EVALUATION OF A SUSTAINABLE HOSPITAL DESIGN BASED ON ITS SOCIAL AND ENVIRONMENTAL OUTCOMES

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by
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ABSTRACT

The study assessed the performance of a newly-built sustainable hospital by comparing the thermal comfort of its patients and staff, and the ambient thermal conditions with those of two other hospitals with less sophisticated designs. Additionally, a facility management perspective was used to understand the role hospital administrators had in contributing to sustainable design outcomes and document the unanticipated challenges and unintended consequences of operating the newly-built sustainable hospital.

Data were collected through thermal environment equipment, a thermal comfort survey, and interviews with care providers, patients, and facility managers. The hypotheses were that the hospital with the modern and more sophisticated sustainable ventilation design features would have a higher level of thermal comfort and lower heat index in the naturally ventilated wards than hospitals without those features and that thermal comfort would be higher in air-conditioned wards than naturally ventilated wards.

The results indicate that sophisticated sustainable hospital designs can improve the ambient thermal environment and occupant thermal comfort but not all those features were necessary. The study also suggests the need for adopting an integrated sustainable design strategy to prevent or mitigate some of the facility operation challenges encountered. Additionally, the study proposes for a shift in thermal comfort standards and green building rating tools to meet the unique thermal comfort needs of hospital users.

BIOGRAPHICAL SKETCH

Ziqi (Zig) Wu originally hails from the Republic of Singapore. He attended St Catherine's College, University of Oxford where he studied Human Sciences. He graduated with a Bachelor of Arts (First Class Honors) in July 2007 and received the St Catherine's College Book Prize for his performance in the Honor School Final Examinations. He also received a college travel award for conducting ethnographic fieldwork in 2006.

Returning to Singapore after graduation, he worked for the Singapore government from 2007 to 2009. At the Singapore Economic Development Board, he developed and executed strategies to attract and evaluate foreign entrepreneurs in growing their business in Singapore. He was promoted to Assistant Director after successfully establishing and growing new markets in North Asia. He then worked for the Ministry of Health in Singapore as a Health Policy Analyst, where he oversaw the development and the financing of a $400 million hospital project and drafted design guidelines for nursing homes. To further his interest in the field of healthcare facilities, he left Singapore to pursue graduate education at Cornell University in 2009.

At Cornell, he received three full-time teaching assistant scholarships and assisted in the teaching of various courses within and outside his department. He won the inaugural student competition at the ASHE Planning and Design Conference in 2011, and was awarded the inaugural IFMA Foundation International Student of the Year Award and Sodexo graduate scholarship in 2010. Upon graduation, he will work as a facilities planner for a hospital system in Orange County, California.

Dedicated to my parents and grandparents, for all their love, inspiration and support.

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LITERATURE REVIEW

1.1 Introduction

Sustainable buildings have been a topic of growing interest among building professionals, enterprises and academics in the last decade. Sustainability is an approach used in the construction industry to design, construct and operate buildings that minimize their ecological footprint and does not compromise the ability of future generations to meet their own needs (Guenther & Vittori, 2008; Kibert et al., 2002; ISO, 2008). A primary goal of designing sustainable buildings is to limit the environmental impact of the building, while improving economic and social consequences of the occupants and surrounding community with equal priority (i.e., the triple bottom line or TBL).[1] TBL is achieved by utilizing key resources such as energy, water, materials, and land much more efficiently than buildings that are simply built to code; and creating healthier, more comfortable and productive indoor environments (Kats, 2003). According to Luetzkendorf & David (2007), sustainable buildings strive to achieve the following:

1. Sound use of the (justified) space requirement in both quantitative and qualitative terms
2. Minimization of life-cycle costs

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[1] The triple bottom line (TBL) concept arose during the mid-1990s (Sustainability and United Nations Environment Program, 2002) and gained popularity with the 1997 publication of the British Edition of John Elkington's (1998) Cannibals with Forks: The Triple Bottom Line of the 21st Century Business. This framework is used to measure and report business performance in three areas: economic, social and environmental rather than maximizing profits or growth. Corporations have realized that business lacking social and ecological integrity are not viable financially in the long run as their costs will eventually increase and customer loyalty decline (Roberts 2006).

3. Preservation of tangible assets

4. Conservation of resources

5. Conservation of the environment and climate

6. Avoidance of risks to the environment and health

7. Safeguarding the health, comfort and safety of users and neighbors

8. Preservation of cultural assets (e.g., in the case of listed monuments)

From a building life cycle cost perspective, sustainable buildings are cheaper in the long run despite the somewhat higher capital investment (Dowdeswell and Erskine, 2006). The cost premium of constructing green buildings over conventional buildings is often lower than is commonly perceived (Kats, 2003). A cost-benefit analysis on green buildings for the state of California determined that "a minimal upfront investment of about 2% of construction costs typically yields life-cycle savings of over ten times the initial investment" (Kats, 2003). Sustainable buildings have also been shown to improve the quality of the indoor environment. Research on school and office environments has indicated that sustainably-designed buildings can improve learning outcomes, worker performance and occupant satisfaction, while reducing health problems such as sick building symptoms (Romm and Browning, 1998). These indirect benefits of green buildings are far larger than the cost of construction or energy savings given that people are the most expensive asset to any organization.

1.2 Green Building Rating Systems

The adoption of green building practices has accelerated globally with the advent of green building rating systems. There are more than six green building rating systems used internationally including the Leadership in Energy and Environmental Design or LEED (United

States, Canada, China and India), Building Research Establishment Environmental Assessment Methods or BREEAM (UK and Netherlands), Green Star (Australia, New Zealand and South Africa), Comprehensive Assessment System for Building Environmental Efficiency or CASBEE (Japan) and Green Mark Scheme (Singapore). Each rating system emphasizes different aspects of sustainability, but all fall into six basic categories: energy efficiency, water efficiency, site and environmental impact, indoor environment quality, material conservation, and facility management and operations (Ying, p. c.).

1.3 Singapore's Sustainable Building Rating System

The Green Mark Scheme is a green building rating system that was developed in 2005 and promoted by the Singapore government to guide the country's construction industry towards green development. The Green Mark Scheme combines features from BREEAM, LEED and Green Star and awards a certificate to individual buildings based on credits obtained for a set of pre-determined building performance criteria (Ng and Runeson, 2008). Table 1-1 compares the assessment criteria between Green Mark Version 3.0, BREEAM and LEED 2.1 and Green Star Version 2. It is worth noting that Green Mark emphasizes energy and water efficiency because these are the two major areas of concern for Singapore. Some of the energy models used was also tailored to tropical climates. The Green Mark Scheme is relatively weaker in materials and resource recycling as Singapore does not have any natural resources for local sourcing.

Table 1-1 Comparison of Green Mark Scheme with other green building rating systems (adapted from Ng and Runeson, 2008)

Main Assessment Categories	Green Mark v.3		LEED 2.1		Green Star v.2		BREEAM '98	
	Points	% of total points	Points	% of total points	Points	% of total points	Points	% of total points
Site/Project development & ecology	10	10	14	20	8	6	128	11
Energy efficiency and atmosphere	30	30	17	25	24	18	208	17
Water efficiency	20	20	5	7	13	10	48	4
Indoor environment quality & environmental protection	15	15	15	22	27	20	0	0
Innovation & design	15	15	5	7	5	4	0	0
Materials & resources	0	0	13	19	20	15	104	9
Transport	0	0	0	0	11	8	240	20
Pollution & emissions	0	0	0	0	14	10	154	13
Health & comfort	0	0	0	0	0	0	150	13
Management	10	10	0	0	12	9	150	13
Total	**100**	**100%**	**69**	**100%**	**134**	**100%**	**1182**	**100%**

The Green Mark Scheme certification has four award categories—Green Mark Certified (scores 50 to <75), Gold (75 to 85), Gold PLUS (scores 85 to <90) and Platinum (scores 90 and above) (Building Construction Authority, 2010a). The scheme is also tailored to various building types but does not differentiate hospitals from other institutional buildings (Building and Construction Authority, 2010b). In 2009, the Singapore government mandated that all new public buildings with a size exceeding 5,000 m^2 air-conditioned floor area including hospitals must attain the Green Mark Platinum rating, while all existing public sector buildings with an air-conditioned floor area exceeding 10,000 m^2 must achieve the Green Mark Gold Plus award by 2020 (Inter-Ministerial Committee on Sustainable Development, 2009).

1.4 Sustainability in Healthcare and Opportunity for Change

The healthcare industries in the U.S. and Singapore are experiencing a construction boom spurred by increased healthcare needs of the aging population, inadequate aging facilities, bed shortages and capacity bottlenecks (Berry et al. 2003; FMI's Construction Outlook, 2009;

Singapore Ministry of Health, 2011). Construction spending on healthcare projects in the U.S. increased by 46 percent in just 2003 alone, with the bulk of the spending focused on large hospital projects (Consortium for Energy Efficiency, 2005). The Singapore government is also investing heavily into constructing acute care hospitals, community (convalescent care) hospitals and nursing homes to develop regional health care capabilities over the next decade (Khamid, 2011).

Although health care facilities still represent a small percentage of the total building stock, they have a disproportionate impact on the environment because of their unique operational requirements (e.g., 24-hour operations, energy-intensive advanced medical equipment and higher ventilation requirements). Hospitals are the second highest energy consumers on a per square foot basis after the food service industry (Department of Energy, 2003). Almost 850 trillion BTUs of energy are consumed yearly in U.S. hospitals, costing over $5 billion each year on energy or 1-3 percent of a typical hospital's operating budget (Department of Energy, 2008). Medical waste generated from hospitals has previously resulted in environmental contamination (BD&C, 2004). Moreover, hospitals have a special responsibility to ensure that their operations do not pose environmental harm (Cohen, 2006). The American Society for Healthcare Engineering (ASHE, 2001) has explicitly defined a role (i.e., the triple bottom line for health) for hospitals in protecting the health of its occupants and broader community through its operations and buildings (Roberts & Guenther, 2006). These reasons underpin hospitals as prime candidates for sustainable building design and operations, and present opportunity for change.

In the last decade, the health care industry started to recognize the environmental consequences of health-care delivery on the broader community and expanded their definition of health to include environmental health. Some progressive hospitals have made steady progress to solve some of their environmental problems by embracing sustainable design (Cohen, 2006). The Green Guide for Health Care (GGHC) modeled on the U.S. Green Building Council's (USGBC) LEED standard was developed by organizations Health Care Without Harm and Center for Maximum Potential Building in 2002 in recognition of the unique challenges of implementing LEED for healthcare buildings (GGHC, 2011). More recently, the USGBC and the GGHC have co-developed a new LEED Certification for health care facilities titled LEED for Healthcare in order to increase adoption of sustainable design practices in the health care industry (GGHC, 2011; USGBC, 2011). Healthcare organizations are also being challenged by the government and employer coalitions such as the Joint Commissions on Accreditation of Healthcare Organizations to become safer, more productive, efficient and effective, as well as financially stronger (The Joint Commission, 2011).

Given the current construction boom in the healthcare industry, hospitals are well positioned to reap multiple benefits by adopting green practices and sustainable design. The Energy Star Financial Value Calculator estimates that if hospitals reduce energy use by 5%, it is the equivalent of increasing the Earnings Per Share (EPS) by 1 cent where each dollar of energy savings is equivalent to $20 of increase in revenue (Consortium for Energy Efficiency, 2005). Financial benefits aside, hospitals will also be better able to fulfill their social responsibility of improving environmental health.

1.5 Sustainable Design Principles

1.5.1 Equatorial Climate Characteristics

Equatorial climates have a relatively constant and high annual average temperature and humidity, with high humidity and rainfall throughout the year. The annual mean temperature is about 27 ºC (80 ºF), and the range of average monthly temperature is about 1-3 ºC (2-5.5 ºF). The relative humidity often is around 90 percent, in part due to the increased evaporation from the leaves of the ample vegetation and the moist soil (Givoni, 1998. 380). Precipitation in equatorial climates is defined by a regular pattern of afternoon rains, often accompanied by violent thunderstorms due to the convergence of moist trade winds at the equatorial zone (Givoni, 1998). Most of the time, the sky is partially cloudy, diffusing solar radiation. As a consequence, shading devices, which intercept only direct solar radiation, is less effective in hot-humid regions than in places with mostly clear skies. The diurnal temperature patterns depend mainly on the cloudiness conditions. On clear days, the diurnal range can be nearly 8 ºC (14.4 ºF), with minima and maxima of about 24 and 32 ºC (75.2 and 89.6 ºF), respectively. On cloudy days the diurnal range is about 4 ºC (7.2 ºF) with minima and maxima of about 23 and 27 ºC (73 and 80 ºF), respectively (Nieuwolt, 1984). Another characteristic of equatorial climates are the lack of winds at night, making naturally ventilated spaces difficult to inhabit.

The equatorial climatic characteristics such as the high temperatures, high humidity and small diurnal ranges present significant challenges for architects to design environments that are comfortable for occupants while reducing the need for mechanical air conditioning. Of all the building energy requirements, heating, ventilation, air-condition systems (HVAC) constitute the majority of energy usage in hospitals, accounting for up to 60% of hospital energy use and costs (Consortium for Energy Efficiency 2005; Environmental Leader, 2010). Alleviating thermal stress is a focus of equatorial architecture (Givoni, 1998). By reducing the need for cooling requirements for buildings located in equatorial climates through the use of passive ventilation means, the potential for energy savings is enormous.

1.5.2 Natural Ventilation as a Sustainable Design Strategy

Before the introduction of mechanical ventilation in hospitals, natural ventilation was the primary mode of ventilation used in hospitals (ASHRAE 2007b). Classical architecture with H, L, T or U-shaped floor plans were used, together with open courts, limited plan depth and maximum window sizes to exploit natural ventilation and daylight. In recent times, natural ventilation has been largely replaced by mechanical ventilation systems in developed and developing countries. With the rising interest in sustainability, natural ventilation has been 'revived' as a strategy to reduce building energy costs.

Natural ventilation relies on the kinetic forces of air pressure differentials from external wind effects on the building, and from temperature differentials to ventilate a building without the use of any mechanical systems. By capitalizing on the location's wind conditions, and designing the building's floor plate and external wall, natural ventilation can be utilized for more effective cooling of interior spaces. Yeang (2006, 218) notes that when evaluating natural ventilation from the human comfort perspective, attention should be paid not only to the overall amount of airflow but also to the distribution of air velocities throughout the ventilated space. Air movement can generate cooling of occupants by increasing heat loss by both convection and evaporation. An air speed between 0.4 and 3.0 m/s is recommended for naturally ventilated spaces in hot and humid climates (Yeang, 2006, 215). For example, air movement of 1 m/s will reduce an air temperature of 30.25 ºC to an effective temperature[2] of 27.25 ºC. Ceiling fans, which uses a sixth of the amount of energy as air conditioning, would be a good strategy to supplement natural ventilation if the required rate of natural ventilation is too low (Yeang, 2006, 215; Heiselberg & Bjorn, 2002).

Simple natural ventilation is usually achieved with operable windows, vents or other openings in narrow buildings, typically on opposing sides of a space. The benefits of simple natural ventilation are limited by practical considerations since simple natural ventilation is only effective up to a depth of about 2.5 times the ceiling height, and the size of the window openings are constrained for safety reasons (Lomas and Ji, 2009). In more complex naturally ventilated systems (i.e., advanced natural ventilation), the warm air of the building is extracted to the outside through openings in the ceiling (i.e., stack effect[3]), allowing cool outside air to be drawn into the building through openings in lower areas using natural buoyancy forces generated by the inside-to-outside air temperature differences. The taller the building, the greater is its potential to ventilate itself by the stack effect. A building simulation study found that, compared to simple natural ventilation, air-flow and indoor temperature can be more carefully controlled and guarded against fluctuations in outdoor weather at all times using advanced natural ventilation systems (Lomas and Ji, 2009). However, advanced natural ventilation strategies have limited use in hot and humid climates since the stack effect is minimal (Lstiburek, 2006).

[2] Effective temperature (ET) is the temperature of a standard environment that would provide the same sensation of warmth as in the actual environment for various combinations of clothing, humidity and air temperatures (Houghton and Yagloglou, 1923, 1924; Yagloglou and Miller, 1925; Vernon and Warner, 1932).

[3] The stack effect is brought about by warm air rising up to be emitted through high-level outlets and so allowing colder, heavier air to be draw in from the outside (Yeang, 2006, 217). The ventilation rate in advanced natural ventilation systems 'automatically' adjusts in line with the prevailing inside-to-outside temperature difference and the ventilation apertures are automatically controlled (Lomas and Ji, 2009).

There are two main sustainable strategies to enhance the rate and quality of natural ventilated air in buildings in hot and humid climates—bioclimatic strategies and passive design. Bioclimatic strategies aim to provide comfort by minimizing the demand for energy used to cool a building. Optimizing architectural design elements such as layout of the building, its orientation, number, size and design of its windows, the shading devices that surround it, and the thermal resistance and heat capacity of its envelop are examples of bioclimatic strategies.

According to Givoni (1998), the main design objectives of bioclimatic design in equatorial climates are to:

- Minimize solar heating of the building;
- Maximize the rate of cooling in the evenings;
- Provide effective natural ventilation, even during rain;
- Prevent rain penetration, even during rainstorms;
- Prevent entry of insects while the windows are open for ventilation;
- Provide spaces for semi-outdoor activities as integral part of the “living space.”

Passive cooling strategies on the other hand provide cooling by transferring heat to various natural heat sinks using non-energy consuming processes. Examples of passive cooling systems include comfort ventilation, nocturnal ventilative cooling, radiant cooling, evaporative cooling, and using the soil as a cooling source. Givoni (1994) and Yeang (2006, 226) defined in great detail passive design strategies for buildings in hot regions to minimize the consumption of conventional exhaustible energy sources. These strategies are summarized below:

- Comfort ventilation, a simple but effective method to ventilate a space by opening windows, provides a cooling effect mainly during the daytime through higher indoor air speeds, which increases the rate of sweat evaporation from the skin. Comfort ventilation is the most appropriate of the five passive design strategies for hot and humid equatorial climates.
- Nighttime ventilation lowers the temperature of the structural mass of the building interior by ventilation during the night and closing building apertures during the daytime, thus lowering the indoor daytime temperatures. This strategy is most appropriate in climates with a minimal diurnal temperature variation between 5-7 ºC.
- Radiant cooling transfers into the building cold energy generated during the night hours by radiant heat loss from the roof or using a special radiator on the roof, with or without cold storage for the daytime.
- Evaporative cooling can be direct or indirect. Air can also be cooled directly by humidifying them and then introduced into the building. Indirect evaporative cooling of interior environments can be achieved by the evaporative cooling of water from the roof, for example by roof ponds without elevation of the humidity.
- Using the soil as a cooling source is effected by berming the walls and the roof with earth, covering the roof with soil, using highly-conductive walls and roof, and by circulating air through air pipes in the soil that acts as a heat sink to cool the air. A climate that has a substantial annual temperature range would result in optimal performance due to the more pronounced difference in ground temperatures and surface temperatures. However, this strategy may also work in

equatorial climates if the soil is covered with a thick layer of mulch or by raising the building off the ground.

- Desiccant dehumidification and cooling involves using a material (e.g., salt solution) that removes moisture from the air. This process may consume some energy but is usually much less compared to conventional cooling.

Based on the strategies described above, Table 1-2 shows the kinds of design features that are most likely to reduce energy costs, increase sustainability, and increase thermal comfort in an equatorial climate building. The most effective way to minimize the physiological effect of the high humidity is through ventilation. The best bioclimatic and passive design practices for equatorial climates include enhancing natural ventilation by spreading out the building in multiple directions for catching the wind, and optimizing window orientation to reduce solar heat gain and increase ventilation rates.

Table 1-2 Design Features for Enhancing Natural Ventilation (Adapted from Givoni, 1998 and Yeang, 2006)

Design Feature	Description
Building Layout	For air-conditioned buildings: ▪ The building should be compact to minimize the surface area of its envelope, relative to the occupied space. ▪ The window areas should also be minimized to reduce the heat gain and cooling loads. For naturally ventilated buildings: ▪ A spread-out building with large operable windows enables better cross-ventilation[4] than a compact one. ▪ The indoor temperatures tend to follow the outdoor pattern for this case. ▪ A larger area of the envelope and larger open windows enable faster cooling and better natural ventilation, thus minimizing disturbances to restful sleep. ▪ The most effective design feature, combining natural ventilation and rain protection, is the breezeway—a passage cutting across or extending alongside the whole width of the floor. This feature allows concentration of the wind, and thus enhances comfort during very humid or even rainy periods with very light winds. The breezeway could be equipped with operable shutters of a type that can prevent rain penetration while allowing airflow during light winds, but are able to block winds during storms. ▪ Buildings should be shaped and oriented to maximize exposure to the required wind direction, and designed with a relatively shallow plan (about 14 meters external wall-to-wall floor-plate depth) to facilitate cross-ventilation.
Wall facades	▪ Natural ventilation can be enhanced by creating different pressures across the building through a principle known as the Venturi effect. When a significant pressure differential is present, and if wall openings are about 15-20% of the wall area, the average wind speeds through the wall openings can have the potential to be 18% higher than the local wind speed. ▪ Increasing the surface areas of walls to allow for cooling during the evening and night hours would reduce the cooling demands of the room during the day.
Orientation of the main rooms and the openings	▪ The relationship of the building to the wind direction is a major consideration in determining the location of the resting areas during the design stage. Equatorial climates typically have winds mainly from the east (the trade winds belt). ▪ Avoid solar radiation on the eastern and western walls, and windows due to the pattern of the sun's motion in equatorial regions. ▪ To solve the apparent conflict between the best orientation from the solar aspect (south-north) and that optimal for ventilation, suitable design details such as orientating the windows at oblique angles to non-east facing walls to maintain effective ventilation or equipping east-facing windows with appropriate shading (architectural elements or vegetation) can be employed.

[4] Cross-ventilation is defined as the situation in which outdoor air can flow from openings on one side of the building (i.e., the inlet openings) through the building and out via openings on the suction sections of the building (Yeang, 2006, 218).

Organization and subdivision of the indoor space	▪ A building plan which is considered as "ideal" for a hot-humid climate is a detached elongated building with a single row of rooms with openings (windows and/or doors) in two opposite walls, allowing cross ventilation of each individual room independently of others.
Relationship of the building to the ground	▪ Raising the buildings off the ground can improve greatly the potential of ventilation since the ground level has restricted wind speed due to the presence of shrub vegetation.
Size and details of openings	▪ The location, number and size of openings determine the ventilation conditions of the building. The best window opening arrangement to maintain cross-ventilation in hot-humid climates is full wall openings on both the windward and leeward sides of the building. In practice, it is difficult in many cases to have independent cross-ventilation of every room in the building, so architects are advised to at least make sure that air can flow in and out of every room, passing through a series of rooms in the building. ▪ When the wind direction is at a very small angle (nearly parallel) to the wall, as in the case of an elongated building facing north and south in a region with winds from southeast to northeast, it is possible to create effective cross ventilation in a given room by having at least two windows in the windward wall, each with a single "wing wall" or vertical projection. Wing walls are useful low-energy devices that can help capture wind using a 'fin' at the façade to channel wind into the building interiors to increase the internal airflow per hour and so create internal conditions similar to the effects of a ceiling fan. In each one of these windows the projection should be installed on alternative (left and right) sides. The windows should preferably be vertical (i.e., narrow and high). One window will be in a wind pressure zone, acting as inlet, and the other window will be in the suction zone, acting as outlet. Architectural elements projecting in front of the main wall, such as alcoves or bookcases, with windows in front and behind them, can be as effective in enhancing ventilation. ▪ Low-emissivity glass can be used to reflect radiant heat to prevent it from entering a building where it would be absorbed by whatever surface it happened to shine on.
Shading of Openings and Walls	▪ Fixed shading for windows should help to block the low sunrays for eastern and western walls. Inclined overhangs are also useful for shading if horizontal narrow strips of windows are used. In single-story buildings it is possible to shade the walls and the windows by wide verandas, designed as roof extensions, or overhangs, above the walls. Such overhangs form, in effect, a covered outdoor open area, shaded and protected from the rain. Shading by vegetation can also be provided relatively easily to low-rise buildings in hot-humid climates. ▪ For walls: significantly increase the insulation of walls to counteract the solar gain or maintain, by repeated painting (due to fungal growth), a white color of unshaded walls so that the sun will help in drying the walls and reducing the growth of fungi.
Provision of verandas and balconies	▪ As the outdoor climate is often more pleasant than the indoors, verandas and balconies can provide shading and rain protection for the entire building periphery.

Thermal and Structural properties of walls and roof	▪ As walls and roofs have the potential to absorb heat and potentially direct heat flow towards the building interiors, the color and shading of the building envelope are key in increasing the resistance to solar heat gain. ▪ Adopt materials and surface finishes that can minimize solar heating of the interior during daytime and maximize the rate of cooling during the evening and nighttime. Thus, medium thermal resistance of the envelope such as wood is recommended. ▪ Roof surfaces should be highly reflective (i.e., light colors) and have high emissivity (at least 0.9) as it can reduce temperatures up to 10-16 °C on hot days and can decrease cooling costs in air-conditioned spaces on average by 20%. ▪ A radiant barrier—an inexpensive type of aluminum foil—on the underside of the roof can be added to keep at least 95% of the radiant heat from seeping through the roof. ▪ High-albedo and vegetated roofs can reduce heat absorption and retain rainwater for evaporative-cooling. Roof vegetation can also add thermal and acoustical insulation, protect and increase the lifespan of the roof underlay, provide spaces for flora and fauna and increase the biodiversity of the locality.
Site Landscaping/ Vegetation near the building	▪ Maximizing the extent of vegetated surfaces, rooftop gardens and tree planting helps to reduce the urban heat-island effect[5] and provide shading to exposed surfaces, reducing the need for the use of energy in air-conditioning and cooling. Evapo-transpiration and evaporative-cooling in vegetated areas also further cool buildings. ▪ The transpiration and shading of trees has found that tree-shaded neighborhoods are up to 3 °C cooler than neighborhoods without trees. ▪ In order to minimize the blockage of winds and maximize shading, a combination of grasses, low flowerbeds and shade trees with high trunks is thus the most appropriate plant combination in hot-humid climates.
Operations and management of Interiors	▪ To reduce cooling costs, it is important to keep heat and sunlight out of a building during the day by closing all windows, doors, curtains and blinds, especially on windows that face east and west.

[5] The urban heat-island effect results in higher temperatures typical of built-up areas as compared to non-built-up areas. The urban heat-island effect is brought about by changes in ground cover, decreased wind velocity as a result of densely built environments, decrease in permeable ground surfaces that increases the amount of heat radiation from the ground, and the higher thermal capacities of the ground (e.g., pavement and concrete) that emits heat absorbed during the day at night, heat generated by the consumption of equipment and building systems, and the ambient pollution that traps heat (Yeang, 2006, 161).

Natural ventilation, a passive design strategy, has the potential to help hospitals improve energy performance, health and safety, and ultimately achieve the triple bottom line. Natural ventilation has a variety of benefits for building occupants. For example, natural ventilation can ensure a fresh air supply to the interiors for health reasons,[6] increase the occupant thermal comfort zone through air movement, or utilizing winds to cool the building (Yeang, 2006, 211). Simple natural ventilation strategies with operable windows also enable occupant control, which is a benefit in most circumstances. However, Lomas and Ji (2009) notes that in most cases, patients and nurses cannot be relied on to logically operate windows. Properly designed natural ventilation can also result in both capital cost, operational (i.e., maintenance costs) and energy savings by minimizing the need for mechanical ventilation and air-conditioning systems given that occupants do not need as cool a temperature as in air-conditioned spaces. DeDear and Brager (2002) showed that when outdoor temperatures were 30 °C, the average occupant preferred temperatures in naturally ventilated buildings were 27 °C compared to 25 °C in air-conditioned buildings. Naturally ventilated buildings typically use about half the energy of those that are air-conditioned (Kolotroni, Kukadia, & Perera, 1996). Furthermore, natural ventilation can create 'healthier' buildings as there are fewer incidents of 'sick building syndrome' (Seppanen & Fisk, 2002).

Many building developers and owners are keen to adopt natural ventilation, but they face the problem of predictability—continuously maintaining satisfactory comfort conditions indoors is difficult since the two driving forces that generate airflow rate (i.e., wind and temperature difference) depend on outside climatic conditions (Atkinson et al., 2009). The difficulty in

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[6] Natural ventilation helps to control indoor air pollution by diluting stale indoor air with fresh outside air.

predicting the likely performance of simple natural ventilation designs furthermore, could undermine confidence in decisions about whether or not such buildings are likely to overheat. This uncertainty is further exacerbated with the impending rising temperatures as a result of global climate change (Lomas and Ji, 2009). Climate modeling software to date has been unable to accurately predict the performance of spaces that utilize simple natural ventilation (Lomas and Ji, 2009).

Furthermore, modern passive-mode designed buildings must meet much higher comfort and performance levels than older vernacular building designs. Naturally ventilated environments have been criticized on the basis that they create dustier or noisier internal conditions, especially at lower levels of high-rise buildings (Yeang, 2006, 211). Naturally ventilated wards are also vulnerable to exposing its occupants to harmful airborne particulates that may have been released into the atmosphere as in the case of Japan's recent nuclear fallout (CNN Wire Staff, 2011) or haze from forest fires (CNA, 2010). Protection of patients from heat waves (Lomas and Ji, 2009) and allergy-inducing pollen/spores from the outdoors, and fears of infection control issues[7] are also other potential barriers to the adoption of natural ventilation in hospitals. The use of natural ventilation precludes the use of particulate filters and the establishment of negative pressure in isolation areas (Atkinson et al., 2009). Although there is still no firm evidence indicating the risk of hospital-acquired infections spread by natural ventilation, in developed countries such as the US, hospitals have decided as a policy not to use

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[7] To date, there is still no common agreement on the relative significance of airborne transmissions and a general lack of evidence-based research (Short and Al-Maiyah, 2009; Li et al., 2007). Natural ventilation can help reduce airborne transmissions through dilution of air as it increases the rate of air changes but may also expose patients to contaminated air as the quality of naturally-ventilated air are generally uncontrollable. Brachman (1970) has suggested that airborne infections might account for 10% of all sporadic cases of hospital-acquired infections, although it is also difficult to rule out transmissions by other routes.

natural ventilation in clinical spaces to insure against hospital-acquired infection and for other reasons as described above despite its potential for energy savings (Short and Al-Maiyah, 2009). Nonetheless, in other countries such as Singapore and the UK, hospitals utilize natural ventilation in the inpatient wards and other clinical areas due to a different policy view towards the current evidence against natural ventilation. British hospital standards such as HTMO3-01 recommend natural ventilation to be used if minimum fresh air ventilation rates of 10 l/s per person or 6 air changes per hour, with an air temperature range from 18 to 28 °C can be maintained within hospital wards (BS EN 13779, 2005). The thermal comfort standard developed by the Chartered Institution of Building Service Engineers (CIBSE) recommend a 25 °C indoors in the summer, with a peak not more than 3 K above the design temperature (CIBSE, 2005). Singapore hospitals however, currently do not have thermal comfort standards for its naturally ventilated spaces.

Table 1-3 summarizes the benefits and drawbacks of using simple natural ventilation, mechanical ventilation and mixed mode ventilation.

Table 1-3 Advantages and disadvantages of ventilation modes (adapted from Atkinson et al., 2009 and Hua, 2010).

	Mechanical Ventilation/ Air-conditioning	**Natural Ventilation**	**Hybrid (mixed-mode) ventilation**
Advantages	▪ Suitable for all climates and weather with air-conditioning as climate dictates ▪ More controlled and comfortable environment ▪ Smaller range of control of environment by occupants	▪ Suitable for warm and temperate climates—moderately useful with natural ventilation possible 50% of the time (expansion of comfort zone) ▪ Lower capital, operational (energy) and maintenance costs ▪ Reduce carbon emissions and use of CFCs ▪ Capable of achieving high ventilation rate (infection control) ▪ Large range of individual control by occupants ▪ Physical/psychological access to outdoor environment	▪ Suitable for most climates and weather ▪ Energy-saving ▪ More flexible
Disadvantages	▪ Expensive to install and maintain ▪ High energy costs, carbon emissions and use of CFCs ▪ Reported failure rate in delivering the required outdoor ventilation rate ▪ Potential for noise from equipment	▪ Easily affected by outdoor climate and/or occupants behavior ▪ More difficult to predict, analyze and design—difficulty in achieving a consistent airflow direction which has implications for infection control. ▪ Reduces comfort levels of occupants when hot, humid or cold. ▪ Inability to establish negative pressure in isolation areas, but may be provided by proper design; depends on situation ▪ Potential for noise intrusion, pollution and dust. ▪ High-tech natural ventilation shares some of the limitations and disadvantages of mechanical ventilation ▪ Air and water leakage ▪ Floor plan design issues (e.g., window placement) ▪ Energy trade-offs ▪ Building height constraints ▪ Integration with HVAC systems- control issues ▪ Harmful airborne particles (e.g., from nuclear fallout) ▪ Fears of discharge of contaminated air to the outdoors	▪ May be expensive ▪ May be more difficult to design ▪ May still incur energy costs, carbon emissions and use of CFCs ▪ Condensation problems in hot-humid climates

1.6 Thermal Comfort in Healthcare

1.6.1 Thermal Comfort

Despite the energy and cost saving potential of employing natural ventilation design strategies in hospitals, it is not always clear how deviations from optimum thermal conditions may affect the occupant's comfort. Studies of human comfort in school and office environments have found that an environment that makes occupants feel too hot or too cold may cause a decrease in productivity, health and well-being (Wyon, 1974; Parsons, 2003).

Thermal comfort is a psychological phenomenon, not directly related to physical environment or physiological state (Parsons, 2003, 196). Thermal comfort is defined according to the American Society of Heating, Refrigeration, Air Conditioning Engineers (ASHRAE) Handbook as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE Standard 55-2010). As a bipolar phenomenon, thermal comfort can range from uncomfortably cold to uncomfortably hot, with "comfort" being somewhere in the middle of these (Parsons, 2003, 196).

As a result of its importance, over the past 50 years much research effort has focused on identifying the conditions that will produce thermal comfort and acceptable thermal environments. Earlier studies on thermal comfort focused on developing indices based on climate chamber studies. These include the Effective Temperature (ET)[8] index (Houghton and

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[8] ET is the temperature of a standard environment that would provide the same sensation of warmth as in the actual environment for various combinations of clothing, humidity and air temperatures (Houghton and Yagloglou, 1923, 1924; Yagloglou and Miller, 1925; Vernon and Warner, 1932).

Yagloglou, 1923, 1924; Yagloglou and Miller, 1925; Vernon and Warner, 1932), the Resultant Temperature index (Missenard, 1935, 1948), and Equivalent Temperature index (Dufton, 1929, 1936; Wyon et al., 1985). Macpherson (1962) identified six factors that affect thermal sensation—air temperature, humidity, air speed, mean radiant temperature, metabolic rate and clothing levels. He also identified nineteen indices for the assessment of the thermal environment, with each index incorporating one or more of the six factors. Nevins et al. (1966) and Rohles and Nevins (1971) subsequently conducted extensive climatic chamber trials to provide recommendations for comfort conditions for the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards.

