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OPTIMISING ENVIRONMENTAL DESIGN STRATEGIES TO IMPROVE THERMAL PERFORMANCE IN OFFICE BUILDINGS IN KENYA

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ABSTRACT

An examination of contemporary office buildings in the warm humid region of Kenya revealed the predominance of highly glazed lightweight buildings that are prone to overheating and rely on costly and unsustainable active climate control systems. In the midst of growing energy demand and a potential deficit in supply, the influx of these poorly designed buildings has intensified the need to explore viable climate-responsive design alternatives suitable to local conditions that can extend occupant comfort and reduce the need for energy intensive environmental control systems. This view is shared by the Kenyan government which has set ambitious targets to develop and enforce national codes for energy efficiency and conservation in buildings by 2030. However, despite the clear and urgent need, research shows that little work has been developed to date that can be applied to the Kenyan context and climate.

In this research, ways of improving the thermal comfort and performance of office buildings in the warm humid city of Mombasa (latitude 4°S) were explored. The work was developed through a series of field studies of local vernacular and modern case study buildings and subsequent computer simulations. From this, vernacular Swahili-inspired design strategies were derived and the application of the potentially most significant mitigation strategy to typical local office buildings examined further. Although other work exists elsewhere that may be comparable to parts of this study, this is the first effort that brings together the post occupancy evaluation of buildings in Mombasa, a thorough investigation of the effectiveness of the vernacular strategies found in Swahili architecture, and the validation of the application of these strategies to modern offices.

Initial findings derived from a parametric study revealed external shading to be the most effective design strategy as it alleviated solar heat gain transmitted through glazing into buildings, resulting in a significant reduction in discomfort hours. Subsequently, using a series of dynamic computer simulations run for a typical office building in Mombasa, the average monthly solar heat gain coefficient (SHGC) values were derived for a typical year. These previously unavailable latitude (and hemisphere) specific solar path indices were deemed critical in the provision of essential data for effective external shading device design. The findings indicated that low SHGC values of under 0.5 gave the general indication of low percentage of discomfort hours (under 10%). Additionally, estimates of potential annual cooling energy savings of up to 60% were made based on the reduction of SHGC values for shading elements of practicable size. The application of these study findings to two local office buildings revealed that the derived SHGC values and energy estimates provide useful references when considered for similar type office buildings on similar latitudes. For both buildings, it was predicted that energy savings of 15% to 61% could be achieved from the application of suitably sized external shading devices. It was suggested that this type of information would encourage designers to use external shading devices as a method of maintaining thermal comfort, conserving energy and lowering operating costs in office buildings. Finally, recommendations for the incorporation of minimum shading standards in building regulations have been made and presented in a design guidance document.

PUBLICATIONS

Published:

KIAMBA, L. N., RODRIGUES, L. & LAU, B. 2014. Climate-responsive Vernacular Swahili Housing. PLEA 2014: Sustainable Habitat for Developing Societies. Ahmedabad, India.

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KIAMBA, L. N., RODRIGUES, L. & LAU, B. 2015. The Potential of External Shading Devices for Comfort Extension and Energy Savings in Kenya. Sustainable Energy Technologies. Nottingham, UK.

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KIAMBA, L. N., RODRIGUES, L. & LAU, B. 2016 - expected. Energy Efficiency Regulations as Drivers for Change in the Built Environment in Hot and Warm Humid Climates.

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KIAMBA, L. N., RODRIGUES, L. & LAU, B. 2016 - expected. The Development of an Assessment Tool for the Design of External Shading.

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LIST OF ACRONYMS

ABCB: Australian Building Codes Board

ABNT: Associação Brasileira de Normas Técnicas (Brazilian Standards Association)

AC: Air Conditioning

ADV: All Day Ventilation

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

BC: Base Case

BCA: Building and Construction Authority (Singapore)

BCA-A: Building Code of Australia

BUS: Building Use Studies

CBD: Central Business District

CIBSE: Chartered Institution of Building Services Engineers

CIS: Corrugated Iron Sheets

DBT: Dry Bulb Temperature

DTS: Deemed To Satisfy

DTV: Day time Ventilation

ECS: Egg Crate Shading

EDSL: Environmental Design Solutions Limited

ET: Effective Temperature

ETTV: Envelope Thermal Transfer Value

GC: Ground Coverage

HS: Horizontal Shading

HSA: Horizontal Shadow Angle

ISO: International Organization for Standardization

MOTCO: Mombasa Old Town Conservation Office

MRT: Mean Radiant Temperature

NABERS: National Australian Built Environment Ratings System

NMK: National Museums of Kenya

NS: No Shading

NSW: News South Wales

NTV: Night Time Ventilation

OTTV: Overall thermal Transfer Value

PF: Projection Factor

PMV: Predicted Mean Vote

POE: Post Occupancy Evaluation

PPD: Percentage People Dissatisfied

RC: Reinforced Concrete

RH: Relative Humidity

RTQ-C: Regulation for Energy Efficiency in Public, Commercial and Service Buildings

RTTV: Roof Thermal Transfer Value

SAA: Solar Altitude Angle

SC: Shading Coefficient

SHGC: Solar Heat Gain Coefficient

SWERA: Solar and Wind Resource Assessment

TAS: Thermal Analysis Software

UN-HABITAT: United Nations Human Settlements Programme

VS: Vertical Shading

VSA: Vertical Shadow Angle

ZV: Zero Ventilation

NOMENCLATURE

ΔT = temperature difference (°C)

A = surface area (m^2)

A_{env} = envelope area (m^2)

A_{proof} = area of the horizontal projection of the building (m^2)

A_{tot} = total floor area (m^2)

clo = clothing insulation (clo)

dT = apparent cooling effect of air movement (°C)

e = Euler's number (2.718)

hc = convective heat transfer coefficient

HSA = horizontal shading angle (deg)

M = metabolic rate (W/m^2)

pa = vapour pressure of air (kPa)

Q_c = conduction heat flow rate (W)

Qe = evaporative heat flow rate (W)

Qi = Internal gains heat flow rate (W)

Qs = solar heat flow rate (W)

Qv = ventilation heat flow rate (W)

Rcl = clothing thermal insulation

$SHGC_{external}$ = solar heat gain coefficient of external shading devices

$SHGC_{glazing}$ = solar heat gain coefficient of the glazing

$SHGC_{internal}$ = solar heat gain coefficient of internal shading

$SHGC_{total}$ = total solar heat gain coefficient of the fenestration system

T_c = comfort temperature (°C)

T_n = neutral temperature (°C)

U = conductance or U-value (W/m^2 degC)

V = air velocity (m/s)

V_e = effective air velocity (m/s)

VSA = vertical shading angle (deg)

V_{tot} = building volume (m^3)

WWR = window to wall ratio

INTRODUCTION

This section presents the topic of study and establishes the scene for its development. The research rationale is defined and the main research aim and objectives are specified. Further, the research method is introduced and the thesis structure outlined.

INTRODUCTION

The majority of the highest populated and fastest evolving cities are located within the tropics (UN-HABITAT, 2010, Lepers et al., 2005). In Kenya, approximately 40% of the population lives in urban areas; a percentage which continues to grow at a steady rate (Kenya National Bureau of Statistics, 2010). A direct result of this has been the rapid growth of the local building and construction sector (African Economic Outlook, 2015, African Economic Outlook, 2012). It has been suggested that this development of urban environments has had a detrimental effect on the environment (Santamouris and Asimakopoulos, 2001, Baker and Steemers, 2000). Similarly, given that urban areas are known to consume 75% of the world's energy and produce 80% of all greenhouse gas emissions (UN-HABITAT, 2012, p.10) this is also a matter of concern from an energy use perspective.

In buildings, this increase in energy consumption is mainly attributed to heavy reliance on high energy demanding active systems to solve climate and comfort related problems largely induced by inadequate design (Goulding et al., 1992, Chenvidyakarn, 2007, Diakaki et al., 2008, Tenorio, 2002, Kitio, 2010). Indeed, a number of studies indicate that majority of building energy is used up during the operational cycle as thermal load for cooling or lighting purposes (Santamouris and Asimakopoulos, 1996, Sosa G, 2007, UN-HABITAT, 2010). In warm regions, climate control systems such as ventilation cooling can account for approximately 70% of building energy consumption (Chenvidyakarn, 2007, p.5). Interestingly, this level of energy consumption is not necessarily an indication of improvement in the degree of comfort. In fact, it has been suggested that complaints relating to comfort are more prevalent in actively controlled buildings than passive ones (Baker and Steemers, 2000).

