show the data for summer and winter conditions respectively.

Overall, the difference in average temperatures between wards during summer is relatively small, whereas these differences are more pronounced during winter. The greater variation in winter occurs by virtue of the greater temperature ranges present; incoming air has a temperature of 12°C and the radiator temperature is 45°C , yet the summer conditions assume the inlet air matches the wall temperatures (22°C) and the radiators are turned off.

As the ventilation rate increases, the temperatures generally drop as the faster airflow removes more heat. For

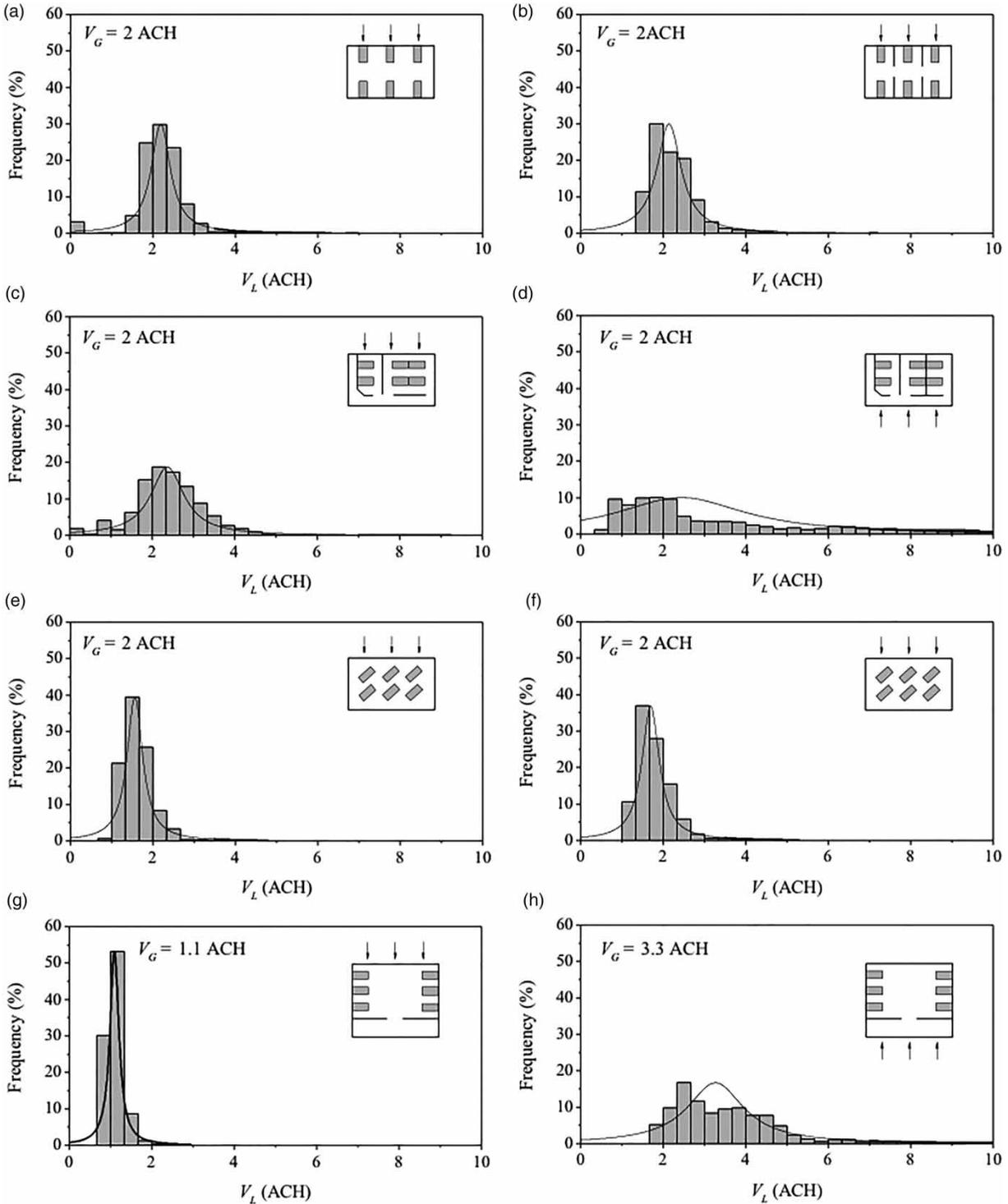


Figure 10 Distribution of local ventilation rates, V_L , in the patient-level breathing plane (1.2 m off the ground) for low wind speed (0.5 m/s) Key: (a) traditional, (b) partitioned, (c) Pullman (windward ventilation), (d) Pullman (leeward ventilation), (e) skewed island, (f) skewed island (raised partitions), (g) external corridor (windward ventilation), and (h) external corridor (leeward ventilation) hospital wards

summer conditions the warmest ward is the Pullman layout (windward ventilation) and the greatest variation in bed-to-bed temperatures is also highest for this case but with a leeward ventilation regime; the

latter observation reinforces the view that this ward induces the greatest variability in ventilation flows (and thus the temperature distribution). For winter conditions, the traditional ward experiences the