The most significant landmark in thermal comfort research and practice was Fanger's book *Thermal Comfort* (1970), which outlines the conditions necessary for thermal comfort and principles for evaluating and analyzing thermal environments with respect to thermal comfort. Fanger (1970) developed the Heat Balance model (or more widely known as the PMV-PPD index), which establishes the relationship between thermal comfort and the environmental factors (i.e., temperature, thermal radiation, humidity and air speed), and the personal factors of activity levels and clothing. Fanger's (1970) research was based on experiments with American college-aged persons exposed to a uniform environment under steady state conditions. The PMV-PPD index also allows predictions of conditions for 'average thermal comfort' and consequences, in terms of thermal discomfort (i.e., percentage of people dissatisfied), of exposure to conditions away from those for 'average thermal comfort.' The PMV-PPD indexes were also found to hold reasonably well across national-geographic locations, age, and gender after correcting for the effects of clothing and activity levels (Parsons, 2003, 223). In parallel to Fanger's work, a number of indices were also developed using the method of relating actual conditions to the air temperature of a standard environment which would give equivalent effect such as the ET* (Gagge et al., 1971), PMV* (Gagge et al., 1972), and the SET (Gagge et al., 1986).[9]

ASHRAE and the International Organization for Standardization (ISO) used the thermal comfort models described above extensively in the development of their thermal comfort standards—the ASHRAE Standard 55 and ISO7730 (ASHRAE, 2004; ISO7730, 2004). By providing 'cool, dry, still indoor air' within the ranges prescribed by Fanger's heat balance equation, these standards assumed (if it has not been actually tested in the field) that building owners and managers will be able to ensure that at least 80% of occupants feel thermally satisfied.

ASHRAE sponsored a series of field studies to evaluate the applicability of thermal comfort models across different climates (Busch 1990; de Dear and Auliciems 1985; de Dear and Fountain, 1994; de Dear et al. 1991, Donnini et al., 1996; Schiller et al. 1988). These studies led to the development of a global database of thermal comfort field experiments (de Dear and Brager, 1998).

Using this body of research, the PMV-PPD model was found to be quite accurate in predicting thermal sensations for naturally ventilated spaces in cold climates and climate-controlled buildings (DeDear et al., 1998; DeDear and Brager, 2002; Wong and Khoo, 2003), but failed to accurately predict comfort levels of occupants that lived in hot and humid climates (Wong et al., 2001; Wong et al., 2009; Yamtraipat, Khedari, & Hirunlabh, 2005). This result was

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[9] ET* refers to the temperature of a standard environment that would give the equivalent effect for a person experiencing the same skin wittedness, the same mean skin temperature, and the same thermal heat loss at the skin (Gagge et al., 1971). The SET is an extension of the ET* index to include a range of activity and clothing values (Gagge et al., 1972). The PMV* is identical to the PMV but with the value for ET* used in the PMV equation to replace operative temperature to account for the effects of humidity (Gagge et al., 1986).

not surprising given that most of the empirical data on which the PMV-PPD model was based were derived from college-aged subjects who lived in cold climates. Fanger's comfort model had also been criticized for its static view of thermal comfort, with recent research indicating that dynamic thermal environments, provided that occupants have control over them, can lead to more pleasurable thermal experiences (DeDear, 2011).

An alternative to Fanger's PMV-PPD model known as the Adaptive Theory was first proposed by Aulicieums (1981) to account for the variations in thermal preferences between people living in different climates. DeDear and Brager (2002) and Nicols and Humphreys (2002) later revived the Adaptive Theory through their own research. The adaptive model posits that behavioral adaptations (e.g., removing an item of clothing, turning on air conditioning, and having a siesta in the heat of day), physiological adaptation (e.g. sweating rate, metabolism) and psychological adaptation (e.g., altered perception of sensory information due to past experience and expectations) can all have an impact on thermal comfort rather than just the six variables in the PMV-PPD model (Auliciems, 1981).

Most thermal comfort research to date had also assumed that a constant temperature within the optimal range would produce maximal comfort, but according to Gerlach's (1974) experiment on fluctuating temperatures, people preferred variation in temperature and would become uncomfortable after a while due to a phenomenon known as 'thermal boredom.' The goal of adaptive behavior is not to simply avoid discomfort, but also to achieve thermal variation that can bring positive delight (de Dear R. , 2011). Although the thermal conditions in naturally ventilated buildings are more variable, De Dear and Brager et al. (1998) found that occupants actually preferred a significantly wider range of thermal conditions compared to occupants in air-conditioned buildings and explained that naturally ventilated buildings afforded their occupants with greater thermal control than air-conditioned buildings, and this sense of control led to the "relaxation of expectations and a greater tolerance of temperature excursions." This shift in perspective implies that buildings should provide occupants with *the means* to achieve their comfort goal rather than *provide* prescriptive comfort conditions (Nicol, 2011).

Based on the adaptive theory of comfort, deDear and Brager (2002) and Nicol and Humphreys (2002) developed models to predict indoor comfort levels based on outdoor temperatures. However, their regression equations lacked the sophistication that a truly behavioral or adaptive paradigm could offer because it only took into account one aspect of the Adaptive Theory, namely the past thermal experience of occupants (Parsons, 2003, 239). Several researchers have suggested ways in which the PMV model may be integrated with the Adaptive Theory. For example, Fanger and Toftum (2002) suggested factoring an expectancy factor ("e") into the PMV model to predict the thermal comfort of occupants in non air-conditioned buildings, where the value of "e" would depend on the duration of the warm weather over the year (i.e., effect of thermal memory on current experiences of the environment) and the proportion of air-conditioned buildings to naturally-ventilated buildings surveyed.

1.6.2 The Importance of Thermal Conditions for Hospitals

Most studies of thermal comfort and the standards that have been developed around them as highlighted above have mainly investigated healthy adult-aged subjects. Special populations such as babies, the elderly and the sick were seldom included in thermal comfort research, and current thermal comfort standards for these groups may be inadequate. Moreover, as more cities experience the urban heat island effect and global warming,[10] the unfavorable thermal environments could lead to serious consequences for vulnerable populations. Thus, in order to improve patient safety and satisfaction, hospitals would have to consider the needs of these special populations for thermal comfort.

Physiological processes greatly depend on the body's ability to maintain its core temperature near 37 °C (98.6 °F) (Parsons, 2003, 31). Human bodies dissipate heat by varying the rate and depth of blood circulation, by losing water through the skin and sweat glands, and by panting. When these processes are inadequate to remove excess amounts of heat from the body, the body's inner core temperature begins to rise and heat-related illnesses may result. Disorders caused by heat stress in increasing order of severity include heat rash, heat cramps, heat exhaustion and heat stroke. Death can eventually result if the body core temperature rises above 45 °C (113 °F) (Bell and Greene, 1982). Hajat et al. (2002) found an increase in mortality rates in London for average daily temperatures above 19 °C (66 °F). Hospitals such as those in the UK serve an important role in protecting its citizens in the event of catastrophes such as heat waves by providing warnings, advice, and more critically a 'safe haven' (Lomas & Ji, 2009).

Patients may be more vulnerable to fluctuations in thermal conditions than the general population because of their already weakened state of health. Babies, for example, have more limited thermoregulatory control than adults (Parsons, 2003, 237). Sweating will also impose a thermoregulatory strain on the body and may cause skin irritation and dehydration, significant aggravators to those already ill (Parsons, 2003, 237). A study conducted during the Chicago heat

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[10] According to Singapore's National Environment Agency, the average temperature in 2009 was 27.9 °C or 1 °C higher than Singapore's average temperature over the last 50 years (Sudderuddin, 2010). The increase in temperature was attributed to global warming and Singapore's rapid urban development over the last five decades.

wave of 1995 found that people with known medical illnesses had the greatest risk of dying from heat stroke (Semenza, et al., 1996). In 2003, France had a heat wave that caused 14,500 deaths from hyperthermia, with the majority of victims being the elderly (USA Today, 2003). Johnson et al. (2005) studied the link between the 2003 heat wave in England and found that mortality rates were greatest in vulnerable groups, including the very young but particularly the elderly, who were physiologically less able to regulate their body temperatures and/or able to take adaptive action. Unfavorable temperatures have also been found to affect patients in terms of recovery rates (Kurz et al., 1996) and increase their stress levels (Wagner et al., 2006). The potential inability for hospitals to fulfill the thermal comfort needs of its occupants was illustrated by the overheating of wards in the newly built Evalina Children's Hospital in Lambeth London, where children and babies had to endure temperatures as high as 32 °C (90 °F) (Telegraph, 2006).

Thermal discomfort also affects the quality of sleep. A British standard comments that acceptable nighttime temperatures may be lower than daytime temperatures; noting that "thermal comfort and quality of sleep begins to decrease if bedroom temperatures rise much above 24 °C and stating that "bedroom temperatures at night should not exceed 26 °C unless ceiling fans are available" (CIBSE, 2005). However, to date, there is no method for assessing the risks of elevated nighttime temperatures (Lomas and Ji, 2009).

Therefore, hospitals need to be capable of supporting patients who may be particularly sensitive to high temperatures: those with weak or impaired thermoregulatory systems (older people; those on multiple medications; on psychiatric medication affecting thermoregulation and sweating; with chronic or severe illness) and those who are unable to take reasonable adaptive action to ameliorate the effect of high temperatures (e.g., the very young, the bed-bound, patients with mental illnesses). The new British Standard BS EN 15251 provides a basis for calculating the risk of overheating in hospitals and recommends for building owners to recognize the need for spaces that provide for the needs of occupants with 'high level of expectations' and people who are 'very sensitive and fragile persons with special requirements like, handicapped, sick, very young children and elderly persons' (British Standard EN1251, 2007). Moreover, in designing naturally ventilated spaces in hospitals, it is crucial to consider the impact of likely climatic warming.

Furthermore, the thermal environment can play an important role in influencing the consumer perceptions of a hospital's image and impact their satisfaction level with services delivered. Bitner (1990) contends that the temperature, together with other environmental factors, all serve to create a holistic assessment of an environment, which will in turn drive affective and behavioral responses towards a given environment. In health care facilities where patients expect relaxing and rejuvenating environments, extreme temperatures, high noise and confusion are often unpopular, while pleasant environments that are well-ventilated, have adequate space, and are well-signposted increase satisfaction and the desirability to stay or revisit the facility and the likelihood of recommendation to others. Moreover, Hutton and Richardson's (1995) research indicated the possibility of how environmental factors could impact the perception of services delivered including clinical care. Given the low price differential and increasing competition within the healthcare industry, creating optimal thermal environments can only benefit hospitals in helping to attract and retain patients, their families and employees.

Suboptimal thermal conditions can also affect the work performance of healthcare professionals. Uncomfortable temperatures have been shown to significantly reduce complex cognitive and perceptual-motor performance (Ramsey and Kwon, 1988),[11] motor tasks (Mackworth, 1950), and vigilance (Mackworth, 1950). Studies conducted in European workplaces found a linear relationship between the symptoms of sick building syndrome (SBS) in office workers and room temperatures above 22 °C (Jaakkola, Heinonen & Seppaenen 1989; Reinikainen & Jaakkola, 2001). Thermal discomfort was also found to cause stress and anxiety for surgeons while they were performing surgical procedures (Wyon et al., 1967). Given that healthcare professionals are required to perform numerous complex tasks, thermal stress and discomfort have the potential to lead to increases in errors and irritability, and have a detrimental effect on patient care.

The thermal comfort standards that have been developed to date (e.g., ASHRAE Standard 55 and ISO 7730) have utilized subjects from settings other than hospitals and are insufficient for meeting satisfactory levels for all hospital users (Hwang et al., 2007). The elderly or frail patients were found to experience the thermal environment very differently from other patients who were well or healthy office workers (Wong et al. 2009; Hwang et al. 2007). An air temperature range between 21.5 °C (70.7 °F) and 22 °C (71.6 °F) was identified as the preferred condition for English patients as compared to an optimal temperature of 25.6 °C (78.1 °F) for the general population as determined by the PMV model (Fanger, 1970) (Smith & Rae, 1976). In Taiwan, patients were found to prefer a higher temperature than healthy populations (Hwang et al. 2007). A study on hospital workers in Malaysia also found that only 50% were satisfied with

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[11] While the sensation of heat or cold are not in themselves stress symptoms, the cognitive resources needed to adapt to a stressor may result in a decline on complex tasks performance (Sanders & McCormick, 1993, 72-73).

the thermal conditions compared to the 80% satisfaction level required by the ASHRAE Standard 55-2010 (Yau & Chew, 2009). Within the same hospital environment, different user groups may prefer different temperatures for comfort because of different clothing, activity and acuity levels, age, and duration in the ward. For instance, the patients staying in the ward for longer periods of time, whether confined to bed or ambulant, will generally be involved in a minimum of activity and are likely to prefer or tolerate higher temperatures than other user groups (Legg, 1971). Secondly, housekeeping, nursing and medical staff who may be working hard physically (e.g., making the bed, carrying patients, walking around the ward) may have different preferred thermal conditions than those doing tasks involving little physical exertion (e.g., clerical work or medical inspections). Owing to the different activity levels and clothing habits and thermal comfort requirements of the different users, some form of compromise has to be struck so that the majority can be satisfied (Smith & Rae, 1976).

1.7 Singapore's Healthcare System

Singapore's health care system is comprised of both public and private entities and is complemented by Singapore's high standards of living, education, housing, sanitation and hygiene practices and preventative medicine (Ministry of Health, 2011). Singapore's health care system is recognized by the World Health Organization to be one of the best health care systems in the world (Tandon et al., 2000) and is well known for providing accessible and affordable quality healthcare to its citizens (Callick, 2008).

About 80 percent of acute health care is provided by Singapore's public hospitals while the remaining 20 percent is provided by private hospitals. The Singapore government's role as the dominant health care provider allows the country to effectively manage the supply of health care infrastructure and services, manage the rate of public health care cost increases, and improve the quality of healthcare delivery through of the introduction of high-tech/high-cost medicine (Singapore Ministry of Health, 2011).

There were a total of about 11,545 hospital beds in the 29 hospitals and specialty centers in Singapore in 2006, giving a ratio of 2.6 beds per 1,000 total population. About 72% of the beds are provided for by the 13 public hospitals and specialty centers with bed complements ranging from 185 to 2,064 beds per facility. The remaining 16 private hospitals tend to be smaller, with a bed capacity ranging from 20 to 505 beds (Singapore Ministry of Health, 2011).

In 1988, the Singapore government restructured all its 13 public acute hospitals and specialty centers to be run as private companies (similar to not-for-profit organizations) wholly owned by the government. These ‘restructured’ hospitals (as they are commonly called) are subject to broad policy guidance by the government through the Ministry of Health. The restructuring process allowed the hospital management greater autonomy and flexibility to respond more adroitly to the needs of the patients. Through the introduction of commercial accounting systems, the government created a more accurate picture of the operating costs and instilled greater financial discipline and accountability. The restructured hospitals receive an annual government subvention or subsidy for the provision of subsidized medical services to the patients as well as funding for capital improvement projects.

1.8 Hospital Design in Singapore

Hospitals in Singapore are designed to meet international standards geared towards Western medical science but reflect the local climate and culture (Lai-Chuah, 2008). Recently constructed hospitals have been designed with more amenities and larger waiting rooms to accommodate the relatively higher number of visitors and family members since it is a cultural norm for family members to accompany patients during their hospital visits. Advanced technology is also used widely in Singapore hospitals to improve efficiency and quality of care, as exemplified by the use of integrated information systems combining patient records, prescriptions and billing. Patient-centered design such as maximizing external views and noise-reducing finishes is also increasing in popularity. Moreover, hospitals are also built for the ease of maintenance and cleaning.

Sustainable design has been a characteristic of Singapore hospitals since the 1930s. The hot and humid climate of Singapore dictates a need to reduce thermal loads of buildings through the incorporation of bioclimatic and passive strategies such as optimizing building orientation and incorporating sunshades to maintain thermal comfort in the naturally ventilated wards. The ventilation of these ward areas is typically supplemented with ceiling fans (which in some hospitals are individually controlled by patients). As Singaporeans became wealthier and increased their expectations, air conditioning was introduced in some parts of the hospital (e.g., outpatient clinics and private wards) while the subsidized inpatient wards continued to use natural ventilation.

Due to the land scarcity in Singapore, hospitals have to be built with a high plot ratio with some hospitals as tall as 14 stories. Consequently, greater vertical transportation using elevators and fire-evacuation strategies have to be factored into the design. As there is limited ground, roofs are typically landscaped to allow patients green spaces for relaxation.

Energy costs in Singapore are particularly high as the country lacks natural resources. As such, restructured hospitals are designed to keep energy usage down. Similar to the British Department of Health's efforts to mitigate rising energy costs and carbon emissions (Department of Health, 2007), one strategy employed by the Ministry of Health in Singapore is the use of natural ventilation wherever possible. About 65 percent of inpatient wards in Singapore's public hospitals are naturally ventilated (Lai-Chuah, 2008). These are categorized as subsidized bed classes, for which patients pay less than those who chose to occupy the private wards, which are fully air-conditioned. Policy regulations imposing natural ventilation in subsidized classes of wards in restructured public hospitals provide an interesting opportunity to study the impact of the natural ventilation on the thermal comfort of patients and nurses in these different ward classes, some of which are naturally ventilated and some of which are air-conditioned.

1.9 Post-Occupancy Evaluation

The study of buildings after their completion is comprised of two types: post-construction evaluation (PCE) and post-occupancy evaluation (POE) (Duerk, 1993, 215). PCE is concerned with the technical measures of a building's systems' performance (i.e., building commissioning) while post-occupancy evaluation deals with the functional measures and assesses 'the fit between the building's use and its form, perceptions of the building environment, enhancement of activities, and the physical comfort of the building occupants' (Duerk, 1993, 215). Typical POE topics include users' satisfaction with different elements of physical design such as lighting, noise, communication and thermal environment. Early studies of POEs involved "users" evaluations in the design of education, housing, offices and health care settings (e.g., Presier, 1988; Becker, 1974). In Becker's (1974) study of multi-family housing, he examined how satisfied residents were with the physical design of the building, and evaluated how the physical and social (including management) aspects of the facility enabled the residents' ability to effect desired activities. Some building professionals view POEs as an extension of the design process (e.g., Duerk, 1993, 215). Preiser (1988, 5) identified three levels of effort that characterize POEs: i) indicative POEs that provide an indication of major strengths and weaknesses of a particular building performance; ii) Investigative POEs that uses objective evaluation criteria to evaluate buildings; iii) Diagnostic POEs that require substantial resources and use sophisticated measurement techniques with the aim of credibly correlating physical environmental measures with subjective occupant responses. Due to the high cost of conducting diagnostic POEs, only topics of considerable interest are selected for closer study.

Some forms of POEs have also examined the facility management and operational implications of building designs (e.g., Diamond, 1990; Wu, French, & Hodges, 2010). An examination of the interaction between building design and facility operations is an especially important aspect of POEs of sustainable buildings since they are generally more complex and often possess new, untested innovations. Facility managers and operations staff may not have the technical knowledge to manage and maintain these buildings successfully over time. Moreover, there was previously a lack of attention to actual building performance in the building industry. A 2008 USGBC study of 121 new buildings certified through 2006, found that 53 percent of the buildings were less energy efficient than 70 percent of comparable buildings indicating that LEED certification is not sufficient to ensure delivery of a high-performance building (Turner and Frankel, 2008). The measurement and verification of actual building performance post building completion would greatly help to narrow the gap between design intent and actual performance outcomes.

The importance of post-occupancy evaluations are arguably more important for hospital building types as hospitals are one of the most complex type of organizations. Thompson and Goldin (1975, 253) likened the hospital building to a living organism that continuously evolves and changes, and that the design intent of the hospital need not necessarily translate well into the hospital's functional and operational effectiveness and efficiency. Hospitals with award-winning architecture may not operate well due to an organization's ecology (i.e., when an organization's culture and operating procedures are at odds with or not supported by the physical design) (Becker and Steele, 1995; Becker, 2004). Therefore, obtaining measures about the organizational context such as the management approach and operations of facilities would only serve to benefit building owners and other interest groups.

POEs are useful to test how well new buildings met their program specifications and can help fine-tune the building (make recommendations for incremental improvements). For the public sector, where public agencies often own large building inventories and carry "cradle-to-grave" responsibility for their buildings, POEs are useful to generate knowledge to continuously improve building designs over time and benchmark individual buildings against pools of similar buildings to make informed, evidence-based decisions (Steinke et al., 2010).

1.10 Evidence-based Design

Evidence-based design has been defined as "a process for the conscientious, explicit, and judicious use of current best evidence from research and practice in making critical decisions, together with an informed client, about the design of each individual and unique project" (Stichler & Hamilton, 2008, 3). According to Becker and Wu (forthcoming), evidence-based design research generally focuses on identifying which unique features of the environment that has:

1. Significant positive outcomes if executed correctly or significantly negative outcomes if done incorrectly;
2. Are extremely expensive, disruptive, and difficult to change once implemented;
3. Are likely to affect patient care and safety directly;
4. Design elements for which there is an absence of a consensus about which would likely work best and under what conditions.

As a result of the general principles above, EBD research literature have focused on issues such as single versus multiple-bed patient rooms and wards, ventilation systems, nursing unit and patient room design, hand washing basins, noise abatement and universal room design. Design decisions about these have the potential to improve health care delivery including better communication processes and increased teamwork among care providers, higher patient satisfaction, faster recovery rates and lower care provider stress levels. Furthermore, guidance from evidence-based design can also lead to business benefits including strengthening brand and marketshare, better resource allocation, attraction and retention of medical workers, and cost containment (Becker and Wu, forthcoming).

1.11 Studying Sustainable Design for Thermal Comfort in Hospital Wards

While sustainable building design strategies are believed to improve indoor environmental quality and should, therefore improve occupant comfort, satisfaction, health and work performance relative to buildings designed around standard practices, few organizations have conducted post-occupancy evaluations to test the empirical performance of such designs (Heerwagen & Zagreus, 2005).

In 2005, the Ministry of Health in Singapore invested over US$400 mil in tax-supported funds to build a new hospital as a replacement site for the Alexandra hospital, originally built in 1934. The hospital's reduction of energy use and improvement of thermal comfort of occupants using natural ventilation were two of the main goals of the design. Although building simulation models were used to optimize design features of the building,[12] to date no POE has been conducted on the hospital to verify if occupants benefitted from the building design after the building was completed. Furthermore, as mentioned previously, a drawback of natural ventilation strategy employed is that climate-modeling software have poor predictive value for actual post-occupancy performance (Lomas and Ji, 2009).

Naturally ventilated wards are particularly worthy of study because they occupy a substantial percentage of space within restructured hospitals in Singapore and thus there is great potential for replication of a sustainable design solutions in new hospitals. The sickest and most vulnerable patients are also the ones who spend most of their time staying in such wards. In addition, nursing staff will spend much of their working life in wards and they are areas visited by the public (friends and relatives of patients). The problem of thermal comfort in wards may be

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[12] A natural ventilation simulation study was conducted during the pre-design stage of the hospital to study the impact of the prevailing wind directions on the design and optimization of the subsidized wards using CFD simulation and Wind Tunnel testing. The BCA Green Mark Scheme required an air flow of at least 0.6 m/s for naturally ventilated spaces with an outdoor temperature of 30- 31 C. Wind Tunnel tests showed that a wind speed of 0.6 m/s was achieved in KTPH naturally ventilated ward configuration with the sustainable design features (Lee, forthcoming).

exacerbated by the trend of increased usage of electrical equipment as a key component of healthcare delivery that adds to the heat gains in spaces.

1.12 Research Questions and Hypothesis

This thesis will assess whether the thermal comfort level of patients and nurses differs in three Singapore hospitals built at different times and employing different designs to support natural ventilation; and whether comfort levels also vary significantly between patients occupying naturally ventilated and air-conditioned wards. It also examines the management's approach in planning for and operating the sustainable building, and the unanticipated challenges and unintended consequences in managing and operating buildings that incorporated sustainable design features intended for and implemented in a hot and humid climate.

The research hypotheses are:

1. The ambient thermal environment of naturally ventilated wards in the new and most sophisticated hospital with sustainable design, Khoo Teck Puat Hospital, as measured by the heat index, will be lower than those in Changi General Hospital and Alexandra Hospital;
2. The ambient thermal environment of naturally ventilated wards in Khoo Teck Puat Hospital, as measured by the air velocities, will be higher than those in Changi General Hospital and Alexandra Hospital;
3. Patients and Nurses in Khoo Teck Puat Hospital will report higher levels of thermal comfort levels in naturally ventilated wards than in the older naturally ventilated wards in Changi General Hospital and Alexandra Hospital;

4. Patients and nurses in air-conditioned medical units will report higher levels of thermal comfort than in naturally ventilated wards;
5. Khoo Teck Puat Hospital will meet the ASHRAE 55-2010 Standard of having at least 80% of nurses and patients satisfied in both its naturally ventilated and air-conditioned wards;
6. Khoo Teck Puat Hospital will have the highest percentage of patients and nurses who will find the thermal environment in the naturally ventilated wards to be acceptable compared to Changi General Hospital and Alexandra Hospital.

The research questions are:

1. How did the Khoo Teck Puat Hospital management approach sustainability particularly from an operational and facilities management perspective?[13]
2. What were the unanticipated consequences and challenges in managing and operating Khoo Teck Puat Hospital's sustainable design?

This research contributes to the growing field of sustainable design and thermal comfort, and it does so in a building type, the acute care hospital, that thus far has received little special attention in terms of the relationship between sustainability design and thermal comfort, despite the evidence that the hospitals' users differ in distinct ways from the healthy population of office workers often used as the study population for such studies. The results will allow hospital administrators, architects and the Singapore Ministry of Health to better understand what aspects of the sustainable features are viable for future hospitals located in hot and humid climates, with

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[13] Facilities management is a management approach used to understand how the facility and other physical assets can be utilized to meet the strategic goals of an organization, and how the components of a business—people, place, process and technology are integrated (IFMA, 2011).

the potential for cost savings and improved facility outcomes that simultaneously meet hospital care providers' and patients' expectations for thermal comfort.

CHAPTER 2

METHODS

2.1 Research Design

The purpose of this study was to evaluate the effectiveness of a hospital's sustainable design in providing for occupant thermal comfort in the naturally ventilated wards, while documenting the facility management challenges associated with the design. The study compared the physical thermal environment and psychological comfort of both patients and nurses in a newly opened hospital in Singapore that used bioclimatic architecture and passive design elements for enhancing occupant comfort in naturally ventilated spaces with a renovated colonial hospital designed vernacularly and a modern hospital that was built with minimal sustainable design elements. Cross-sectional (patients and nurses) and longitudinal data (nurses only) for thermal comfort across the three hospitals was collected. The study also compared the physical thermal environment and psychological comfort of nurses and patients between the air-conditioned and naturally ventilated wards.

2.2 Site Selection

The Hospitals

Singapore was chosen as the country for study because of its government policies to maintain natural ventilation for subsidized inpatient wards in restructured hospitals. Out of the thirteen possible restructured hospitals in Singapore, three hospitals—Khoo Teck Puat Hospital

(KTPH), Changi General Hospital (CGH) and Alexandra Hospital (AH)[14] were chosen because they met the following criteria:

1. Had naturally ventilated inpatient medical units;
2. Differed in sustainable design elements for naturally ventilated inpatient medical units;
3. Share similar patient room density;
4. Accessibility to survey inpatients and nurses within the inpatient wards;
5. Accessibility to key facilities and operations staff for interviews;
6. Buy-in of senior management.

The Nursing Unit

The orthopedic and surgical wards (nursing units) that were air-conditioned (AC) and naturally ventilated (NV) were selected because of all patient types, orthopedic/surgical patients were the most likely to be lucid and therefore, more capable of accurately reporting their experience of thermal comfort. They were also more likely to stay for extended periods in the ward and less likely to be having fevers that could disrupt their thermoregulatory processes compared to other patient groups. In addition, the orthopedic and surgical ward, being one of the largest in terms of patient beds and staffing would help provide sufficient sample sizes. Within the nursing units, Patients had the option to stay in either NV or AC wards, the latter being the more expensive option. Ward classes B1 (4 bedded) and B2 (5 or 6 bedded) were chosen out of

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[14] Alexandra Hospital remained in operations after relocation of staff to KTPH as a new hospital management (Jurong General Hospital) temporarily occupied the premises. The researcher was unable to gain access to collect data at Alexandra Hospital after the management changed.

the four possible ward classes for comparison as they had similar patient room densities. Another reason for choosing the orthopedic and surgical disciplines was due to the typical ward layouts and designs used as compared to other more specialized ward disciplines. As these ward types were more representative, the external validity of the results from the study could be increased.

2.3 Site Description

Climatic Conditions of Singapore

Singapore is situated 1° 20'N latitude and possesses a consistently hot and humid climate with abundant annual rainfall. The mean annual temperature averages 26.6 °C (with a mean monthly range within 1.1 °C and a diurnal temperature range from 23 °C to a maximum of 34 °C (Wong et al., 2001). The annual relative humidity averages 80.4% with a high of 82% and low of 79% (Climate Temp, 2011). As the country is also only 247 square miles in size, thermal conditions across the different regions do not vary greatly.

Singapore also experiences limited monsoon seasons with two slight variation seasons, the North East monsoon (November-March) and South West monsoon seasons (May-September). These seasons are characterized generally by rainy periods with persistent trade winds, and separated by two relatively short inter-monsoon periods with light and variable winds.

Khoo Teck Puat Hospital

Figure 2-1 Khoo Teck Puat Hospital

Khoo Teck Puat Hospital (KTPH) is a community hospital in the northern region of Singapore. It is comprised of three building blocks and has facilities for outpatient treatment, inpatient, and emergency services. KTPH was completed in July 2010 as a replacement hospital for Alexandra Hospital, which was constructed during the British colonial era in the 1930s. The hospital was designed by US-based Hillier Architecture (now RMRJ) in partnership with a Singapore-based architecture firm, CPG Architects, and built at a cost of approximately US$ 406,360 million.[15]

The hospital is comprised of the following building complexes:

- Two basements (B1 and B2) for parking lots, M&E utilities, workplace shelter, HPVF and other building support facilities

[15] Based on foreign currency exchange rate of $1 US Dollar = $1.30 Singapore Dollars

- A part public landscape plaza, retail pharmacy, and food court at Level 1.
- A six story subsidized outpatient clinic (Level 2 to 6 plus roof)
- A common two story clinic and Diagnostic and Treatment floor (Level 2 to 4) above which is located the a) private inpatient wards (spanning Levels 5 to 8 plus roof) and subsidized inpatient wards (levels 5 to 10 plus roof).

With the extensive use of natural ventilation (about 55% of the hospital is naturally ventilated, see Appendix A for breakdown of spaces by ventilation type), the hospital was projected to operate 35% more efficiently in energy consumption than conventional public hospitals in Singapore (ZEB, 2010). The hospital incorporated a variety of sustainable design features to reduce energy costs while addressing comfort in the naturally ventilated areas of the hospital (See Appendix A for more details):

- Narrow buildings with high ceilings to encourage cross ventilation
- Venturi design to increase wind pressure
- Siting of hospital next to a storm water reservoir to maximize unblocked airflows
- Orientation of building towards prevailing winds to maximize air flow in naturally ventilated wards
- Wing wall design to increase airflow into naturally ventilated wards
- Use of shading devices and low-emissivity (low-e) glass to reduce solar gain
- Lush landscaping to reduce heat island impact
- Building envelope designed to minimize heat gain
- Central atrium to assist passive natural ventilation
- Lab simulation studies to optimize performance of fixtures and site orientation

The hospital was awarded Singapore's Building and Construction Authority's inaugural Platinum Green Mark award in 2009, and scored the highest points in that year according to the KTPH's Facilities Planner (See Appendix B).

Changi General Hospital

Figure 2-2 Changi General Hospital

Changi General Hospital (CGH) is a community hospital located in the eastern region of Singapore. CGH is comprised of two building blocks and has facilities for outpatient treatment, inpatient and emergency services. Like KTPH, the hospital was also designed by CPG Corporation. It has an H-shaped ward tower stacked on a diagnostic and treatment base. The building was oriented to maximize daylight, minimize solar gain, and take advantage of prevailing winds for natural ventilation, but did not have additional façade features to enhance airflow rate. As CGH's site had a height restriction due to the hospital's proximity to the airport, architects designed its inpatient ward ceiling heights relatively lower (by about 0.42 m) than other hospitals in order fit nine stories on the site. All the patient rooms have operable windows. The naturally ventilated wards have efficient ceiling fans that are rotatable on its axis and can save 146,905 kWh annually compared with old ceiling fans.

Alexandra Hospital

Figure 2-3 Alexandra Hospital

Alexandra Hospital (AH) is a community hospital[16] housed in a renovated British military hospital occupying a site of 12.2 hectares in the Southern region of Singapore. AH was constructed during the colonial era of Singapore in 1934 and consists of old colonial buildings that are scattered in various locations linked by long corridors. AH was built with vernacular architectural elements such as high ceilings, articulated layouts and a large numbers of operable windows suited to the hot and humid climate. The facility was awarded with a Green Mark Scheme Gold Award for existing buildings in 2005 (see Appendix C). The Ministry of Health assessed that the sprawling layout of AH as sub-optimal and operationally inefficient for the continued hospital operations, and consequently supported the development of the new KTPH as its replacement (AH@Yishun Primary Design Brief, 2005). A comparison of the three hospitals' facilities is detailed in Table 2-1.

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[16] In 1985, the Singapore government decided to "privatize" the public sector hospitals through a restructuring process. This resulted in the concept of the "restructured hospital". The restructured hospital is a publicly funded hospital, but given fairly autonomous reign to operate, with the aim to improve operational efficiency and cost-effectiveness.

The Nursing Unit

The orthopedic and surgical wards in all three hospitals are comprised of four types: Class A (single-bedded with air-conditioning), Class B1 (four-bedded, with air-conditioning), Class B2 (five- or six-bedded, with natural ventilation) and Class C (ten-bedded, with natural ventilation). Only the orthopedic and surgical ward classes B1 (air-conditioned) and B2 (naturally ventilated) in each of the three hospitals were chosen for the study. Table 2-2 compares the characteristics of the B1 and B2 wards of the three hospitals while table 2-3 provides graphic images of patient bed areas and nursing stations where the study was conducted.