In the warm humid region of Kenya, a review of contemporary office buildings reveals an increasing dependence on energy intensive active measures for climate control. This is attributed to the predominance of highly glazed lightweight buildings better suited to more temperate climates. In warm humid climatic zones, high temperatures coupled by high relative humidity levels can often lead to overheating resulting in the thermal discomfort of occupants in these types of buildings. Despite the fact that these buildings are not necessarily applicable to the local climate nor are they reflective of any regionalist tendencies, their numbers continue to grow (Musau, 1994, Kiamba, 2010a).

More recently, growing concern over issues of climate change and fast dwindling natural resources has presented the Kenyan government with the challenge to cut down on energy consumption and reduce carbon emissions (Levine et al., 2007, Kitio, 2010, Ministry of Environment and Mineral Resources - Kenya, 2010). Given that buildings are responsible for approximately 41% of Kenya's total final consumed energy (International Energy Agency, 2009, Electricity/Heat in Kenya in 2009), the Kenyan government has set ambitious targets to develop and enforce national codes for energy efficiency and conservation in buildings by 2030 (Ministry of Energy, 2012). This is expected to be developed in tandem with a system for the energy labelling of buildings. Through this, the government hopes to encourage the design of buildings that offer reductions in energy use (especially those that eliminate the need for air conditioning systems) and the retrofit of existing buildings to offer greater energy savings (Ministry of Energy, 2004). A review by Kitio (2010, p.9) indicates that this would result in a reduction of energy consumption by 40% to 50% in new buildings and 20% to 30% in existing buildings.

Save for setting out the aforementioned goals, little work has been developed to date that can be applied to the Kenyan context and climate. A review of the latest National Building Regulations (National Planning and Building Authority - Kenya, 2009) reveals that broad generalisations and recommendations are given with regards to sustainable design and energy efficiency matters. Although this is a step in the right direction, the lack of adequate and specific guidance on climate-responsive design has continued to help propagate the influx of poorly designed buildings.

In light of the local situation, this study was undertaken to explore viable climate-responsive design alternatives that can extend occupant comfort and reduce the need for energy intensive environmental control systems. Specifically, the main aim of the research was to investigate ways of improving thermal comfort and energy efficiency in office buildings in the warm humid city of Mombasa in Kenya. This focus was defined to help develop design strategies that limit the need energy intensive environmental control systems. To achieve this, the following objectives were set:

- To gain an understanding of local climate conditions and related comfort considerations. Besides identifying any main areas of concern, this process also helped to identify if and for how long it would be possible to run a building using sole passive measures within the local warm humid climate and thermal comfort requirements.
- To review the design strategies recommended for office buildings in similar hot and warm humid regions. This helped to review precedents of design methods and to develop an analytical framework for empirical data interpretation in succeeding sections of the work.
- Using the selected case study buildings as a research vehicle, to identify suitable design strategies for office buildings in warm humid regions of Kenya. The vernacular typology forms the foundation of this investigation as it is critically examined with a view of deriving design solutions that have been developed over time to fit within its local context.
- Guided by research outcomes, to give recommendations for the incorporation of minimum standards in building regulations.

The research methodology revolves primarily around a case study approach and is developed through a series of local vernacular and modern case studies, post occupancy evaluations and subsequent computer simulations. This facilitated the exploration of selected case study buildings to determine the thermal comfort and energy use implications of varying the selected design strategies. From this, vernacular Swahili-inspired design strategies were derived and the application of external shading devices (the most significant mitigation strategy) to typical office buildings examined further.

The novelty of this research lies within the fact that this is the first effort that combines the post occupancy evaluation of buildings in Mombasa, investigates the efficacy of vernacular Swahili design strategies and validates their application to modern office buildings. Further, in as much as the eventual outcome of this work is a piece of academic research, the practical approach employed in the methodology enabled easy translation into a simplified analytical method applicable to the local building design industry. These guidelines include previously unavailable latitude specific solar path indices critical in the provision of essential data for effective external shading device design; and have the potential to encourage designers to apply external shading devices as a method of maintaining thermal comfort and conserving energy in office buildings.

In terms of structure, the thesis was divided into the following sections:

Chapter 1: Describes the context of the study, including a review of climate conditions and aspects related to thermal comfort. It also provides an overview of local vernacular and modern architectural typologies.

Chapter 2: Presents a background study of recommended passive design strategies in warm humid climates. Also, energy efficiency building regulations in similar hot and warm humid climatic regions are examined to determine the commonly recommended design strategies. As part of this review, a journal paper entitled *"Energy Efficiency Regulations as Drivers for Change in the Built Environment in Hot and Warm Humid Climates"* (Kiamba and Rodrigues, 2016 - expected) was prepared.

Chapter 3: Case study analysis of the Old Post Office (a vernacular Swahili building). Using an intensive field study including post occupancy evaluation and the subsequent analyses of monitoring data, potentially suitable Swahili-inspired design strategies are identified. A paper entitled "*Climate-responsive Vernacular Swahili Housing"* (Kiamba et al., 2014) was prepared as part of this analysis.

Chapter 4: Presents the case study analysis of Mombasa Uni Plaza (a typical modern office building), including an overview of construction type and materials used. Using a field study and post occupancy evaluation the environmental performance of the building is assessed. A simplified model of this building is used in simulations conducted in Chapters 5 and 6.

Chapter 5: With the aid of extensive computer based dynamic simulations, the impact of specific design strategies (thermal mass, ventilation and shading) on the thermal performance and the thermal comfort of occupants is quantified and meaningful conclusions are drawn. From this, a paper entitled *"The Application of Vernacular Swahili Architecture Strategies to Contemporary Office Buildings in Kenya"* (Kiamba et al., 2015a) was prepared.

Chapter 6: The efficacy of various external shading configurations (horizontal, vertical and egg crate) on occupant thermal comfort and energy savings is examined using extensive computer simulations. Further, solar heat gain coefficients are derived for sixteen cardinal orientations to help define this performance. From this, a paper entitled *"The Potential of External Shading Devices for Comfort Extension and Energy Savings in Kenya"* (Kiamba et al., 2015b) was prepared.

Chapter 7: Using two modern office buildings (Olem House and Combrook House), the application of the external shading devices to a typical office building is examined to establish the thermal comfort and energy savings implications. To test the validity of these findings, dynamic simulations of the selected buildings are carried out and the results compared. A guidance document (APPENDIX D) for the application of external shading devices was prepared as an outcome of this study. From this, a series of papers highlighted in the publication section were prepared and are awaiting submission.

Chapter 8: Presents the overall research conclusions, limitations of the current work and recommendations for the incorporation of minimum shading standards in building regulations. In addition, suggestions for future research are made.

1 THE CONTEXT IN KENYA

In this chapter, an overview of warm humid climate is presented with focus on aspects related to thermal comfort conditions and local climate considerations. In addition, local vernacular and modern architectural responses in Mombasa are examined.

1 THE CONTEXT IN KENYA

In around 30 B.C., Vitruvius wrote of the need to lay out buildings in a manner that was sensitive to climate and site conditions (Thomas, 2006). Setting out the basis of environmental design as we know it today, Vitruvius acknowledged that local climate and site conditions have a significant role in determining building form (Blewitt and Cullingford, 2013). Since Vitruvius, notable researchers have demonstrated that the key to mitigating environmental design issues lies with a design response to climate (Szokolay, 2008, Givoni, 1976, Koenigsberger et al., 1973, Olgyay and Olgyay, 1963).

Evidence of this approach has been found in manifestations of vernacular architecture across the world (Oliver, 2007, Oliver, 1997a, Rapoport, 1969). Similarly, in newer buildings, the thermal comfort and energy use provisions are often directly related to the given climate zones (Wong et al., 2012). By being aware of the characteristics of given climatic zones, designers are more mindful of the challenges that one needs to address to ensure user comfort (Koenigsberger et al., 1973).