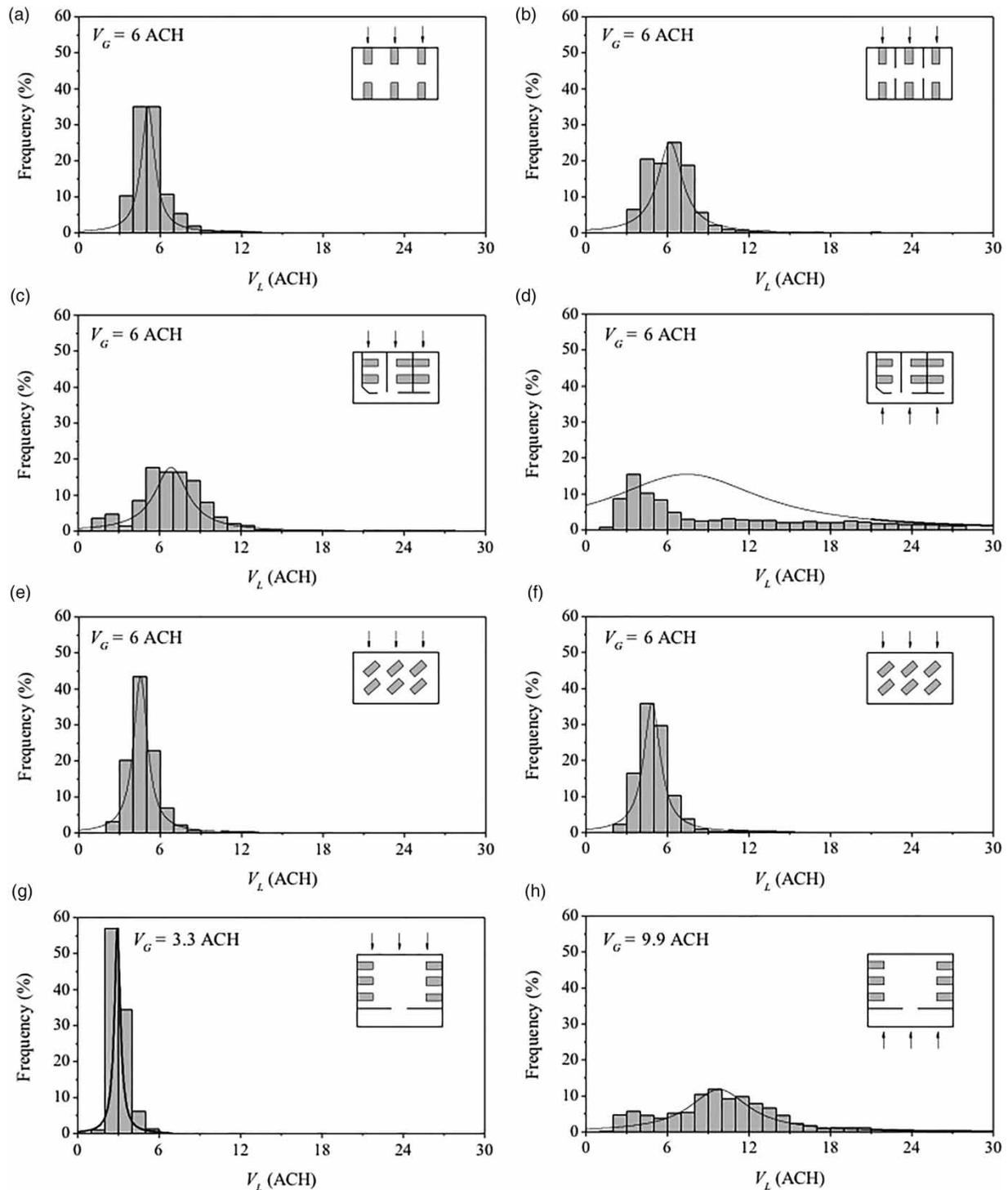


Figure 11 Distribution of local ventilation rates, V_L , in the patient-level breathing plane (1.2 m off the ground) for high wind speed (1.5 m/s) Key: (a) traditional, (b) partitioned, (c) Pullman (windward ventilation), (d) Pullman (leeward ventilation), (e) skewed island, (f) skewed island (raised partitions), (g) external corridor (windward ventilation), and (h) external corridor (leeward ventilation) hospital wards

coolest bed-average temperature because the airflow encounters practically no obstacles which would stagnate the flow and suppress heat removal. In most of the other cases there is a restriction of one form or other (partitions, walls, doorways etc.) which serves to

increase the temperatures accordingly. An implication of this is that less energy could be lost through natural ventilation with features such as partitions present. It should be noted that radiant temperatures are not considered in evaluating comfort conditions;

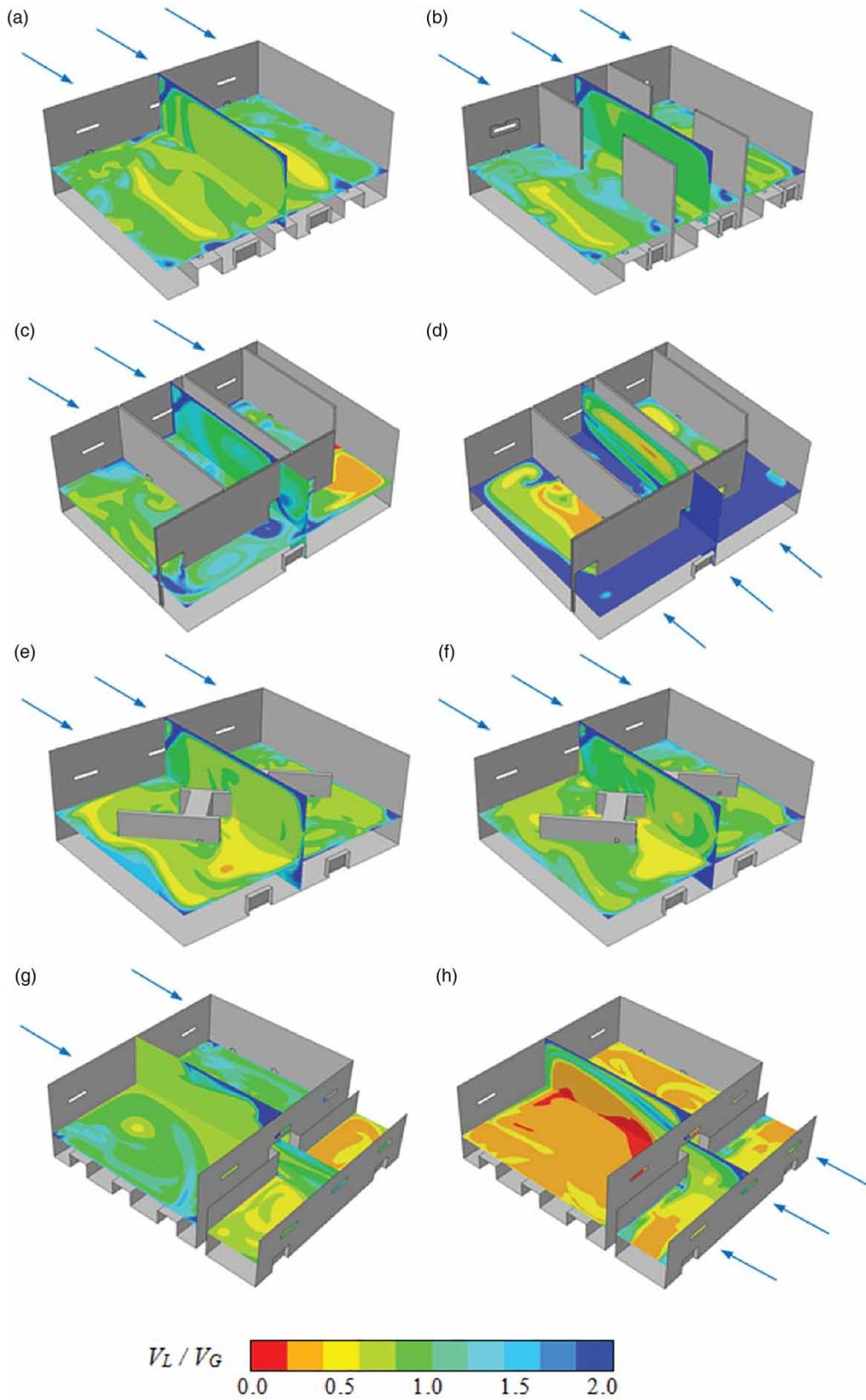


Figure 12 Contour plots of the relative ventilation rate, V_L/V_G , for high wind speed (1.5 m/s)
 Key: (a) traditional, (b) partitioned, (c) Pullman (windward ventilation), (d) Pullman (leeward ventilation), (e) skewed island, (f) skewed island (raised partitions), (g) external corridor (windward ventilation), and (h) external corridor (leeward ventilation) hospital wards

Table 3 Thermal distribution within each ward for summer conditions

Hospital layout	Summer low ventilation		Summer high ventilation	
	T_{B-AVE} (°C)	ΔT (°C)	T_{B-AVE} (°C)	ΔT (°C)
Traditional	22.4	0.4	22.2	0.1
Partitioned	22.4	0.3	22.2	0.1
Pullman – windward	22.8	1.0	22.5	0.5
Pullman – leeward	22.5	1.2	22.6	0.7
Skewed island	22.6	0.5	22.4	0.1
Skewed island – raised	22.5	0.3	22.3	0.1
External corridor – windward	22.4	0.2	22.3	0.1
External corridor – leeward	22.3	0.2	22.2	0.2

Note: Bold numbers denote maximum temperature per column.