Table 2-1 Comparison of Selected Hospitals

	Khoo Teck Puat Hospital	Changi General Hospital	Alexandra Hospital
Building Completion Date	2010	1997	1934 (Renovated in 2000)
Green Mark Scheme Rating	Platinum (New Construction)	None	Gold (Existing Building)
Sustainable Design Type	Sophisticated	Traditional modern hospital	Vernacular
Design features in naturally ventilated wards	▪ Narrow buildings with high ceilings to encourage cross ventilation ▪ Venturi Design ▪ Siting of hospital next to a storm water reservoir to maximize unblocked airflows ▪ Orientation of building towards prevailing winds to maximize air flow in naturally ventilated wards ▪ Wing wall design to increase airflow into naturally ventilated wards ▪ Use of shading devices and low-E glass to reduce solar gain ▪ Lush landscaping to reduce heat island impact ▪ Lab simulation studies to optimize performance of fixtures and site orientation	▪ Operable Windows with Mechanical Fans ▪ Site Orientation ▪ Mechanical Fans	▪ Articulated Spinal Pavilions ▪ High ceilings ▪ Operable windows on opposite facades ▪ Mechanical Fans ▪ Lush landscaping
Total Square Footage	102,245 sq m (1,100,556 sq ft); Site area: 3.0 ha (7.4 acres)	107,000 sq m (1,152,000 sq ft); Site area: 5.2 ha (12.8 acres)	34,150 sq m (367,587 sq ft) Site area:12.2 ha (30.2 acres)
Facilities Description	Total inpatient beds : 476 in operation (556 licensed) Class B1 (AC) – 64 beds Class B2 (NV) – 160 beds	753/776 inpatient beds Class B1 (AC) – 70 beds Class B2 (NV) – 264 beds	393 inpatient beds Class B1 (AC) – 34 beds Class B2 (NV) – 86 beds

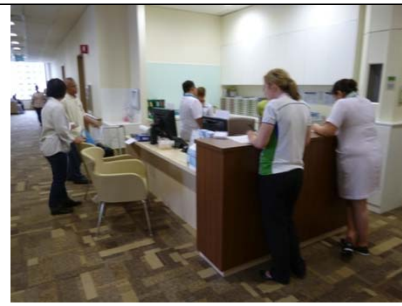
Table 2-2 Comparison of Hospital Ward Characteristics

	Khoo Teck Puat Hospital		Changi General Hospital		Alexandra Hospital	
Ward Name	51_a & 61_a	86_b & 96_b	16_c & 26_c	36_d & 46_d	7	12
Ward Type	B1	B2	B1	B2	B1	B2
Ventilation	AC	NV with fans	AC	NV with fans	AC	NV with fans
Floor Level	5 & 6	8 & 9	6	6	3	3
Ward Size per Ward	511 m^2 (5,500 sq ft)	926 m^2 (9,970 sq ft)	923 m^2 (9,940 sq ft)	754 m^2 (8,118 sq ft)	1384m^2 (14,900 sq ft)	186 m^2 (2,000 sq ft)
Number of Fans/Air-con diffusers and location	4 diffusers and located above patients	5 ceiling fans located directly above patients	4 diffusers located above patients	5 wall-mounted fans located above patients	4 diffusers and located above patients	5 ceiling fans located directly above patients
Height of Room	3 m (10 ft)	3 m (10 ft)	2.58 m (8.5 ft)	258 cm (8.5 ft)	3.20 m (10.5 ft)	3 m (10 ft)
Number and Size of operable windows in a room	None used	9 sets of 70 cm 120 cm Jalousie windows and 6 sets of 70 cm x 55 cm monsoon louvers	None	5 sets of 102 cm x 38 cm Top Hung windows	5 Sets of 63 cm x 46 cm Top Hung Windows	None
Type of Windows	Non- operable	Operable Jalousie[17]	Non- operable	Operable	Non- operable	Operable Jalousie
Room/Cubicle Size						
Number of Beds	4 bedded	5 bedded	4 bedded	6 bedded	4 bedded	5 bedded
Micro-sustainable design features	Light Shelf User-controlled Air-conditioning	Jalousie windows Monsoon Louvers Light Shelf Ceiling Fans	User-controlled Air-conditioning	Plane Windows Mechanical Wall-mounted fans	User-controlled Air-conditioning	Jalousie Windows Wall-mounted fans
Other notes	4 beds per room, air-conditioned room with attached bathroom, television and telephone.	5 beds per cubicle, with natural ventilation and shared bathroom facilities.	4 beds per room, air-conditioned with attached bathroom facilities, television and telephone.	6 beds per cubicle, with natural ventilation and common bathroom facilities.	4 beds per room, air-conditioned with attached bathroom, television, telephone and newspaper.	Six beds per cubicle, with natural ventilation and common bathroom facilities.
Cost per night	\$180 \$214	\$55 \$83	\$176.55 \$197.95	\$53 \$78	\$169 \$192	\$80 \$96

Note: Ward numbers with same lower case indicates wards have the same layout configurations. Please see Appendix D for hospital floor plans.

[17] A jalousie window is comprised of parallel glass set in a frame. The louvers are locked together onto a track, so that they may be tilted open and shut in unison, to control airflow through the window and are usually controlled by a crank mechanism.

Table 2-3 Images of Selected Wards

Hospital	Air-conditioned (B1) Ward: Patient Bed Area	Naturally Ventilated (B2) Ward: Patient Bed Area	Air-conditioned (B1) Ward: Nursing Station Area	Naturally Ventilated (B2) Ward: Nursing Station Area
KTPH				
CGH				
AH				

2.4 Sample Size and Selection

Patients

Three hundred orthopedic and surgical patients were selected to participate in the thermal comfort survey (response rate, 73.7 %). Respondents ranged between the ages of 14-82 years, with an average of 55 patients from each AC and NV orthopedic wards from KTPH and CGH. Patients were selected for the questionnaire as follows: every week, nurses generated a list of 7-8 patients in the ward who were eligible to take the survey. Of those patients, 5 patients were randomly selected and approached to take the survey. To be eligible for the survey, patients were either able to comprehend or understand English or Chinese (Mandarin). They also had to be fever-free and have not taken thermoregulatory drugs in the last 4 hours. Further, patients had to be dressed in standard patient gown/pajamas provided by the hospital without any other outer clothing or blankets covering the body. The patient gowns were of light material (clothing insulation = 0.30 clo) and assumed to be similar across both hospitals. Surveys were distributed by a research assistant during a daytime shift, and collected at the end of the survey. Patients were given a token of appreciation (e.g., sandals, nail clippers, night shades and ear buds) for participating in the survey. The same basic procedure for selecting patients was used in each hospital.

Nurses

Three hundred nurses were selected to participate in the survey (82.3% response rate). The respondents who completed the survey ranged in age from 18 to 68 with an average of 40 nurses from each AC and NV orthopedic and surgical wards from KTPH, CGH and AH (See

Table 2.5). The nurses were all wearing standard nursing uniforms provided by the hospital. The nursing uniforms were of light material (clothing insulation = 0.31 clo) and assumed to be similar across all three hospitals. Nurses were selected for the questionnaire as follows: every week, the nurse manager generated a list of 7-8 nurses in the ward who were eligible to take the survey. Of the 7 nurses, 5 were randomly selected and approached to take the survey. Within a hospital, nurses who have been surveyed previously were not allowed to take the survey again. A subset of AH nurses in the sample (29 out for 52 nurses) retook the survey when they moved to KTPH and were tracked longitudinally. Surveys were distributed by a research assistant during a daytime shift, and collected by the end of the survey period. The same basic procedure for selecting nurses was used in each hospital.

Managing a Sustainable Facility

To better understand the organizational approach to sustainable design and the unanticipated challenges and unintended consequences associated with managing KTPH's contemporary sustainable design, eight interviews were conducted with employees of KTPH with the respective roles:

1. Chief Executive Officer
2. Director of Operations
3. Facilities Planning Director
4. Facilities Manager
5. Nursing Manager
6. Project Manager
7. Project Architect

8. Housekeeping Staff

2.5 Data Collection

Before data collection began, initial steps were taken to insure buy-in from administrative and clinical staff at Khoo Tech Puat Hospital, Alexandra Hospital and Changi General Hospital. This was achieved through presentations describing the background and purpose of the study to the Chief Operating Officers, Directors of Operations, Facility Planners, Facility Managers, Senior Nursing Officers and Operation Executives from the three hospitals. The hospital administration teams from the hospitals were very supportive and genuinely interested to participate in academic research.

Thermal Comfort

A paper/pencil survey was developed to measure perceived thermal comfort levels for both patients and nursing staff (see Appendix E and Appendix F). Both the survey for the patients and nurses were similar except for specific questions regarding nursing performance and patient sleep. The thermal comfort survey addressed four areas:

1. Thermal comfort and sensation;
2. General satisfaction with indoor environment;
3. Habituation
4. Demographic information.

Pre-existing single-item scales such as the ASHRAE thermal sensation scale (ASHRAE Standards 55-2004), the Bedford Comfort Scale (Bedford, 1936) and the McIntyre scale

(McIntyre and Gonzalez, 1976) were selected for the instrument because they have been used widely in the field of thermal comfort research. Other single-item scales from thermal comfort research such as those measuring humidity, air velocity, exposure to sunlight (used by some thermal comfort research) were modified to fit the requirements of developing a seven-point scale. Seven items from the survey were combined to develop a thermal comfort scale (Cronbach alpha= 0.841, Test-Retest Reliability Pearson Correlation=0.507, p=0.016, and 0.381, p=0.102 after controlling for hospital, ward and subject type). The seven items were recoded to be in the same direction and standardized into a Z-score, which were then summed and re-zeroed to create a thermal comfort score that ranged from 0 (completely dissatisfied with thermal conditions) to 24 (complete satisfaction with thermal conditions).[18] A low Test-Retest correlation score was expected as the indoor thermal environment might have varied across days. Summary data that provided the total number of patients and nurses, time spent in Singapore, patient acuity levels, nurses activity levels, general satisfaction with indoor environment, and habituation to air-conditioned environments was collected simultaneously. A listing of data collected in the thermal comfort survey is presented in Table 2-4. In addition, as some of the single-item scales such as the Bedford Comfort Scale (Bedford, 1936) and McIntyre's Acceptability of the thermal environment and thermal preference (McIntyre and Gonzalez, 1976) were used for analyzing the percentage of occupants who were satisfied with the thermal environment, a correlation of the individual items was performed to establish the reliability of these items (as illustrated in Appendix G).

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[18] Based on a sample of 451 subjects, the thermal comfort scale developed had a significant correlation of 0.638 with the standard ASHRAE thermal sensation scale (p=0.000) and 0.786 with the Bedford thermal comfort scale (p=0.000), indicating that the new scale was a good measure of thermal comfort, while taking into account the threat of mono-operation bias that the original individual scales were susceptible to.

Table 2-4 Data collected for Dependent Variable

Tool used	Item	Examples	Rationale
Observations	Hospital	KTPH, AH, CGH	To determine hospital sustainable design type
	Ward	B1, B2	To determine ward that patient was in when survey was conducted
	Location	Bed number 4	To determine the location within the ward
	Clothing Insulation	0.4 clo	Clothing insulation can affect thermal comfort perception
	Actions employed to improve thermal comfort	Drinking cold drinks, wearing blankets	These actions when performed during the period of the survey can distort reporting of thermal comfort
Physical	Air Temperature, relative humidity, air velocity (spot measurements)	27.4 C, 48%, 0.2 m/s	Physical measurements of thermal environment are correlated with psychological perceptions of the thermal environment.
	Air temperature, relative humidity (24-hour cycle)	27.4 C, 48%	Instead of spot measurements, physical variables were measured on a 24-hour cycle
Participant Survey	Sex	Male, Female	To determine gender of subject.
	Race	Chinese, Malay	To determine the race of the subject.
	Age	29 years old	To determine age. Some age groups are more vulnerable to extremes in the thermal environment
	Acuity levels (patients only)	Health status of 2	Acuity levels can affect thermoregulatory processes and perception of comfort
	Activity levels (nurses only)	Walking, Fast-walking	Activity levels can affect perception of thermal comfort
	Thermal Sensation	Cold, Neutral, Hot	Widely used scale in thermal comfort research (Rohles, 1971; 1973) and ASHRAE Standard 55-2010. An ordinal scale that was originally developed to determine how college students responded in climate chamber studies, ranging from 1 to 7, where 1 was Cold and 7 was Hot.
	Acceptability of Thermal Environment	Acceptable, not acceptable	The scale focuses more directly on "thermal satisfaction by probing the participants' judgment of whether conditions are acceptable (McIntyre 1976).
	Satisfaction with indoor air quality	Strongly agree, Strongly disagree	Possible confounding factor of thermal comfort
	Satisfaction with noise/music levels	Strongly agree, Strongly disagree	Possible confounding factor of thermal comfort
	Satisfaction with lighting/daylight levels	Strongly agree, Strongly disagree	Possible confounding factor of thermal comfort
	Satisfaction with views of nature	Strongly agree, Strongly disagree	Possible confounding factor of thermal comfort
	Satisfaction with interior design	Strongly agree, Strongly disagree	Possible confounding factor of thermal comfort
	Reliance on air-conditioning at home	Strongly agree, Strongly disagree	Individuals used to air-conditioning may expect greater comfort in the hospital ward
	Years spent in Singapore	2 years, 5 years	Acclimatization to hot and humid climates will have an impact on thermal comfort perception.
	Choice of wards	Cost-savings, preference for air-conditioning	Individual's choice to stay or work in an air-conditioned ward or naturally ventilated ward will influence their satisfaction levels with the thermal environment.
	Belief in traditional medical theories/ sensitivity to air-conditioning	Agree, Disagree	Can influence patients' decision to stay in air-conditioned versus naturally ventilated wards

Physical Thermal Environment

In addition to the thermal comfort survey, objective physical measurements were taken to determine the thermal conditions corresponding to the subjective thermal comfort ratings. The physical thermal conditions refer to the air temperature, air velocity and relative humidity. Regressing physical environmental data with thermal comfort measures helped increase the validity of the survey.

Figure 2-4 Thermal Environmental (TE) Meter

A Thermal Environmental (TE) meter (Lutron ® LM-5102) as illustrated in Figure 2-4 was used to record the instantaneous air temperature, relative humidity, and air speed at locations where patients and nurses took the survey (spot measurements). Two TE meters of the same model were used for the purpose of allowing each hospital's data collection to happen synchronously.

The direct environment measures were translated into a heat index, which combined the thermal effects of air temperature and humidity.[19] Air velocity data was also collected to explain why there might be large differences in comfort when air temperatures and humidity were comparable.

In addition to these spot measurements of the thermal environment, an indoor air quality meter (Model: IQM AeroQual Air Quality Monitor) as illustrated in Figure 2-5 was used to measure air temperature and relative humidity to provide the heat index in both the air-conditioned and naturally ventilated wards over a 24-hour cycle. The IQM meter was located at the central nursing station of each ward.

Figure 2.4 Indoor Air Quality Meter

[19] The heat index equation was derived from Steadman (1979). The equation for heat index calculated is as follows:

$$\text{Heat Index} = -42.379 + (2.04901523 \times T) + (10.14333127 \times RH) - (0.22475541 \times T \times RH) - (6.83783 \times 10^{-3} \times T^2) - (5.481717 \times 10^{-2} \times RH^2) + (1.22874 \times 10^{-3} \times T^2 \times RH) + (8.5282 \times 10^{-4} \times T \times RH^2) - (1.99 \times 10^{-6} \times T^2 \times RH^2)$$

Where T = air temperature (°F) and RH = Relative Humidity (%)

Behavioral Observations

A tool was developed and used to observe behaviors of subjects that indicated thermal discomfort, actions employed to improve comfort, presence or absence of physical signs of thermal discomfort (e.g., perspiration or shivering), clothing insulation values, activity levels and location within the ward (see Appendix H). The items were based on the theories of the Heat-Balance Model and Adaptive model as described in Chapter 1.

Data Collection Procedures

Both qualitative and quantitative data was collected, and included the use of three methods. These were a thermal comfort questionnaire, physical environment measurements and behavioral observations. A multi-method approach (triangulation) allowed the strengths of each data collection method to buttress the weaknesses of the other methods. In combination the three approaches generated data that addressed hypotheses 1-6 identified at the end of Chapter One.

Thermal comfort and the spot physical environmental data was collected at Alexandra Hospital over a three week period in June 2010 while the same data was collected at Khoo Teck Puat Hospital and Changi General Hospital over a three month period from January 2011 to March 2011. Both the physical environment measurements and the questionnaire were administered every Tuesday between 11.30 am to 3 pm at the three sites. This time period was chosen as the 24 hour thermal data revealed that this was the period where thermal conditions were the most unfavorable. The 24-hour thermal data was collected over 6 days at each of the three hospitals' air-conditioned (AC) and naturally ventilated (NV) wards as indicated in Table 2-5.

Table 2-5 24-hour Thermal Environment Measurement

Hospital	Ward Numbers	Period of measurement
AH	8 (AC)	May 24, 2010 (12.30 am)- May 30, 2010 (11.30 pm)
AH	13 (NV)	May 24, 2010 (12.30 am)- May 30, 2010 (11.30 pm)
CGH	16 (AC)	Feb 15, 2011 (4.30 pm) - Feb 21, 2011 (11.30 pm)
CGH	36 (NV)	Feb 15, 2011 (4.30 pm) - Feb 21, 2011 (11.30 pm)
KTPH	61 (AC)	Jan 26, 2011 (12.30 pm) – Jan 31, 2011 (11.30 pm)
KTPH	86 (NV)	Jan 26, 2011 (1.30 pm) – Jan 31, 2011 (3.30 pm)

Two research assistants were recruited to help with the thermal comfort and the spot physical thermal environmental measures for data collection at KTPH and CGH. KTPH and CGH also offered the assistance of four operation executives from each hospital with the data collection effort. The research assistants and operation executives were trained to explain to subjects the nature of the research, provide instructions and administer the thermal comfort questionnaire. They were also trained to conduct behavioral observations of the subjects while they were taking a survey and conduct measurements of the thermal environment using the TE meter. A PhD student from the University of New South Wales who collaborated with this study was responsible for setting up the IQM meter and contributing the 24-hours ambient thermal data.[20]

Patients and nurses who participated in the survey were briefed on the nature of the research and informed that their participation in all or any part of the survey was voluntary. Patients were required not to have exercised one hour before taking the survey, since higher activity levels might impact their level of thermal comfort. Participants were also instructed not to have consumed any food and drinks 1 hour before the survey. Patients were instructed to be in their patient gowns while nurses were assumed to be wearing standard nursing uniform clothing.

[20] Kok Wee Ng, PhD Student from the University of New South Wales collaborated in the study by contributing the 24-hours ambient thermal data.

Nurses were instructed to take the survey while standing at the nursing station. Occasionally, some nurses completed the survey while standing together as a group (not more than 3 at a time) around the nursing station; so only one physical measurement was conducted per session. The measurements were taken as close as possible to the nurses at three height levels (0.5 m, 1 m and 1.5 m) to account for vertical differences in temperatures. Patients were instructed to take the survey while sitting upright on their bed. Physical measurements were made as close to the patient's main body trunk at a height of 1.0 m.

As the thermal conditions fluctuated in naturally ventilated settings, the survey was administered twice during the first week to patients and nursing staff in both the naturally ventilated and air-conditioned wards to determine the test-retest reliability of the scales. A time lapse of two days in between the surveys was enforced to minimize the possibility of subjects memorizing their responses from the first survey. Subsequently, due to manpower limitations, the survey was only conducted once per subject. Subjects who have taken the survey previously were not asked to take the survey again.

At each location, while the subjects were taking the survey, the research assistants used the TE meter and observation tool to record physical thermal conditions, the location of the subject, notable behavioral adaptations and responses to the thermal environment, clothing, and activity levels of the patient.

Managing the Sustainable Facility

Focused interviews were conducted with the chief executive officer, facilities planner, facilities manager and operations director at Khoo Teck Puat hospital to understand why the hospital adopted sustainable design, what they expected the hospital design team to deliver and what the unanticipated challenges were in operating and managing the sustainable hospital. The interview questions developed are listed in Appendix I. A PowerPoint slideshow depicting the various sustainable design features related to the natural ventilation design in the hospital was used to help interviewees recall the reasons why those features were selected and the facility management issues associated with them.

2.6 Limitations of the Data

The following assumptions were made in this study.

Spot Physical Measurements of Thermal Environment

Assumption 1: The variation in outdoor thermal conditions between the hospital sites were minimal. This assumes that climate conditions across each of the three hospitals were similar during the time of the study. It also assumes that the micro-climatic variations due to their different locations would not significantly affect the physical measures of air temperature, relative humidity and air velocity.

Assumption 2: The two TE meters used to measure physical aspects of the thermal environment functioned properly and were not subject to calibration error. It also assumed that standard techniques in measuring the data were employed throughout the duration of the study. Proper training of research assistants helped to reduce the variation in using the research instruments.

Assumption 3: There were no significant differences in the weather in June 2010 and January to March 2011, periods during which the study was conducted.

Twenty-four hour Ambient Thermal Data

Assumption 1: The data was only collected in one fixed location over a 5-day period. Although this procedure assumed that the temperature in other areas of the ward would not fluctuate drastically from this location, it was not be able to detect problem areas, unlike the spot measurements collected using the TE Meter.

Thermal Comfort Data

Assumption 1: The clothing insulation (clo) values and activity levels between patients from each of the three hospitals, and nurses from each of the three hospitals were assumed to be similar so that they would not be factors accounting for differences across the three sites.

Assumption 2: The thermal conditions between 11.30 am to 3 pm of a day during which the surveys were conducted would not fluctuate too greatly as to significantly affect the reporting of thermal comfort within those time periods.

Assumption 3: It was assumed that participants taking the thermal comfort survey were fever-free and not taking medication that could affect their thermoregulatory processes. Instructions were provided to patients and nurses to not participate in the survey if they were experiencing fever symptoms or taking fever medication within the last 4 hours prior to taking the thermal comfort survey.

CHAPTER 3

RESULTS

3.1 General Ambient Thermal Environment Characteristics

Figures 3-1 through 3-3 illustrate the changes in heat index over a 24-hour period in both wards of the three hospitals. The hottest period in the naturally ventilated wards was around 2.30 pm while the coolest periods were early morning around 6 am. The selected time period (11.30 am – 3 pm) for conducting the thermal comfort survey was found to be significantly warmer than the other time periods (p=0.004) (See Appendix J). This finding indicates that the choice of conducting the thermal comfort survey from 11.30 am to 3 pm is justified given that subjects would most likely be experiencing the most uncomfortable thermal conditions during that period. This physical data correlated well with feedback from occupants indicating the afternoons (from 1 pm to 5 pm) to be the 'most uncomfortable time of the day' (See Appendix K).

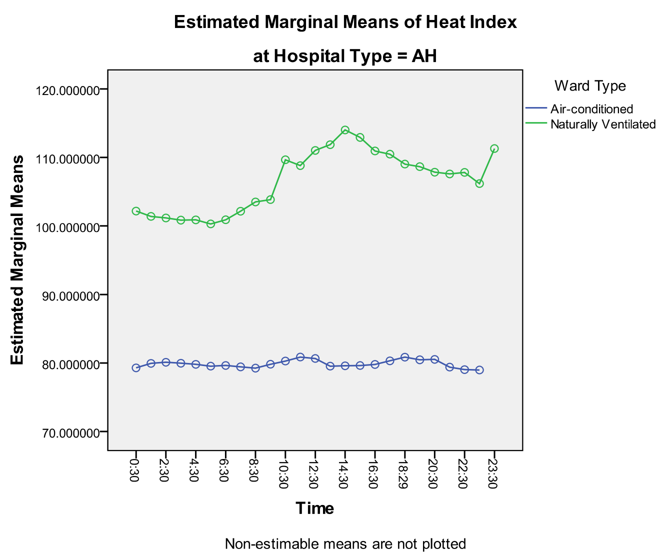

Figure 3-1. Diurnal Heat Index for AH

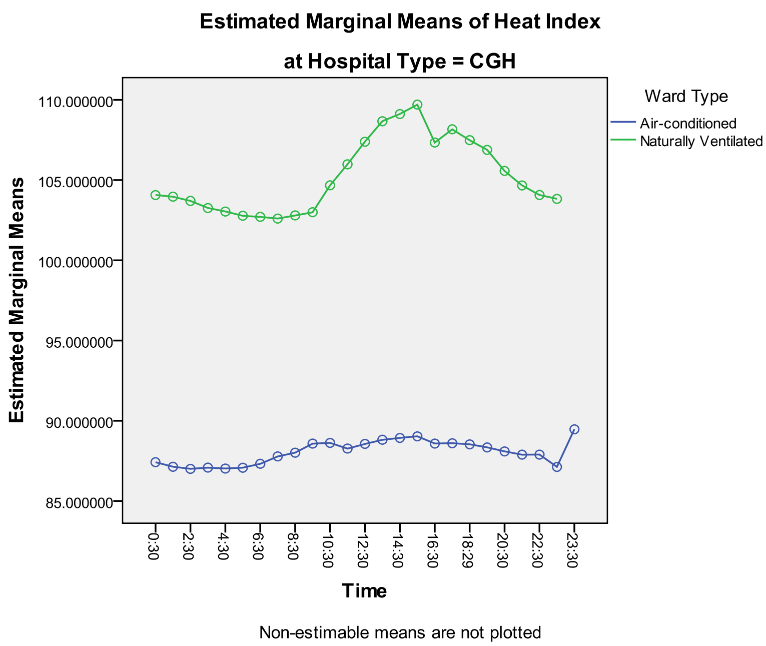

Figure 3-2. Diurnal Heat Index for CGH

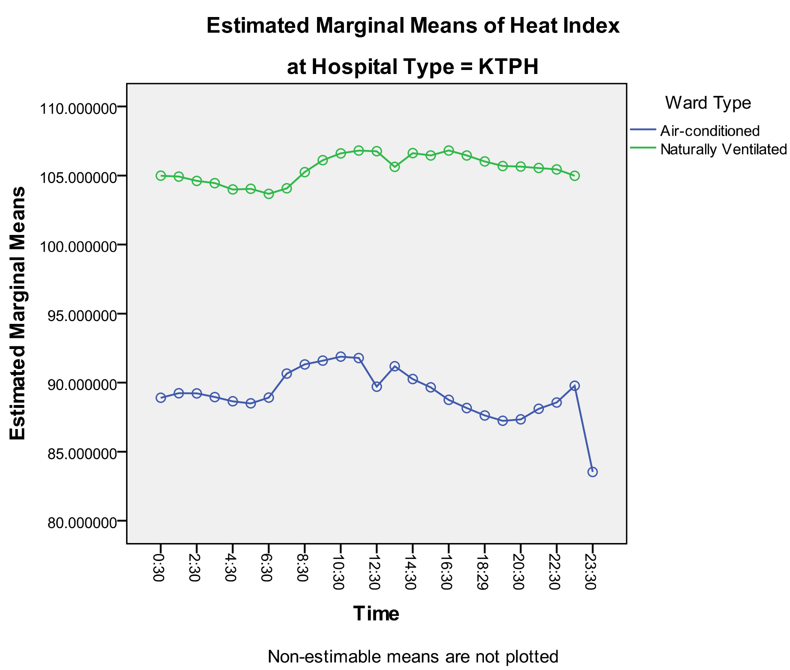

Figure 3-3. Diurnal Heat Index Variation for KTPH

3.2 Effects of Hospital Type, Ventilation Type and Occupant Areas on Thermal Conditions

To test the effect of hospital type, ventilation type and occupant type on each of the dependent thermal variables (heat index and air velocity), a three-way analysis of variance and a series of three-way analyses of variance[21] were performed respectively. Figure 3-4 illustrates the variance in heat index for both types of wards between the three hospitals, while Tables 3-1 through 3-2 summarizes the significant heat index results of the ANOVA. Figures 3-4 illustrates the variance in air velocity across the three hospitals for the naturally ventilated wards, while Tables 3-3 through 3-4 summarizes the significant air velocity results of the final ANOVA model.

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[21] As fan speed was a potential confounding variable, its interaction terms between fan speed, hospital type and subject type were included in the series of ANOVA. These interaction terms were then iteratively removed until no interaction terms between fan speed and the other two variables remained in the model as they were not significant ($p>0.05$).

Heat Index

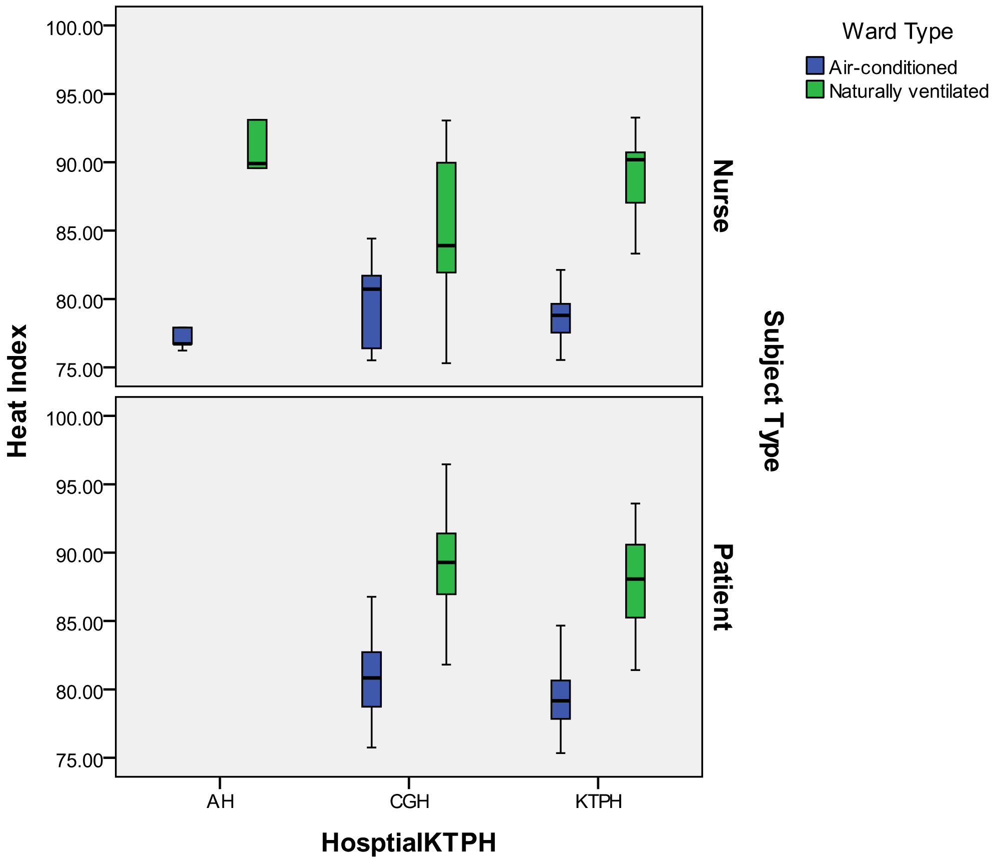


Figure 3-4 Heat Index for Naturally Ventilated and Air-Conditioned Wards across AH, CGH and KTPH

Table 3-1 Estimated Mean Heat Index

	KTPH		CGH		AH	
	AC	NV	AC	NV	AC	NV
Estimated Mean Heat Index at Nursing stations	78.73 (.435) n=51	89.13 (.474) n=43	79.87 (.419) n=55	84.96 (.415) n=56	77.19 (.609) n=26	90.90 (.609) n=26
Estimated Mean Heat Index (SE) at Patient Bed Areas	79.49 (.448) n=48	87.76 (.423) n=54	80.96 (.439) n=50	89.21 (.408) n=58	-	-

Note. Standard Errors appear in parentheses below estimated means.

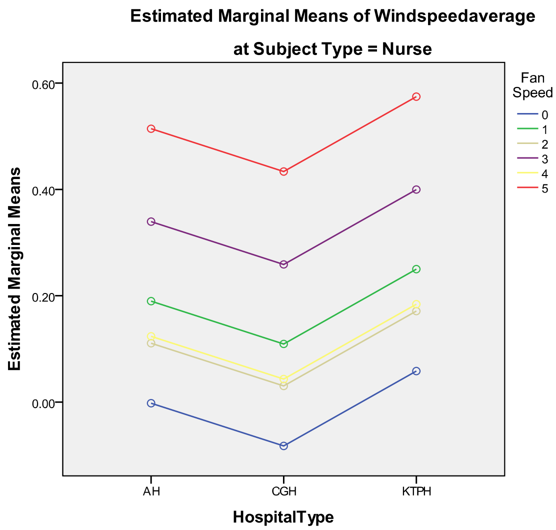
Table 3-2 Source Table for 3 (Hospital Type) x 2(Ward Type) x 2 (Subject Area Type) Completely Between-Subjects ANOVA

Source	SS	Df	MS	F	p
HospitalType	31.4	2	15.7	1.6	.198
WardType	8462.9	1	8462.9	877.2	.000
SubjectAreaType	143.2	1	143.2	14.8	.000
HospitalType*WardType	566.5	2	283.3	29.4	.000
HospitalType*SubjectAreaType	227.7	1	227.7	23.6	.000
WardType*SubjectType	7.1	1	7.1	.7	.392
HospitalType*WardType*SubjectAreaType	179.7	1	179.7	18.6	.000
Error	4408.8	457	9.6		
Total	3295393.8	467			

Note: R^2 = .688 (Adjusted R^2 = .682)

The three-way analysis of variance yielded a main effect for ward type, F (9, 457)= 877.2, p=0.000, such that the heat index was significantly higher for naturally ventilated wards (M= 87.63, SD = 4.68) than air-conditioned wards (M=78.90, SD= 2.44). The main effect of hospital type was non-significant, F(9, 457)=1.6, p=.198. However, there was a significant hospital type by ventilation type by ward location interaction. Nursing stations in AH's air-conditioned wards were significantly cooler than nursing stations in CGH's air-conditioned wards by 2.7 ºF (p=0.000). The nursing stations in AH's naturally ventilated wards were also significantly warmer than that of CGH by 5.9 ºF (p=0.000) but only marginally significantly warmer than KTPH's by 1.8 ºF (p=0.084) respectively. Nursing stations in naturally ventilated wards in KTPH were also significantly warmer than CGH's naturally ventilated wards by 4.2 ºF (p=0.000). In contrast, patient bed areas in KTPH's naturally ventilated wards were significantly cooler than those of CGH's by 1.4ºF (p=0.033).

Air Velocity



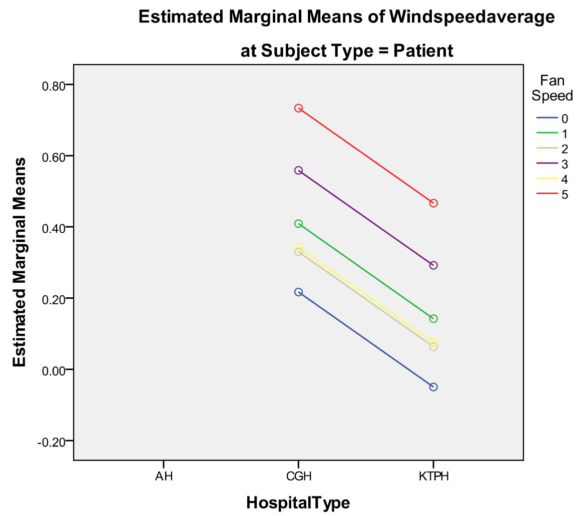


Figure 3-3 Air Velocity for Naturally Ventilated and Air-Conditioned Wards across AH, CGH and KTPH

Table 3-3 Estimated Mean Air Velocity

	KTPH	CGH	AH
Estimated Mean Air Velocity at Nursing stations (m/s)	.273 (.093)	.132 (.060)	.213 (.125)
Estimated Mean Air Velocity at Patient Bed Areas (m/s)	.165 (.059)	.432 (.050)	-

Note. Air-conditioned areas were not included as air velocity was negligible. Air velocity of patient bed areas in AH was not measured.

Table 3-4 Source Table for 3 (Hospital Type) x 2 (Ward Type) x 2 (Subject Area Type) Completely Between-Subjects ANCOVA for Air Velocity

Source	SS	Df	MS	F	p
HospitalType	.165	2	.082	.579	.561
SubjectType	.330	1	.330	2.32	.129
HospitalType * SubjectType	1.813	1	1.813	12.75	.000
FanSpeed	3.939	5	.788	5.54	.000
Error	30.713	216	.142		
Total	53.426	226			

Note: R^2 = .272 (Adjusted R^2 = .242)

The three-way analysis of variance yielded no main effects of hospital type on air velocity, F (9, 216) = .579, p=.561 and subject type, F (9,216)=2.320,p=.129. There was a significant main effect for fan speeds. The higher the fan speeds, the higher the air velocity. In addition, there was a significant hospital type by subject type interaction. A post-hoc Bonferonni's Correction test showed that while the nursing station areas across the three hospitals did not differ significantly for air velocity (p>0.05), the air velocity for patient bed areas was higher in CGH (M=.432, SE=.050) than KTPH (.165, SE=.052) by .267 m/s after controlling for fan speed (p=0.000).