In addition to climate, socio-cultural and economic influences were found to impact on the final building form (Rapoport, 1969, Kiamba et al., 2014). Perhaps this is ever so clear when examining the typical multi-storey buildings found across the developing world. In these cases, the impact of the 20th century modern architecture movement and the effects of globalisation have led to the 'borrowing' of architectural typologies from western developed countries (Musau, 1994, Kiamba, 2010a). A general characteristic of this type of architecture is the use of highly glazed facades as shown in Figure 1-1.

Whereas these types of buildings might work adequately in cooler climates, numerous studies have found that they tend to cause overheating in warmer climates (Building Research Establishment, 1985, Emmanuel, 2005, Juanjuan et al., 2009, Sosa G, 2007, Stouter, 2008, Givoni, 1998). This poor performance is attributed to the large areas of glazing that promote solar heat gain (Koenigsberger et al., 1973, Szokolay, 2008). In most cases, the end effect of designing these types of buildings is usually the introduction of costly and unsustainable active climate control systems.

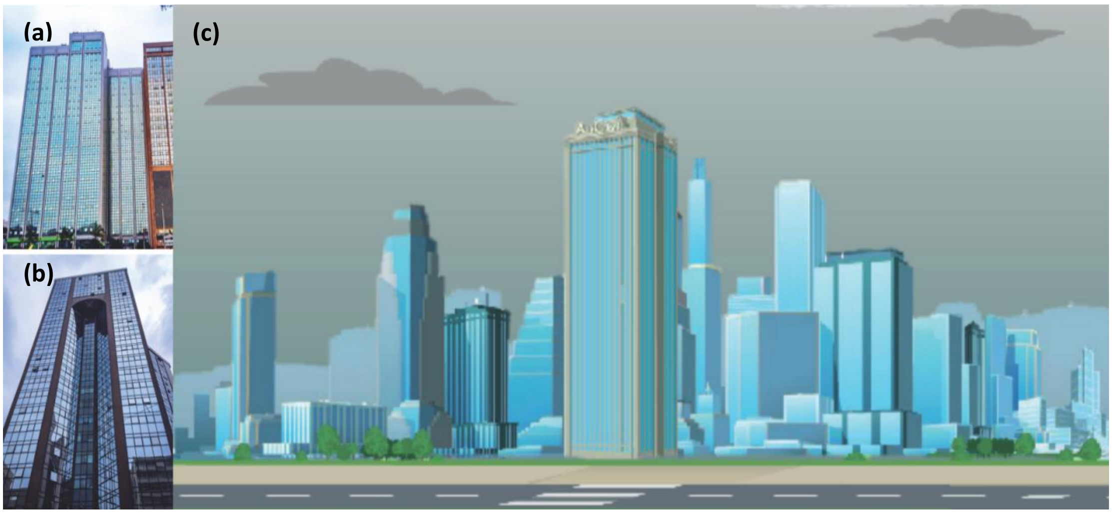


Figure 1-1 Typically glazed office buildings in Kenya (a) Anniversary Towers (b) View Park Towers. (c) An illustration of characteristic commercial and office buildings in Kenya.

In keeping with the Vitruvian tenets of design, this study begins with an examination of the local climate and thermal comfort conditions. Further, to get a clearer understanding of the study setting, a review of both vernacular and modern architectural responses in undertaken.

1.1 An Overview of Warm Humid Climate

Climate may be described as the characteristic condition of the atmosphere near the earth's surface at a certain place on earth (Reddy, 2008). This includes the region's general pattern of weather conditions, seasons and weather extremes like hurricanes, droughts, or rainy periods. According to the World Meteorological Organization (WMO, 2016), the conventional period of time to record weather data to determine the climate for any particular place is 30 years. The 30 year interval was selected by international agreement, based on the recommendations of the International Meteorological Conference in Warsaw in 1933.

The quantities most often observed during the 30 year period are temperature, precipitation, and wind which are defined as the climate “normals”. Climatologists define a climatic normal as the arithmetic average of a climate element such as temperature over a prescribed 30-year interval. The normals are computed once every 10 years to help smooth out year-to-year variations (Spellman and Price-Bayer, 2011). Usually, the climate of a region will determine what plants will grow there, and what animals will inhabit it. Where building design is concerned, a designer can work towards achieving occupant thermal and visual comfort with little or no recourse to non-renewable energy sources, by incorporating the elements of the local climate effectively (Koenigsberger et al., 1973).

In the definition of climatic boundaries or regions, numerous methods have been developed based on the reason for classification. According to Kottek et al. (2006b), one of the earlier and most widely recognised definitions came from a German climatologist and amateur botanist Vladimir Köppen who first published what is now referred to as ‘Köppen Climate classification’ in 1900. This empirical system was based on observable features which divided the earth's surface into climatic regions that generally coincided with world patterns of vegetation and soils (biomes). This method has since been modified and is now referred to as the Köppen-Geiger climate classification (Figure 1-2 and Figure 1-3). It is considered suitable for describing a more general world pattern of climates as it is based on annual and monthly averages of temperature and precipitation (Triantafyllou and Tsonis, 1994).

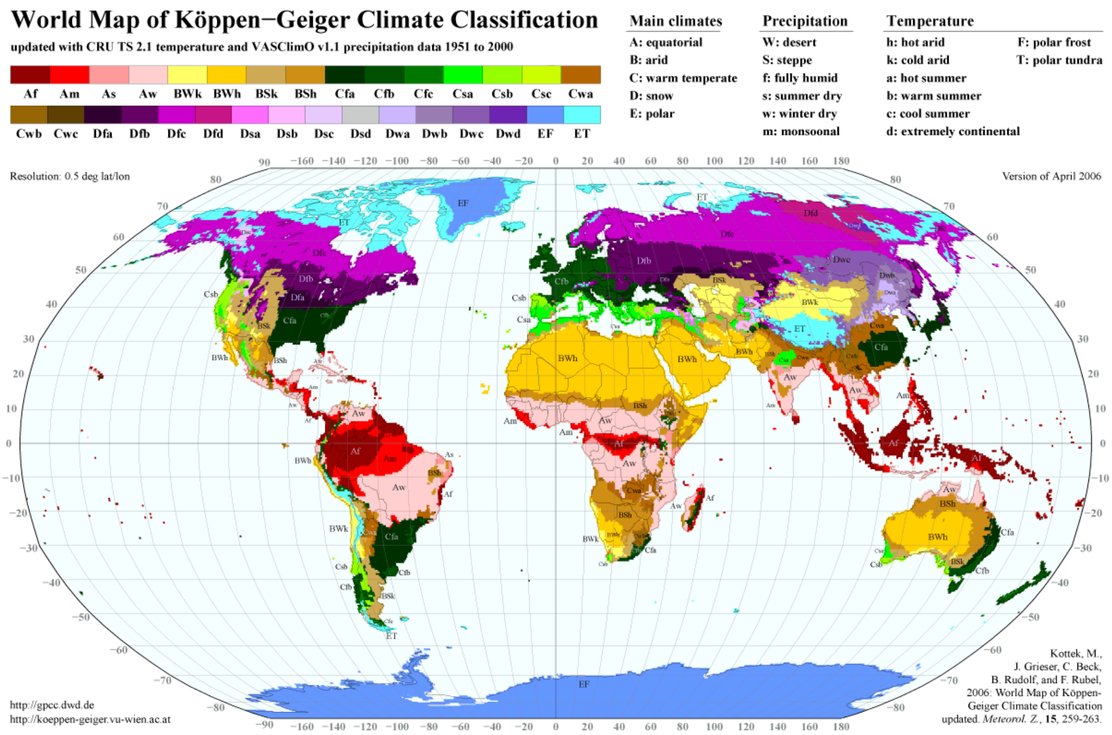


Figure 1-2 Köppen-Geiger world climate classification map (Kottek et al., 2006a, p. 261).