Table 4 Thermal distribution within each ward for winter conditions

Hospital layout	Winter low ventilation		Winter high ventilation	
	T_{B-AVE} (°C)	ΔT (°C)	T_{B-AVE} (°C)	ΔT (°C)
Traditional	19.3	1.4	18.0	0.7
Partitioned	19.6	1.1	18.7	1.0
Pullman – windward	20.4	1.6	19.2	1.1
Pullman – leeward	21.0	1.6	20.0	1.4
Skewed island	20.3	1.1	19.1	1.0
Skewed island – raised	20.3	0.9	19.1	1.2
External corridor – windward	21.5	2.2	20.8	2.6
External corridor – leeward	19.5	1.1	18.4	0.8

Note: Bold numbers denote minimum temperature per column.

in reality variation in surface temperatures and proximity of patients to radiators and external walls will influence thermal comfort as well as the air temperatures.

Functional evaluation of the adaptation options

Figure 13 records the original plan of the BRI Nightingale wards. The adaptation options were interrogated

by clinical staff at BRI responsible for the care of elderly patients within Ward 3, a Nightingale ward in its original configuration but broadly divided by gender into three sections. Those consulted were the divisional general manager, nursing sister, head of nursing, a consultant in elderly care and various staff nurses. They all reported positive operational benefits in caring for the elderly from the open arrangement, echoing Maben: for the exceptionally frail and fearful, the other patients are a resource, intervisibility between patients is a positive benefit. Staff were keenly aware of coroners' reports into the ward deaths criticizing the use of side rooms, verdicts recording that patients were not viewed sufficiently often and were generally isolated. Divisional General Manager Neary believed: "security" was equated directly with "dignity", using 'security' in the broadest sense to include infection risk, and this was a misconception.² Patrolling of wards had been phased out, but was likely to be reintroduced. Relatives needed to be able to locate staff quickly. Ease of circulation within the ward was critical, nurses' stations were more effective as mobile trolleys, particularly for the patient admission process; 'crash' trolleys for use in treating cardiac arrest needed to be 'on hand', not parked in corridors; relatives should not be parked in corridors; trolleys bringing food and drink, dispensing pharmaceuticals, bearing X-ray equipment, ultrasound, all required to pass each other. Medical students progressed in groups of six at BRI. The central aisle of the Nightingale enables staff to assess patients' walking capability in judging their potential for home discharge.

Discussion of the adaptation options recorded the following observations by the staff and allowed the options to be developed further in light of their likely operational use:

- *Subdivision of the ward to create single-bedded bays*

This approach moves the ward closer to the DH ideal (and ironically is the pattern of the mediaeval hospital, e.g. the Heiligen Geist in Lubeck). Cubicles are formed in full-height partitioning, the doors likely to be maintained open. Twelve beds can be accommodated with a nurses' station rather than the 20 currently accommodated. Dimensionally the subdivision of open Nightingale wards into single rooms with dedicated bathrooms is inherently inefficient, not least because of the minimum bed spacing dimension and therefore the window spacing dictated by Nightingale. The drawing depicts the arrangement within a Nightingale pavilion at Bradford somewhat narrower than the norm so that circulation is restricted but in a full-width ward the additional 2–3 ft would enable greater functionality. Access to bathrooms

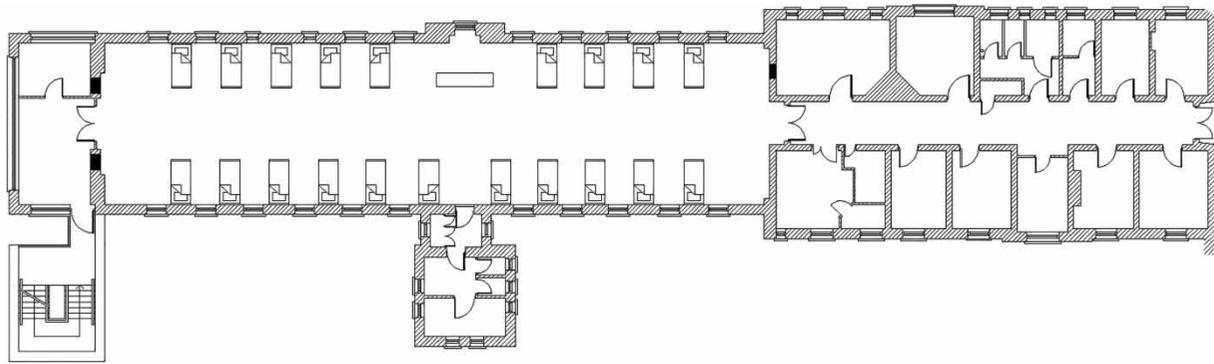


Figure 13 Bradford Royal Infirmary, Nightingale ward: original plan form

remains limited, providing external bathroom pods to each stack of rooms would remove almost all glazing, however four are shown at the each corner of the ward (Figure 14). The BRI clinical staff opposed this configuration for elderly care but were more positive about its potential for short-stay, day-case elective surgery. Nonetheless many of the positive benefits associated with the open-ward arrangement are negated.

- *Subdivision of the ward to create multi-bedded bays on one side of the ward and a corridor on the other*

This approach is reminiscent of a traditional first class ‘Pullman’ railway carriage forming six compartments of two beds. Each two-bed ward is provided with a bathroom pod, a significant step towards the NHS modernization aspiration. The additional width of a standard ward would ease the space available for the ward rooms

(Figure 15). BRI clinical staff were enthusiastic. Rooms could be organized by gender but on a flexible basis, beds could be offset to break immediate intervisibility.