Apart from the patient bed areas and nursing stations, measurements of air velocities along the main corridor of KTPH's naturally ventilated wards reached an average of 0.6 m/s, indicating that there were areas in the naturally ventilated ward that met the simulated predictions despite the lower than expected readings in the patient bed areas and nursing station areas.

In summary, analysis of the ambient thermal environment revealed the following:

- Naturally ventilated wards were significantly warmer than air-conditioned wards
- CGH's nursing stations in naturally ventilated wards had the lowest heat index followed by KTPH and AH
- In naturally ventilated wards, KTPH's patient bed areas had a lower heat index than CGH's patient bed areas
- There was no difference in air velocities for nursing stations in the naturally ventilated wards between the three hospitals after controlling for fan speeds.

- CGH's naturally ventilated patient ward bed areas had higher air velocities than KTPH's naturally ventilated patient ward bed areas after controlling for fan speeds.

3.3 Patient Demographic Information

A total of two hundred and twenty one patients from KTPH and CGH responded in the thermal comfort survey (i.e., each week there were approximately 5 patients per ward per hospital from January to March 2011). The patient sample was obtained from the orthopedic and surgical wards in both air-conditioned (B1) wards and naturally ventilated (B2) wards. A cross-sectional comparison for patient thermal comfort was performed between CGH and KTPH.[22]

Table 3-5 Patient Sample Characteristics

	KTPH		CGH		Total
	AC	NV	AC	NV	
Responded Patient Sample Size	53	57	55	56	221
Age	44.6	42.0	51.2	44.7	45.6
Gender (% Female)	55.8%	43.9%	58.5%	17.9%	44.3%
Median Number of days stayed in ward	3.44	4.21	4.52	4.77	4.25

Note: There were no patients sampled for AH. Although there were a larger proportion of males in CGH's NV wards than the other groups, no significant effect of ward type by gender interaction on thermal comfort was found.[23]

[22] Patients could not be sampled from AH in June 2010 as there was insufficient time and resources to collect patient data at the time of the study.
[23] A univariate GLM analysis was performed to determine if gender had an interaction effect with ward type, and it revealed that Gender by Ward Type had no significant effect on thermal comfort, $F(3,195)=1.62$, $p=.205$.

3.4 Patient Satisfaction with Thermal Conditions

To determine the percentage of patients that found their thermal environments to be acceptable, cross-tab comparisons were performed between CGH and KTPH for patients' responses on the McIntyre two-point scale of direct acceptability of their thermal environment (McIntyre and Gonzalez, 1976).[24] Analyses using less direct scales of acceptability (i.e., Bedford Comfort Scale and Thermal Preference) were also performed and reported in Appendix L.

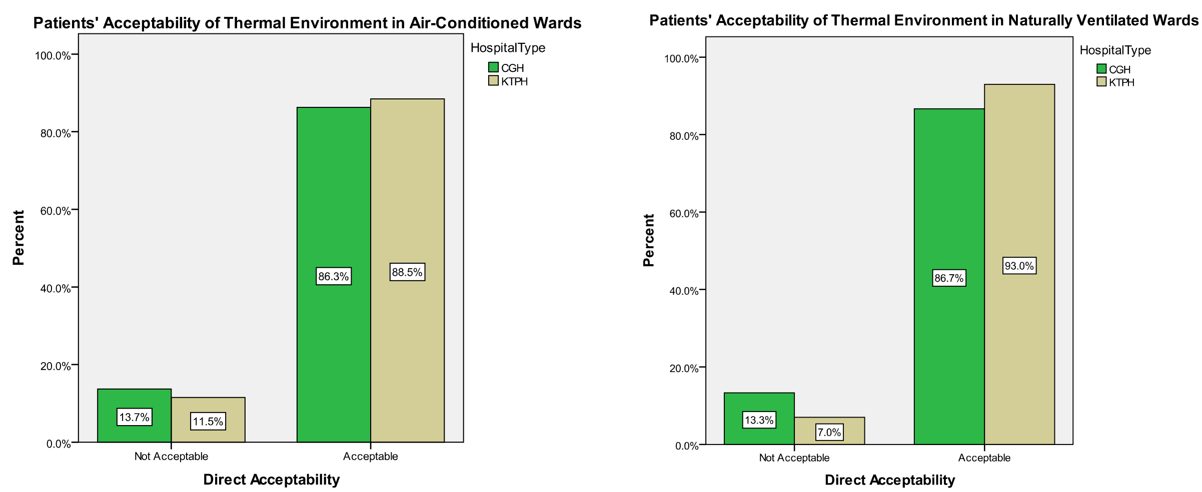


Figure 3-6 Patients' Acceptability of Thermal Environment in CGH and KTPH

Both CGH and KTPH met the ASHRAE 55-2010 thermal satisfaction requirements for their air-conditioned and naturally ventilated wards, since in all ward groups, more than 80% of patients reported that they found their thermal environment to be acceptable. There was no significant difference in the percentage of patients in the air-conditioned wards between the two hospitals who found their thermal environments to be acceptable χ^2 (1, N = 103) = .112, p =.738.

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[24] According to thermal comfort research literature, McIntyre's scale of acceptability provides the most direct indication of the proportion of patients who found their thermal environment to be satisfactory and whether the hospital met the ASRHAE Standards 2010 thermal satisfaction requirement (Wong and Khoo, 2003; Tablada et al., 2005).

Interestingly, there was also no significant difference between the percentage of patients in KTPH's air-conditioned wards and naturally ventilated wards that found their thermal environment to be acceptable (p=.514, two-tailed Fisher's Exact Test). Patients in CGH's air-conditioned wards and naturally ventilated wards similarly did not significantly differ in the rates of acceptability (p=1.000, two-tailed Fisher's Exact Test). There was no significant difference between CGH and KTPH in terms of acceptability of the thermal environment for patients in the naturally ventilated wards χ^2 (1, N = 117) = 1.267, p =.260.

3.5 Effects of Hospital Type and Ward Type on Patients' Thermal Comfort

To test the effect of hospital type, ventilation type and occupant type on patients' thermal comfort, a series of univariate General Linear Model (GLM) analyses were performed. An initial analysis was conducted between reported thermal comfort and independent variables (i.e., possible confounders and mediating factors—heat index and air velocity). The results of these tests are shown in Appendix M. The significant confounding variables and mediators were included as fixed factors or covariates in the univariate GLM analysis. The univariate GLM analyses were performed by removing confounding variables iteratively until no significant confounder or mediator variables[25] were left in model.

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[25] There were no significant effects of the mediators heat index and air velocity on thermal comfort or interaction effects with the independent variables hospital type and ward type.

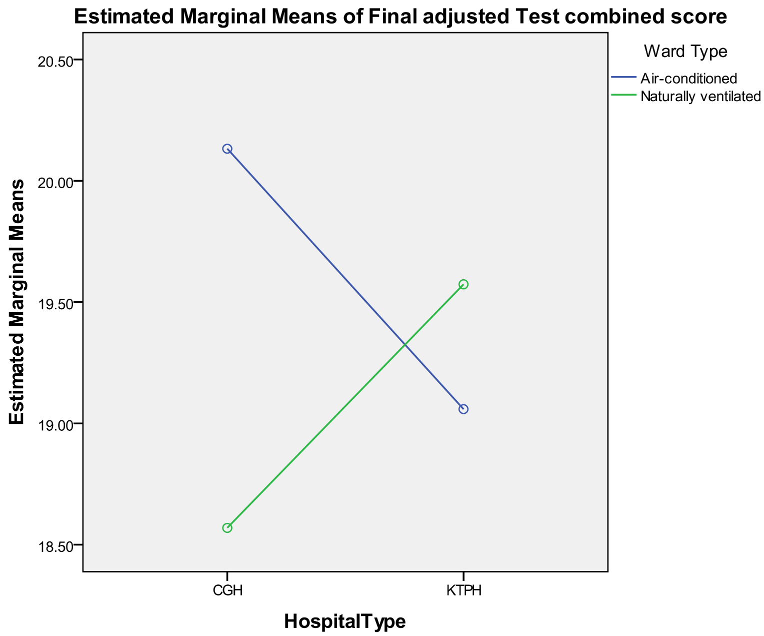

Figure 3-7 Patients' Thermal Comfort Scores for Naturally Ventilated and Air-Conditioned Wards across CGH and KTPH

Table 3-6 Source Table for 3 (Hospital Type) x 2(Ward Type) Completely Between-Subjects ANOVA

Source	SS	Df	MS	F	p
HospitalType	.06	1	.059	.006	.941
WardType	13.57	1	13.565	1.277	.260
HospitalType*WardType	53.26	1	53.26	5.012	.026
Error	2093.05	197	10.625		
Total	76752.62	201			

Note: R^2= .03 (Adjusted R^2 = .015)

Table 3-7 Estimated Mean Thermal Comfort for Patients

	KTPH		CGH	
	AC	NV	AC	NV
Estimated Mean Thermal Comfort for Patients	19.06 (.515) n=51	19.57 (.452) n=52	20.13 (.515) n=40	18.57 (.428) n=58

Note. Thermal Comfort Score ranges from 0 (minimum comfort) to 24 (maximum comfort). Standard Errors appear in parentheses below estimated means.

The univariate GLM analysis of variance yielded no main effect for hospital type F (3, 197) = 0.006, p=.941, and ward type F(3,196)=1.277, p=.260. However, there was a significant hospital type by ward type interaction (p=0.026). A post-hoc Bonferroni's Correction showed that patient thermal comfort scores did not differ significantly between KTPH and CGH for their naturally ventilated wards (p=.108). There was also no significant difference in patient thermal comfort scores between CGH's air-conditioned wards and KTPH's air-conditioned wards (p=.117). However, patients from CGH's air-conditioned wards (M=20.13, SE=.515) were significantly more comfortable than patients from CGH's naturally ventilated wards (M=18.57) (p=0.042), while patients from KTPH's naturally ventilated wards and air-conditioned wards did not differ significantly in their thermal comfort scores (p=0.424).

3.6 Nurse Demographic Information

A total of two hundred and forty seven nurses from AH, KTPH and CGH responded in the thermal comfort survey that was conducted over 3 weeks in AH (June 2010) and 3 months from January to March 2011 in KTPH and CGH. The nurse samples were obtained from the orthopedic and surgical wards in both air-conditioned (B1) wards and naturally ventilated (B2) wards. A cross sectional comparison of nurses' thermal comfort was performed across the three hospitals. In addition, 29 nurses from AH retook the thermal comfort survey after they moved to KTPH, allowing for a longitudinal analysis of differences in thermal comfort scores between AH and KTPH. The responses from these nurses while they were in KTPH (but not their responses while they were in AH) were excluded from the cross-sectional analysis to minimize the threat of subject response bias. Table 3-8 illustrates the nurse sample characteristics.

Table 3-8 Nurse Sample Characteristics

	KTPH		CGH		AH		Total
	AC	NV	AC	NV	AC	NV	
Responded Nurse Sample Size	38	47	54	56	26	26	247
Mean Age	27.8	26.9	31.6	26.1	28.4	28.9	28.2
Gender (% Female)	100%	86.7%	98.1%	94.6%	100%	96%	95.5%
Median years lived in Singapore	3-5	3-5	3-5	3-5	3-5	1-3	3-5
Mean Number of Years worked in Singapore Hospitals	4.6	4.9	7.1	4.3	N.A.	N.A.	4.9

Note: 29 out of 52 nurses from AH retook the survey in KTPH. The mean number of years worked in Singapore was higher than the median years lived in Singapore as there was a high proportion of foreign-trained nurses who moved to Singapore recently (within 1-3 years), resulting in an deflated value for the median number of years lived in Singapore, while many local nurses have worked for a large number of years in Singapore hospitals, inflating the mean number of years worked in Singapore hospitals.

3.7 Nurse Satisfaction with Thermal Conditions

To determine the percentage of nurses that found their thermal environments to be acceptable, cross-tab comparisons were performed between the three hospitals' nurses' responses on the McIntyre two-point scale of direct acceptability of their thermal environment (McIntyre and Gonzalez, 1976).[26] Figure 3-8 illustrates the nurses' percentage of acceptability of the thermal environment. Analyses using less direct scales of acceptability (i.e., Bedford Comfort Scale and Thermal Preference) were also performed and reported in Appendix N.

[26] According to thermal comfort research literature, McIntyre's scale of acceptability provides the most direct indication of the proportion of patients who found their thermal environment to be satisfactory and whether the hospital met the ASRHAE Standards 2010 thermal satisfaction requirement (Wong and Khoo, 2003; Tablada et al., 2005).

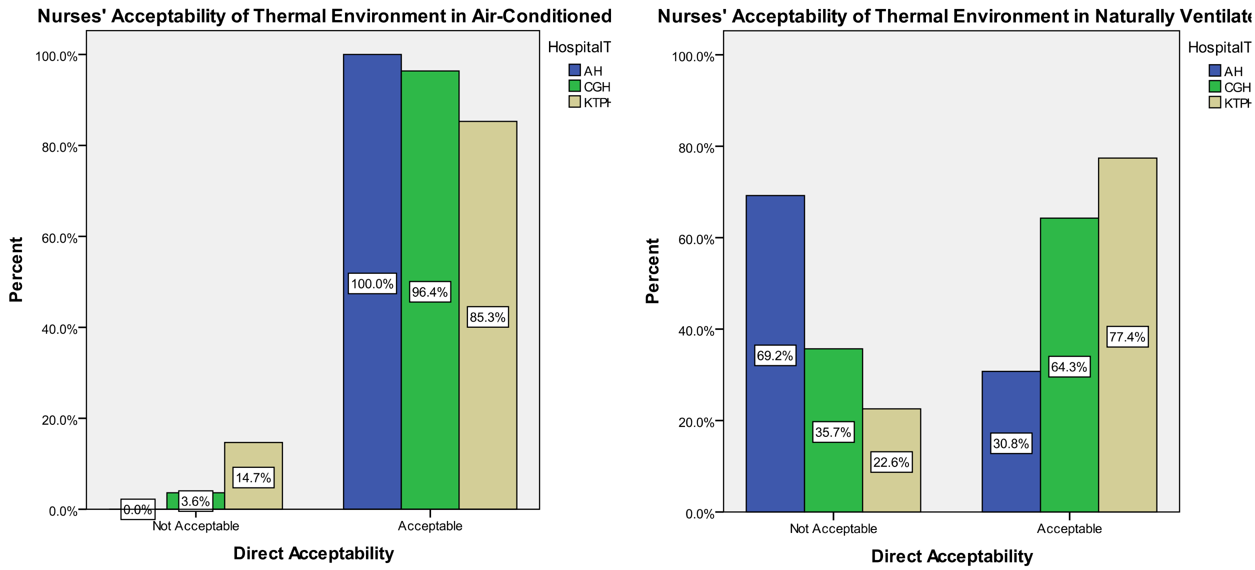

Figure 3-8 Nurses' Acceptability of Thermal Environment

All three hospitals met the ASHRAE 55-2010 thermal satisfaction requirements for their air-conditioned wards, since more than 80% of nurses reported that they found their thermal environment to be acceptable. While none of the nurses in the naturally ventilated wards of the three hospitals met the minimum ASHRAE 55-2010 standards requirement, nurses in KTPH's naturally ventilated wards had the highest percentage (77.4%) who found their thermal conditions to be satisfactory compared to CGH (64.3%) and AH (30.8%). The percentage of nurses from KTPH's naturally ventilated wards that found their thermal environment to be acceptable was significantly higher than that of nurses from AH χ^2 (1, N = 57) = .12.498, p =.000, but not for nurses from CGH χ^2 (1, N = 87) = 1.608, p =.205.

3.8 Effects of Hospital Type and Ventilation Type on Nurse's Thermal Comfort (Cross-sectional Analysis)

To test the effect of hospital type and ventilation type on nurses' thermal comfort, a univariate GLM analysis was performed. An initial analysis was conducted between reported thermal comfort and possible confounding variables as shown in Appendix O. Eight significant confounding variables (air quality, noise, positive acoustic sounds, views of nature, light levels, daylighting, reliance on air-conditioning and control) were included as covariates in the univariate analysis. The univariate analysis was performed by removing confounding variables iteratively until only the significant confounding variables (indoor air quality and reliance on air-conditioning) were left in model as shown in Table 3-9.

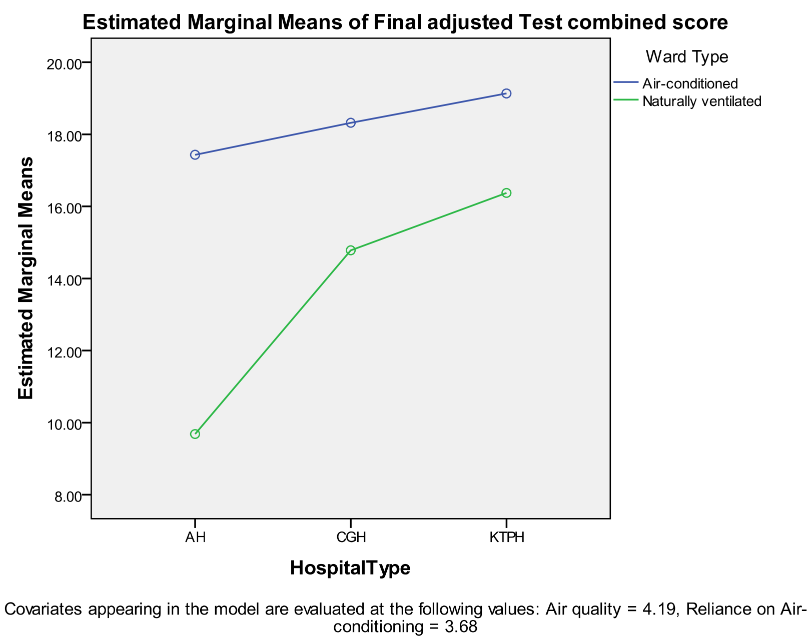

Figure 3-9 Nurses' Thermal Comfort Scores for Naturally Ventilated and Air-Conditioned Wards across AH, CGH and KTPH

Table 3-9 Source Table for 3 (Hospital Type) x 2(Ward Type) Completely Between-Subjects ANOVA

Source	SS	Df	MS	F	p
HospitalType	434.7	2	217.4	15.1	.000
WardType	806.5	1	806.5	55.81	.000
Satisfaction with Indoor Air Quality	174.8	1	174.8	12.11	.001
Reliance on Air-conditioning at Home	62.7	1	62.7	4.31	.038
HospitalType*WardType	167.3	2	83.7	5.8	.004
Error	2830.9	196	14.4		
Total	58891.8	204			

Note. R Squared = .466 (Adjusted R Squared = .447)

Table 3-10 Estimated Mean Thermal Comfort for Nurses

	KTPH		CGH		AH	
	AC	NV	AC	NV	AC	NV
Estimated Mean Thermal Comfort for Nurses	19.1 (.725) n=28	16.4 (.716) n=29	18.3 (.552) n=50	14.8 (.543) n=53	17.4 (.839) n=22	9.7 (.864) n=22

Note. Thermal Comfort Score ranges from 0 (minimum comfort) to 24 (maximum comfort). Standard Errors appear in parentheses below estimated means.

The univariate analysis yielded a main effect for hospital type, F (9, 196) = 15.1, p=0.000, such that the thermal comfort score for KTPH (M= 17.8, SE = .514) was 1.2 points non-significantly higher than CGH (M=16.6, SE=.375, p=.183) and 4.2 points significantly higher than AH (M=13.6, SE= .580, p=0.000). There was also a significant main effect of ward type (p=0.000), such that the thermal comfort score of nurses who worked in air-conditioned wards (M=18.3, SE=.425) was 4.7 points higher than the score of nurses who worked in naturally ventilated wards (M=13.6, SE=.420) (p=0.000). Satisfaction on air quality and reliance on air-conditioning at home also had significant main effects (p<0.05). Furthermore, there was a significant hospital type by ward type interaction (p=0.004), whereby a post-hoc Bonferroni's Correction test revealed that while there were no significant differences in thermal comfort scores across the three hospitals for air-conditioned wards (p>0.05), nurses who worked in KTPH's naturally ventilated wards reported higher thermal comfort scores (M=16.4, SE=.716) than those who worked in AH's naturally ventilated wards (M=9.7, SE=.864) by 6.7 points (p=.000). However, there was no significant difference between thermal comfort reports between nurses who worked in naturally ventilated wards between KTPH and CGH (p=.492).

3.9 Effect of Hospital Type on Nurse's Thermal Comfort (Longitudinal Analysis)

Of the 29 nurses from KTPH surveyed who also participated in the AH thermal comfort survey, 15 of them were assigned to wards of similar ventilation types in KTPH. A two-tailed and one tailed paired sample t-tests was performed to compare thermal comfort of nurses in AH and KTPH for both air-conditioned and naturally ventilated wards respectively. The results are indicated in Table 3-11. There seemed to be two outliers in the dataset as illustrated in Figure 3-10 but they were kept in the paired sample t-tests since there were insufficient grounds to remove them from the analysis.

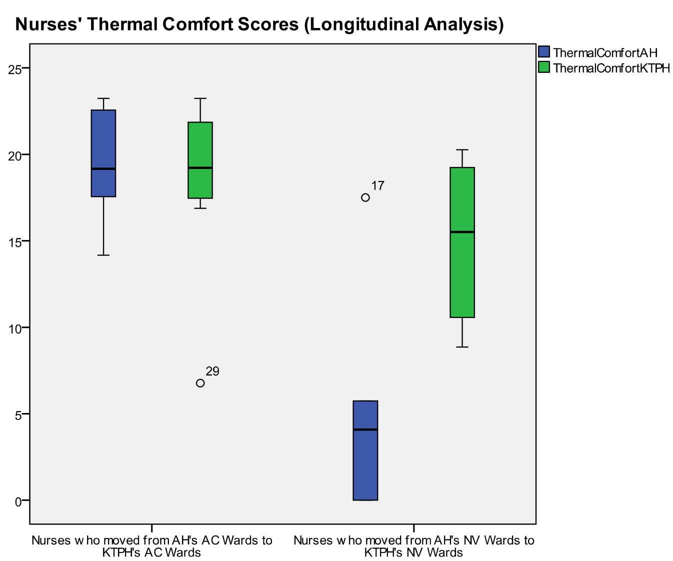

Figure 3-10 Nurses Thermal Comfort Scores Across AH and KTPH

Table 3-11 Paired Sample t-test for Nurses' Thermal Comfort across AH and KTPH

Ward Type	Hospital Type			
	AH	KTPH	t	df
Air-conditioned	19.31 (3.08)	18.46 (4.64)	.493	9
Naturally Ventilated	5.23 (4.68)	14.99 (4.68)	-2.35*	5

Note. Thermal Comfort Score ranges from 0 (minimum comfort) to 24 (maximum comfort). * = $p \leq 0.05$. Standard Deviations appear in parentheses below means.

The paired sample t-test yielded a significant difference in thermal comfort scores reported between the naturally ventilated wards (One-tailed, p=0.033) but no significant difference in thermal comfort scores reported between the air-conditioned wards (Two-tailed, p=.634). The naturally ventilated wards in KTPH (M=14.99, SD=4.68) had a higher thermal comfort score than the naturally ventilated wards in AH (M=5.23, SD=6.51). These results suggest that nurses' thermal comfort scores improved in the naturally ventilated wards for KTPH over its predecessor AH.

3.10 Effect of Ambient Thermal Conditions on Thermal Comfort

Heat index significantly predicted thermal comfort scores, β=-.200, t(403)=-4.861, p<.001. Heat index also explained a significant proportion of variance in thermal comfort scores, R^2=.055, $F(1,403)$= 23.63, p<0.001. However, air velocity did not significantly predict thermal comfort scores, β=-.099, t(402)=-1.927, p=0.055.

Table 3-12. Multiple Regression of Ambient Thermal Conditions on Thermal Comfort

	B	*SE B*	Β
Step 1			
Constant	32.16	3.64	
Heat Index	-0.171	0.04	-.201*
Wind Speed	-1.38	0.715	-.099
Step 2			
Constant	34.41	3.46	
Heat Index	-.200	0.041	-.235*

Note: R^2=.064 for step 1. R^2=-.009 for step 2 (p<0.001). *p < .001.

In summary, analysis of the subject survey responses revealed the following:

- Both KTPH and CGH met the ASHRAE Standard 55-2010's requirement for percentage for patient satisfaction with the thermal environment.
- There was no significant difference in patient's acceptability of the thermal environment between CGH and KTPH for naturally ventilated wards, but there was also no difference between air-conditioned and naturally ventilated wards for both hospitals.
- There was no significant difference in patient thermal comfort scores between KTPH's and CGH's naturally ventilated wards.
- Patient thermal comfort scores in CGH's air-conditioned wards were significantly higher than CGH's naturally ventilated wards while there was no significant difference between patient thermal comfort scores between KTPH's naturally ventilated wards and air-conditioned wards.
- There were no significant differences in nurses' thermal comfort scores between the air-conditioned wards for AH, CGH and KTPH and no significant difference

in patients' thermal comfort in thermal comfort scores between the air-conditioned wards for CGH and KTPH.

- None of the naturally ventilated wards in the three hospitals met the ASHRAE Standard 55-2010 requirement for percentage nurse satisfaction with the thermal environment (but KTPH managed to achieve nearly 80% satisfaction among its nurses).
- The percentage of nurses in KTPH's naturally ventilated wards who found their thermal environment to be acceptable was significantly higher than that of nurses from AH but not CGH.
- In the cross sectional analysis, the thermal comfort scores for KTPH's nurses in the naturally ventilated wards was significantly higher than that of nurses in AH but not CGH but there were no significant differences in thermal comfort scores for the air-conditioned wards across the three hospitals.
- In the longitudinal analysis, the thermal comfort scores obtained for nurses that took the survey in KTPH were significantly higher than the reported thermal comfort scores when the same nurses took the survey in AH.
- Heat index significantly predicts thermal comfort scores but air velocity was found not to be a significant predictor of thermal comfort scores.

3.11 Operational Issues and Challenges

Although there are many benefits associated with sustainable design such as reduced energy usage and improved comfort and health, some of these design innovations come with unintended consequences and unanticipated challenges that may have serious repercussions for facility operations. As part of this study, interviews were conducted to assess the problems encountered by facility operators and management of the hospital with an emphasis on passive design features that served to enhance thermal comfort.

3.11.1 Rainwater

The utilization and placement of open-air corridors at the Specialist Outpatient Clinics on the perimeter of the building and high ceilings had benefits such as improved natural ventilation and energy savings. Despite rain guards and overhangs, the open-air areas were prone to becoming wet or flooded during stormy weather as the winds easily carried rain into the corridors. Wet areas increased the risk of slipping and during the time of the study, there had been two reports of patient falls due to the wet floors. Rain had serious consequences for housekeeping and facility maintenance. Singapore experiences on average 100 days with rain in a year, with most of the heavy rainfall occurring during the 10 months of the monsoon seasons (between November to March and May to September).

Figure 3.11.1 Custodian drying wet areas of open-air corridors

The hospital facilities are cleaned and maintained by two to three custodians per floor on a regular basis. They work from 7 am to 1 pm and from 3pm to 9 pm (two shifts) daily. The director of operations mentioned that every time it rained, custodians had to put up warning signs of wet areas in the hospital and dry the affected areas. An interview with a custodian also revealed that in the three months of her work at KTPH, 1.5 hours were spent on an average daily basis drying the affected areas, and that this task took valuable time away from her other custodial responsibilities. More recently, the hospital purchased three water-suction machines at US$8,000 a piece to dry the affected areas in larger areas (see Figure 3-12).

Figure 3-12 Water-Suction Machines

The efficient equipment helped to reduce time and effort spent in drying rainwater but still required one person to operate each of the machines. According to KTPH's director of operations, the manpower required during the end-of-year rainy season (from November 2010 to January 2011) was twice that during the dry inter-monsoon months (September to October 2010).

Figure 3-13 Rain-exposed vertical transportation (Left: Escalator showing rainwater seepage; Right: staircase showing flooded area)

Based on observations during rainy days, water had also been found to seep onto the escalator tracks (See Figure 3-13). The rainwater might also cause damage to the escalators as the water might seep into the machinery. Also, given the extensive landscaping in the courtyard area, soil from the planter boxes have been flushed out into the corridor areas due to strong rains.

Furthermore, during periods of heavy rainfall, closing the jalousie windows in the inpatient wards presented operational difficulties for the nurses because there were too many to close at once. When the jalousies were left open, the winds might carry the rainwater into the building. There has also been anecdotal feedback from the operations staff that rainwater was able to seep through the fine gaps between the jalousie windows even when they were shut.

As the escalators and staircase were exposed to the outdoors, during heavy downpours they were not accessible to the public. The public would instead use the elevators. But as the elevators were not designed to serve a large number of people in a short amount of time, problems such as crowding in the elevators and long waits for the elevators ensued. As there were no service elevators in the subsidized outpatient tower, crowding and waiting also presented challenges for the emergency transportation of patients or linens. In this case, the rainwater issue is not only a facility maintenance issue but has clear implications for medical care considering the criticality of timely transportation in a healthcare setting.

Figure 3-14 Prototypes of rain guards

At the time of the study, hospital administrators were testing prototypes of rain guards to prevent rainwater from blowing into the open-air corridors at the outpatient clinic building. The operations team also installed bamboo blinds to minimize rainwater seepage onto corridors that were prone to flooding.

Figure 3-15 Planter Boxes at Monsoon Windows

In the naturally ventilated inpatient wards, custodians and nurses would also have to shut the windows. Despite windows being shut, there have also been reports of strong winds carrying rainwater into the building interior through the fine crevices in between the window louvers in certain areas of the medical unit. Planter boxes were put behind the windows to intersept some of the incoming rainwater (as shown in Figure 3-15).

Figure 3-16 Corridors without rainwater issues

Some corridors such as Figure 3-16 did not experience the same rain issues because the hospital planning committee specified that those corridors be kept dry. Overhangs that extended outwards beyond the length of the corridors and the lower ceilings helped to prevent rainwater from the outside entering those areas.

3.11.2 Window Cleaning Issues

Figure 3-17 Custodian cleaning glass façade

The extensive use of glass in KTPH's façade (a feature that is popular in temperate climates) posed significant operational issues for cleaning and maintenance. Custodians were required to clean the glass windows once a day, everyday, on both the inside and outside of the buildings. Feedback from custodians also indicated that the jalousie windows in the naturally ventilated wards were difficult to clean as each jalousie windowpane collected dust—there were 120 windowpanes used per patient room.

3.11.3 Operable Window and Control Issues

Figure 3-18 Operable window issues (Left: lack of operable windows in outpatient clinics; Right: difficulty opening operable windows in private inpatient rooms)

Airing out spaces to reduce infection using natural ventilation is a common practice in Singapore hospitals. Despite the hospital planning committee’s intention of maximizing the use of operable windows, critical areas such as the isolation room and the outpatient clinics were overlooked during the design process, resulting in the use of fixed glass windows instead. According to operation staff, patients in the isolation rooms who preferred the room to be without air-conditioning because they felt too cold would report stuffiness as the room could not be naturally ventilated, or reported feeling hot in the morning if they left the air-conditioning off overnight. Patients in the air-conditioned wards mentioned that they often were reluctant to change the air temperature of the air-conditioning units or open the windows when they felt thermally dissatisfied, as they were mindful that other patients might not feel the same way. In contrast, each patient in KTPH's naturally ventilated wards had their own ceiling fan and could easily adjust their fan speeds.[27]

The air-conditioned inpatient rooms with mixed-mode ventilation as part of the hospital's sustainable design have also been reported to be difficult to open due its low position and the placement of the safety bars (as shown in Figure 3-18).

3.11.4 Inappropriate use of window treatment

Figure 3-19 Inappropriate use of window treatments (Left: Low-e glass used for façade in basement of hospital (as highlighted in red); Right: tinted windows for pharmacy)

[27] A post hoc Bonferroni's Correction in a three-way ANOVA found that patients in KTPH's naturally ventilated wards indicated a significantly higher control over their thermal environment (M=5.228, SE=.218) than patients in KTPH's air-conditioned wards (M=4.02, SE=.107) $F(1,107)=14.71$, $p=.000$.

Low-emissivity (low-e) glass[28] and sun control coating[29] are expensive window treatments intended to reduce heat gain. These treatments are usually recommended for use only in areas where there are high solar gain or with significant glare issues. KTPH used low-e glass and sun control coating for retail shops and offices in the basement where there was not much sunlight, which indicated a waste of resources since these areas received little sunlight. Moreover, these window treatments presented other unanticipated problems in terms of wayfinding for patients and visitors to the hospital. Some clinics, retail shops and pharmacies in the outpatient tower that used tinted glass for their windows had poor visibility into the interiors; patients and visitors to the hospital were not able to easily identifying those areas. Investments in signage (as illustrated in Figure 3-19) had to be done to improve wayfinding for patients and visitors.

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[28] Low-emissivity glass reflects radiant infrared energy, thus tending to keep radiant heat on the same side of the glass from which it originated, while letting visible light pass.

[29] Sun control coating is an external film applied to windows to reduce glare, reduce UV rays and solar heat gain.

3.11.5 Direct Sun Exposure

Figure 3-20 Sun exposure issues for beds in naturally ventilated wards

In the naturally ventilated B2 ward areas, patients located on beds near windows on the southeast and northwest facing facades were reported to suffer from direct exposure to morning and afternoon sun, causing thermal discomfort. Based on interviews with facility managers and operations staff, this occurrence was mainly attributed to the sub-performing shading devices and building orientation. Curtains were installed to prevent direct sunlight from reaching patients whose beds are next to the windows. When these curtains are drawn, airflow from the windows could be compromised, thus reducing the efficacy of KTPH's sustainable designs. Also, the windows located on the southeastern and northwestern facades were tinted with sun control coating, which like the curtain, reduced the visual performance within the ward and obscured the views to the outside. The use of curtains reduced airflow into the ward while the tinted windows darkened the room significantly, requiring the use of artificial lighting in severely affected areas. Three beds that had severe sun exposure problems necessitated the use of roller blinds to cover the windows everyday in the afternoon (around 2 to 3 pm) to reduce thermal discomfort and glare for patients.

Figure 3-21 Sub-performing shading devices/light shelves

The vertical wing walls that doubled as shading devices were not able to keep the sun out. Due to aesthetic reasons, the external shading devices were kept to the same dimensions and fixed in position. As a result, the wing walls were ineffective with accommodating to the changing angles of the sun over the course of the day and during the course of the year.

The horizontal elements as illustrated in Figure 3-21 were supposed to double as light shelves and shading devices. Feedback from the operations and facilities staff indicated that the elements did not serve their shading function nor brought the daylight deep into the room as intended. Furthermore, the light shelves were prone to collecting dust and presented operational challenges for cleaning. There was anecdotal feedback from some patients because of their superstitious beliefs, that the light shelves resembled coffin covers and served as a bad omen.