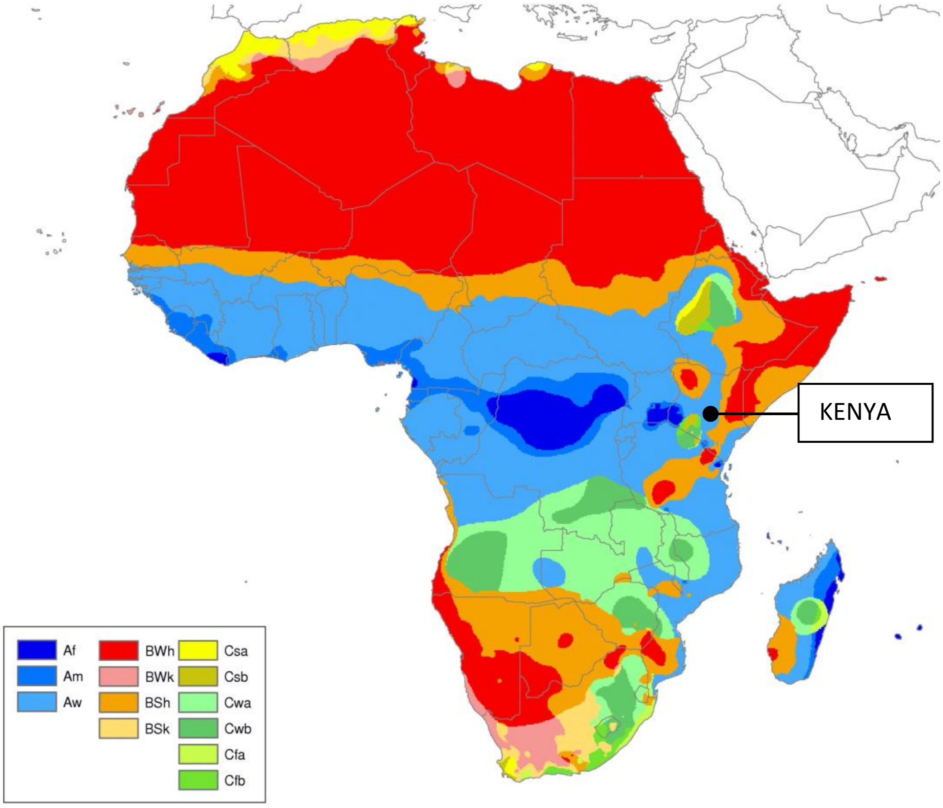


Figure 1-3 Africa Köppen-Geiger climate map, with Kenya highlighted (Murray, 2010).

Ogunsote and Prucnal-Ogunsote (2002), citing Olgay, (1963) and Evans, (1990) noted that although the Köppen-Geiger climate classification is widely used the world over, it is not suitable for building design purposes as it does not consider humidity - a key environmental factor of human thermal comfort. The identification of the role of climate in building design led to the need for a more suitable climate classification (Griffiths, 1983, Koenigsberger et al., 1973).

A suitable alternative was developed for tropical climates by Atkinson (1953), where he defined climate with respect to air temperature and humidity. According to Koenigsberger et al. (1973), this method is especially useful to building designers as it highlights the two main factors that would be the most likely to cause discomfort in tropical climates as indicated in Table 1-1. The classification has been widely accepted and is constantly referred to by the building design research community (Koenigsberger et al., 1973, Oakley, 1961, Szokolay, 2008).

Table 1-1 Atkinson's tropical climate classification (Koenigsberger et al., 1973).

Climate zone		Subgroup
A	Warm humid equatorial climate	Warm humid island or trade wind climate
B	Hot-dry desert/ Semi desert climate	Hot-dry maritime desert climate
C	Composite/ Monsoon climate (Combination of climate types A and B).	Tropical upland climate

Using Atkinson's classification, the selected study area of Mombasa was found to lie within the 'warm humid' climate zone which falls within 15° north and south of the equator. As illustrated in Figure 1-4 (Modified from Bruce Jones Inc. (2009), U.S Department of Energy (2013)), a significant number of cities fall within this climate band including, Recife (1), Lagos (2), Mombasa (3), Singapore City (4) and Darwin (5).

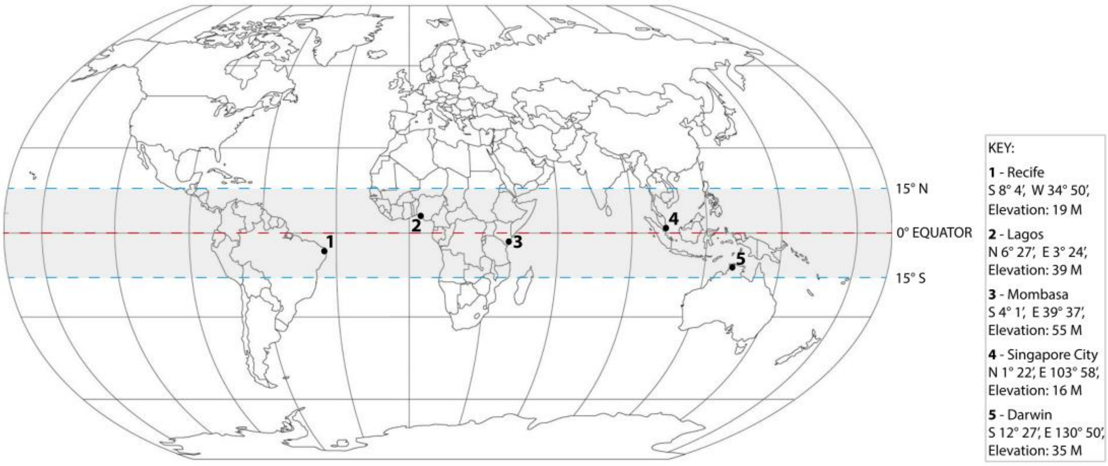


Figure 1-4 World map showing a selection of cities that fall within the warm humid climate band.

The characteristics of warm humid climate are discussed in detail by Koenigsberger et al. (1973, p.26) who explain that this climate has a fairly small seasonal variation, characterised by relatively high temperature of between 27 to 32°C (daytime) and 21 to 27°C (night-time) and humidity levels of 75% but often ranging from 55 to 100%. High levels of rainfall are common with annual rainfall ranging from 2000mm to 5000mm. Sky conditions may be cloudy throughout the year with coverage of 60 to 90% mainly due to high moisture content in the atmosphere, especially in the afternoons. Due to the regional proximity to the equator, the sun is almost always directly overhead resulting in high radiation intensities especially at the zenith and on western orientations. Solar radiation is strong with a high diffuse component due to dense cloud cover and high moisture content in the atmosphere. Winds tend to be in one or two general constant directions and can sometimes be of low and variable speeds.

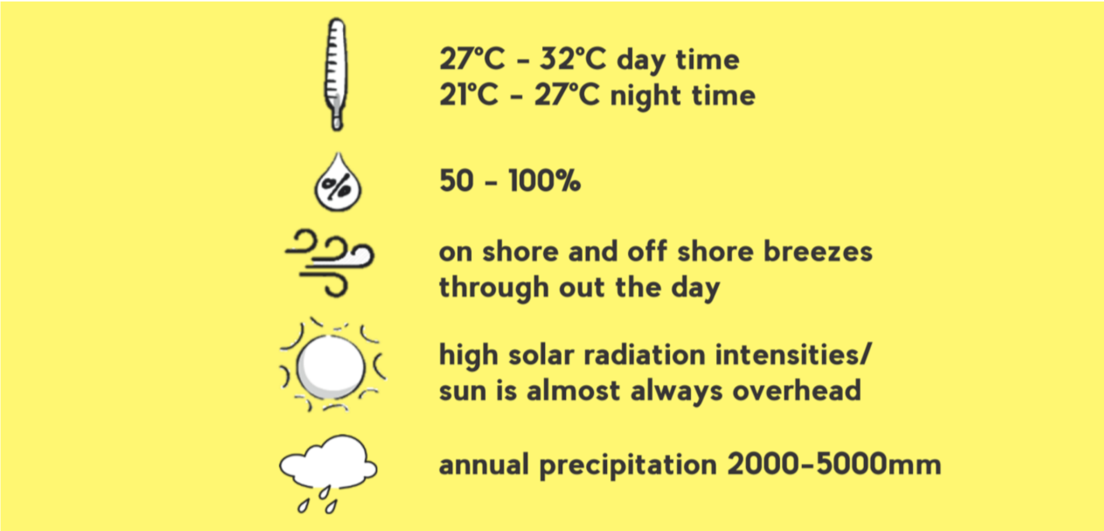


Figure 1-5 Typical characteristics of warm humid climate.