- *Centralization of the beds*

This option places a wardrobe-height spine bulkhead carrying water supply and other services required at the bedhead, along the centre of the wards, with 14 beds facing the windows. The Cabinet Office showed some enthusiasm for this configuration, which the authors do not claim to have invented.³ It is vaguely reminiscent of an airline business class cabin arrangement. Patients no longer face each other but enjoy a view protected from direct solar gain and glare, retain some contact with patients to either side, and can receive visitors in relative privacy. Each patient has an individual washbasin, wardrobe and drawer unit. Tracked curtains could provide

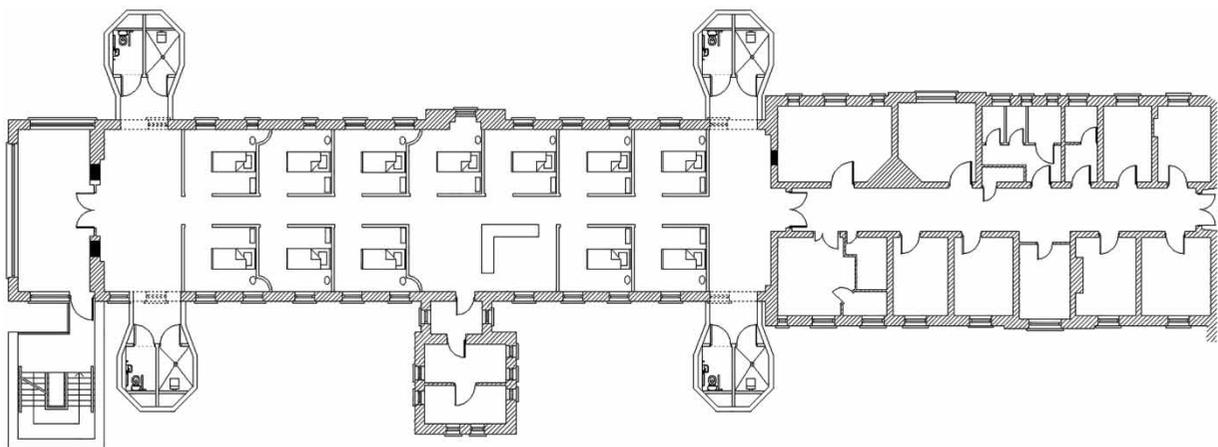


Figure 14 Adaptive reconfiguration: partitioned, single-bed bays

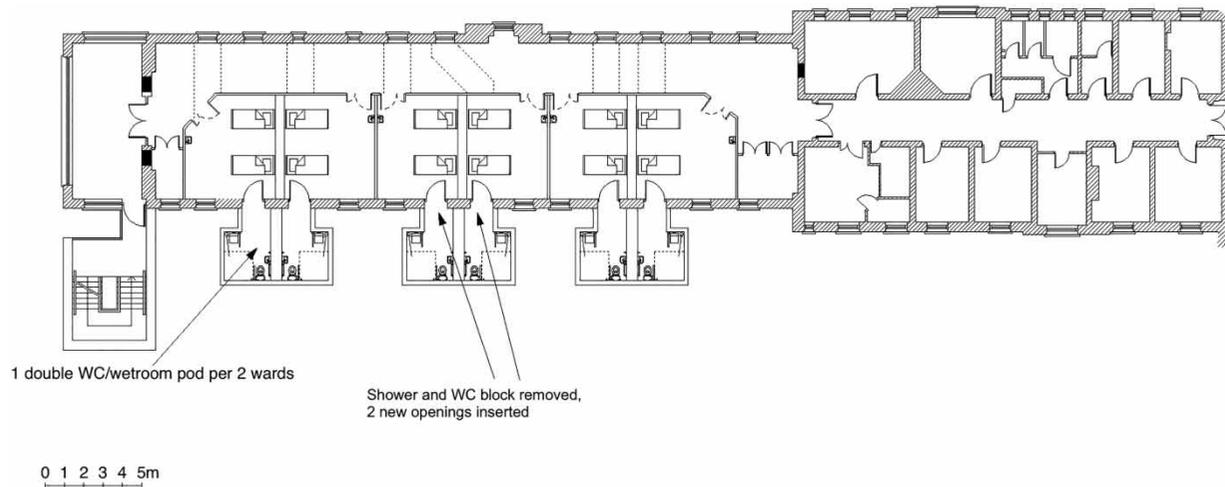


Figure 15 Adaptive reconfiguration: Pullman

complete visual if not acoustic privacy for treatment. Discussion with hospital staff suggested that earlier versions with a straight central spine could develop a ‘zigzag’ geometry in plan, with beds offset for greater privacy, enabling beds to be pushed in and out of the ward to operating theatres, imaging suites and treatment rooms (Figure 16). BRI staff were unconvinced that this arrangement offered benefits for elderly care because there is no direct intervisibility between beds. ‘Wayfinding’ may be difficult for the confused, delirious and alcoholic who would have difficulty identifying their allocated bed. However, the arrangement provides an interesting compromise for care of the less vulnerable, preserving the beneficial airflows observed within the original type.

- *Externalized circulation*

An external corridor is added to the eastern perimeter of each floor, steel-framed with timber stud construction clad in lightweight materials, insulated to contemporary UK Building Regulation standards, accessed through doorways formed in window openings cut down to floor level. The design attempts to recover opening window area on the corridor side but the asymmetry affects the dispersion of pathogens as reported above. The removal of circulation from the main body of the building releases spaces to take three to five beds, each ward served by a new bathroom tower (Figures 17–19). Here the additional width gained within the ward rooms is highly beneficial, the full width available afforded adequate space between beds for