The operations team also found it difficult to install the curtains. At the time of the study, the operations staff was experimenting with removing the light shelves in the inpatient ward entirely.

3.11.6 Inconsistencies in cross-ventilation

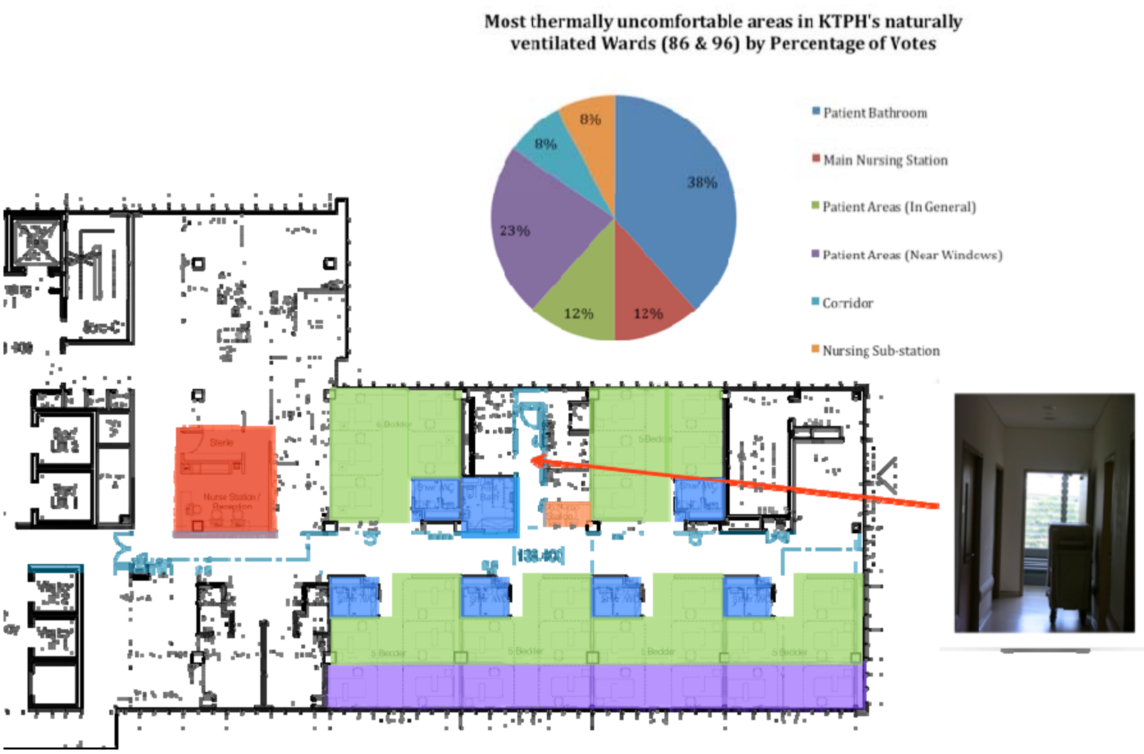

Figure 3-22 Areas of Thermal Discomfort within KTPH's Naturally Ventilated Wards

In certain areas of KTPH's naturally ventilated wards, cross-ventilation could not be maintained due to the layout and positioning of the windows. For example, in the middle of the B2 wards, the nursing counter, air would be stagnant as the neighboring trash handling room limited access to windows on one side of the façade when the doors were closed. Doors to the trash handling room had to be opened to increase cross ventilation but that led to odor issues in those areas (See Figure 3-22). Furthermore, patient bathrooms were cited to be the most uncomfortable area within KTPH's naturally ventilated wards. Feedback from nurses indicated that there was a lack of ventilation in the patient bathrooms in the ward, due to the lack of access to natural ventilation (See Figure 3-22).

3.11.7 Positioning of mechanical fans

Ceiling fans were located near the foot of the patients' beds instead of over their trunk where winds from the fans would deliver the most comfort. Furthermore, the fans were fixed on their axes, hence the direction of the air flow could not be controlled by patients (CGH's ceiling fans were rotatable on their axes). The 'off-centered' placement of the fans occurred because lighting took precedence over the ceiling fans in order for physicians and nurses to examine patients. The lack of an integrated ceiling plan during the design development stage of the hospital, stemming from inadequate coordination amongst the lighting designers and the ventilation engineers, was attributed as a key factor for this outcome.

3.11.8 Maintenance of aluminum cladding

The aluminum cladding used for cladding surfaces of the exterior walls was prone to scratches, dents and stains easily. If damaged, the cladding cannot be repaired and has to be replaced. Compared to reinforced concrete, it has a higher envelope thermal transfer value (ETTV) indicating that heat is more easily transferred across the building envelope (less effective than concrete in minimizing solar heat gain).

In summary, the unanticipated and unintended challenges of KTPH's sustainable design identified include:

- Rainwater spilling into naturally ventilated areas of hospital
- Window cleaning issues

- Operable windows and control issues
- Inappropriate use of window treatment
- Direct sun exposure
- Inconsistencies in cross-ventilation
- Positioning of mechanical fans
- Maintenance of aluminum cladding

CHAPTER 4

DISCUSSION

This study tested associations between a hospital's sustainable design for natural ventilation, the ventilation type and patients' and nurses' thermal comfort in three Singapore hospitals that differed in their approach to sustainable design. The operation and maintenance of KTPH's sustainable design features were also documented through a series of interviews with key stakeholders. Finally, the study examined the management philosophy and approach to sustainability in the organization.

4.1 Effects of Hospital Type and Ward Type on Ambient Thermal Conditions

The effect of hospital type and ward type on the heat index in the naturally ventilated ward differed between nursing station areas and patient bed areas. The results indicated that the heat index of nursing stations in CGH's naturally ventilated wards had the lowest heat index, followed by KTPH and then AH. However, for patient bed areas in the naturally ventilated wards, KTPH had a lower heat index than CGH. The initial hypothesis that the heat index in naturally ventilated wards would be lower is thus only partially supported by the results; the sustainable design of KTPH successfully attained a lower heat index for patient bed areas and nursing station areas than AH, but did not achieve a lower heat index than CGH for its nursing station areas. The reason for the lower heat index in CGH than KTPH could possibly be due to its greater proximity to the South China Sea, where the large water body could have moderated the air temperature outside CGH during the day to a larger extent than KTPH (CGH is about 5.5 miles closer than KTPH).

The effect of hospital type on air velocities in the naturally ventilated ward also seemed to differ between nursing station areas and patient bed areas. While there were no differences in air velocities for nursing stations in the naturally ventilated wards between the three hospitals, in CGH's naturally ventilated ward, patient bed areas had higher air velocities than patient ward bed areas in KTPH's naturally ventilated wards. The result seemed to indicate that KTPH's more sophisticated sustainable design features did not result in higher air velocities in the naturally ventilated wards than CGH but only conjectures can be made at this point. Although the study intended to measure the rate of natural ventilation, this measure was confounded by the effect of airstreams generated by mechanical fans. Several factors could explain the lower than expected air velocities in KTPH compared to AH and CGH. Firstly, different fan models were used by CGH, AH and KPTH and their placement varied in relation to occupants. It is possible that CGH had a higher air velocity than KTPH because its fan model was able to generate higher air velocities than KTPH for the same fan speed. The ceiling fans in KTPH were placed closer to the patient's feet than to their trunk, possibly resulting in lowered air velocities measured. Comparatively, in CGH, its ceiling fans could be rotated on their axes so that the airflow could be directed onto the patient's trunk, possibly increasing air velocities measured at that point. The relatively lower air velocities in KTPH could also be due to its layout of the naturally ventilated ward, which might have compromised the increased airflow that the sustainable features would have otherwise created. For example, the nursing station and patient bed areas had lower than expected air velocities, but other areas such as the main corridors were able to achieve wind speeds up to 0.6 m/s (without mechanical fans). Due to glare issues in KTPH, curtains in KTPH that were drawn could have reduced the natural ventilation from the windows. Lastly, CGH's closer proximity to the sea could have increased the air velocity sea breezes.

4.2 Thermal Satisfaction Assessment using ASHRAE Standard 55-2010

ASRHAE Standard 55-2010 specifies that at least 80% of occupants in a building should be satisfied with thermal conditions. Both KTPH and CGH met the ASHRAE Standard 55-2010's requirement for patient satisfaction with the thermal environment (using McIntyre's Scale of Acceptability) in both the air-conditioned and naturally ventilated wards, with no significant differences between the two hospitals.[30]

Nurses in the air-conditioned wards met the ASHRAE requirement for thermal satisfaction but not nurses in the naturally ventilated wards. While patients in both air-conditioned wards and naturally ventilated wards of CGH and KTPH experienced no significant differences in acceptability of the thermal environment, the relatively higher activity levels of nurses compared to patients (Smith & Rae, 1976) could have made them more sensitive to deviations from ideal thermal conditions. This theory could explain why a higher proportion of nurses in the naturally ventilated wards reported were dissatisfied with the thermal environment than nurses in air-conditioned settings. While none of the naturally ventilated wards in the three hospitals met the ASHRAE standard for the percentage of nurses who found the naturally ventilated wards to be acceptable (using McIntyre's scale of direct acceptability), there were a significantly higher percentage of nurses who were satisfied with the thermal conditions in KTPH (77.4%) than AH (30.8%). There was similarly a higher percentage of nurses who were satisfied with the thermal environment in KTPH's naturally ventilated wards (77.4%) compared

[30] The indirect scales of acceptability (i.e., Bedford Comfort scale and the McIntyre's Thermal Preference scale) found a significantly higher percentage of patients in KTPH reporting the thermal environment to be acceptable than in CGH (See Appendix L). However, despite the significance of these analyses, no firm conclusion about KTPH's sustainable features can be made from the results as these single-item scales could have been subject to the threat of mono-operation bias.

to CGH (64.3%) but this result was not statistically significant.[31] There was no difference in the acceptability of nurses between KTPH's and CGH's naturally ventilated and air-conditioned wards, indicating that the acceptability of thermal condition can be achieved without the use of energy intensive air-conditioning.

4.3 Effects of Hospital Type and Ward Type on Occupant Thermal Comfort

Although the analysis of the acceptability of the thermal environment provides a clear indication of whether the ASHRAE 55-2010 standard has been met, it is prone to the threat of mono-operation bias[32] and did not take into account the effects of confounding variables such as age, gender and reliance on air-conditioning at home. A more rigorous measure of satisfaction with the thermal environment, the thermal comfort score, uses a variety of scales to elicit occupant perceptions of satisfaction with the thermal environment. It was used to compare the thermal satisfaction of patients and nurses across the three hospitals' air-conditioned and naturally ventilated wards. In addition, confounding variables such as indoor air quality and reliance on air-conditioning that could significantly affect thermal comfort were taken into account in the analysis of the comfort responses. Furthermore, the responses of patients and nurses in air-conditioned wards were used as a control to determine if the hospital management and the newness of the KTPH facility could have an effect on thermal comfort for nurses in the naturally ventilated wards. Since there was no significant difference in the patients' and nurses'

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[31] The McIntyre's Thermal Preference scale found a significantly higher percentage of nurses reporting the thermal environment to be acceptable in KTPH than in AH or CGH(See Appendix M). However, despite the significance of these analyses, no firm conclusion about KTPH's sustainable features can be made from the results as these single-item scales could have been subject to the threat of mono-operation bias and not controlling for other confounding variables.

[32] Single operations of a construct (e.g., using only one item representing thermal satisfaction) may contain irrelevancies and underrepresent constructs, and will lower construct validity compared to research multiply operationalized constructs (Shadish et al. 2002, 75).

thermal comfort scores for the air-conditioned wards across the three hospitals, the role of management and the "newness" effect in influencing perceptions of thermal comfort can be ruled out as factors influencing the observed thermal comfort between the naturally ventilated wards of the three hospitals.

4.3.1 Patient Thermal Comfort

There did not appear to be any significant difference in patient thermal comfort scores between KTPH's and CGH's naturally ventilated wards, thus it did not support the hypothesis that KTPH would perform better than CGH for thermal comfort levels in its naturally ventilated wards due to its more sophisticated sustainable design. A plausible reason for this was the higher air velocities in CGH's patient bed areas compared to KTPH's patient bed areas (due to the positioning and type of fans), which could explain the better than expected thermal comfort outcome for CGH's patients in the naturally ventilated wards. However, while there was a significant difference in thermal comfort scores for patients between CGH's naturally ventilated wards and CGH's air-conditioned wards, there was no significant difference in thermal comfort scores for patients between KTPH's naturally ventilated and KTPH's air-conditioned wards. This result indicates that patient thermal comfort scores between KTPH's naturally ventilated and air-conditioned wards were much more equitable when compared to CGH, and could have arisen for a variety of reasons as enumerated in the following paragraph.

Despite the relatively lower heat index of patient bed areas in KTPH's air-conditioned wards compared to patient bed areas of CGH's air-conditioned wards, patients in KTPH's air-conditioned wards felt less comfortable than patients in CGH's air-conditioned wards. One possible reason is that patients in KTPH's air-conditioned wards had higher expectations of the hospital facility than CGH's air-conditioned wards because KTPH was newer and more sophisticatedly built than CGH. The higher expectations could have narrowed the differences in thermal comfort levels between patients in KTPH's air-conditioned wards and patients in KTPH's naturally ventilated wards. On top of the possible higher patient expectations, patients in KTPH's multi-bedded air-conditioned orthopedic wards also frequently complained that they were not able to adjust air-conditioning temperatures to preferred levels because other patients in the room did not necessarily felt the same way. This finding was consistent with previous human subject experiments on personalized ventilation in hot and humid climates that found large differences in preferred air temperatures and air velocity between individuals (Sekhar, et al., 2011; Gong et al., 2011). Another reason for the lower than expected performance of KTPH's air-conditioned wards relative to CGH based from informal interviews with several patients was the abrupt change in thermal conditions (from the air-conditioned ward to the naturally ventilated corridors) when patients were transported to the operating room, resulting in reported experiences of discomfort and poorer air quality. The naturally ventilated corridors that linked patients in the air-conditioned wards to the operating rooms were situated right above the hospital's main waste storage area, which gave off unpleasant odors.

Patients from both KTPH and CGH also provided feedback about their experience of thermal conditions in the ward. The majority of patients (36.7%) perceived that the lack of thermal comfort could disrupt their sleep (See Appendix P). An analysis of the duration of sleep the night prior to the survey also found that patients who were more dissatisfied with the thermal environment (felt that they wanted to change the temperature to either warmer or cooler) slept around 50 minutes less than individuals who were satisfied (did not want to change the temperature) (see Appendix P).

4.3.2 Nurses Thermal Comfort

The study of the nurses' thermal comfort was comprised of both a cross-sectional comparison of thermal comfort scores across AH, CGH and KTPH and a longitudinal comparison across AH and KTPH (the same nurses were surveyed across the two hospitals).

The cross-sectional study found significantly higher thermal comfort scores for nurses in KTPH's naturally ventilated wards than AH's naturally ventilated wards but not between KTPH and CGH. The longitudinal analysis provided stronger evidence that the thermal comfort was higher in KTPH than AH in the naturally ventilated wards. This result partially supported the hypothesis that nurses in KTPH's naturally ventilated wards would have higher thermal comfort levels than in AH, but also implied that similar levels of the thermal comfort can be achieved using less sophisticated sustainable designs as with CGH's case. Nonetheless, the study confirms that KTPH's sustainable design features had been successful in increasing thermal comfort levels for nurses over its predecessor, AH.

The thermal comfort levels within KTPH's naturally ventilated wards were also not homogenous. Although this study did not study the reported thermal comfort in other areas of the ward other than the patient bed areas and nursing stations, nurses indicated that the areas of greatest thermal discomfort included the patient bathrooms and the patient bed areas that were close to the windows. Appendix Q provides an analysis of the frequency of complaints by the area type within KTPH's naturally ventilated wards.

An important consequence of the poor thermal conditions in AH's naturally ventilated wards was its effect on rounding physicians. Anecdotal feedback from a nurse indicated that the physicians who were assigned to naturally ventilated wards in AH for rounds “tried to spend as little time there as possible because of the heat in the naturally ventilated wards,” since unlike the nurses, rounding physicians were not required by their work to stay for extended periods in the wards and had their own air-conditioned offices to return to after their rounds. The reluctance of healthcare workers to spend time in a thermally unpleasant setting might undermine the quality and quantity of communication and face-to-face interactions between physicians and nurses. Given the importance of communication and team work between nurses and physicians in reducing medical errors and improving patient care (Coiera et al., 2002; Kalisch and Begeny, 2005), hospitals need to pay greater attention to providing satisfactory thermal conditions for healthcare staff.

The higher acceptability levels of patients over nurses in the naturally ventilated wards were consistent with previous research indicating that because nurses experienced higher activity levels than patients who were sedentary, they were more likely to experience greater discomfort for the same thermal ambient environment (Smith & Rae, 1977). A possible solution to improve the thermal comfort of nurses working in naturally ventilated wards is to reduce the clothing insulation (clo) value of their uniforms. In 2005, the government’s “Cool Biz initiative” in Japan successfully managed to reduce the cooling requirements and carbon emissions during the country’s warm summer months simply by encouraging a higher air-conditioning set temperature in offices and getting workers to wear work clothes made of lighter materials (Kestenbaum, 2007).

Furthermore, 58% of the nurses who participated in the survey indicated that thermal discomfort could have an effect on their productivity (See Appendix R). Thermal discomfort in naturally ventilated wards was perceived to have the greatest effect on nurses in terms of increased fatigue, followed by increased stress levels and reduced inability to concentrate, while thermal discomfort in air-conditioned wards was perceived to have the greatest impact of reduced the ability to concentrate, followed by decreased speed of work and increased stress levels.

4.4 Ambient Thermal Conditions and Thermal Comfort

Heat index temperatures significantly predicted the reported thermal comfort scores. This significant relationship supported previous thermal comfort research by Fanger (1970) indicating that air temperature and relative humidity (the components of heat index) as two of the four physical environment factors affecting thermal comfort. However, the relationship between heat index and thermal comfort becomes complicated when thermal comfort and heat index are compared across hospital types and ward types. While in general, warmer naturally ventilated wards tend to elicit lower thermal comfort scores from its occupants than air-conditioned wards, nursing stations in KTPH’s naturally ventilated wards did not differ significantly in thermal comfort scores from CGH despite CGH having a lower heat index than KTPH. One possible reason for this discrepancy is the higher job satisfaction of nurses in KTPH than CGH (Ng et al., 2011), leading to equitable thermal satisfaction levels despite the poorer thermal conditions.

Air velocity, on the other hand, did not appear to significantly predict thermal comfort scores. Previous thermal comfort research has shown that psychological variables can be even more important than environmental variables in predicting thermal comfort (DeDear and Brager, 2002). Given that air velocity is just one of the four physical environmental variables that could affect thermal comfort (Fanger, 1970), and that there might be other psychological factors that were influencing thermal comfort during the time of the survey, it is likely that the effects of air velocity might have been masked by these other variables.

4.5 Organizational Management Approach towards Sustainability in KTPH

The hospital management can be described as one of the most progressive and innovative hospital management organizations in Singapore. Led by Chief Executive Liak Teng Lit, MBA graduate and pharmacist by training, the hospital's mission is to improve the health of Singaporeans through patient-centered quality care through research and continuous learning (Alexandra Health, 2005).

The CEO had a tremendous impact in shaping the planning and operations of KTPH as well as the organizational culture (see Appendix S for organization structure). He personally interviews all his employees, selecting only those that would fit well within the organizational culture, and conducts every new staff orientation. All the senior managers are also expected to speak to new staff for two days during their orientation to ensure that they are aware of the various departments of the hospital. His intention is to provide his employees with the background and context of KTPH's service delivery model. Eleven key industry leaders including Jennie Chua, Cornell University Hotel School alumnus and former Chairman of the famous Raffles Hotel Group joined the hospital's board of directors to offer different perspectives.

As an innovator, the CEO believes strongly in reading widely and keeping abreast of the latest trends in healthcare and management issues. Using a reading list of recommended books in healthcare management and business, he requires his managers to read a recommended book every week, and reviews a book during his meeting with his managers weekly. At these meetings, he would also share with his managers lessons from his interactions with senior government officials and business leaders, and insights from attending conferences.

The CEO views sustainability as an integral way of life, and his vision was to promote sustainability as a lifestyle to his staff and the community. His ideas of sustainability started in his youth with his earlier ambitions to be an agriculturalist and architect. He previously served on the board of directors of the Singapore National Parks Board, a government agency responsible for providing and enhancing the greenery of Singapore, and is currently the Chairman of the Water Network, an advisory council for Singapore's water conservation policies and programs. Many of the CEO's immediate subordinates such as the Chief Operating Officer and Director of Operations share the same views as he did towards sustainability.

As a result of the mindset of the senior management at KTPH, the hospital planning committee, comprised of senior executives and clinical staff from KTPH, envisioned the new KTPH hospital to be a "hassle-free" hospital designed with patients as the primary focus. According to the architectural program for KTPH (CPG-Hillier, 2005; See Appendix T for more details), the planning and design objectives included:

- "A hospital for the future, with a visually pleasing design which is timeless;
- Design and material selection which facilitates low operating and maintenance costs;
- Planning for scalability, including breathability, flexibility, adaptability and modular design;
- Patient-centric design, including intuitive wayfinding and "one-stop-shopping"

clustering of services and facilities;

- Incorporation of technology as an enabler and time-saver for staff, patients and families;
- A hospital which requires only half the energy from conventional sources as existing Singapore hospitals;
- A "high-touch" hospital, which is warm, inviting, calm and cheerful;
- A healing environment with "hospital in a garden, garden in the hospital."

In a food resource-constrained world, the hospital CEO believes that his hospital needed to do their part through urban agriculture, and utilized his political influence to lobby for a rooftop urban farm at KTPH to demonstrate that it could be achieved. The hospital management formed partnerships with retired farmers in the community who previously had their land acquired by the government to volunteer and take ownership of the rooftop farm. As part of his ecological worldview, the CEO rejected the use of pesticides for the rooftop farm, advocating instead for introducing natural predators and the use of earthworms to aerate the soil. Some sustainability features at KTPH worked on multiple levels. For instance, KTPH's roof top farm's green carpet absorbs heat and rainwater. But it also produces food: tomatoes, melons, and bananas to name a few. Composted food waste from the hospital's industrial kitchen and food court is also used to provide organic fertilizers to grow the crops.

Figure 4-1 Urban Farm at KTPH

Vast areas of KTPH were earmarked for landscaping to encourage the creation of habitats and a healthy environmental ecosystem. The hospital planning committee sought to increase the indigenous wild life biodiversity by introducing native species of plants in the hospital's landscaping. The courtyard landscapes and ponds in KTPH were planned and maintained voluntarily by a retired veterinarian, a personal friend of the hospital CEO.

The hospital planning committee viewed the site as critical for the hospital's sustainable design and creation of a healing environment. A site was selected next to a storm water pond and the hospital building was oriented to capitalize on the pond. The planning team proposed restoring the storm water pond and surrounding grasslands into a health and wellness park for patients and the community in the neighborhood, and managed to garner financing from several government agencies and philanthropic sources to implement the plan.

The management approach towards sustainability coupled with the energy costs of air-conditioning and the government mandates for subsidized wards led to very ambitious design goals in terms of energy efficiency and the use of natural ventilation for the new KTPH facility. KTPH was designed to be 50 percent more energy efficient than other restructured hospitals by using passive design strategies wherever possible to promote air movement and reduce heat gain. The hospital design also responded to the tropical context using features such as high ceilings and overhangs. When the hospital was completed, about 55 percent of the total floor area of the hospital facility was naturally ventilated although a more ambitious 70 percent natural ventilation target was initially set. Air-conditioning was only to be used in areas where thermal comfort was clearly specified such as the private wards and offices. Subsidized wards were planned to create good cross ventilation. In order to minimize condensation issues and escape of conditioned air, which is common in partially air-conditioned buildings, the areas that were air-conditioned were segregated from areas that were naturally ventilated. There was also a requirement to use cheap alternative energy sources, that led to the consideration of adopting Combined Heat and Power (CHP) co-generation[33] and solar photovoltaic technologies.

The hospital was also designed to create a healing environment according to Erik Asmussen's seven principles--unity of form and function, polarity, metamorphosis, harmony

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[33] Combined heat and power (CHP) or co-generation is an onsite power plant that generates useful heat and electricity simultaneously. CHP could not implemented at the end as the town in which KTPH was located could not get access to the required natural gas pipelines.

with nature and site, living wall, color luminosity and color perspective and dynamic equilibrium of spatial experience (Coates, 2000) as well as Ulrich's theory of supportive design (Ulrich, 1991, 1999 and 2000). These principles manifested in the provision of internal courtyards, greenery to provide patients with a visual, aural and olfactory connection to nature. All the patient beds were also positioned to have a view to the greenery or at least a view of the outdoors. Natural daylight also was to be encouraged. Additionally, control, privacy and social support were also built into the design as much as possible. Elements to reduce stress and create a feeling of "home" through the use of familiar spaces and furnishings were also encouraged.

Much of the analysis in this study thus far has explored the impact of design of naturally ventilated spaces on the thermal comfort of occupants. However, it is also important to understand why such a commitment to natural ventilation was made in the first place. The above examples illustrate how management philosophies and the CEO's vision helped to shape the design decisions in the use and enhancement of naturally ventilated spaces. These examples also showed the potential for sustainable designs to work on multiple levels simultaneously, and how inexpensive and clever strategies can help an organization to minimize costs, while achieving its sustainability and business objectives.

4.6 Facility Management of KTPH's Green Facility

In addition to assessing the success of KTPH's sustainable design using the measure of thermal comfort and ambient thermal environment, the study examined the operational issues in the hospital related to these features to understand the operational implications of the design and recommend changes for future Singapore hospital designs. Design features such as the use of open-air corridors, jalousie windows and venturi design reduced the need for air-conditioning (and therefore generated savings in capital and energy costs), while maintaining the thermal comfort of occupants (since there were no significant differences in the acceptability and thermal comfort of patients and nurses between KTPH's naturally ventilated and air-conditioned wards). However, the unintended consequences and unanticipated challenges directly associated with some of these designs were necessitating additional capital costs to fix unanticipated problems (e.g., installing operable windows in specialist outpatient clinics) or additional operational costs, as with the case of dealing with rainwater. Some design features can only be changed during the earlier stages of design and construction as they would be too costly to change once the building has been completed (such as extending the overhangs for the open-air corridors), which might lead to incremental facility operating costs (as with the case in KTPH). Some of the unintended consequences of one sustainable design feature might also reduce the performance of another sustainable design feature, as described by the blockage of natural ventilation because of the use of curtains for shading. Although the multiple facility problems resulting from KTPH's sustainable were mitigated because of the management's leadership and innovative workarounds, the time and energy spent to overcome these challenges could have been put to better use. To paraphrase architecture historian James Marston Fitch, the goal of architecture should not test the limits of human adaptability (Fitch, 1947).

Tables 4-1 to 4-3 illustrate the expected benefits and drawbacks associated with these sustainable design features. The exact cost figures of these operational implications were however, unavailable at the time of the study. As such, a cost effectiveness analysis of the thermal comfort design implications for hospital operations could not be completed.

The sustainable design features listed in Table 4-1 provide clear benefits to occupants and pose minimal problems for the operations and maintenance of the facility, and are recommended for future hospital designs in Singapore. These features include siting next to ponds, extensive landscaping, high building thermal transfer value, and individual fan control. Other features that may have benefits to building occupants while posing minimal facility operation issues such as the central atrium can be considered in future hospital designs if accurate building simulation studies can be done to determine their efficacy.

Table 4-1 Assessment of Sustainable Design Features' Benefits and Drawbacks (Part 1)

Design Feature	Expected Benefits	Actual Occupant Experience	Actual Facility Operational Challenges (if any)	Recommendation
Siting/Location next to Pond	Provide unblocked airflow to hospital and provide views of nature.	Although there were no increased airflows at the patient bed areas or nursing station areas, the main corridor of the naturally ventilated inpatient ward managed to achieve 0.6 m/s as predicted by the simulation study (Lee et al., 2006). The study found views of nature to be higher than CGH or AH.[26]	None reported.	Recommended for use in future designs.
Extensive Landscaping	Reduced heat island impact and provision of views of nature for building occupants.	The urban heat island effect was not directly measured in this study. The study found occupant views of nature to be higher than CGH or AH.[34]	None reported.	Recommended for use in future designs.
Low Building Envelope Thermal Transfer Value (ETTV)	Reduced thermal transfer from exterior to interior of building	ETTV was tested and shown to be effective in reducing heat transfer.	None reported	Recommended for use in future designs.
Individual fan control	Provided patients in naturally ventilated wards with ability to control air velocities	Greater control provides increased thermal comfort.	None reported	Recommended for use in future designs.

[34] A one-way ANOVA showed that occupants (patients and nurses) in KTPH (M=5.11, SE=.104) were more satisfied than CGH (M=4.33, SE=.093) and AH (M=4.22, SE=.194) with their views of nature $F(2, 432)=18.267$, $p=0.000$.

Central Atrium	Increased ventilation	Not measured directly. Air velocity in patient and nursing station areas was not higher than CGH or AH, but CGH and AH also has courtyards.	None reported.	Can consider for use in future designs.

Other sustainable design features that presented challenges to the occupant experience or facility operations but could still be replicated in future hospitals if their designs were improved upon are illustrated in Table 4-2. Recommendations to improve these design features should they be continued in hospitals are also included in the same table. However, not all of the strategies listed in Table 4-2 are equal in their cost effectiveness and thermal comfort outcomes. Inexpensive changes like installing ceiling fans with rotatable bases so that the airflow can be channeled towards the occupants (as with CGH's example), could improve the thermal comfort of occupants to a larger extent than investing resources to refine sophisticated, but expensive design features such as the venturi design to improve occupant comfort.

Table 4-2 Assessment of Sustainable Design Features' Benefits and Drawbacks (Part 2)

Design Feature	Expected Benefits	Actual Occupant Experience	Actual Facility Operational Challenges (if any)	Recommendation
Venturi Design	Increased cross-ventilation	Air velocities were not higher than CGH or AH.	None reported.	Adjustments made to shape of building to increase air flow.
Open-air corridors	Reduced need for air-conditioning	Risks of falls.	Ongoing need to dry floors and notify users of wet floors.	Easily preventable with change in non-slip tiles and use of extended overhangs.
Jalousie Windows and Monsoon windows	Increased cross-ventilation	Air velocities were not higher than CGH or AH.	Operational challenge of shutting and cleaning windows. This finding is consistent with literature citing that patients and nurses cannot be relied on to logically operate windows (Lomas & Ji 2009)	Window redesign and automation needs to be considered if incorporated in future designs.
Mechanical Fans	To enhance ventilation in non air-conditioned areas	Patients do utilize fans.	Located at feet of patient and patients are not able to control direction of airflow.	Easily preventable and cheap. Use an integrated ceiling plan, fans that are rotable on their axes or using mechanical fans with built-in lighting.

Fixed external shading devices	Solar shading	Effectiveness reduced with changing sun angles. Resulted in direct sun exposure on some patients.	None reported.	Curtains had to be drawn to reduce direct sun exposure, but would inadvertently reduce air velocities. Preventable with one-time investment in dynamic external shading devices.

Finally, sustainable design features that presented no clear benefits to hospital occupants while at the same time increased capital or operational costs should not be reconsidered for future hospital designs in Singapore are illustrated in Table 4-3 below.

Table 4-3 Assessment of Sustainable Design Features' Benefits and Drawbacks (Part 3)

Design Feature	Expected Benefits	Actual Occupant Experience	Actual Facility Operational Challenges (if any)	Recommendation
Lack of operable windows in outpatient clinics and isolation wards	To reduce occupant access to natural ventilation to prevent loss of air-conditioning and energy wastage.	Reduced occupant control.	Unable to ventilate room with natural ventilation to accommodate local practices and facility lacks flexibility in change of use.	Provide operable windows (mixed-mode ventilation).
Extensive and inappropriate use of treated glass windows	To reduce solar gain	Patients and visitors were not able to see into the outpatient clinics, reducing ease of wayfinding.	Cleaning and operational difficulties	Window treatments should be used only for appropriate areas.
Aluminum Cladding	To reduce solar gain	N.A.	Easily scratched and dented. High cost of replacement.	Use of aluminum cladding should be discontinued. Substitutes (e.g. concrete) should be used for cladding instead.

Light Shelves	Increased daylight in wards while providing some shading from direct sun exposure.	Some patients did not like the light shelves because of superstitious beliefs. Anecdotal feedback that light shelves did not work well.	Dust collected on light shelves. Furthermore, given that KTPH inpatient tower had a narrow floor plate with access to windows on both sides, light shelves seemed to be unnecessary.	Light shelves should only be used if necessary, and needs to be re-designed taking into consideration of cultural values.

4.7 Additional Sustainable Design Features For Future Hospital Designs

Apart from replicating and improving on existing features of KTPH in future Singapore hospital designs, additional sustainable design features based on a literature review of sustainable design could be considered going forward to improve the thermal comfort of occupants. These features include:

- Dynamic external shading systems
- Personal ventilation controls for patients in multi-bedded air-conditioned wards
- Motorized operable windows

Detailed descriptions of the above sustainable design features have been included in Appendix U.

4.8 Integrated Sustainable Design Planning

Sustainable designs and their performance levels in relation to one another need to be planned in an integrated fashion. Furthermore, facilities operations and management issues of features need to be factored early on in the design stage so that costly mistakes can be avoided.

Reflecting on the facility operational challenges in managing KTPH, the facilities planning director mentioned that some of the issues such as rainwater described above could have been anticipated if the hospital planning committee had access to building information modeling (BIM) models of the hospital.[35] The architecture firm did not use three-dimensional building models in their design development, citing the argument that developing a building information model was too time-consuming and too expensive. Moreover, despite the fact that building simulations for Wind Tunnel tests and Shading Coefficients studies were performed, they were limited in their ability to anticipate issues outside their realm of interest. A holistic perspective is thus needed in the planning and selection of sustainable design features. Studying the effects that the performance and operation/maintenance of one feature can have on another, and simulating the performance of these features as a totality can avoid costly design mistakes.

In the development of future hospitals, hospital facility planning teams could consider using a facility-planning checklist to communicate design requirements to the hospital architect with the eventual facility operation and management goals in mind (i.e., sustained reduction in energy costs, optimize performance over time and minimize operating costs throughout the building lifecycle). This checklist could be developed with insights generated from post-occupancy evaluations such as this present study. The checklist tool would serve an important role for the hospital design to be refined based on downstream facility management implications. For example, the checklist could ask architects or hospital planning team to check if the proposed hospital design could hold up to routine bad weather conditions or unexpected catastrophes such

[35] Building Information Modeling (BIM) is the process of developing and managing building data during its life cycle (Lee, Sacks and Eastman (2006). BIM commonly utilizes three-dimensional, dynamic building modeling software to increase productivity, reduce errors and improve communication during building design and construction stages (Holness, 2008).

as pollution from forest fires. The checklist could also trigger building professionals to reflect on whether serious operational issues could arise from those designs (e.g., patient transportation issues during rain when open-air corridors were used); how the design would impact the cleaning and maintenance of the facility; if the design features would incur additional operating costs; and whether the building design is flexible enough to adapt to future needs. Ultimately, the checklist serves as a contingency planning tool and helps raise issues and concerns that could have been easily overlooked or missed by the architect or planning team, and help prompt design changes before the facility is even constructed, saving potentially incremental capital and operational costs down the road.