Generally, although warm humid regions experience similar climatic characteristics, slight differences may arise from differences in altitude and exposure. This is evident when observing the territorial extent of the climatic band illustrated in Figure 1-4. Bearing in mind the focus of the study on Mombasa, Kenya, three other cities, Singapore City (Singapore), Darwin (Australia) and Recife (Brazil) were selected for comparative purposes (see Table 1-2, Figure 1-6 and Figure 1-7). The selection of these three cities for was also partly based on the fact that the energy efficiency regulations of their respective countries were later examined in Chapter 2. Climate data for this analysis was sourced from the U.S Department of Energy (2013) which holds an online database for more than 2100 locations in EnergyPlus (.epw) format.

Table 1-2 Select warm humid climate cities (U.S Department of Energy, 2013).

City	Mombasa	Singapore City	Darwin	Recife
Latitude	S 4° 1’	N 1° 22’	S 12° 27’	S 8° 4’
Longitude	E 39° 37’	E 103° 58’	E 130° 50’	W 34° 50’
Altitude	55m	16m	35m	19m

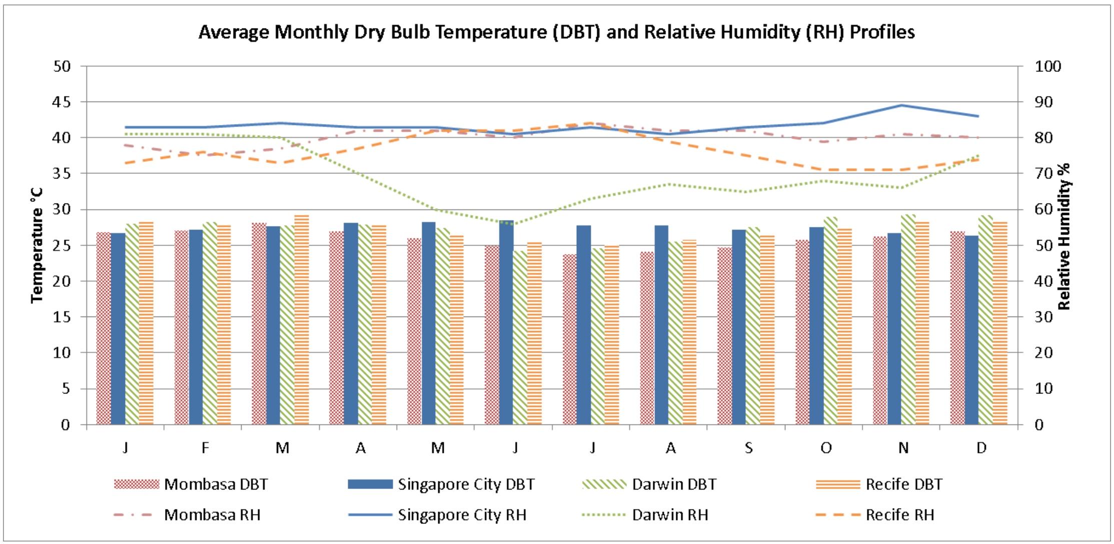


Figure 1-6 Average monthly dry bulb temperature and relative humidity profiles for Mombasa, Singapore City , Darwin and Recife.

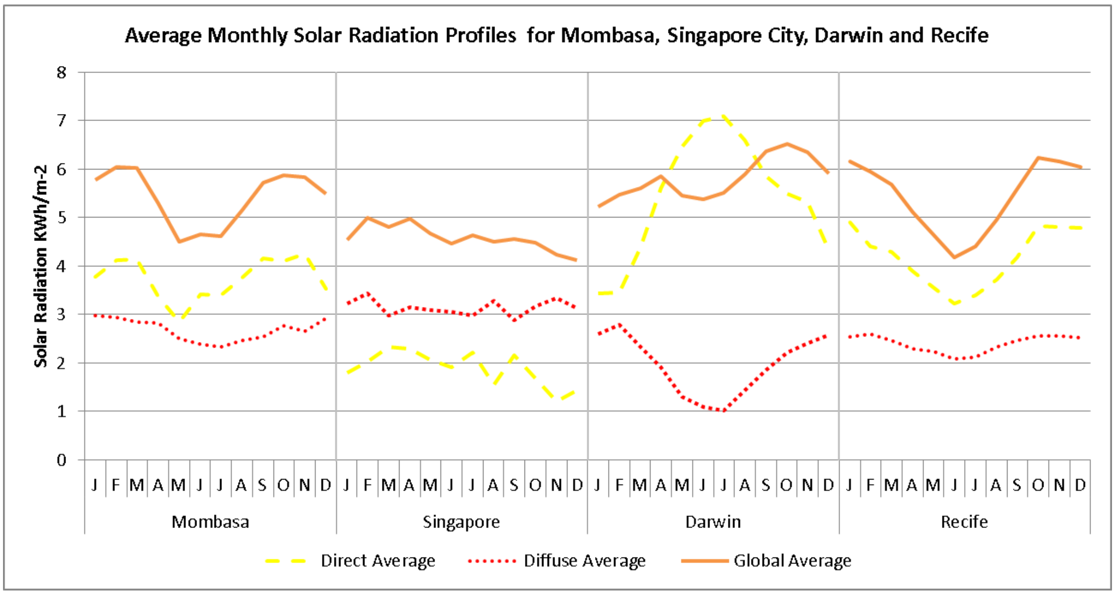


Figure 1-7 Average monthly solar radiation profiles of Mombasa, Singapore, Darwin and Recife.

The review indicated that all the cities showed little temperature variation with average monthly values of between 23.7°C and 28.5°C. Of all the cities, Singapore had the steadiest temperatures and lowest variation of 2.2°C. Darwin and Mombasa showed the greatest variation in average monthly temperatures with a diurnal temperature range of 5°C to 6°C. Further, despite Recife being warmer than Mombasa, they both shared similar trends over most of the year with temperatures peaking in March and being at their lowest in July. Unlike the other three cities, the temperature levels in Singapore peaked in July (part of the cooler periods in the other cities). This was attributed to hemispherical differences brought about by their position in relation to the sun (Szokolay, 2008, Trenberth, 1983).

All the cities experience fairly high average monthly relative humidity (RH) levels ranging from between 55 and 90%. As with the temperature values, these levels were found to be fairly steady and constant for Mombasa, Singapore and Recife. Of these, both Mombasa and Recife showed similar trends in their RH fluctuations. On the other hand, Darwin had significantly lower values, and especially during its cooler season. Notably, Singapore was found to have the highest RH values. This was attributed to Singapore's extensive maritime exposure.

In addition to the review of the temperature and RH data, the solar radiation components were also considered. The global irradiance value consists of two components, direct radiation (reaches the earth's surface along a straight line – vectorial in nature) and diffuse radiation (is scattered by the atmosphere – depends on hemisphere to 'receiving' surface exposure) (Szokolay, 2008). Of all the cities, Darwin had the highest radiation levels, majority of which comprised of direct radiation. Unlike the other cities it had a significantly low diffuse component; this was attributed to comparatively lower RH levels. Conversely, Singapore had a significantly high diffuse component attributed to high moisture/ RH content. Both Mombasa and Recife had relatively high global average solar radiation components, albeit at significantly lower levels than Darwin. In all the cases, high diffuse radiation indicated potential glare problems (Koenigsberger et al., 1973).

It was noted that peaks in global solar radiation could be related to the apparent movement of the sun and the hemispherical location of the selected cities. For instance, Mombasa experienced peak solar radiation in March (northward equinox) and September (southward equinox). Similarly, it was noted that these times corresponded to when Mombasa experienced peak temperatures. This finding illustrated the importance of fluctuating solar radiation on temperatures, more so in Mombasa, Darwin and Recife which had notably higher instances of direct radiation component compared to Singapore.

Overall, it was determined that the discomfort levels arising from the relatively high temperatures coupled with high RH levels were most evident in Singapore and Recife. On the other hand, relatively lower temperature and RH levels gave Mombasa and Darwin signalled slightly milder conditions.

A brief overview of the four cities confirmed that whereas they fall within the warm humid zone, slight variances are common due to differences in exposure and altitude. Nonetheless, given the general similarity in temperature and RH levels, similar design strategies (customised to site location) would be applicable in either one of the cities.

Following this insight into warm humid climate, a review of thermal comfort in warm humid climate was undertaken. This set the basis for an in-depth review of the local climate considerations of Mombasa.