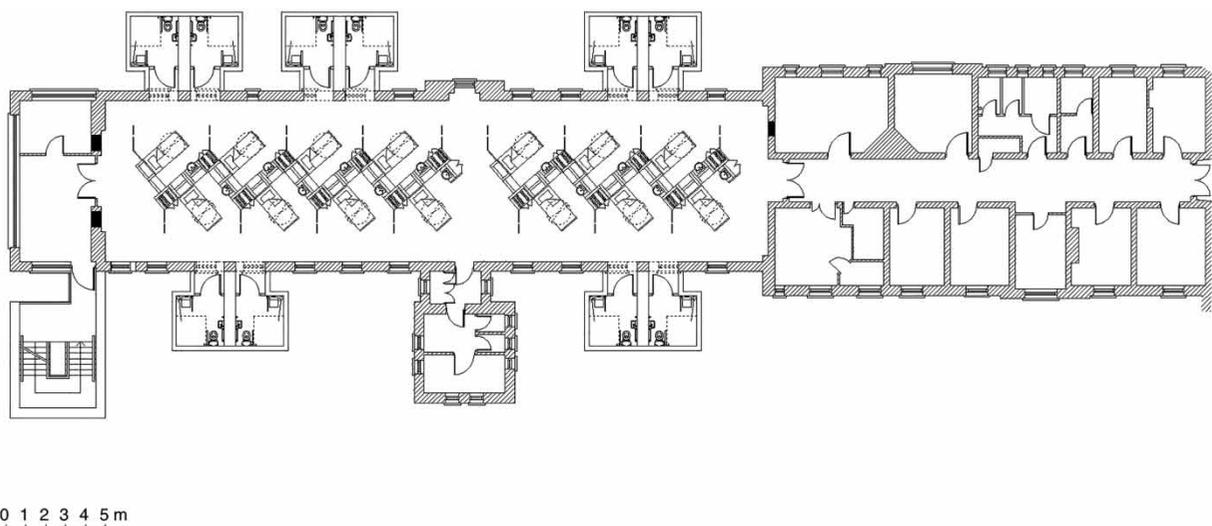


Figure 16 Adaptive reconfiguration: central spine, zigzag

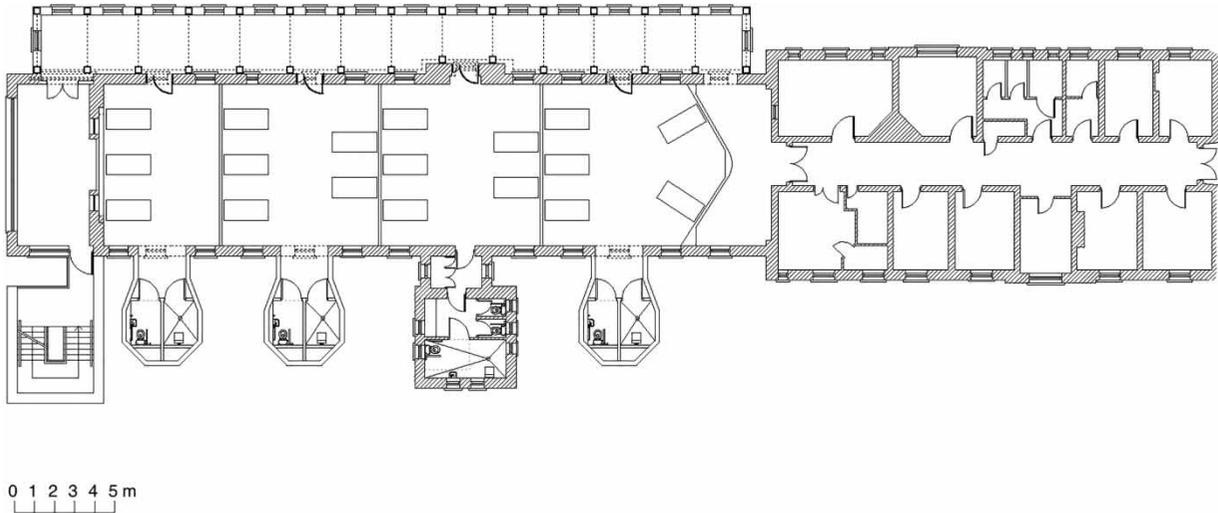


Figure 17 Adaptive reconfiguration: externalized circulation – extended corridor

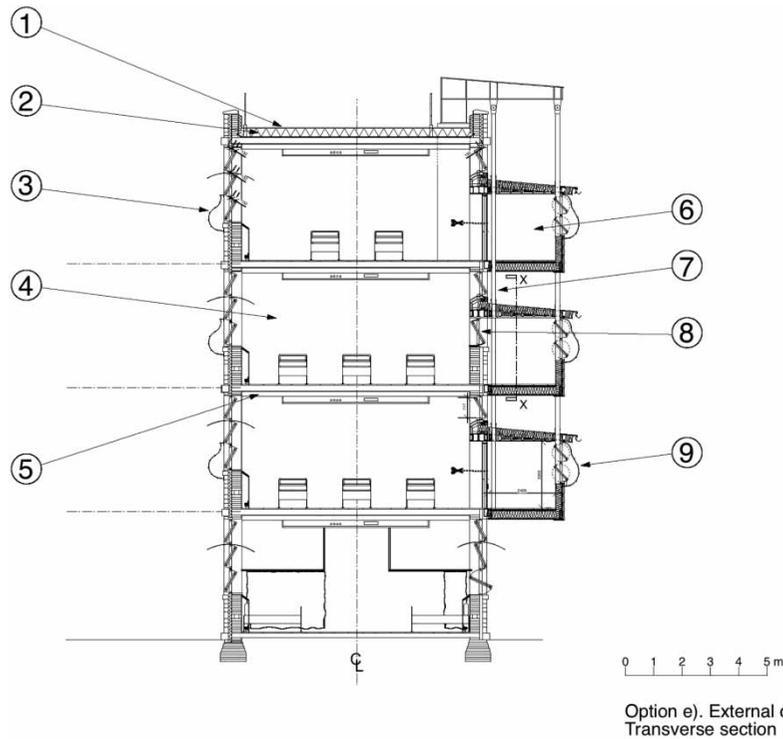


Figure 18 Adaptive reconfiguration: cross-section of the externalized circulation option

Key: (1) windowsill dropped to the floor and the opening widened to form a door into the ward; (2) upper section of the window opening retained to vent/light directly into the ward; (3) floor to new external circulation, 200 mm insulation; (4) steel hangers carry additional corridors and suspend steel frames of added circulation; (5) steel-framed roof construction, 300 mm insulation; (6) elevation of the added circulation element; and (7) horizontal centre pivot windows retain the former opening window areas in the Nightingale ward behind

patient hoists, equipment and relatives in an emergency. Clinical staff emphasized that the width of the proposed new corridor would be critical and that embayments to offer passing places, trolley recharging docks and storage would enhance functionality.

It emerges, therefore, that different ward arrangements are appropriate for different care purposes, that more open arrangements may have higher functionality, if only in patient safety terms, and this safety is less likely to be imperilled by enhanced risk of airborne cross infection than hitherto

understood. The various alternative arrangements are promising in air quality expected with minor enhancements in some cases. This raises interesting questions about viable levels of standardization and particularization in the refurbishment of the national health estate in the UK.

Costs

Table 5 records elemental costings of the four fundamental refurbishment options per floor. These costs were calculated by DeDeRHECC project partners Davis Langdon AECOM. Services renewals account for 40–50% of overall construction cost, weighting the Skewed island option in particular.

Table 6 reveals however that the Skewed island and Pullman options are the less cost-intensive in costs per m² and 60–70% of the equivalent new-build cost. The benefit of reduced contract time is only indicated indirectly by the allowances for main contractor preliminaries. Six months to one year to recover lost

bed spaces may be saved with additional value-for-money (VfM) benefits.

Table 7 records discounted lifecycle energy costs for the base case ‘do nothing’ option against option 1. Little lifecycle cost difference between the various refurbishment options emerged. The only major difference affecting energy performance between the ‘do nothing’ case and the four other options is the addition of insulation resulting in a reduction in heating energy.

The four options, then, by reconfiguring patient environments to offer more privacy and dignity, recover inherently resilient buildings. Savings in energy use are available but trivial in comparison with other operational costs. More significant are the potential savings in the avoidance of mechanical cooling installation later in the century. Current UK Treasury VfM models are unable to include such future savings, let alone intangibles such as business continuity or reduced mortality as a consequence of more effective observation.