4.9 Thermal Comfort Standards for Singapore's Hospitals

Singapore's building codes[36] only prescribe guidelines for air-conditioned spaces, not naturally ventilated spaces. As evident from the results, the three hospitals in the study had no problems achieving the minimum 80% occupant satisfaction requirement for their air-conditioning wards. However, none of the buildings were able to meet this requirement in the naturally ventilated wards. Given the restructured hospitals' commitment to patient centered care, if natural ventilation is going to be a main stay in Singapore's restructured hospitals, it raises the question of whether the current building standards and rating tool methodologies are adequate for future hospital projects.

[36] Singapore's building codes are stipulated in SS 554:2009 (Singapore's code of practice for indoor air quality for air-conditioned buildings) —indoor operative temperature must be set between 24°C to 26°C, air movement between 0.10-0.30 m/s and relative humidity settings below 65% for new buildings or 70% for existing buildings (Spring Singapore, 2009). The SS 554-2009 Standard also does not have a minimum occupant satisfaction requirement unlike ASHRAE 55-2010.

Authorities in Singapore might benefit from learning from the British National Healthcare Service example in defining standards for naturally ventilated spaces specifically for hospitals, and planning ahead for resilience to heat waves and other catastrophes that naturally ventilated wards might otherwise be vulnerable to.

Further, although the Green Mark Assessment rating tool provided a maximum of 2 points out of a possible total 160 points for thermal comfort, the points were awarded on the condition that the HVAC systems were designed to meet the indoor air quality codes, whereby only ambient conditions were considered. Occupant satisfaction in general and naturally ventilated spaces in particular were not included as requirements in the Green Mark Scheme. A case in point is that while KTPH managed to achieve the maximum 2 points for thermal comfort for the Green Mark Scheme assessment because its air-conditioned spaces met the requirements, a large proportion of spaces in KTPH (54.5%) were naturally ventilated and the actual occupant satisfaction with the thermal environment was unaccounted for when the certification was completed. Moreover, AH being a "Gold"-rated facility by the Green Mark Scheme, also managed to achieve the full 2 points for thermal comfort for meeting the air-conditioning requirements, despite it performing significantly worse than CGH (not certified by Green Mark) and KTPH (Green Mark Platinum).

Other green building tools such as LEED have required new buildings to meet the ASHRAE 55-2004 Thermal Comfort Standard of satisfying at least 80% of its occupants in terms of thermal comfort for all spaces (including naturally ventilated ones), providing user control and verifying this requirement by doing a survey 6 to 18 months after the building has been occupied (USGBC, 2009). The Green Mark Scheme would benefit from following LEED's example with respect to assessing green buildings by assessing occupant outcomes rather than prescribing ambient thermal requirements and incorporating naturally ventilated spaces into its evaluation criteria.

CHAPTER 5

CONCLUSIONS

5.1 Overall Conclusions

Overall, the results of the study show that the newer hospital with more sophisticated sustainable design features, Khoo Teck Puat Hospital, performed better than its predecessor, Alexandra Hospital, a former British Military hospital designed with vernacular features in terms of the ambient thermal environment and subjective thermal comfort. The study also demonstrated that similar levels of thermal comfort of occupants could be achieved in the naturally ventilated wards as in air-conditioned wards. However, the study failed to show conclusive evidence of higher performance levels of Khoo Teck Puat Hospital compared to traditional modern hospital designs as characterized by Changi General Hospital in terms of the ambient thermal conditions and subjective thermal comfort, raising questions on whether the same level of sophisticated sustainable design features were necessary to achieve satisfactory thermal comfort outcomes. An interesting conjecture from this research is that simple details such as the position of the fans and the ability for patients to control the direction of the fan could have a disproportionate impact on thermal comfort than other more sophisticated design features to improve thermal comfort in the naturally ventilated ward. The study supports previous research that emphasizes the benefits of using natural ventilation as a sustainable design strategy in reducing the use of air-conditioning and their associated costs, and maintaining satisfactory levels of thermal comfort while also noting the unanticipated challenges and unintended consequences in the operation of the green hospital facilities.

5.2 Limitations of Study

While the study provides valuable insights into the actual thermal conditions and perceived comfort by occupants, the study of thermal comfort in the field makes it difficult to control other environmental, social and personal variables. This study took into consideration a large number of factors that might have affected thermal comfort, and through careful statistical analysis identified which had an impact and which did not. In addition, this study was an exploratory comparative case study of three facilities with varying levels of sophistication in their sustainable designs. A larger sample of hospitals should be pursued to increase the validity of the findings. At the time of the study, KTPH did not have energy consumption data for a full year since the building only reached full operation in August 2010 and electricity consumption in the three hospitals were not sub-metered. Therefore, comparisons with CGH and AH in terms of energy savings attributed by natural ventilation design features could not be made. Furthermore, detailed information on the incremental costs of dealing with the operational issues that arose from the implementation of KTPH's sustainable design features were not available at the time of the study as KTPH was only started its operations less than a year ago, and the hospital was still experimenting with different strategies to cope with the multiple problems in operating and managing the facility. A follow-up study once the hospital has stabilized its operational policies to deal with the unanticipated challenges and unintended consequences arising from the facility design would present a good opportunity to analyze the costs in operating and managing the sustainable hospital facility as well as the medical costs if clinical processes were affected. A root cause analysis[37] for these facility challenges could also be completed to identify and eliminate the sources of these failures.

5.3 Future Research Directions

Designing hospitals to be sustainable and effective environments for occupant thermal comfort is important because hospitals are the most expensive building types to construct and operate and the patients in whom they house are typically more vulnerable than the general population to unfavorable environmental conditions. As evident from Khoo Teck Puat Hospital's experience, not all of these sustainable design features led to positive outcomes but instead caused multiple facility operational challenges. More research is needed to identify specific design elements that can improve the ambient thermal environment and thermal comfort of occupants and investigate ways to optimize these design features to reduce unexpected facility operational costs. Specifically, future research should consider:

- Performing a cost efficiency analysis of the unanticipated challenges and unintended consequences in operating and managing KTPH's sustainable design features;
- Performing a root cause analysis of the unanticipated challenges and unintended consequences of KTPH's sustainable design features.

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[37] Root cause analysis (RCA) is a systematic method to identify the fundamental source of a problem so that the recurrence of the problem may be prevented. Although doing a RCA require a great deal of upfront investment in time and money, RCA can benefit the hospital in the long run because it can help the hospital identify the causes of expensive failures and enable it to take effective and targeted actions to prevent it from happening again.

- Developing a facility planning checklist used during the hospital planning and design stages to minimize the unintended and unanticipated consequences in operating and managing a sustainable hospital;
- Identifying the individual effects of sustainable design elements on the ambient thermal conditions and thermal comfort;
- Identifying and examining how effective but inexpensive sustainable design solutions allow for optimal thermal comfort levels to be achieved (i.e., value-for-money concept);
- Comparing the results of building simulations for thermal comfort with actual outcomes;
- The relationship between hospital management philosophies and the selection of sustainable design features;
- The effects of thermal discomfort on physician and nurse social interaction and communication;
- Random assignment of patients and nurses to ward ventilation types to eliminate selection bias;
- Controlling for the floor levels of naturally ventilated wards between hospitals;
- The effects of thermal discomfort on nursing performance;
- The effects of thermal discomfort on patient health and wellbeing;
- The effects of ambient thermal environment on patients with fevers or problems with thermoregulation;
- The relationship between thermal comfort and overall satisfaction with the hospital's service quality.

5.4 Implications for Practice

The findings in this study confirm the potential of design features in improving the thermal comfort and ambient environment of occupants. The study also suggests the need for better planning of sustainable designs using an integrated design and operational perspective to mitigate difficult and costly facility operational challenges post building completion using tools such as BIM and facility planning checklists. The study calls for government authorities to revise current building standards and sustainability rating tools, so that architects, engineers and building owners would be incentivized to pay greater attention to the special thermal comfort needs of hospital occupants.

If Singapore's outdoor temperatures do not rise significantly over the next few decades due to global warming, the Ministry of Health's current policy of using natural ventilation in the subsidized inpatient wards of Singapore's restructured hospitals could be continued given that similar levels of patient thermal comfort were achieved between the air-conditioned and naturally ventilated wards as with KTPH's case. Natural ventilation is a sustainable design strategy for hospitals in Singapore to reduce energy usage, but the design features that support natural ventilation need to be carefully selected to minimize unanticipated facility challenges while maximizing benefits to all stakeholders.

Implementing sustainable design elements to enhance natural ventilation within the hospital is a complex process, and is a strategy that requires careful planning and systematic thinking, taking into account many factors, including the operational demands, different stakeholders, organizational/community cultures and financial constraints of the hospital. If these are be dealt with appropriately, there could be many opportunities to capitalize on using natural ventilation in hospitals.

APPENDICES

APPENDIX A

Appendix A: Khoo Teck Puat Hospital's Sustainable Design Strategies

KTPH was designed to utilize only 50% of conventional energy sources than other existing hospitals, resulting in the decision to use extensive natural ventilation in both the common areas and subsidized inpatient medical units. Table A-1 summarizes how ventilation in common areas of KTPH are treated:

Table A-1 Breakdown of functional areas by ventilation type

Building Use	Air-conditioned Area (m^2)	Non Air-conditioned Area (m^2)	Total Area (m^2)	Floor Area Non Air-conditioned (%)
Inpatient Medical Units	12835.1	15710.3	28545.4	55.0
Specialist Clinics	18619.7	0	18619.7	0.0
Operating Theater	7488.2	0	7488.2	0.0
Offices/Labs	15323.55	490.2	15813.75	3.1
M&E	1045.14	9853.68	10898.82	90.4
Common Areas	414.7	22217.8	22632.5	98.2
Kitchen	1694.6	0	1694.6	0.0
Retail	765.8	0	765.8	0.0
Driveway/Parking	0	17166.66	17166.66	100.0
Stairs	0	4046.34	4046.34	100.0
Toilet	0	308.9	308.9	100.0
Total	58186.79	69793.88	127980.67	54.5

In addition, mixed mode ventilation was implemented in the air-conditioned private inpatient rooms through the provision of operable windows. Due to the extensive areas that are naturally ventilated, sustainable design strategies were employed by architects and engineers to improve the thermal comfort of occupants in those areas of the hospital. Table A-2 summarizes the sustainable design strategies based on information obtained from interviews with architects, facility planners, and sustainable design reports prepared by the architecture firm and the BCA Green Mark Scheme certification documents.

Table A-2 Sustainable Design Strategies Employed by KTPH for thermal comfort in naturally ventilated areas of the hospital

Design Strategy	Description
Site Planning	The hospital was located next to Yishun Pond and Yishun Park. The siting of the hospital next to a storm water reservoir helped to maximize unblocked airflows. The naturally ventilated inpatient tower and the outpatient clinic tower were designed to improve natural ventilation and "opened up" towards the pond.
Venturi Design	The narrow building layout coupled with a Venturi design would help to create air movement in the absence of active fans. As the outpatient tower is built next to the subsidized inpatient tower, leaving only a narrow open space between them, as wind reaches the building, the wind is sucked through the space by the air that is moving through it (i.e., the Venturi effect). The speed of the wind as it is channeled into the internal courtyard will speed up and create a negative pressure zone. This in turn would help to generate cross ventilation in the subsidized inpatient ward tower as air moves from the side with the higher pressure into the courtyard area of a lower pressure zone.
Landscaping	The overall landscape of KTPH was integrated with Yishun Pond as an extension of the outdoor/indoor space connection with one seamless visual landscape connection from the time one arrives at the arrival area. A courtyard centrally-located in between the subsidized inpatient tower and the outpatient clinic tower was landscaped to evoke a resort-like tropical landscape that features a stream-like water element that integrates the pond into the courtyard environment, with spaces for relaxation and interaction between the users. Myriads of green spaces and tree canopies were strategically placed to provide both visual feast and shading while a generous paved area was also designed to provide more movement and accessibility. Design coherence between the pond and the hospital courtyard was achieved by providing a series of water features that linked the inside area to the outside. Yishun Pond would also be transformed into a well-landscaped water body with wetlands and vegetation on the edges of the pond and boardwalks and nature trails for the public. The extensive vegetation also helps to reduce the heat island impact and improves thermal insulation, hence resulting in a cooler microclimate that cuts air-conditioning demand.
Building shape and layout	The hospital utilizes narrow buildings with high ceilings to facilitate cross ventilation. The building is also oriented towards prevailing wind conditions to achieve adequate cross ventilation. Ventilation simulation software (computational fluid dynamics) and wind tunnel testing was also carried out to identify the most effective building design and layout to achieve good natural ventilation. The Wind Tunnel Study verifies that the naturally ventilated wards can achieve 0.6 m/s ventilation in most spaces (Center for Total Building Performance, 2005). The subsidized inpatient tower was also oriented to ensure

	that there is no west facing façade or west facing window openings. For the private inpatient tower, effective sun shading was used to provide windows on the west façade with minimum shading of 30%. A Solar Coefficient simulation study was also conducted to determine the optimal building orientation to minimize exposure to the east and west sun.
Building Envelope	The building envelope was designed to minimize heat gain indoors. There was no direct west facing façade for the non air-conditioned block. The thermal transmittance (U-value) of external west facing walls and thermal transmittance of roof were less than 2 W/m^2 K and 0.38 W/m^2 K respectively.
Façade Design	The hospital was designed using an optimal combination of window openings and internal layouts in order to produce adequate natural air movement indoors during mean external wind conditions (at least minimum fresh air exchange rates during low wind speed conditions). The wing wall design (fins) on the façade helps to increase wind pressure build up at the window openings, channeling winds into the interiors and facilitating cross ventilation. Fully operable center-pivot windows (jalousies) were also employed to facilitate controlled/enhanced airflow contingent on external climatic factors. These windows are angled at 45° for the best airflow and least rain penetration. Monsoon windows below the jalousies help to provide minimum air exchange even during heavy rains. Shading devices and light shelves were also installed to reduce glare and direct solar exposure. The windows were all low-emissivity glass to reduce solar heat gain and some had additional 3M coating to reduce glare.
Central Atrium	At the macro-level, a central atrium void that runs through the height of the ward block helps to assist passive ventilation through the natural buoyancy of the air.
Interiors	The partition heights that separate individual wards from the main corridor also had a 300mm gap from floor level to allow a separate air movement path to the top opening. Mechanical fans with individual patient control were also provided.
Recycled cooled air	Cool air from the operating rooms are recycled, cleaned with a hepafilter and blown into the courtyard to generate a cooling effect. Anecdotal feedback indicates that it could lower the ambient air temperature by 1 °C.

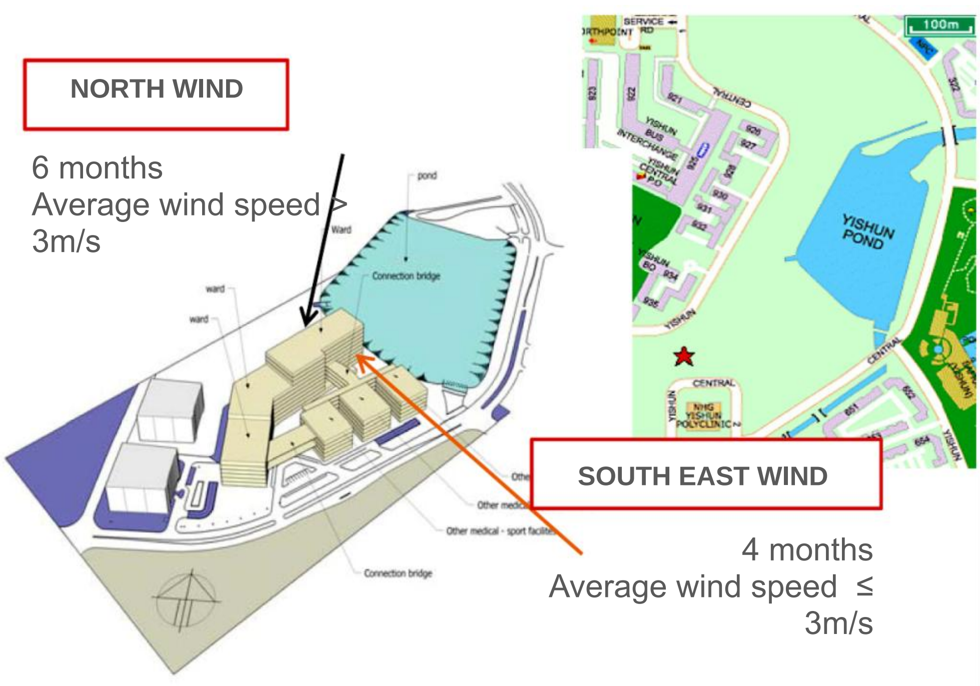


Figure A-1 Site Layout, building shape and layout to enhance natural ventilation (CPG Architects, 2009)

Figure A-2 Landscaping at Internal Courtyard of KTPH

Figure A-3 Façade Design (Left: Jalousie Windows; Middle: Monsoon Windows; Right: Shading Devices/Wing Wall Design) (CPG Architects, 2009)

Figure A-4 Interior of naturally ventilated medical unit (Left: Partition wall; Right: Patient-controlled mechanical fans)

APPENDIX B

Appendix B: BCA Green Mark Assessment for KTPH

KTPH was the first hospital building to be awarded the Green Mark Scheme Platinum award in 2009 and also achieved the highest points for buildings that were certified in that year. There are at present 60 buildings that have achieved a Green Mark Platinum status. Table B-1 details the points awarded for KTPH's sustainable design.

Table B-1 BCA Green Mark Assessment Report for KTPH

No.	Item	Total Achievable Points	Achieved
Energy Efficiency			
1	Building Envelope – ETTV	15	15
2	Air-conditioning System	27	27
3	Building envelope – Design/Thermal Parameters	29	29
4	Natural Ventilation (Exclude Parking Lots)	13	13
5	Artificial Lighting	12	9.85
6	Ventilation in Parking Lots	5	3
7	Ventilation in Common Areas	5	2.5
8	Lifts and Escalators	3	3
9	Energy Efficient Practices and Features	12	12
10	Renewable Energy (bonus)	20	4.69
Water Efficiency			
1	Water Efficient Fittings	8	6.08
2	Water Usage and Leak Detection	2	2
3	Irrigation System	2	2
4	Water Consumption of Cooling Tower	2	2
Environmental Protection			
1	Sustainable Construction	14	4.5
2	Greenery	6	6
3	Environmental Management Practice	8	8
4	Public Transport Accessibility	2	2
5	Refrigerants	2	2
Indoor Environment Quality			
1	Thermal Comfort	2	2
2	Noise Level	2	2
3	Indoor Air Pollutants	2	2
4	High Frequency Ballast	2	2
Other Green Features			
1	Green features and innovations	7	5
Total		160	101.27 (Green Mark Platinum)[38]

[38] To achieve a BCA Green Mark Platinum status, the building must achieve at least 90 points or more.

As much of the preliminary assessment was based on projected building performance data, KTPH is required to submit a report one year after the building was commissioned to ascertain that the building performance targets have been met or exceeded. The architecture firm was also awarded a cash incentive of $100,000 Singapore dollars for achieving BCA Green Mark Platinum. However, if they do not reach those targets, the cash incentive will have to be returned to BCA. The BCA Green Mark Scheme certification would also need to be recertified every three years. If the hospital fails to achieve the performance targets, the hospital's facilities team would be counseled by BCA officials and have a six months probation period to make the necessary changes or risk forfeiting their status.

APPENDIX C

Appendix C: Green Mark Scheme Evaluation for Alexandra Hospital

The assessment for Alexandra Hospital was completed using the first version of Green Mark Scheme. Alexandra Hospital was awarded "Gold" in 2005. At that time, gold was the highest standard achievable. A comparison of KTPH and AH in terms of their Green Mark ratings would not be accurate since the weightage of points for the various evaluation criteria were different. However, the thermal comfort criteria was the same for both KTPH and AH. Table C-1 illustrates the assessment criteria and the points achieved in AH's Green Mark Scheme Certification.

Table C-1 BCA Green Mark Assessment Report for AH

No.	Item	Total Achievable Points	Achieved
Energy Efficiency			
1	Building Envelope – ETTV	6	5
2	Energy Efficiency Index	4	3
3	Electrical Sub-metering	1	1
4	Tenancy Sub-metering	1	1
5	Energy Efficient Features	12	10
6	Office Lighting Zoning	1	1
7	Roof Top Gardens & Landscaping	5	5
Water Efficiency			
1	Water Efficient Fittings	6	5
2	Water Usage and Leak Detection	4	4
3	Irrigation System	4	4
4	Water Consumption of Cooling Tower	6	4
Environmental Protection			
1	Conservation & restoration of site ecology	3	3
2	Building meeting quality standards based on CONQUAS score	2	0
3	Public Transport Accessibility	1	1
4	Environment Management System	6	6
5	Environment Friendly Material	5	5
6	Building Users' Guide	3	1
Indoor Environment Quality			
1.	Carbon Dioxide & CO Monitoring and Control	2	2
2.	High Frequency Ballasts	2	2
3.	Electric Lighting Levels	2	2
4.	Thermal Comfort	2	2
5.	Noise Level	2	2
6.	Indoor Air Pollutants	2	2
7.	Refrigerant Ozone Depletion Potential	1	1
8.	Refrigerant Leak Detection	1	1
9.	Refrigerant Recovery	1	1

Other Green Features			
1	Green features and innovations	15	10
Total		160	100 (Green Mark Gold Plus)[39]

[39] To achieve a BCA Green Mark Platinum status, the building must achieve at least 90 points or more.