1.2 Thermal Comfort in Warm Humid Climate

Thermal comfort is defined by British Standard EN ISO 7730 (2005) as: *"That condition of mind which expresses satisfaction with the thermal environment".* This description is derived directly from ASHRAE Standard 55 (2004) which includes the statement that: *"…and is assessed by subjective evaluation"*. Over the last few decades, an extensive amount of research has been conducted into human thermal comfort. According to Aulicems and Szokolay (2007), this research is generally divided into two methods that are based on closed climate chamber studies (heat balance model) or field surveys (adaptive comfort model).

Generally, both methodologies seek to investigate the varying aspects affecting thermal response or perception; and try to establish the acceptability of the thermal sensation felt under given conditions (de Dear and Brager, 2002). Conclusions derived from both approaches have given rise to comfort standards that set out comfort zone limits for various climatic conditions. These standards are essential to building designers as they offer insights into predicted thermal comfort of occupants. A review of both methods was conducted to identify the most suitable model for purposes of this study.

1.2.1 Heat Balance Model

Often referred to as the 'rational' approach, the heat balance model is based on the calculation of the heat balance of the human body. In this method, subjects are placed within a stable climate chamber with a range of environmental conditions while performing different activities. Thereafter, an index is developed to express the state of the human body based on the responses of subjects to the thermal environment with focus on temperature, humidity, air movement, clothing levels and activity (Nicol and Humphreys, 2002). This approach forms the basis of a significant number of theoretical comfort models including Predicted Mean Vote index (PMV) by Ole Fanger (1970), Effective Temperature scale (ET*) by Gagge et al. (1986) and later ISO 7730 and various pre-2004 ASHRAE 55 standards (Yun, 2008).

Most of the later models are based on the PMV model which links thermal comfort to the heat exchange process of the body. The heat load of the body can be estimated using Equation 1-1:

$$\mathrm{Q} = \mathrm{M} \pm \mathrm{R} \pm \mathrm{C} - \mathrm{E}$$

Equation 1-1 Heat exchange process (Aulicems and Szokolay, 2007, p.16)

Where: Q is the heat load of the body, M is the metabolic rate and R, C and E are the radiative, convective and evaporative heat exchange processes of the body, respectively. R, C and E are functions of four environmental variables including air temperature, mean radiant temperature, vapour pressure and air movement and two personal variables including clothing types and activity. Based on this, the PMV model is determined by a function of the metabolic rate and the heat load to the body as shown in Equation 1-2:

$$\begin{aligned}\mathrm{PMV} = [0.303\mathrm{e}^{-0.036\mathrm{M}} + 0.028]\{&(M-W) - 3.96E^{-8} fcl[(t_r+273)^4] \\ &- f_{cl}h_c(t_c - t_{a)} - 3.05[5.73 - 0.007\,(M-W) - p_a] \\ &- 0.42\,[(M-W) - 58.15] - 0.0173M\,(5.87 - p_a) \\ &- 0.0014M\,(34 - t_a)\}\end{aligned}$$

With:

$$f_{cl} = \frac{1.0 + 0.21I_{cl}}{1.05 + 0.1I_{cl}}$$

$$\begin{aligned} t_{cl} = 35.7 - 0.0275(M - W) - R_{cl}\{(M - W) - 3.05[5.73 - 0.007(M - W) - p_a] \\ - 0.42[(M - W) - 58.15] - 0.0173M(5.87M - p_a) \\ - 0.0014M(34 - t_a)\} \end{aligned}$$

$$R_{cl} = 0.155I_{cl}$$

$$h_c = 12.1(V)^{1/2}$$

Equation 1-2 Predicted mean vote, PMV (Aulicems and Szokolay, 2007, p.35).

Where: e is Euler's number (2.718), f_{cl} is the clothing factor, h_c is the convective heat transfer coefficient, I_{cl} is the clothing insulation (clo), M is the metabolic rate (W/m^2), p_a is the vapour pressure of air (kPa), R_{cl} is the clothing thermal insulation, t_a is the air temperature (°C), t_{cl} is the surface temperature of clothing (°C), t_r is the mean radiant temperature (°C), V is the air velocity (m/s) and W is the external work.

The PMV equation is only applicable to humans exposed to constant conditions at a constant metabolic rate for a lengthy period of time. A deviation from the heat load to the body will tend to increase PMV and thus increase discomfort.

The PMV model gave rise to a thermal comfort scale that runs from cold (-3) to hot (+3) as illustrated in Figure 1-8 (ASHRAE Standard 55, 2004).

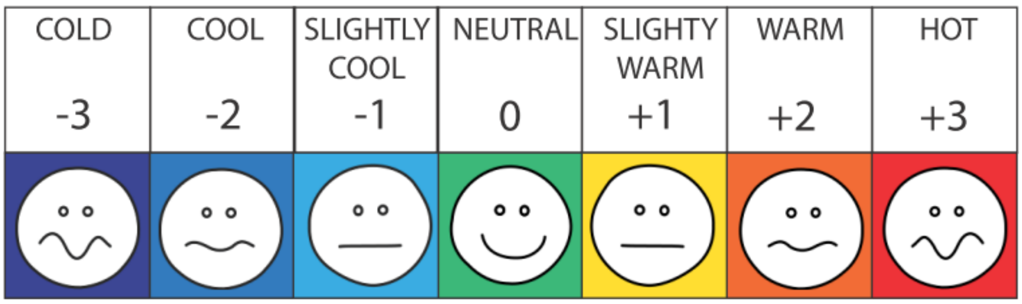


Figure 1-8 Predicted mean vote sensation scale showing anticipated the sensation and the value.

The percentage people dissatisfied (PPD) is a function of PMV that predicts the percentage of occupants that will be dissatisfied with thermal conditions. The further away PMV moves from 0, the greater the value of PPD. To maintain comfort, ASHRAE Standard 55 (2004) recommends a PPD of under 10% for interior spaces.

1.2.2 Adaptive Comfort Model

The adaptive comfort model is based on the findings of field surveys of thermal comfort. Data indicating the thermal response of subjects and the simultaneous thermal environment is collected while subjects go about with their daily activities. The data is thereafter analysed with the aim of establishing the temperature or combination of thermal variables at which the majority of the subjects feel comfortable in. This is then used to predict the comfort limits of similar conditions elsewhere (Nicol and Humphreys, 2002).

From the onset, the adaptive model highlights the role of building occupants as being central to achieving comfort. According to Brager and de Dear (1998), the main premise of this model is that the occupant interacts with and adjusts to the given environment. In reference to the ASHRAE Standard 55-2004 definition for thermal comfort that embraces the idea of the 'condition of mind' and 'subjective evaluation' of comfort, Brager and de Dear (1998), de Dear and Brager (2002)and later Szokolay (2008) suggested that thermal comfort is affected by more than just physical and physiological factors. This view is shared by Fountain et al. (1996) who explains the notion that comfort is largely dependent on the state of mind of a subject and would therefore be influenced by other variables that are not considered in static heat balance models (such as PMV). These other variables are attributed to thermal adaptation and may be broken down into three different processes as illustrated in Table 1-3.

Table 1-3 Modes of adaptation (Brager and de Dear, 1998, Yun, 2008).

Mode	Definition	Example/s
Behavioural adaptation	Refers to any modification by the occupant that affects the heat exchange process between the body and the environment.	Wearing a sweater when cold, opening a window when warm or drawing a shade when there is glare.
Physiological adaptation (acclimatization)	Gradual reduction in the strain from thermal stimulus due to repeated exposure to thermal environment factors.	Increased sweating capacity in hot climates.
Psychological	Change in perception of and reaction to thermal stimulus as a result of past experience and expectation.	Expectation of cooler temperatures in winter.

In keeping with the modes of adaptation highlighted in Table 1-3, Baker and Standeven (1996) suggested that adaptive opportunities allow for the extension of comfort. Further, they observed that in cases where temperatures fall outside of the neutral or comfort temperature zone and no further adaptation by occupants is possible then discomfort will be experienced.

1.2.3 A Comparison of the Heat Balance and Adaptive Comfort Models

The core difference between the heat balance and adaptive comfort models stems from their interpretation of the role of building occupants. In contrast to the heat balance model, the adaptive model reveals that thermal sensations are related to more factors than just the heat exchange of the body. Citing de Dear and Brager (1998), Yun (2008) explains that the adaptive model accounts for the climatic context of the building, past thermal experiences and current thermal expectations of the occupants.