Table 6 Summary of the refurbishment option costs relative to new-build equivalents at approximately £3404/m²

Refurbishment option	Area (m ²)	Total (£)	Total including external insulation	Cost/m ²	Equivalent new-build cost (£)	Refurbishment/new-build proportional cost (%)
1. Partitions	436	1 054 543	1 204 543	2763	1 500 000	80.3
2. Pullman	559	1 033 880	1 183 880	2118	2 000 000	59.2
3. Zigzag	705	1 458 325	1 608 325	2281	2 400 000	67.0
4. External corridor	498	1 259 762	1 409 762	2831	1 700 000	82.9

Note: Refurbishment costs include external insulation installed behind the existing outer stone skin, allowing for removal and reinstatement, at £150 000. Source: Derived from the Davis Langdon AECOM cost database.

Table 7 Discounted lifecycle energy costs for the base case versus option 1

Case	30-year cumulative discounted energy costs at 3.5% of the Treasury Green Book discount rate	60-year cumulative discounted energy costs at 3.5%, declining after 30 years as the Treasury Green Book directs
Base case (do nothing)	£51 860	£72 255
Add cavity insulation to option 1 above	£33 432	£46 766
Cumulative saving	£18 429	£25 489

Notes: (1) Costs represent energy costs for one floor only to allow a comparison to be made with the cost model. Simplistically these energy costs could be prorated by floor area for multiple floors.

(2) Energy costs only include energy demands included in the Loughborough model (Lomas et al., 2012). It is believed that these energy demands only include space heating, some small power and lighting. They therefore do not include various other energy demands commonly found in hospitals, such as medical equipment.

(3) No maintenance or replacement costs are included since these are thought to be similar between the base case and the various architectural/building services options.

(4) Retail energy costs are taken from Department for Energy and Climate Change projections – IAG guidance.

(5) The reduction in costs is mainly a result of the addition of insulation, which should be seen in the light of the estimated £150 000 costs for insulation rather than the full costs of refurbishment which result in functional improvements (improved privacy, for example) but do not have a benefit that could be monetized easily.

Conclusions

This paper has amplified previous work on the resilience of Nightingale wards by analysing new internal configurations, devised in close consultation with clinicians. These arrangements all introduce higher levels of privacy and dignity (in line with current policy) into the resilient envelopes of Nightingale ward buildings without compromising that innate resilience. Insofar as the desire to achieve greater control of airborne pathogens drove recent disenchantment with Nightingale wards, the reconfiguration options are modelled to predict patterns of airflow and likely concentrations of pathogens in air with a higher dwell time. Model results indicate that good cross-ventilation is still possible with adjustment to the internal layout, provided care is taken to ensure there are appropriate ventilation openings to enable through flow of air. This is particularly important in the two cases with a corridor at the side of the patient rooms (options c and e) where the presence of an internal wall can act to block effective airflows. The construction detail of the adaptation schemes is developed and costed in detail. It is significantly lower than new-build alternatives and quicker to deliver. Net present value calculations using the UK government discount rate are undertaken to predict payback periods, the fundamental data required by HM Treasury in determining viable policy.

The authors argue for a review of policy as the deep financial retrenchment required of the NHS redirects emphasis towards refurbishment. Current economic circumstances place a particular premium on light-touch refurbishment of NHS sites; similarly, a wholly reasonable concern to improve the patient experience also means that cosmetic changes can be favoured over more substantial interventions. In addition, Trusts are reluctant to lose capacity and have concerns about construction noise and dust transmission. The options presented here address these concerns whilst delivering fundamental improvements in privacy and dignity and demonstrating that, with sensible reconfiguration, Florence Nightingale's original approach might yet be viable for the 21st-century NHS. Indeed, this work implies that designers might productively re-evaluate techniques and strategies for good ventilation first deployed in the pre-modern era in order to answer the challenges of contemporary low-energy architecture.

Acknowledgements

The project is a collaboration between Cambridge, Loughborough and Leeds Universities and the Open University. Cambridge is the lead partner, responsible for identifying and interrogating the various NHS sites, archival research, reconstruction of original

intent and construction detail, recording of the current state of the buildings with a focus on developing design and refurbishment strategies; the Loughborough team are responsible for environmental monitoring and the modelling of current and future thermal environments. Dr Catherine Noakes and her team at the University of Leeds investigated the infection control implications of the proposals. Short and Associates Architects drew the building as designed, as is, and our refurbishment options. The project team is grateful for the support of the Department of Health and four hospital trusts: Cambridge University Hospitals NHS Foundation Trust, Bradford Teaching Hospitals NHS Foundation Trust, West Hertfordshire NHS Trust, and University Hospitals of Leicester NHS Trust. The work reported here would not have been possible without the co-operation of Bradford Teaching Hospitals NHS Foundation Trust, Dr Brown, Nursing Sister Mosley and their colleagues at BRI Ward 3 (interviews held on 22nd March 2012) and members of the Estates Department, who provided access for data collection. Ian Hinitt, Deputy Director of Estates, has been particularly helpful to the work. The 'Prometheus' project team at the University of Exeter provided the future climate data sets and the British Atmospheric Data Centre facilitated access to current weather data. Paul Banks and Sam Archer of Davis Langdon AECOM provided regular and insightful comment on costs, Phil Nedin's healthcare team at Arup provided important insights into the mechanical and electrical servicing implications of the emerging designs including detailed costs.

Funding

This work was undertaken at part of the UK Engineering and Physical Sciences Research Council project, 'Design and Delivery of Robust Hospital Environments in a Changing Climate' [grant number EP/G061327/1], which was funded through the 'Adaptation and Resilience to a Changing Climate' (ARCC) programme under the auspices of the 'Living with Environmental Change' (LWEC) initiative. The Project also received funding directly from the Department of Health and the Sir Isaac Newton Trust.

References

- American Society of Heating, Refrigeration and Air-Conditioning Engineers. (2003). *HVAC design manual for hospitals and clinics*. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers.
- Ayliffe, G.A.J. & English, M.P. (2003). *Hospital infection: from miasmas to MRSA*. Cambridge: Cambridge University Press.
- Beggs, C. B., Noakes, C. J., Shepherd, S. J., Kerr, K. G., Sleight, P. A., & Banfield, K. (2006). The influence of nurse cohorting on hand hygiene effectiveness. *American Journal of Infection Control*, 34(10), 621–626.