APPENDIX D

Appendix D: Floor Plans for Hospitals

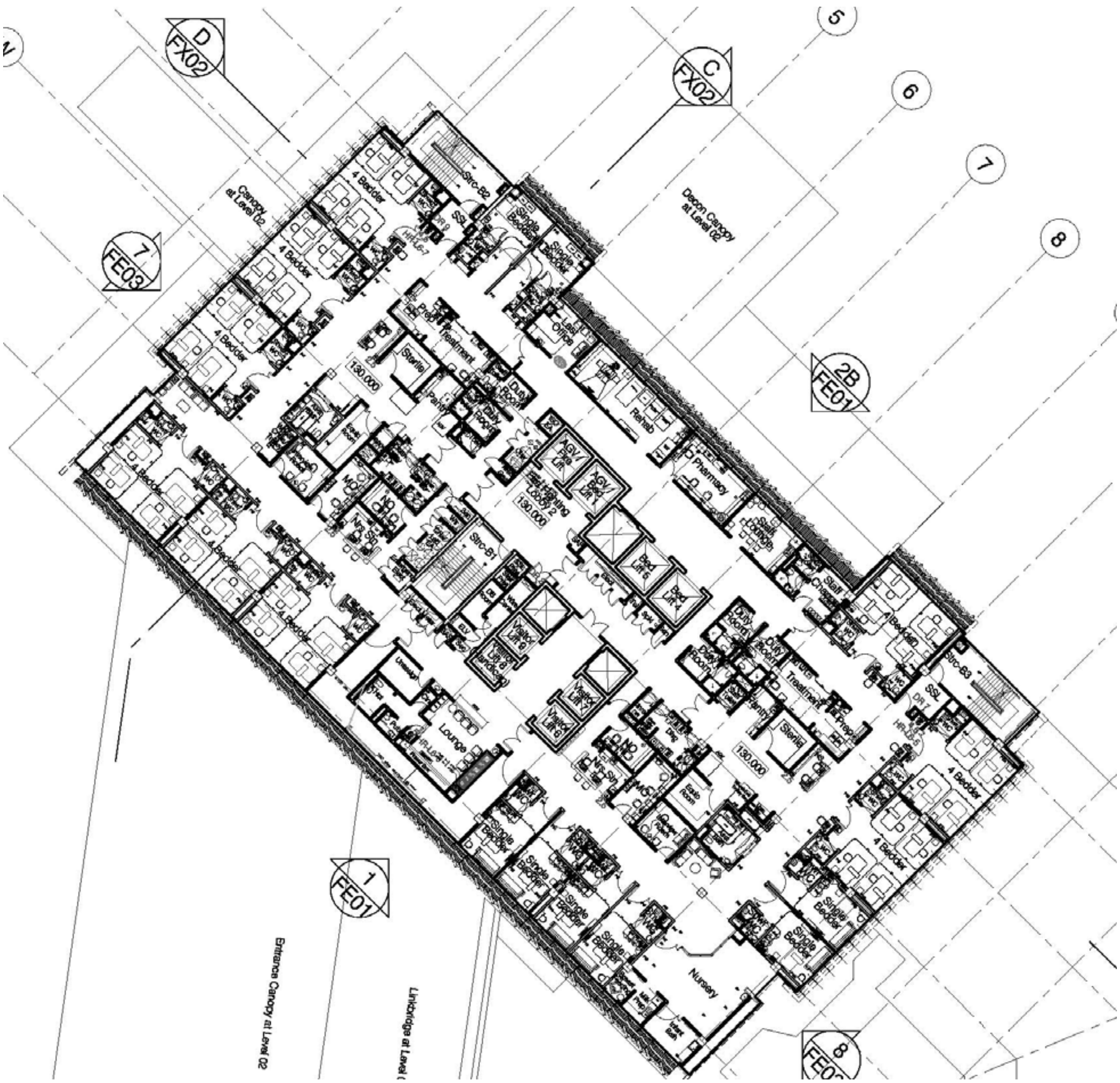


Figure D-1 Floor Plan of KTPH Air-Conditioned Ward

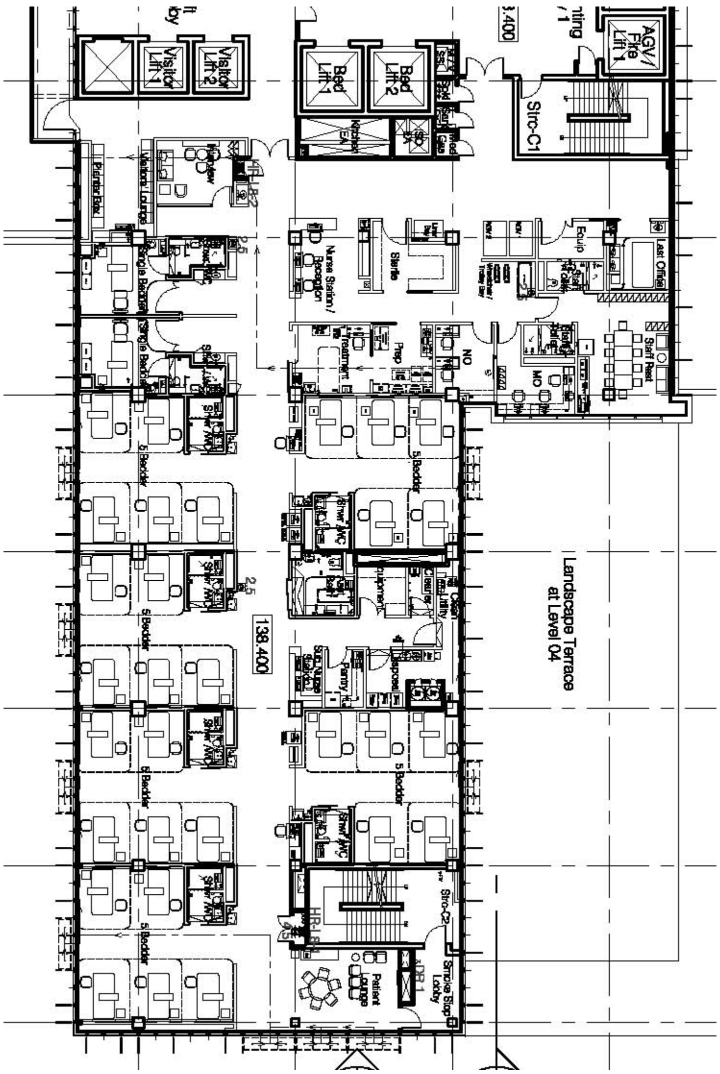


Figure D-2 Floor Plan of KTPH Naturally-Ventilated Ward

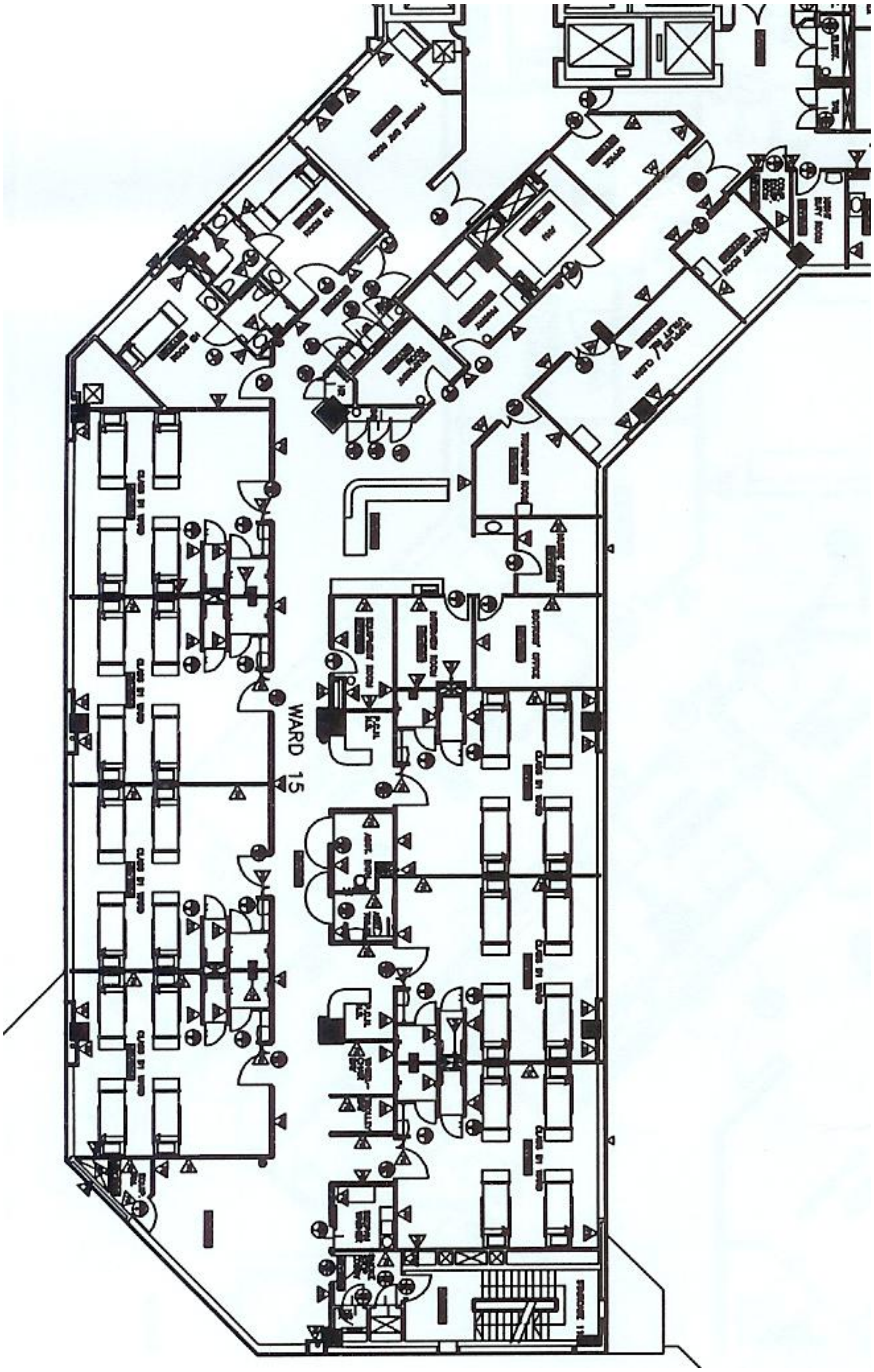


Figure D-3 Floor Plan of CGH Air-conditioned Ward

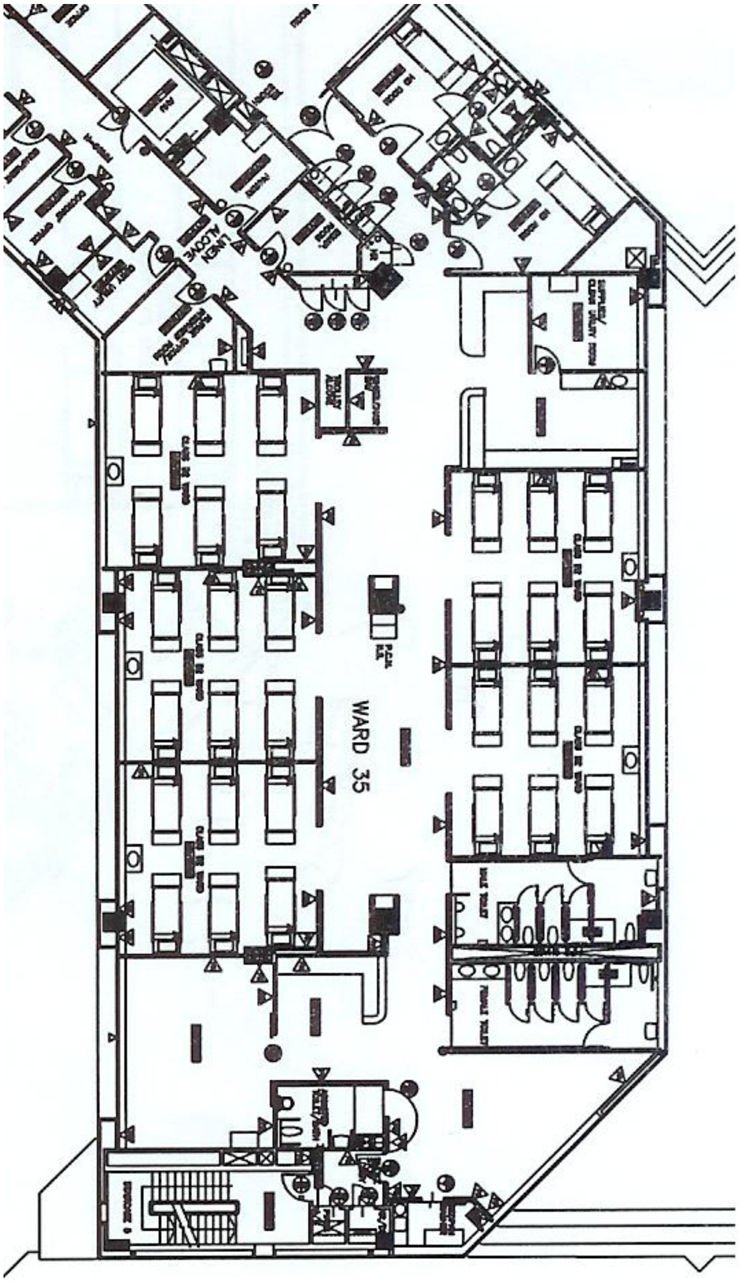


Figure D-4 Floor Plan of CGH Naturally Ventilated Ward

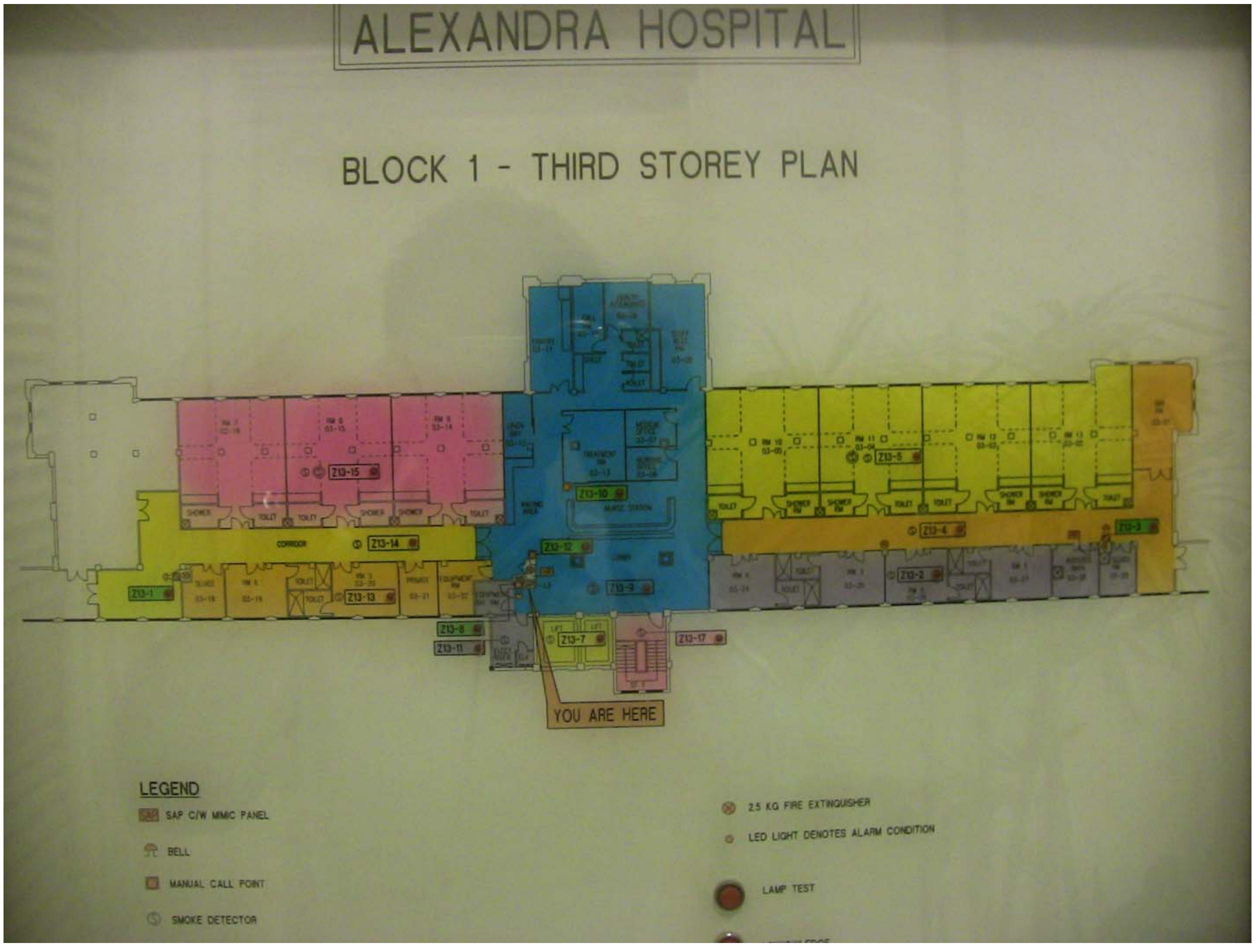


Figure D-5 Floor Plan for AH Air-conditioned Ward

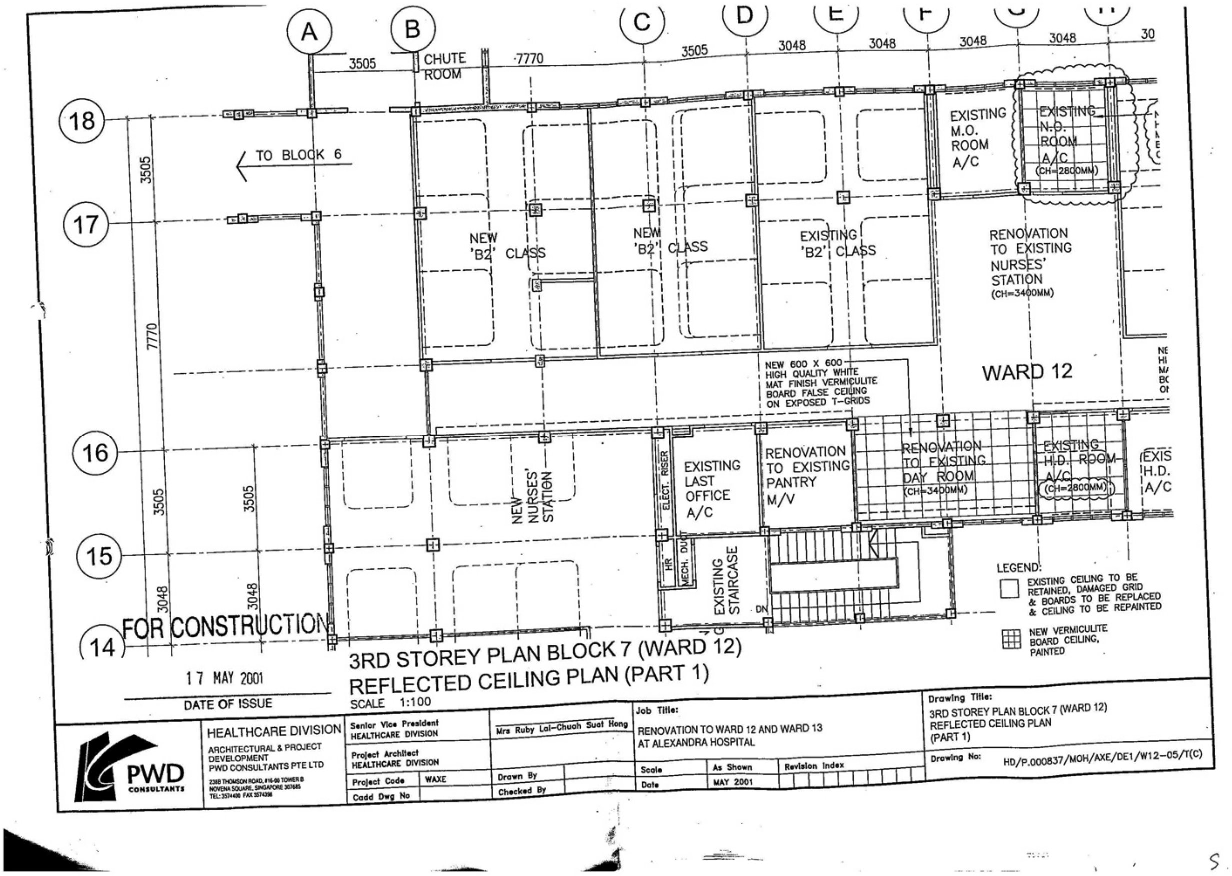


Figure D-6 Floor Plan for AH Naturally Ventilated Ward

APPENDIX E

Appendix E: Thermal Comfort Survey for Patients

Dear Patient,

A research team from Cornell University is examining the levels of thermal comfort in the inpatient ward tower.

Your participation in this survey is entirely voluntary and your responses will be kept confidential and anonymous.

By participating in this survey, you will provide important feedback and allow the hospital to improve the thermal environment for patients and staff. Please read the following instructions carefully and ask any questions you may have before agreeing to take part in the study.

Instructions for Survey Participants

Please be dressed only in your patient gown/pajamas without any other outer clothing or blankets covering your body.

Please sit up on your bed to answer this questionnaire.

The total time for doing this survey is about 15 minutes.

For participating in the survey, you will receive a small token of appreciation.

If you have any further questions, please contact the lead researcher, Wu Ziqi at zw74@cornell.edu or at +1 607 351 5883.

Survey Number: __________

Date:		Time of Start of Survey:	
Hospital Name:		Ward Number:	
Room Number:			

I. Temperature Sensation

For questions 1 to 15, please answer between 11.30 am - 3.00 pm. If now is not the appropriate time to respond, you may continue with the other sections before returning to questions 1 to 14 at the appropriate time. For all questions, please tick the appropriate box.

1. How do you feel about the temperature at this moment?

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

2. How comfortable do you feel with the thermal conditions at this moment?

Much too cool	Too Cool	Comfortably cool	Comfortable	Comfortably warm	Too warm	Much too warm

3. How much do you agree with this statement—"You are satisfied with the thermal conditions at this moment."

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

4. How would you rate the overall acceptability of the thermal environment at this moment?

Acceptable	Not Acceptable

5. How would you like the temperature to change at this moment?

Cooler	No Change	Warmer

6. How do you feel about the humidity at this moment?

Much too dry	Too Dry	Slightly Dry	Just Right	Slightly Humid	Too Humid	Much too Humid

7. How do you feel about the airflow at this moment?

Much too still	Too Still	Slightly Still	Just Right	Slightly Breezy	Too Breezy	Much Too Breezy

8. How do you feel about the amount of sunlight at this moment?

Much too shady	Too shady	Slightly shady	Just Right	Slightly Sunny	Too Sunny	Much Too Sunny

9. If you have experienced thermal discomfort during your current hospital stay, which of the following best describes it? (Tick all that apply)

- ☐ Too much/too little air movement
- ☐ Incoming sunlight heats up space
- ☐ Drafty windows
- ☐ Vented air is too hot
- ☐ Vented air is too cold
- ☐ My bed area is hotter than other areas
- ☐ My bed area is colder than other areas
- ☐ Hot floors and walls
- ☐ Cold floors and walls
- ☐ Windows/Thermostat is inaccessible
- ☐ Other (Please explain below):

____

10. Based on your current experience of staying in the ward, when are temperatures the most uncomfortable? (Tick all that applies). Also, please write the reason for your thermal discomfort.

- ☐ Morning (6 am – 10 am)
- ☐ Noon (11 am – 1 pm)
- ☐ Afternoon (1 pm – 5 pm)
- ☐ Evening (5 pm- 9 pm)
- ☐ Night (9 pm- 6 am)

Reason for thermal discomfort:

____

____

11. How much do you agree with this statement—“If the temperature of the room is uncomfortable, your sleep will be disrupted.”

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

12. Please indicate approximately how many hours of sleep did you sleep yesterday?

- ☐ 0 hours
- ☐ 1 – 2 hours
- ☐ 3 – 4 hours
- ☐ 4 – 5 hours
- ☐ 5 – 6 hours
- ☐ 6 – 7 hours
- ☐ 7 – 8 hours
- ☐ 8 – 9 hours
- ☐ 9 – 10 hours
- ☐ 10 – 11 hours
- ☐ > 11 hours

13. How much do you agree with this statement—"You are able to adjust the air--conditioning temperature/ fan speeds in the hospital room to your satisfaction."

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

14. Please indicate what actions you employed within the last 3 hours to feel better in terms of thermal comfort? (Please tick all that applies)

<u>Actions to feel warmer</u>

- ☐ Increasing the thermostat temperature or decreasing the fan speed.
- ☐ Putting on extra clothing (e.g., jackets, sweaters)
- ☐ Closing the windows
- ☐ Go to non air-conditioned areas
- ☐ Drink hot/warm drinks

<u>Actions to feel cooler</u>

- ☐ Removing extra clothing (e.g., jackets, sweaters)
- ☐ Decreasing the thermostat temperature or increasing the fan speed
- ☐ Opening the windows
- ☐ Showering/bathing
- ☐ Go to air-conditioned areas
- ☐ Drink cool drinks

15. Please describe any other issues related to your thermal comfort in your hospital room:

____

____

____

II. General Satisfaction

Please read the following statements and indicate your level of agreement with those statements by ticking the appropriate box.

16. You are satisfied with the air quality in your hospital room.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

17. Please indicate your perception of air quality in your hospital room. (Tick all that applies)

☐ Stuffy/Stale
☐ Odorous
☐ Neutral
☐ Fresh
☐ Other, please specify: ______________

18. You are satisfied with the noise levels in your hospital room.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

19. You are satisfied with the positive acoustic sounds (e.g., relaxing music, water sounds, etc.) in your hospital room.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

20. You are satisfied with access to views of nature from your hospital bed.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

21. You are satisfied with the light levels in your hospital room.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

22. You are satisfied with the amounts of daylight in your hospital room.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

23. You are satisfied with the interior design and décor in your hospital room.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

III. Conditioning and Expectations

24. How much do you agree with the following statement- "You always rely on air-conditioning to make yourself comfortable at home."

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

25. If you use air-conditioning at home, what temperature do you normally set the air-conditioning to be in June and December? Please skip this question if you do not use/have air-conditioning at home.

June: _____ ^{o}C
December: _____ ^{o}C

26. You are always reliant on fans to make yourself comfortable at home.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

27. Number of days you have stayed in the ward this time? (Tick appropriate box)

☐ 0 (Today is your first day of stay in the ward)
☐ 1 day
☐ 2 days
☐ 3 days
☐ 4 days
☐ 5 days
☐ >5 days

28. How would you rate your health status at this moment?

Very Poor	Poor	Below Average	Fair	Good	Very Good	Excellent

29. Why did you choose the particular class of wards for your hospital accommodation? (Tick all that applies)

- ☐ Cost-savings (economics)
- ☐ Preference for non-air-conditioned wards
- ☐ Preference for air-conditioned wards
- ☐ All other wards were full (no choice)
- ☐ Other reasons, please state:

____

30. How much do you agree with the following statement- “You are sensitive to being in an air-conditioned environment.”

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

31. How much do you agree with the following statement- “Your belief in these traditional medicine has influenced your decision on your choice of air-conditioned or non air-conditioned wards.”

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

IV. General Information (Tick the appropriate box for each of the following questions)

32. Please indicate your current age: _______ years old

33. Gender:

☐ Male
☐ Female

34. How long have you lived in Singapore?

☐ < 6 months	☐ 3 – 5 years
☐ 6 months – 1 year	☐ > 5 years
☐ 1 – 3 years	

35. What is your country of birth/origin?

☐ Singapore	☐ Myanmar
☐ Malaysia	☐ China
☐ Philippines	☐ India
☐ Thailand	☐ Others, please specify:
☐ Indonesia	_______________________________

36. What is your race/ethnicity?

☐ Malay
☐ Indian
☐ Chinese
☐ Filipino
☐ Others: ___________________

~End of Survey~

APPENDIX F

Appendix F: Thermal Comfort Survey for Nurses

Dear Nurse,

A research team from Cornell University is examining the levels of thermal comfort in the inpatient ward tower.

Your participation in this survey is entirely voluntary and your responses will be kept confidential and anonymous.

By participating in this survey, you will provide important feedback and allow the hospital to improve the thermal environment for patients and staff. Please read the following instructions carefully and ask any questions you may have before agreeing to take part in the study.

Instructions for Survey Participants

1. Please only answer this survey only if:
   You have not consumed any food or hot/cold drinks 15 minutes before. Consumption of water that is room temperature is permitted.
   You do not have a fever or are not taking medication that could affect your body's thermoregulation.

2. Please be dressed only in your uniform without any other outer clothing or blankets covering your body.

3. Please answer this survey while you are standing at the nursing station/unit.

The total time for doing this survey is about 15 minutes.

If you have any further questions, please contact the lead researcher, Wu Ziqi at zw74@cornell.edu or at +1 607 351 5883.

Survey Number: __________

Date:		Time of Start of Survey:	
Hospital Name:		Ward Number:	
Room Number:			

I. Temperature Sensation

For questions 1 to 18, please answer between 11.30 am - 3.00 pm. If now is not the appropriate time to respond, you may continue with the other sections before returning to questions 1 to 18 at the appropriate time. For all questions, please tick the appropriate box.

1. How do you feel about the temperature at this moment?

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

2. How comfortable do you feel with the thermal conditions at this moment?

Much too cool	Too Cool	Comfortably cool	Comfortable	Comfortably warm	Too warm	Much too warm

3. How much do you agree with this statement—"You are satisfied with the thermal conditions at this moment."

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

4. How would you rate the overall acceptability of the thermal environment at this moment?

Acceptable	Not Acceptable

5. How would you like the temperature to change at this moment?

Cooler	No Change	Warmer

6. How do you feel about the humidity at this moment?

Much too dry	Too Dry	Slightly Dry	Just Right	Slightly Humid	Too Humid	Much too Humid

7. How do you feel about the airflow at this moment?

Much too still	Too Still	Slightly Still	Just Right	Slightly Breezy	Too Breezy	Much Too Breezy

8. How do you feel about the amount of sunlight at this moment?

Much too shady	Too shady	Slightly shady	Just Right	Slightly Sunny	Too Sunny	Much Too Sunny

9. If you have experienced thermal discomfort while working in the ward, which of the following best describes it? (Tick all that apply)

- ☐ Too much/too little air movement
- ☐ Incoming sunlight heats up space
- ☐ Drafty windows
- ☐ Vented air is too hot
- ☐ Vented air is too cold
- ☐ My work area is hotter than other areas
- ☐ My work area is colder than other areas
- ☐ Hot floors and walls
- ☐ Cold floors and walls
- ☐ Windows/Thermostat is inaccessible
- ☐ Other (Please explain below):

____

10. Based on your past experience of working in the ward, when are temperatures the most uncomfortable? (Tick all that applies). Also, please write the reason for your thermal discomfort.

Within a day	Across Days
☐ Morning (6 am – 10 am)	☐ Weekends
☐ Noon (11 am – 1 pm)	☐ Holidays
☐ Afternoon (1 pm – 5 pm)	☐ Monday Mornings
☐ Evening (5 pm- 9 pm)	☐ Always
☐ Night (9 pm- 6 am)	☐ Other, please specify: ____________________

Reason for thermal discomfort:

____
____

11. Based on your past experience of working in the ward, please specify which areas in the ward are the most thermally uncomfortable:

____
____
____

12. You are able to adjust the air-conditioning temperature/ fan speeds in the ward to your satisfaction.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

13. Please indicate what actions you employed within the last 3 hours to feel better in terms of thermal comfort? (Please tick all that applies)

Actions to feel warmer

☐ Increasing the thermostat temperature or decreasing the fan speed.
☐ Putting on extra clothing (e.g., jackets, sweaters)
☐ Closing the windows
☐ Go to non air-conditioned areas
☐ Drink hot/warm drinks

Actions to feel cooler

☐ Removing extra clothing (e.g., jackets, sweaters)
☐ Decreasing the thermostat temperature or increasing the fan speed
☐ Opening the windows
☐ Showering/bathing
☐ Go to air-conditioned areas
☐ Drink cool drinks

14. Please indicate what level of physical activity performed the last 10 minutes before taking this survey? (Tick all that applies)

☐ Sitting
☐ Standing
☐ Walking
☐ Fast Walking
☐ Other, please specify: _______________

15. How much do you agree with this statement—"You are always walking at work."

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

16. Does the thermal conditions in the ward affect your work performance and quality of care for the patient?

☐ Yes. Please answer Question 17.
☐ No. Please ignore Question 17.

17. If your answer to the previous question is yes, please specify how thermal comfort affects your work performance and quality of care for the patient? (Please indicate all that applies)

- ☐ Increases impatience
- ☐ Reduces ability to concentrate
- ☐ Increases chances of making mistakes
- ☐ Increases stress levels
- ☐ Decreases speed of work
- ☐ Causes fatigue
- ☐ Others, please specify: ______________________

18. Please describe any other issues related to your thermal comfort in the ward:

____

____

____

General Satisfaction
Please read the following statements and indicate your level of agreement with those statements by ticking the appropriate box.

19. You are satisfied with the air quality in the ward.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

20. Please indicate your perception of air quality in the ward. (Tick all that applies)

- ☐ Stuffy/Stale
- ☐ Odorous
- ☐ Neutral
- ☐ Fresh
- ☐ Other, please specify:

____

21. You are satisfied with the noise levels in the ward.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

22. You are satisfied with the positive acoustic sounds (e.g., relaxing music, water sounds, etc.) in the ward.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

23. You are satisfied with access to views of nature from your work area?

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

24. You are satisfied with the light levels in the ward.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

25. You are satisfied with the amounts of daylight in the ward.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

26. You are satisfied with the interior design and décor in the ward.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

III. Conditioning and Expectations

27. How much do you agree with the following statement- "You always rely on air-conditioning to make yourself comfortable at home."

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

28. If you use air-conditioning at home, what temperature do you normally set the air-conditioning to be in June and December? Please skip this question if you do not use/have air-conditioning at home.

June: _____ ^{o}C
December: _____ ^{o}C

29. You are always reliant on fans to make yourself comfortable at home.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

30. In the last five years, please indicate the ventilation type of ward you have worked in?

Year 2010:	☐ Naturally Ventilated	☐ Air-conditioned	☐ N.A.
Year 2009:	☐ Naturally Ventilated	☐ Air-conditioned	☐ N.A.
Year 2008:	☐ Naturally Ventilated	☐ Air-conditioned	☐ N.A.
Year 2007:	☐ Naturally Ventilated	☐ Air-conditioned	☐N.A.
Year 2006:	☐ Naturally Ventilated	☐ Air-conditioned	☐ N.A.

31. Would you prefer to work in the air-conditioned ward?

☐ Yes, Please indicate reason:_________________________
☐ No, Please indicate reason:________________________

32. How many hours do you spend per day working your ward?

☐ <4 hours
☐ 4 hours – 5 hours
☐ 5 hours – 6 hours
☐ 6 hours – 7 hours
☐ 7 hours – 8 hours
☐ 8 hours – 9 hours
☐ 9 hours – 10 hours
☐ 10 hours – 11 hours
☐ 11 hours – 12 hours
☐ > 12 hours

33. How much do you agree with the following statement- "You are sensitive to being in an air-conditioned environment."

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

34. How much do you agree with the following statement- "Your belief in traditional medicine has influenced your decision on your choice of working in air-conditioned or naturally-ventilated wards."

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

35. Did you choose to work in this particular ward due to the presence or absence of air-conditioning?

☐ Yes. Please specify reason: ___________________
☐ No

IV. General Information (Tick the appropriate box for each of the following questions)

36. Please indicate your current age: _______ years old

37. Gender:
   - ☐ Male
   - ☐ Female

38. How long have you lived in Singapore?
   - ☐ < 6 months
   - ☐ 6 months – 1 year
   - ☐ 1 – 3 years
   - ☐ 3 – 5 years
   - ☐ > 5 years

39. How long have you worked in a hospital in Singapore?

   _______Years _______Months

40. What is your country of birth/origin?
   - ☐ Singapore
   - ☐ Malaysia
   - ☐ Philippines
   - ☐ Thailand
   - ☐ Indonesia
   - ☐ Myanmar
   - ☐ China
   - ☐ India
   - ☐ Others, please specify: ______________________________

41. What is your race/ethnicity?
   - ☐ Malay
   - ☐ Indian
   - ☐ Chinese
   - ☐ Filipino

~End of Survey~

APPENDIX G

Appendix G: Test Retest Reliability Analysis

Pearson Correlation Scores

23 subjects were asked to complete the survey on their satisfaction with the thermal environment twice to determine the reliability of the scales. To date, many thermal comfort researchers have not conducted this fundamental analysis to establish the reliability of the scales that were used. To calculate the test-retest reliability of the individual items within the scale, a bivariate correlation was conducted and the following scores were obtained as illustrated in Tables G-1. To be strong, a Pearson Correlation (R) value must exceed 0.60 and be statistically significant. The items "thermal comfort," "acceptability of the thermal environment," and "change in temperature" were used for the analysis of satisfaction with the thermal environment, and have moderate to strong reliability of the construct of thermal satisfaction.

Table G-1 Bivariate Correlation with No Control

Scale	Pearson Correlation Score	Significance	Reliability
Thermal Sensation	.703	.000	Strong
Thermal Comfort	.587	.000	Moderate
Satisfaction with Thermal Environment	.446	.000	Moderate
Acceptability of Thermal Environment	.652	.001	Strong
Change in temperature	.599	.003	Strong
Humidity	.426	.043	Moderate
Air Flow	0	1	Very Weak
Sunlight	.467	.025	Moderate

APPENDIX H

Appendix H: Research Assistant's Observation Tool

Corresponding Survey Number: ________________ Date: ________ Time: __________ Subject Type: Patient / Nurses

Location: ___________ Patient Ward/Bed Number (if applicable):__________________

Table 1: Physical Thermal Environment Measurement Tool

	Day 1		
	0.5 m	**1.0 m**	**1.5 m**
Air Temperature			
Relative Humidity			
Air Velocity/Wind Speed			
Light Intensity			

Air-con Temperature: _________ °C
Air-con Speed (Circle One):
Off Low Med High
Fan Speed (Circle One):
Off 1 2 3 4 5

Note: Please measure the physical variables as close as possible to the subject with the *Lutron LM 8000* Thermal Environment Measurement tool.

Table 2: Observation Tool for Behavior Responses to Thermal Environment

Behavioral adaptations (Observed continuously throughout the period of survey)			
Physical Activity		**Physical Appearance**	
☐ Lying Down ☐ Sitting Upright on Bed ☐ Sitting Upright on Chair ☐ Standing ☐ Other activity: ___________________________		☐ Subject was pregnant ☐ Subject looks obese Other notable features: ____ _______________________________	
Subject feels too hot		**Subject feels too cold**	
Subject is drinking cold food or drinks	☐	Individual is drinking warm food or drinks	☐
Subject is perspiring	☐	Body hair is standing/has goose pimples	☐
Subject lowered the temperature of the HVAC thermostat	☐	Subject is shivering	☐
Subject or caretaker is fanning himself/herself on the face	☐	Subject increase temperature of the HVAC thermostat	☐
		Subject is asking for more blankets	☐

<table>
<tr><td colspan="2">Clothing Behavior</td></tr>
<tr><td>Subject’s clothing (tick or write all that applies)</td><td>Patients Only:</td></tr>
<tr><td>☐ Standard Nurse Uniform
☐ Nurse’s Scrub
☐ Patient Gown/Pajamas
☐ Others: ____________________</td><td>Location of Patient’s bed:
<u>B1 Ward</u>
☐ Next to Window
☐ Further from Window
<u>B2 Ward</u>
☐ Next to Window
☐ Middle
☐ Furthest from Window

If patients has blankets covering body, indicate number of layers of blankets on subjects: __________
Number of visitors with patient at time of survey: ___________
Number of times patient was distracted by visitors: ___________</td></tr>
<tr><td colspan="2">Other observations:</td></tr>
</table>

***Note*:** The third out of every five subjects selected for the survey every week should be observed. Thus, only one observation should only be performed every week.

~Please staple the observation sheet on the survey form when completed~

Appendix I

Appendix I: Interview Questions for Hospital Staff

1. Who and what were the main drivers for implementing sustainable design in the new hospital?

2. What is Khoo Teck Puat's approach to sustainability?

3. What is the cost premium (both capital costs and operational maintenance costs) for the systems to increase natural ventilation?

4. What was the decision-making process in choosing the sustainable design for increasing natural ventilation?

5. In regards to ventilation, what are some of the features at Alexandra Hospital that you found challenging and was subsequently improved upon at Khoo Teck Puat Hospital? What were some things that were positive at Alexandra Hospital that were difficult to implement at Khoo Teck Puat Hospital?

6. What guidelines did the architects or engineers follow (if any) to achieve thermal comfort in the naturally ventilated areas of the hospital?

7. How do you plan to measure the cost-savings and other benefits from the implementation of the sustainable design strategy?

8. What were some of the unanticipated challenges encountered for Khoo Teck Puat Hospital's sustainable design? What solutions have you implemented to overcome these challenges and what were the costs?

9. If you could redesign KTPH all over again, what are some of the things you would avoid and things that you would implement?

10. What does it takes to manage and operate a green facility over time in a manner that helps realize the initial investment made in sustainable building design

11. How many workers, hours put in, and costs are used to clean and maintain AH versus Khoo Teck Puat hospital?

12. What were some of the issues and challenges faced in associated with the Green Mark application process?

13. What are the plans to maintain the Green Mark Platinum status?

14. Did anyone help people understand what behavioral changes are required to take advantage of the sustainable strategies implemented?

15. What were the training and education provided to users such as nurses or staff in using the ventilation features in the hospital?

16. How are patients educated about their control of thermal conditions in the space?

Appendix J

Appendix J: Time of day Effects on Heat Index

To determine if there was a significant difference between the heat index between the selected time period (11.30 am – 3 pm) for conducting the survey on thermal comfort and the other time periods, an independent sample t-test was performed on the difference in heat index temperatures between the naturally ventilated wards and air-conditioned wards (the direction of the difference was consistent for all data points).

Table J-1 Effects of Time of day on Heat Index in Wards

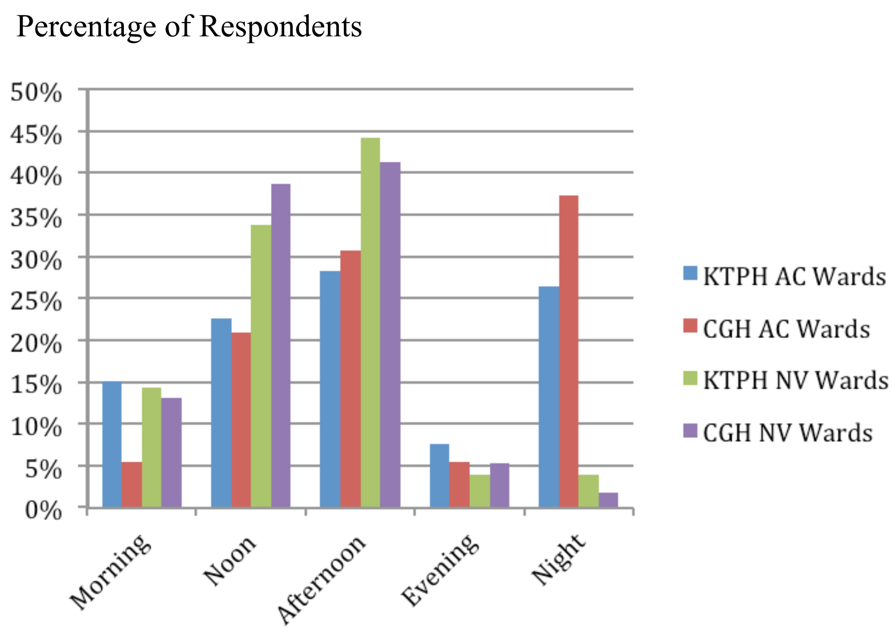
	Selected Time	N	Mean	SE Mean	t	Df	Sig
Difference in Heat Index	Other Times	369	20.0254	.38701	-2.871	440	0.004
	Selected Time (11.30am-3pm)	73	22.7980	.94317			

There was a significant effect for time of day, $t(440) = -2.871$, $p = 0.004$, with the selected time period (11.30 am – 3 pm) (M=22.8 SD=8.06) having a higher heat index than other times (M=20.0; SD=7.43). This finding indicates that the choice of conducting the thermal comfort survey from 11.30 am to 3 pm is justified given that subjects would most likely be experiencing the most unfavorable thermal conditions during that period.

Appendix K

Appendix K: Thermal Discomfort by Time of Day

Of the patient and nurse respondents who experienced thermal discomfort during their time in the wards, they were asked to indicate which times of the day they felt uncomfortable (results as illustrated in Figure K-1). In the naturally ventilated wards, respondents in both KTPH and CGH felt that the afternoon was the most uncomfortable period compared to other times of the day. In the air-conditioned wards, the afternoons were the most uncomfortable in KTPH, whereas for CGH the most uncomfortable time of day was at night. The main complaint in naturally ventilated wards was that the environment was too warm in the afternoon whereas for the air-conditioned wards, the environment was too warm in the afternoons and too cool at night.



Time of Day	Time
Morning	6 am - 10 am
Noon	11 am - 1 pm
Afternoon	1 pm - 5 pm
Evening	5 pm - 9 pm
Night	9 pm - 6 am

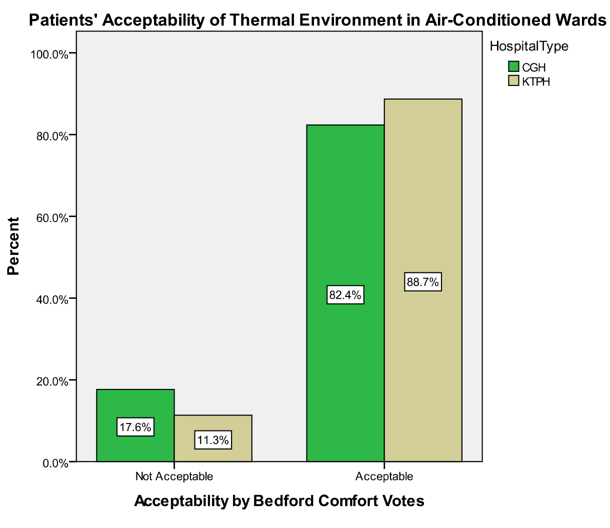
Figure K-1 Percentage of Respondents Indicating Most Thermally Uncomfortable Times of Day

Appendix L

Appendix L: Indirect Measures of Patient Satisfaction with Thermal Conditions

To determine the percentage of patients that found their thermal environments to be acceptable, Cross-Tab comparisons were performed between AH, CGH and KTPH for patients' responses on the Bedford Comfort scale and Thermal Preference scale that have been converted into binary outcomes of acceptable versus not acceptable. The three central categories of the Bedford Comfort Scale (Comfortably Cool, Comfortable, Comfortably Warm) were categorized as "acceptable," while the remaining four categories (Too warm, Much too warm, Too cool, Much too cool) were categorized as "unacceptable." For the Thermal Preference scale, subject responses indicating that they wanted to be warmer or cooler were categorized as "unacceptable" while responses indicating that they did not want to change their thermal conditions were categorized as "acceptable."

Bedford Comfort Votes as Acceptability Votes



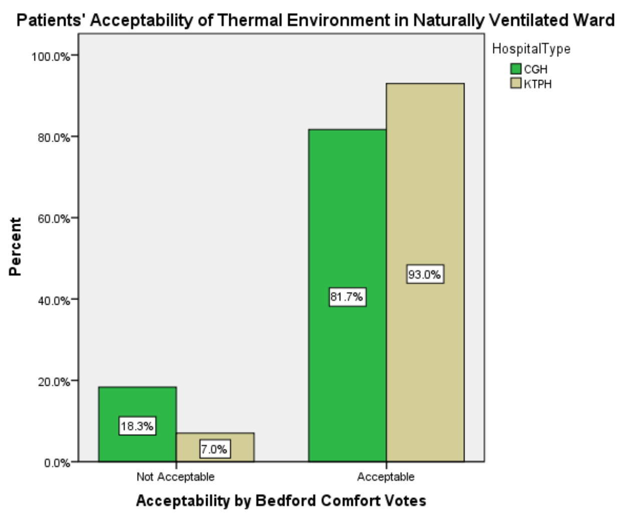
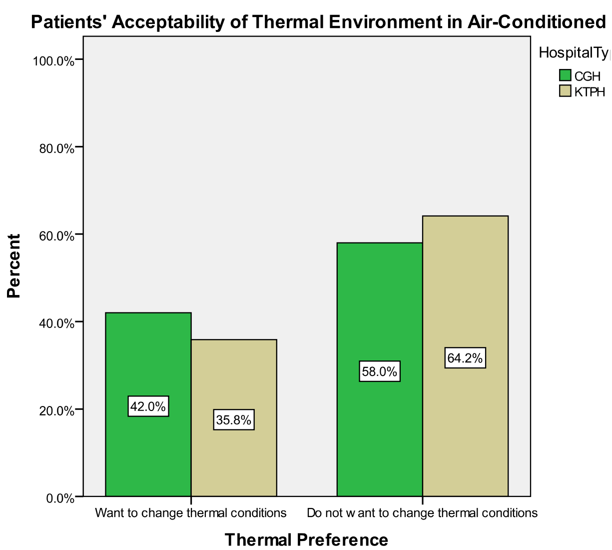


Figure L-1 Patients' Acceptability of Thermal Environment (Bedford Comfort Votes)

As illustrated in Figure L-1, both CGH and KTPH met the ASHRAE 55-2010 thermal satisfaction requirements for their air-conditioned wards and naturally ventilated wards, since more than 80% of nurses reported that they found their thermal environment to be acceptable. The percentage of patients that were satisfied with the thermal conditions in the naturally ventilated wards was significantly higher in KTPH (93%) than CGH (81.7%) one-tailed χ^2 (1, N = 117) = 3.349, p =.0335.