Whereas the heat balance method presumes that the comfort zone is fixed irrespective of location and only varies as per the changes to its equation, the adaptive comfort zone tends to vary worldwide according to the prevalent local climate. Orosa and Oliveira (2011) suggest that the varying result may be attributed to the fact that people tend to become acclimatised to their thermal environments and as such will exhibit varying comfort preferences across the world. For instance, Givoni (1998) suggested that persons acclimatised to warmer climates will tend to be comfortable at warmer temperatures.

Further, in an extensive evaluation of thermal comfort and indoor air quality in office buildings, it was found that the heat balance model overestimated the comfort zone by up to 2°C and underestimated the comfort requirement when temperature deviated from the neutral zone (Croome et al., 1992). This was attributed to the inaccurate estimation of the metabolic rate and clothing values used in the PMV equation (Brager et al., 1993). On the other hand, the close agreement between the PMV predicted optimum indoor temperature and that observed in studies of air conditioned buildings suggested that the thermal adaptation in those buildings was of the behavioural type (adjustments to clothing and air speed). In contrast acclimatisation and psychological adaptations tended to override this factor in naturally ventilated buildings (Brager et al., 1993).

Following a significant number of similar study outcomes, it was suggested that international comfort standards based mainly on Fanger's PMV equations did not sufficiently describe comfort conditions for tropical climates (Brager and de Dear, 1998, Nicol, 2004). This may be explained by the fact that the basic heat balance model does not allow for the adaptation by users as is found to be the case in naturally ventilated buildings. Furthermore, research has shown that subjects tend to be comfortable at temperatures very close to those that they are experiencing (Humphreys et al., 1975, Nicol, 2004, Nicol and Humphreys, 2002); an aspect which does not particularly fit into the rational approach.

These viewpoints are supported by the results of field studies that have been conducted in warm tropical regions that indicate deviations from PMV results. For instance, investigations carried out in an urban residential development in Singapore by de Dear and Leow (1990) revealed that, due to acclimatisation, users preferred temperatures that were about 2°C warmer than those derived from the PMV index. Busch (1992, p.235) in a field survey involving over 1100 office workers in Bangkok, Thailand recorded a preference for air temperature of 28°C for those accustomed to naturally ventilated buildings; a figure which would undoubtedly signal discomfort in the heat balance model. Similarly, Mallick (1996) notes that for people living in warm humid regions, thermal comfort perception is influenced by acclimatization to high temperature and humidity levels. For an urban housing estate in Bangladesh, he revealed an acceptability of air temperature range of 24 to 32°C with relative humidity values of 50 to 90% coupled by very little air movement (Mallick, 1996, p.164). Wijewardane and Jayasinghe (2008, p.2057) found that acclimatized workers in a factory building in the warm humid region of Sri Lanka could tolerate indoor temperature of 30°C without much air movement; this increased to 34°C when indoor air velocity was maintained at 0.6m/s. Tanabe and Kimura (1994, p.953) revealed that subjects in hot and humid conditions are comfortable at relative humidity levels of up to 80% on condition that there is increased air movement. In a review of thermal comfort standards in the hot humid tropics Nicol (2004, p. 629) noted that air temperature levels above 30°C coupled by air speeds of over 1m/s are not at all rare in tropical buildings, and oftentimes occupants are comfortable under those conditions. Overall, these studies signal that higher temperature and humidity levels than those advocated by the heat balance model are acceptable to occupants.

Following a review of the aforementioned studies and their findings, it was determined that thermal adaptation played a significant role in the definition of comfort. Further it was concluded that subjects can be comfortable even when the air temperature is considered high by static comfort assessment methods such as PMV, and increasingly so if air movement is enhanced (Aynsley, 2004, Cândido et al., 2011a, Cândido et al., 2010, Khedari et al., 2000, Szokolay, 2008). Nicol (2004) suggested that the inadequacies of international standards may be remedied by the use of conclusions drawn from data collected from local field studies. These studies would also need to consider the role of the effects of air movement and humidity due to their specific importance in extending comfort limits in hot humid regions. This view was shared by Nicol and Humphreys (2002) who found that research conducted through field surveys indicated that the heat balance model is not suitable for use in real life situations as they are poor indicators of comfort in buildings. They also resolved that laboratory research should be tested out in field evaluations before their inclusion in any standards or regulations; more so when considering free running buildings.

1.2.4 Adaptive Comfort Applicability

When trying to predict the comfort zone or limits of a location using the adaptive approach, thermal perception can be explained by the idea of thermal neutrality which considers aspects of thermal acceptability (when one feels neither hot nor cold) (Brager and de Dear, 1998, Jayasinghe et al., 2003, Smith-Masis, 2009). In this case, the comfort temperature is expressed as a function of outdoor air temperature (Halawa and van Hoof, 2012). This is expressed quite well by Szokolay (2008) who presented an equation of thermal neutrality based on Aulicems' (1981) representation and interpretation of the same by de Dear et al. (1997). He explains that the comfort zone is relative to the neutral temperature (T_n), which is given by Equation 1-3:

$$T_n = 17.8 + 0.31 \times T_{o.av}$$

Equation 1-3 Neutral temperature, T_n (Szokolay, 2008, p.20).

Where: $T_{o.av}$ is the mean temperature of the select month.

Szokolay (2008, p.20) further notes that the comfort limits for a given region can then be set by extending the neutral temperature by ±2.5°C for 90% acceptability.

Similarly, Nicol and Humphreys (2002) proposed that indoor comfort temperatures are closely related to outdoor temperatures as indicated in Equation 1-4:

$$T_c = 13.5 + 0.54T_o$$

Equation 1-4 Comfort temperature (Nicol and Humphreys, 2002, p. 569).

Where: T_c is the comfort temperature and T_o is the monthly mean of the outdoor temperature. In this case, the comfort temperature has a range of ±2.0°C with the possibility of extending it further on the provision of adaptive opportunities (Nicol and Humphreys, 2002).

Both of the aforementioned equations and similar adaptive comfort models are frequently used to approximate comfort temperatures in naturally ventilated buildings. Specifically, it has been acknowledged that the adaptive approach offers building designers a close approximation of the internal temperatures that users will find to be satisfactory within passive buildings (Nicol and Humphreys, 2002).

In a comparative review of adaptive and PMV models of comfort, Orosa and Oliveira (2011) note that the adaptive model gives a more precise estimate for passive buildings. However, they also caution that the adaptive approach may sometimes be lacking, in that it may predict the same neutral temperature for areas with similar outdoor temperature but of different relative humidity levels. Halawa and van Hoof (2012) also note with concern that the over dependence on the outdoor temperature values ignores the fact that there are other variables highlighted in the PMV model that are still quite valid and do not seem to receive similar weighting in this approach. Instead, they suggest that the way forward should be to integrate both approaches to arrive at a more comprehensive method of evaluating thermal comfort.

Nevertheless, as explained by Brager and de Dear (1998) in their review of numerous significant field research studies, the fact remains that users of naturally ventilated buildings show a preference of temperature levels that closely followed the outdoor temperature and are more tolerant of temperature swings. Similarly, Aulicems and Szokolay (2007) suggest that significant field investigations and verification of the adaptive model in warm humid regions such as Darwin and Singapore reveal that the static model is not suitable for warm regions.

Given the findings of this review, it would appear that the adaptive method allows for a better understanding and appreciation of warm humid climates. It has been suggested that it would be of good use to building designers to incorporate standards that consider how a building will run within its given climate and take into account locally acceptable comfort as opposed to simply aiming to create an indoor environment independent of this; as seems to be the case with the PMV models (Koch-Nielsen, 2002, Nicol and Humphreys, 2002).

A recent review of adaptive thermal comfort reveals that the model has continued to gain traction across the world. Undoubtedly, the most significant effect of this has been its integration into two international standards: ASHRAE Standard 55 (2004) and later European Standard EN 15251 (2007) (Halawa and van Hoof, 2012). More recently, the ASHRAE Standard 55 has been revised to incorporate findings from the latest research on adaptive comfort (ASHRAE, 2013a). A significant change (2010 version) has included provisions for evaluating the impacts of elevated air speed. In warm regions, countries such as Brazil (where much of its territory may be classified as hot humid) have already had a direct shift towards the adoption of the adaptive approach into local jurisdiction by way of bio-climatic design (Cândido et al., 2011a). As highlighted earlier, a similar approach is planned for Kenya.