- Burdett, H. C. (1893). *Hospitals and asylums of the world*. London: Churchill.
- Carmichael, C., Bickler, G., Kovats, S., Pencheon, D., Murray, V., West, C., & Doyle, Y. (2012). Overheating and hospitals – what do we know?. *Journal of Hospital Administration*, 2(1), 1–7. <http://dx.doi.org/10.5430/jha.v2n1p1>
- CIBSE. (2008). *The use of climate change scenarios for building simulation: The CIBSE future weather years*. London: CIBSE.
- Commission for Healthcare Audit and Inspection. (2007). *Investigation into outbreaks of Clostridium difficile at Maidstone and Tunbridge Wells NHS Trust*. Retrieved from BBC website. Retrieved February 6, 2014, from http://news.bbc.co.uk/1/shared/bsp/hi/pdfs/11_10_07maidstone_and_tunbridge_wells_investigation_report_oct_2007.pdf
- David, D. (2011). ‘We should not dismiss the value of nightingale wards’. *Nursing Times*, 28 May. Retrieved February 6, 2014, from <http://www.nursingtimes.net/nursing-practice/clinical-zones/management/we-should-not-dismiss-the-value-of-nightingale-wards/5030393.article>
- Department of Health. (2001). *Department of health, national service framework – for older people*. Retrieved July 21, 2011, from http://www.dh.gov.uk/prod_consum_dh/groups/dh_digitalassets/@dh/@en/documents/digitalasset/dh_4071283.pdf
- Department of Health. (2002). £40 million to eliminate outdated Nightingale wards. Press release. Retrieved November 18, 2013, from <http://www.prnewswire.co.uk/news-releases/40-million-to-eliminate-outdated-nightingale-wards-154713785.html>
- Department of Health. (2006). *Health technical memorandum 07-02: EnCO2de: Making energy work in healthcare*. London: The Stationery Office.
- Department of Health. (2007). *Health technical memorandum 03-01: Specialised ventilation for healthcare premises*. London: The Stationery Office.
- Department of Health. (2008a). *In-patient care Health Building Note 04-01: Adult in-patient facilities*, Gateway Ref. 8554. London: The Stationery Office.
- Department of Health. (2008b). *High quality care for all*, ed. Darzi et al, CM 7432. London, The Stationery Office.
- Department of Health. (2008c). *Estates returns information collection (ERIC) [data set]*. Retrieved October 1, 2009 from <http://www.dh.gov.uk>
- Department of Health. (2009). *Health Technical Memorandum 07-07: Sustainable health and social care buildings*. London: The Stationery Office.
- Department of Health. (2010). Privacy and dignity. Retrieved July 21, 2011, from http://webarchive.nationalarchives.gov.uk/+www.dh.gov.uk/en/Managingyourorganisation/Workforce/Leadership/Healthcareenvironment/DH_4116444
- Department of Health. (2012). Gateway information 1838: ‘Improving energy efficiency in the NHS, applications for capital funding 2012–13’, Foreword by Dr. Dan Poulter, Under Secretary of State for Health, issued 17th December 2012 for internal circulation within the NHS only.
- Department of Health. (2013) *Health building note 04-01 – Adult in-patient facilities*. Retrieved June 24, 2014 from http://www.dhsspsni.gov.uk/hbn_04-01_adult_in-patient_facilities_final.pdf
- Eames, M., Kershaw, T., & Coley, D. (2011). On the creation of future probabilistic design weather years from UKCP09. *Building Services Engineering Research and Technology*, 32(2), 127–142.
- Escombe, A. R., Oeser, C. C., Gilman, R. H., Navincopa, M., Ticona, E., Pan, W., . . . Evans, C. A. (2007). Natural ventilation for the prevention of airborne contagion. *Plos Medicine*, 4(2), 309–317.
- Fair, A. (2014). A laboratory of heating and ventilation: The Johns Hopkins hospital as experimental architecture. *Journal of Architecture*, 19(3), 356–380.
- Gilkeson, C. A., Camargo-Valero, M. A., Pickin, L. E., & Noakes, C. J. (2013). Measurement of ventilation and airborne infection risk in large naturally ventilated hospital wards. *Building and Environment*, 65, 35–48.
- Gilkeson, C. A., Noakes, C. J., Sleigh, P. A., Khan, M. A. I., & Camargo-Valero, M. A. (2011). Simulating pathogen transport within a naturally ventilated hospital ward. *World Academy of Science, Engineering and Technology*, 79, 119–125.
- Godwin, G. (1858). Hospital construction – wards. *The Builder*, 25 September 1858.
- Halliday, S. (2001). Death and miasma in Victorian London: An obstinate belief. *British Medical Journal*, 323, 1469–1471.
- IES. (2011). IES VE Software version 6.4.0.8. Integrated Environmental Solutions, <http://www.iesve.com>.
- Kibbler, C. C., Quick, A., & O’Neill, A. M. (1998). The effect of increased bed numbers on MRSA transmission in acute medical wards. *Journal of Hospital Infection*, 39, 213–219.
- King, A. J. (1966). Hospital planning: Revised thoughts on the origin of the pavilion principle in England. *Medical History*, 10, 360–373.
- Kovats, R. S., Johnson, H., & Griffiths, C. (2006). Mortality in southern England during the 2003 heat wave by place of death. *Health Statistics Quarterly*, 29, 6–8.
- Kumari, D. N. P., Haji, T. C., Keer, V., Hawkey, P. M., Duncanson, V., & Flower, E. (1998). Ventilation grilles as a potential source of methicillin-resistant Staphylococcus aureus causing an outbreak in an orthopaedic ward at a district general hospital. *Journal of Hospital Infection*, 39, 127–133.
- Labour Party. (2001). Renewing public services: NHS reform. Retrieved November 25, 2013, from <http://www.labourparty.org.uk/manifestos/2001/2001-labour-manifesto.shtml>
- Li, Y., Leung, G. M., Tang, J. W., Yang, X., Chao, C. Y. H., Lin, J. Z., . . . Yuen, P. L. (2007). Role of ventilation in airborne transmission of infectious agents in the built environment – A multidisciplinary systematic review. *Indoor Air*, 17, 2–18.
- Lidwell, O. M., Lowbury, E. J. L., Whyte, W., Blowers, R., Stanley, S. J., & Lowe, D. (1982). Effect of ultraclean air in operating rooms on deep sepsis in the joint after total hip or knee replacement: A randomized study. *British Medical Journal*, 285, 10–14.
- Lomas, K. J., & Giridharan, R. (2012). Thermal comfort standards, measured internal temperatures and resilience to climate change of free-running buildings: A case study of hospital wards. *Building and Environment*, 55, 57–72.
- Lomas, K. J., Giridharan, R., Short, C. A., & Fair, A. J. (2012). Resilience of ‘Nightingale’ hospital wards in a changing climate. *Building Services Engineering Research and Technology*, 33(1), 81–103.
- Maben, J. (2009). Splendid isolation? The pros and cons of single rooms for the NHS. *Nursing Management*, 16(2), 18–19.
- Marks, P. J., Vipond, I. B., Regan, F. M., Wedgwood, K., Fey, R. E., & Caul, E. O. (2003). A school outbreak of Norwalk-like virus: Evidence for airborne transmission. *Epidemiology and Infection*, 131, 727–736.
- Milton, D. K., Fabian, M. P., Cowling, B. J., Grantham, M. L., & McDevitt, J. J. (2013). Influenza virus aerosols in human exhaled breath: Particle size, culturability, and effect of surgical masks. *PLoS Pathog*, 9(3), e1003205. doi: 10.1371/journal.ppat.1003205
- Mooney, H. (2008). Single rooms: A blueprint for better care? *Nursing Times*, 104(45), 14–16.
- NHS Sustainable Development Unit. (consultation draft 2008, published 2009). *Saving carbon, improving health: NHS carbon reduction strategy for England*. Cambridge: NHS SDU.
- NHS Sustainable Development Unit. (2010). *Saving carbon, improving health: UPDATE NHS carbon reduction strategy for England*. Cambridge: NHS SDU.