Thermal Preference



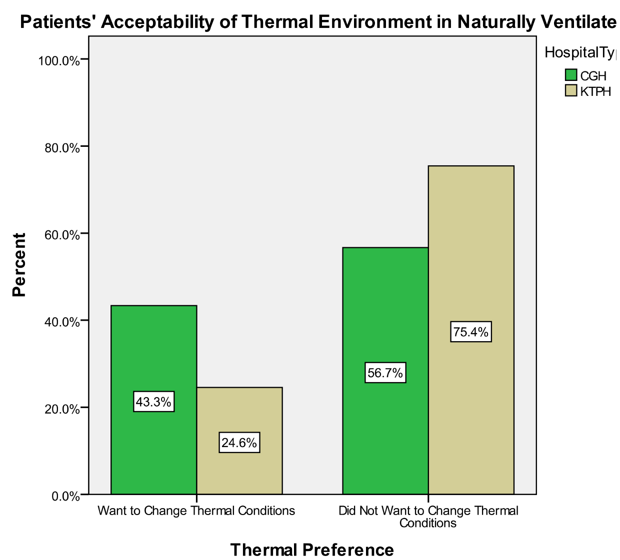


Figure L-2 Patients' Thermal Preference

Thermal preference can be viewed as a more sensitive measure of patients' acceptability of the thermal environment than the McIntyre scale of direct acceptability or the Bedford Comfort Votes as it asked whether they would like to change their temperature rather than if they were found their environment to be acceptable. While none of the hospitals met the ASHRAE

55-2010 requirement for both air-conditioned and naturally ventilated settings as illustrated in Figure L-2, an important finding was that significantly more patients were satisfied with their thermal conditions in KTPH's naturally ventilated wards (75.4%) than CGH's naturally ventilated wards (56.7%) χ^2 (1, N = 117) = 4.578, p =.032.

Appendix M

Appendix M: Potential Confounding Variables for Patient Thermal Comfort

Table M-1 Potential Confounding Variables for Patient Thermal Comfort

Confounding Variable	Test Performed	Correlation/F or T Statistic	Df (if applicable)	P-Value	Significance (2-tailed)
Sensitivity to Air-conditioning	Pearson Correlation	-.149		.034	Sig
Country of Birth	ANOVA	F=3.155	4	.018	Sig
Race	ANOVA	F=5.602	6	.000	Sig
Heat Index	Pearson Correlation	-.119		.050	Sig
Air Velocity	Pearson Correlation	-.088		.106	NS
Air Quality	Pearson Correlation	.116		.103	NS
Noise Levels	Pearson Correlation	.045		.524	NS
Positive acoustic sounds	Pearson Correlation	-.043		.569	NS
Views of nature	Pearson Correlation	.003		.964	NS
Light Levels		-.007		.918	NS
Daylight Levels	Pearson Correlation	.087		.218	NS
Interior Design	Pearson Correlation	.060		.396	NS
Reliance on air-conditioning	Pearson Correlation	-.010		.885	NS
Control over thermal environment	Pearson Correlation	0.066		.353	NS
Health Status	Pearson Correlation	.092		.194	NS
Age of Participants	Pearson Correlation	.106		.136	NS
Gender	Independent Sample T-test	T=.002	197	.999	NS
Duration in Singapore	Pearson Correlation	-.038		.593	NS
Duration in the ward	Pearson Correlation	-.092		.197	NS
Belief in Traditional	Pearson Correlation	-.016		.136	NS

Medicine				
Age	Pearson Correlation	.106	.136	NS
Chose ward due to Economic Reasons	ANOVA	F=.049	.825	NS
Preference for non-air conditioned wards	ANOVA	F=.721	.398	NS
Preference for air-conditioned wards	ANOVA	F=.122	.727	NS

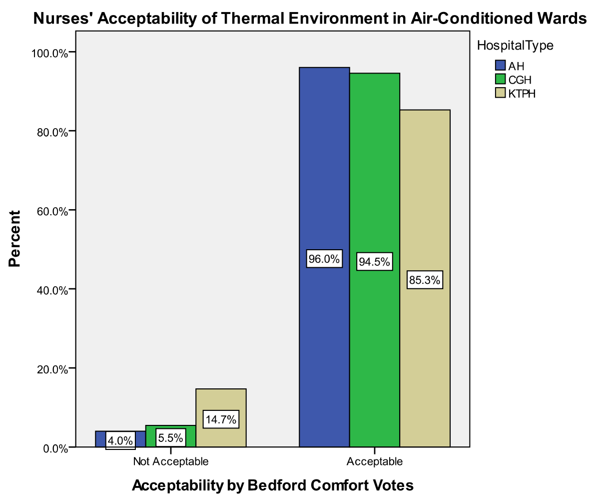
Note: Significant variables were added to a series of univariate analyses and iteratively removed from the univariate model if they were subsequently found to be insignificant (from largest p-values to smallest p-values). None of the significant variables of the correlation remained significant in the final univariate model.

Appendix N

Appendix N: Indirect Measures of Nurse Satisfaction with Thermal Conditions

To determine the percentage of nurses that found their thermal environments to be acceptable, cross-tab comparisons were performed between AH, CGH and KTPH for nurses' responses on the Bedford Comfort Scale and Thermal Preference.

Bedford Comfort Votes as Acceptability Votes



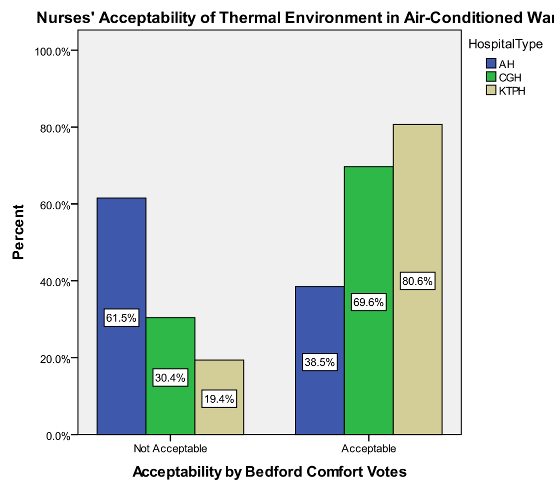
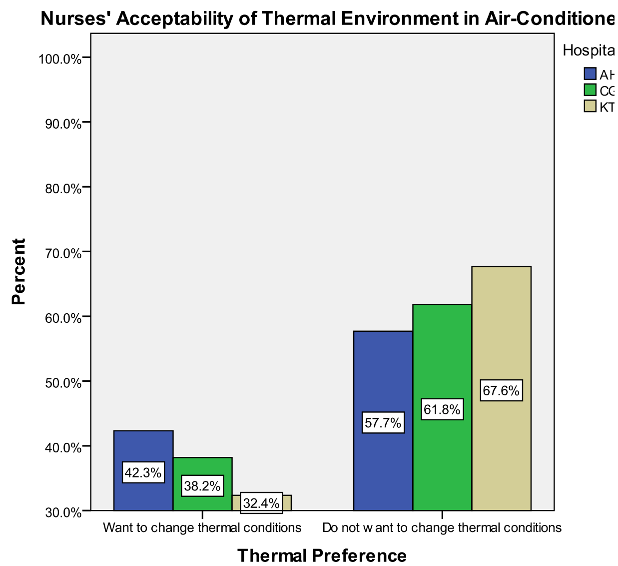


Figure N-1 Nurses' Acceptability of Thermal Environment (Bedford Comfort Votes)

All three hospitals met the ASHRAE 55-2010 thermal satisfaction requirements for their air-conditioned wards, since more than 80% of nurses reported that they found their thermal environment to be acceptable. While nurses in AH and CGH of the naturally ventilated wards of the three hospitals did not meet the minimum ASHRAE 55-2010 standards requirement, nurses in KTPH's naturally ventilated wards did (80.8% of the nurses found their thermal conditions to be satisfactory). The percentage of nurses from naturally ventilated wards that found their thermal environment to be acceptable was significantly higher than that of nurses from AH χ^2 (1, N = 57) = 10.617, p =.001, but not nurse from CGH χ^2 (1, N = 87) = 1.242, p =.265.

Thermal Preference



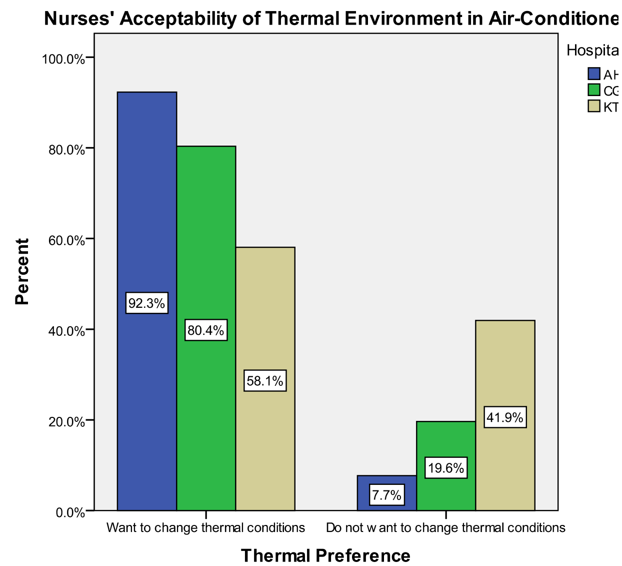


Figure N-2 Nurses' Thermal Preference

Thermal preference can be viewed as a more sensitive measure of nurses' acceptability of the thermal environment than the McIntyre scale of direct acceptability or the Bedford Comfort Votes as it asked whether they would like to change their temperature. While none of the hospitals met the ASHRAE 55-2010 requirement for both air-conditioned and naturally ventilated settings, an important finding was that KTPH had the highest percentage of nurses who did not want any change in their temperature in the naturally ventilated wards (41.9%), and this result was found to be significantly higher than AH (7.7%) χ^2 (1, N = 57) = 8.551, p =.003 and CGH (19.6%) χ^2 (1, N = 87) = 4.964, p =.026.

Appendix O

Appendix O: Confounding Variables for Nurses' Thermal Comfort

Table O-1 Confounding Variables for Nurses' Thermal Comfort

Confounding Variable	Test Performed	Correlation/F or T Statistic	Df (if applicable)	P-Value	Significance (2-tailed)
Air Quality	Pearson Correlation	.460	-	.000	Sig
Noise Levels	Pearson Correlation	.187	-	.007	Sig
Positive acoustic sounds	Pearson Correlation	.238	-	.001	Sig
Views of nature	Pearson Correlation	.189	-	.007	Sig
Light Levels		.191	-	.006	Sig
Daylight Levels	Pearson Correlation	.133	-	.057	Sig
Reliance on air-conditioning	Pearson Correlation	-.190	-	.006	Sig
Control over thermal environment	Pearson Correlation	.143	-	.043	Sig
Heat Index	Pearson Correlation	-.389		.000	Sig
Air Velocity	Pearson Correlation	-.374		.000	Sig
Country of Birth	ANOVA	F=.770	5	.573	Not Sig
Race	ANOVA	F=.912	6	.488	Not Sig
Age of Participants	Pearson Correlation	0.096	-	.172	Not Sig
Gender	Independent Sample T-test	T=.885	206	.377	Not Sig
Duration in Singapore	Pearson Correlation	-.004	-	.959	Not Sig

Note: Significant variables were added to a series of univariate analyses and iteratively removed from the univariate model if they were subsequently found to be insignificant (from largest p-values to smallest p-values). Only reliance on air conditioning, heat index and reliance on air-conditioning remained significant in the final univariate model.

Appendix P

Appendix P: Thermal Discomfort and Patient Sleep Quantity

Most of the patients (36.7%) surveyed agreed that thermal discomfort could disrupt their sleep (See Figure P-1). Patients were also asked to self-report the number of hours they slept the night prior in the hospital. A univariate GLM analysis was performed to determine if their preference based on the experience of the thermal environment had an impact on their quantity of sleep (results as illustrated by Tables P-1 and P-2). As shown in Figure P-2, patients who wanted to be cooler (Option 1) had 0.845 hours of sleep less than patients who did not want their thermal environment to change (Option 2). Patients who wanted to be warmer (Option 3) also had 0.917 hours of sleep less than patients who did not want their thermal environment to change.

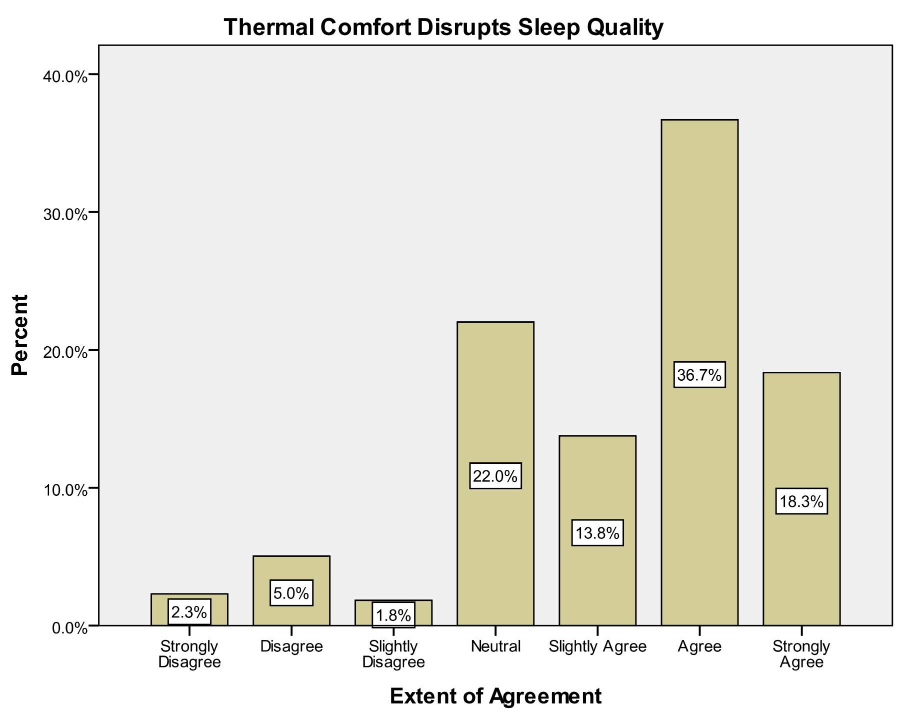


Figure P-1 Perception of Thermal Discomfort and Patient Sleep Quality

Table P-1 Source Table for 3 (Thermal Preference) x 1 (Sleep Quantity) Completely Between-Subjects ANOVA

Source	SS	Df	MS	F	p
Thermal Preference	37.564	2	18.78	4.971	.008
Error	812.35	215	3.778		
Total	7593.75	218			

Note. R Squared = .044 (Adjusted R Squared = .035)

Table P-2 Estimated Mean Sleep Duration for Patients by Thermal Preference

	Thermal Preference		
	Wanted to be cooler	No Change	Wanted to be warmer
Estimated Mean Duration of Sleep	5.03 (.260)	5.87 (.164)	4.96 (.414)

Note. Standard Errors appear in parentheses below estimated means.

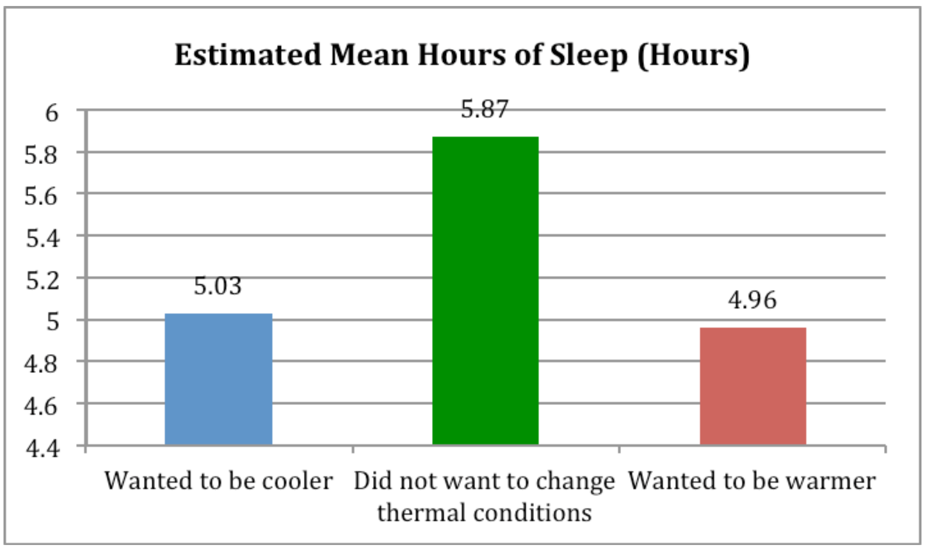


Figure P-2 Estimated Mean Hours of Sleep and Thermal Preference

Appendix Q

Appendix Q: Areas of hospital's naturally ventilated ward, which felt the most uncomfortable for nurses

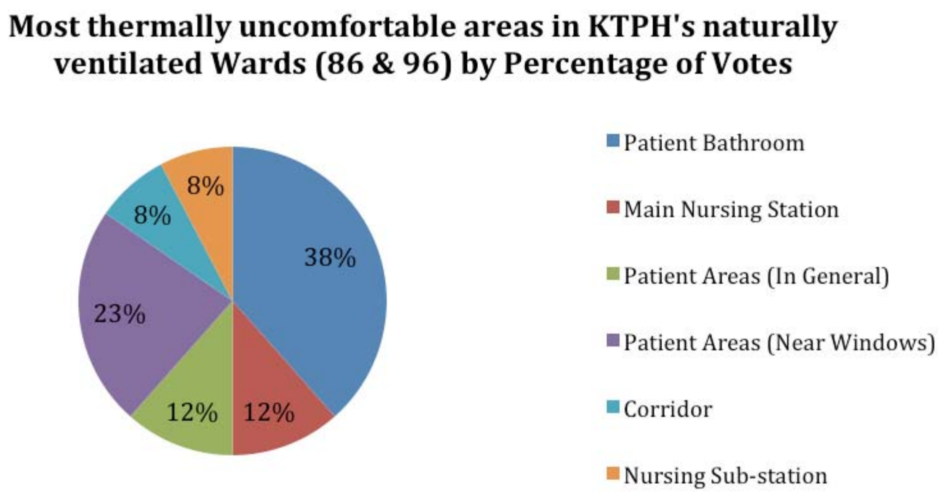


Figure Q-1. Most Uncomfortable Areas of KTPH's Naturally Ventilated Wards

Figure Q-1 illustrates the most thermally uncomfortable areas within KTPH's naturally ventilated wards 86 and 96 by the percentage of votes where the thermal comfort survey was conducted. The area with the highest number of complaints by nurses in KTPH's naturally ventilated wards 86 and 96 were the patient bathrooms. Nurses indicated that the patient bathrooms lacked ventilation and felt uncomfortable when they had to assist patients in the shower although exhaust fans were installed. Another frequent complaint by the nurses was that the patient bed areas of numbers 18-22 were the worst areas because of the direct sun exposure from the windows in the morning. Beds numbers 3 to 7 and 8 to 12 were also poor due to same issue although they were not as severely affected as beds 18 to 22.

Appendix R

Appendix R: Perceived Effects of Thermal Discomfort on Nurses' Productivity

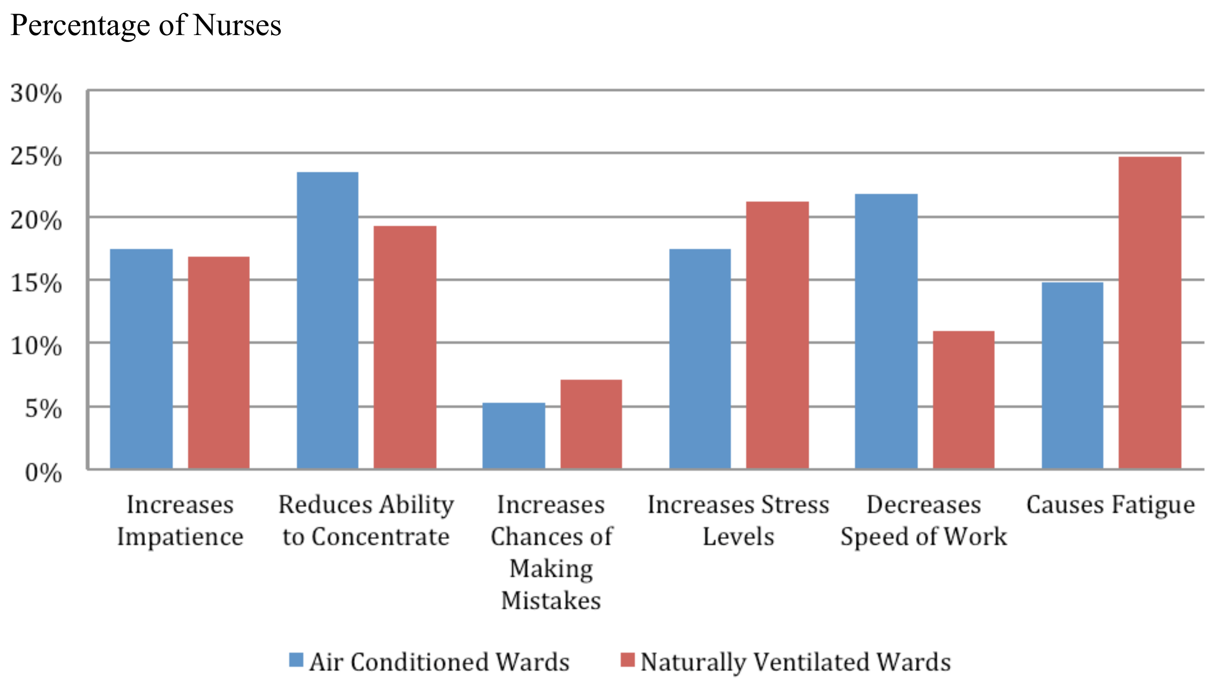
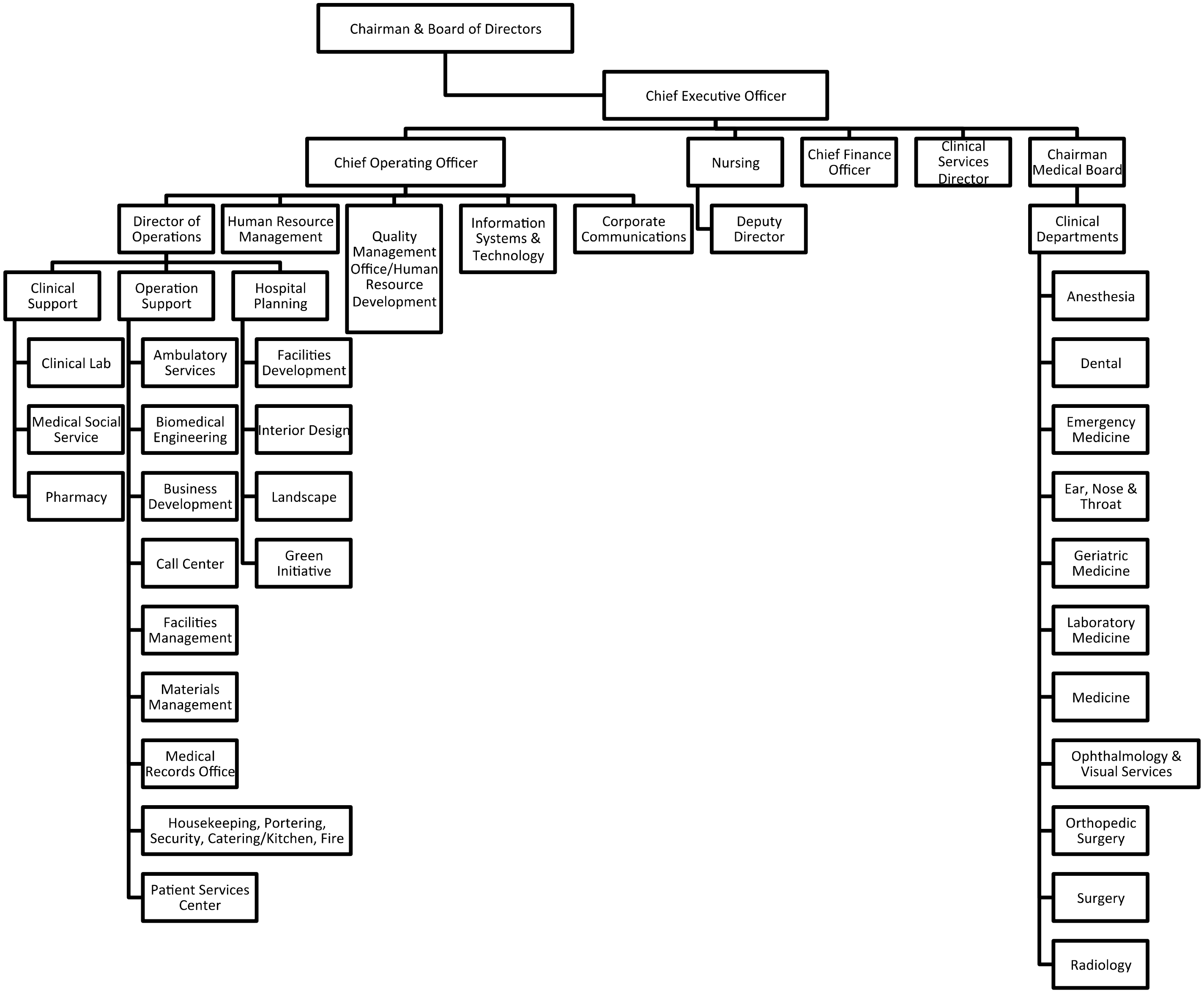


Figure T-1 Perceived Effects of Thermal Discomfort on Nurses' Productivity

Thermal discomfort can have a tremendous impact on the productivity of nurses, and consequently the quality of patient care. Of the 230 nurses who participated in the survey, 134 or 58% of them indicated that thermal discomfort could have an impact on their work productivity, regardless of the type of impact. Figure T-1 indicates the specific perceived effects of thermal discomfort on nursing productivity based on these 134 nurses. The perceived affect of thermal discomfort on nurses' productivity was different between nurses in naturally ventilated wards in the three hospitals and the nurses in the air-conditioned wards in the three hospitals. Assuming that the main cause of thermal discomfort in the naturally ventilated wards was that the ward was too warm, the major consequence was fatigue. In the air-conditioned wards, assuming the main cause of thermal discomfort was due to the ward being too cool, the major consequence was the reduced ability to concentrate. Other effects of thermal discomfort mentioned included sickness and caused reduced self-esteem due to body odor.

Appendix S

Appendix S: Khoo Teck Puat Hospital / Alexandra Health Organization Chart



Appendix T

Appendix T: Abbreviated Design Brief for KTPH architects from AH team

The design philosophy of KTPH is to provide a physical environment that will be part of the healing process and promote health outcomes, and to cultivate the healing of the patient's mind, body and spirit. As such the following programming goals were set for architects and design consultants (Adapted from AH@Yishun Primary Design Brief, 2005):

1. Scalability in Design:

The hospital shall be designed to effectively support a changing healthcare delivery system. Its master plan design needs to incorporate features that allows for:

- Flexibility and adaptability
    - For future adaptability, the layout of all ward types should be as similar as possible. This will also allow the staff to be efficient, as they will be assigned to different ward.
    - The ward designs should allow the following conversions in the long-term future without significant capital or running costs:
        a. From naturally-ventilated wards to air-conditioned wards; and
        b. From C wards into B2.
- Modular design for ease of conversion
- Breathability in master planning
- Ability for lock-down of the hospital by zoning for emergencies

2. Sustainability in Design:

The hospital shall be a hospital unlike any other, designed for the future. It shall have the following:

- Visually pleasing design that sustains with time.
- Ease and low cost of maintainability from careful overall design and material selection.

3. A Patient Centric Hospital:

- Hassle-free processes designed for patient's convenience
- Engaging patients and their families as partners
- Ensuring the safety of patients
- Intuitive easy movement for patients and visitors
- Minimal movement for patients
- Clustering of services and facilities

4. Hospital with Technology as an Enabler

- Extensive use of wireless technology
- Digitalized hospital
- Portability of information and technology
- Use of automation and robotics

5. Energy efficient Hospital

- 50% more energy efficient than present hospitals
- Tropical building with high ceilings and overhangs
- Extensive natural ventilation

- As close to 70%[40] of the hospital facility will be naturally ventilated, the architecture shall be designed for tropical climate. It shall promote natural air movement and use passive elements to reduce heat.
- The hospital is to be naturally ventilated wherever possible. Air-conditioning is required only in areas where thermal comfort is clearly specified, such as private wards, and offices.
- Subsidized (naturally ventilated) wards should be planned to create good cross ventilation.
- In order to minimize problems of condensation and escape of conditioned air, which is common in partially air-conditioned buildings, the segregation of air- conditioned and naturally ventilated areas respectively is to be maximized.

- Use of cheap alternative energy sources

6. High Touch

- Warm cuddling feeling
- Calming and cheerful environment

7. Healing environment

- Hospital within a garden, garden within a hospital

---

[40] Only 55% of natural ventilation was achieved at the end of KTPH's design stage. The original intention was to use natural ventilation in the subsidized outpatient clinics. However due to market demands for comfort, the CEO decided not to pursue natural ventilation in those areas (Liak, p.c.).

- Tranquil, restful and healing environment
- Sight, scent and sound of nature surrounding patients
- Surrounding patients with nature
- All patient beds should preferably have a view to the greenery and/or the outside.
- Natural light is strongly encouraged.

8. Architecture:

The architecture shall encompass the seven principles of Erik Asmussen's healing architecture (Coates, 2000):

- The unity of form and function
- Polarity
- Metamorphosis
- Harmony with nature and site
- Living wall
- Color luminosity and color perspective
- Dynamic equilibrium of spatial experience

The architecture shall be inviting and allow for easy flow of both pedestrian and vehicular traffic at street level. At the podium, integration of social, communal and hospital spaces shall be seamless. The public and the neighboring community can freely utilize the space to gather and mingle.

9. Interior:

The design concept shall incorporate the broad design guidelines of Ulrich's Theory of Supportive Design (Ulrich, 1991, 1999 & 2000):

- Foster control, including privacy
- Promote social support
- Provide access to nature and other positive distractions

The design concept shall promote stress reduction, buffering and coping. The design concept shall also create:

- A sense of community
- Provide a visual connection to the landscape and gardens
- Create the feeling of home that will contribute to the staff's, visitors' and patients' comfort and relaxation through the use of familiar spaces and furnishings.
- Create the feeling of hospitality
- Cognitive environment
- Provide a safe and comfortable environment
- Address specific cognitive and behavior needs through design that provide privacy, dignity and independence for patients, their families, visitors and staff
- Reduce patients' agitation
- Use of environment as a therapeutic resource
- Provide adequate, efficient and flexible space to accommodate activities
- Barrier-free design

10. Infrastructure

The infrastructure design shall take into consideration:

- Capable of rapid response to change at a number of levels from a short term to long term in a very cost effective way
- Low life cycle cost
- Able to support healing and green design
- An armature for growth
- Allow accessibility without disturbing functional areas

Outcomes

In summary, the design goals expected to achieve are:

- A healing and humane environment.
- Operationally efficient hospital to maximize effective use of resources.
- Flexible and scalable to accommodate and adapt evolving changes as a result of technologies – both clinical and technical, and processes.
- Reduced first cost by making modular functional units
- Special energy conservation methods to reduce operational costs.
- Built environment that is welcoming to patients, improves their quality of life, promotes well-being and supports families and employees.
- Built environment that reflects the Hospital's core values.

Appendix U

Appendix U: Additional Sustainable Design Features For Future Hospitals

U-1 Dynamic exterior shading systems

Dynamic exterior shading is a strategy to reduce solar gain and glare while optimizing daylight and natural ventilation, leading to reductions in the need for cooling interior spaces by HVAC systems or mechanical fans. Movable louvers, fins or roller shades are applied to the exterior of the building. In hot climates and summer months, these shading devices can automatically be angled by integrated sensors to react to the changing angles of the sun during the time of the day and over the course of the year with the aim of minimizing the amount of incoming solar radiation entering into the building through the windows. Dynamic exterior shading systems are more effective than internal blinds in reducing solar heat gain, which dissipate the heat to the air gap between the shading device and the glazing (Datta 2001; Offiong and Ukpoho, 2004; Loutzenhiser et al., 2007). Other solar shading alternatives such as the use of curtains reduce the effectiveness of natural ventilation, while external shading would not have this problem. The drawbacks of dynamic exterior shading include the maintenance of the motors of the exterior shading system, cleaning and aesthetic concerns.

U-2 Personal ventilation controls for patients in multi-bedded air-conditioned wards

Personalized ventilation control systems can be used to improve the thermal comfort of patients in multi-bedded air-conditioned wards where individual control of the thermal environment is typically absent. Personal ventilation control systems supply clean and cool air directly to the breathing zone of each occupant and are used typically in closed offices in

Scandinavian countries. Individual occupants are able to control the supply flow rate, the direction of air flow and the air temperature of the supplied air, thereby improving the thermal comfort and perceived air quality (Melikov, 2004; Kaczmarczyk et al., 2004). In addition, the control strategies of a personal ventilation control system has energy saving potential as it reduces the outdoor airflow rate due to higher ventilation effectiveness, expands the room temperature comfort limits and supplying the personalized air only when the occupant is present at the desk (Schiavon & Melikov, 2009). Furthermore, the system has the ability to reduce the level of pollution in inhaled air and the risk of infection transmission (Cermak & Melikov, 2007; Nielsen, et al., 2007). The main issues with personal ventilation control systems that needs to be considered prior to implementation include i) the need to replace air filters for each individual air-handling unit, which could be both laborious and expensive; ii) the unpredictability of user demand for conditioned air, which makes it difficult for building engineers to manage the air supply required; and iii) the reluctance of people in changing the controls of personal ventilation control units (Hedge, p. c.).

U-3 Motorized operable windows

An automated window system fitted with humidity and temperature sensors could be programmed to open and close different sets of windows at different time periods of the day. Although, the window system requires energy for operation, it can help a building to regulate the internal environment's airflow, prevent rain from entering the building, and eliminate the manpower required to open or close the windows. However, some drawbacks for consideration the high capital costs and possibly high maintenance and repair costs if the system were to fail. Some automated window systems might also restrict the occupants' ability to control the windows directly, which could reduce their level of thermal comfort according to De Dear and

Brager's (1998) findings linking the importance of control with thermal comfort. Therefore, an option to manually operate the windows would need to be incorporated if an automated window system is to be used.

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