- NHS. (2010). *National health service information centre, hospital estates and facilities statistics 2010* [data set]. Retrieved May 25, 2011 from <http://www.hefs.ic.nhs.uk/ReportFilter.asp>
- NHS. (2011). *NHS research report, evidence-based design*. Health Facilities Scotland, a Division of NHS National Services Scotland.
- NHS England Carbon Footprint. (2012). NHS sustainable development unit. Retrieved May 12, 2014 from http://www.sduhealth.org.uk/documents/publications/NHS_Carbon_Footprint_Published_2012.pdf
- NHS. (2013a). Same-sex hospital accommodation. Retrieved November 28, 2013, from <http://www.nhs.uk/choiceinthenhs/rightsandpledges/samesexaccommodation/pages/overview.aspx>
- NHS. (2013b). NHS constitution 26 March 2013: Respect and Dignity. Retrieved November 28, 2013, from <http://www.nhs.uk/choiceinthenhs/rightsandpledges/NHSConstitution/Documents/2013/the-nhs-constitution-for-england-2013.pdf>
- NHS. (2013c). NHS information centre for health and social care, estates returns information collection (ERIC) 2012/13 [data set]. Retrieved November 28, from <http://www.hefs.ic.nhs.uk/>
- Nightingale, F. (1859). *Notes on hospitals: Being two papers read before the national association for the promotion of social science with evidence given to the royal commissioners on the state of the army in 1857*. London: John Parker & Son.
- Noakes, C. J., Sleight, P. A., Escombe, A. R., & Beggs, C. B. (2006). Use of CFD Analysis in Modifying a TB Ward in Lima, Peru. *Indoor and Built Environment*, 15(1), 41–47.
- Nuffield Provincial Hospitals Trust. (1955). *Studies in the functions and design of hospitals*. London: Oxford University Press.
- Plowman, R., Graves, N., Griffin, M. A., Roberts, J. A., Swan, A. V., Cookson, B., & Taylor, L. (2001). The rate and cost of hospital-acquired infections occurring in patients admitted to selected specialties of a district general hospital in England and the national burden imposed. *Journal of Hospital Infection*, 47(3), 198–209.
- Pollock, A.M., Shaoul, J., & Vickers, N. (2002). Private finance and “value for money” in NHS hospitals: a policy in search of a rationale? *BMJ*, 2002 (324). doi: <http://dx.doi.org/10.1136/bmj.324.7347.1205>
- Qian, H., Li, Y., Nielsen, P. V., & Huang, X. H. (2009). Spatial distribution of infection risk of SARS transmission in a hospital ward. *Building and Environment*, 44, 1651–1658.
- Qian, H., Li, Y., Seto, W. H., Ching, P., Ching, W. H., & Sun, H. G. (2010). Natural ventilation for reducing airborne infection in hospitals. *Building and Environment*, 45(3), 559–565.
- Riley, R. L., Wells, W. F., Mills, C. G., Nyka, W., & McLean, R. (1957). Air hygiene in tuberculosis: Quantitative studies of infectivity and control in a pilot ward. *American Review Tuberculosis and Pulmonary Diseases*, 75, 420–431.
- Roberts, K., Smith, C. F., Snelling, A. M., Kerr, K. G., Banfield, K. R., Sleight, P. A., & Beggs, C. B. (2008). Aerial dissemination of clostridium difficile spores. *BMC Infectious Diseases*, 8(7). doi:10.1186/1471-2334-8-7
- Sadler, B. L., DuBose, J. R., Malone, E. B., & Zimring, C. M. (2008). Business case for building better hospitals through evidence-based design. The Center for Health Design and Georgia Institute of Technology, College of Architecture. Retrieved November 25, 2013, from <https://www.healthdesign.org/chd/research/business-case-building-better-hospitals-through-evidence-based-design>
- Short, C. A., Lomas, K. J., Renganathan, G., & Fair, A. (2012). Building resilience to overheating into 1960’s UK hospital buildings within the constraint of the national carbon reduction target: Adaptive strategies. *Building and Environment*, 55, 73–95.
- Snow, T. (2008). Planning the future of ward design. *Nursing Standard*, 23(11), 2–13.
- Tang, J. W., Noakes, C. J., Nielsen, P. V., Eames, I., Nicolle, A., Li, Y., & Settles, G. S. (2011). Observing and quantifying airflows in the infection control of aerosol- and airborne-transmitted diseases: An overview of approaches. *Journal of Hospital Infection*, 77(3), 213–22.
- Taylor, J. (1988). Circular hospital wards: Professor John Marshall’s concept and its exploration by the architectural community in the 1880s. *Medical History*, 32(4), 426–448.
- Tellier, R. (2009). Aerosol transmission of influenza a virus: A review of new studies. *Journal of the Royal Society Interface*, 6(6 Suppl 6), S783–790. doi: 10.1098/rsif.2009.0302.focus
- Thompson, J. D., & Goldin, G. (1975). *The hospital: A social and architectural history*. New Haven and London: Yale University Press.
- Tomes, N. (1998). *The gospel of germs: Men, women, and the microbe in American life*. Cambridge, MA: Harvard University Press.
- Ulrich, R. S., Zimring, C., Zhu, X., DuBose, J., Seo, H.-B., Choi, Y.-S., ... Joseph, A. (2008). A review of the research literature on evidence-based healthcare design. *Health Environments Research & Design Journal*, 1(3). Retrieved February 6, 2013, from https://smartech.gatech.edu/bitstream/handle/1853/25676/zimring_HERD_2008_research_litreview.pdf?sequence=1
- Wells, W. F. (1935). Air-borne infection and sanitary control. *Journal of Industrial Hygiene*, 17, 253–257.
- World Health Organisation. (2009). Natural ventilation for infection control in health-care settings. Retrieved from WHO website. Retrieved February 6, 2014 http://whqlibdoc.who.int/publications/2009/9789241547857_eng.pdf
- Yu, I. T. C., Li, Y., Wong, T. W., Tam, W., Chan, A. T., Lee, J. H. W., ... Ho, T. (2004). Evidence of airborne transmission of the severe acute respiratory syndrome virus. *New England Journal of Medicine*, 350, 1731–1739.

Endnotes

¹25 GJ/100 m³ ≈ 14 × 1.78 GJ/100 m³.

²Meeting at Bradford Royal Infirmary (BRI), 22 March 2012.

³Cabinet Office presentation to Nelja Sabberton Head of Resilience Planning, an interdepartmental initiative and Department for Environment, Food and Rural Affairs (DEFRA) and Department for Communities and Local Government (DCLG) officers, 24 July 2012).