Based on the findings of this literature review, a similar adaptive approach was adopted as the main model for this research. This decision was founded on these two findings:

1. A significant number of thermal comfort field studies conducted in warm regions have found that building occupants (acclimatised to local climate conditions) tend to be comfortable at higher temperatures.

   Therefore, it would be unreasonable to propose the use of PMV methods that tend to recommend small comfort ranges that could only be met by the provision of active ventilation systems.
2. The method promotes the provision of adaptive opportunities to occupants for the restoration of comfort, if need be.

   Unlike the PMV method, adaptive comfort models are more responsive to human behaviour and assume that, if changes occur in the thermal environment to produce discomfort, then occupants will generally change their behaviour and act in a way that will restore their comfort. The main effect of such adaptive models is to increase the range of conditions that designers can consider as comfortable, especially in naturally ventilated buildings where the occupants have a greater degree of control over their thermal environment.

It was determined that the PMV model is better utilised when designing air conditioned zones or buildings where conditions are more tightly controlled. Therefore, it was recommended that the PMV 'traditional' model be considered as the primary prediction method for buildings that use active conditioning methods, whereas adaptive comfort model be used for naturally ventilated systems.

1.3 Local Climatic Considerations in Kenya

Covering an area of 585,363 km², Kenya extends between latitudes 5° 30' N and 5° S and longitudes 34° E and 40° E and (Figure 1-9). Kenya is a tropical country with a variety of climatic subzones resulting from differences in topography, the presence of significant water bodies (including Lake Victoria and the Indian Ocean), and extensive vegetative cover in some regions (Figure 1-10). Given its location and prominence in Kenya, the city of Mombasa was selected to provide a focus for the study of the warm humid region of Kenya (denoted as 'coast' in Figure 1-10). Mombasa is the second largest city in Kenya (after the capital city of Nairobi) with a population of approximately 940,000 people (Kenya National Bureau of Statistics, 2010). It has served as the most significant port city in East Africa for a number of centuries to date (Mombasa Municipal Council and National Museums of Kenya, 1990).

(a)

(b)

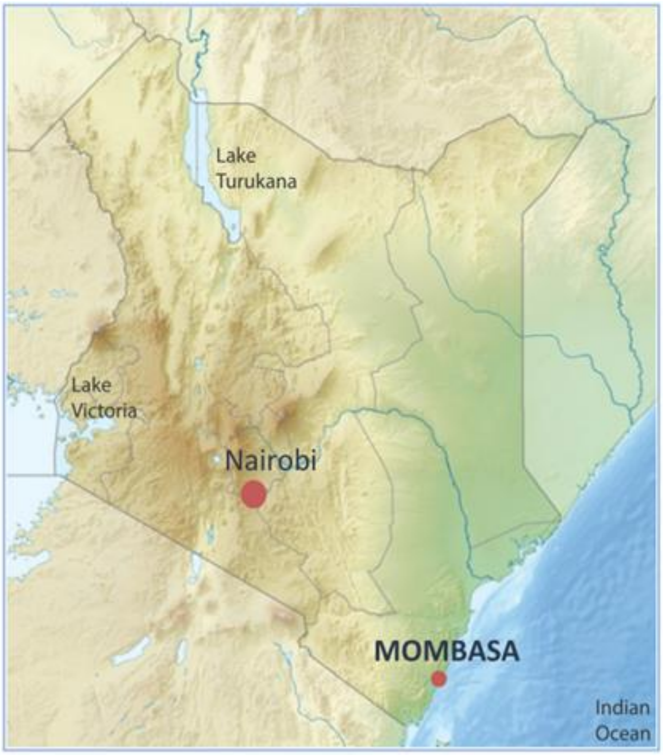


Figure 1-9 (a) Map of Africa showing location of Kenya. (b) Topographical map of Kenya showing the location of Mombasa (Author-modified from Maps for Design, 2013, Maps of the World, 2013).

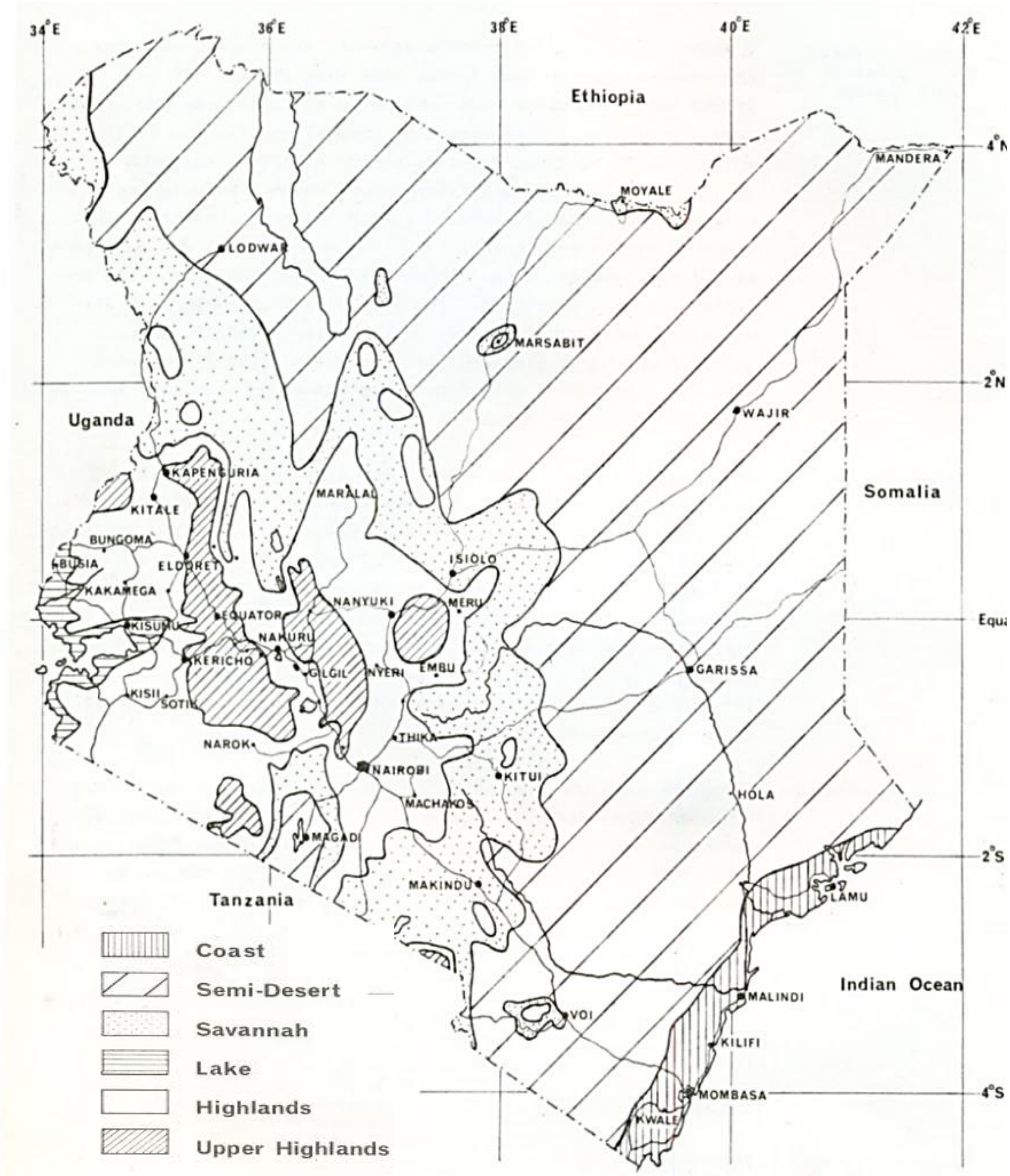


Figure 1-10 Climatic zones in Kenya (Hooper, 1975, p.3).

Previously in section 1.1, it was established that Mombasa experienced relatively high temperatures and relative humidity levels for majority of the year. This was coupled by instances of high solar radiation. In this section, a more in depth analysis is presented. To begin with, a climate graph was prepared to present the basic climate data for Mombasa Figure 1-11.

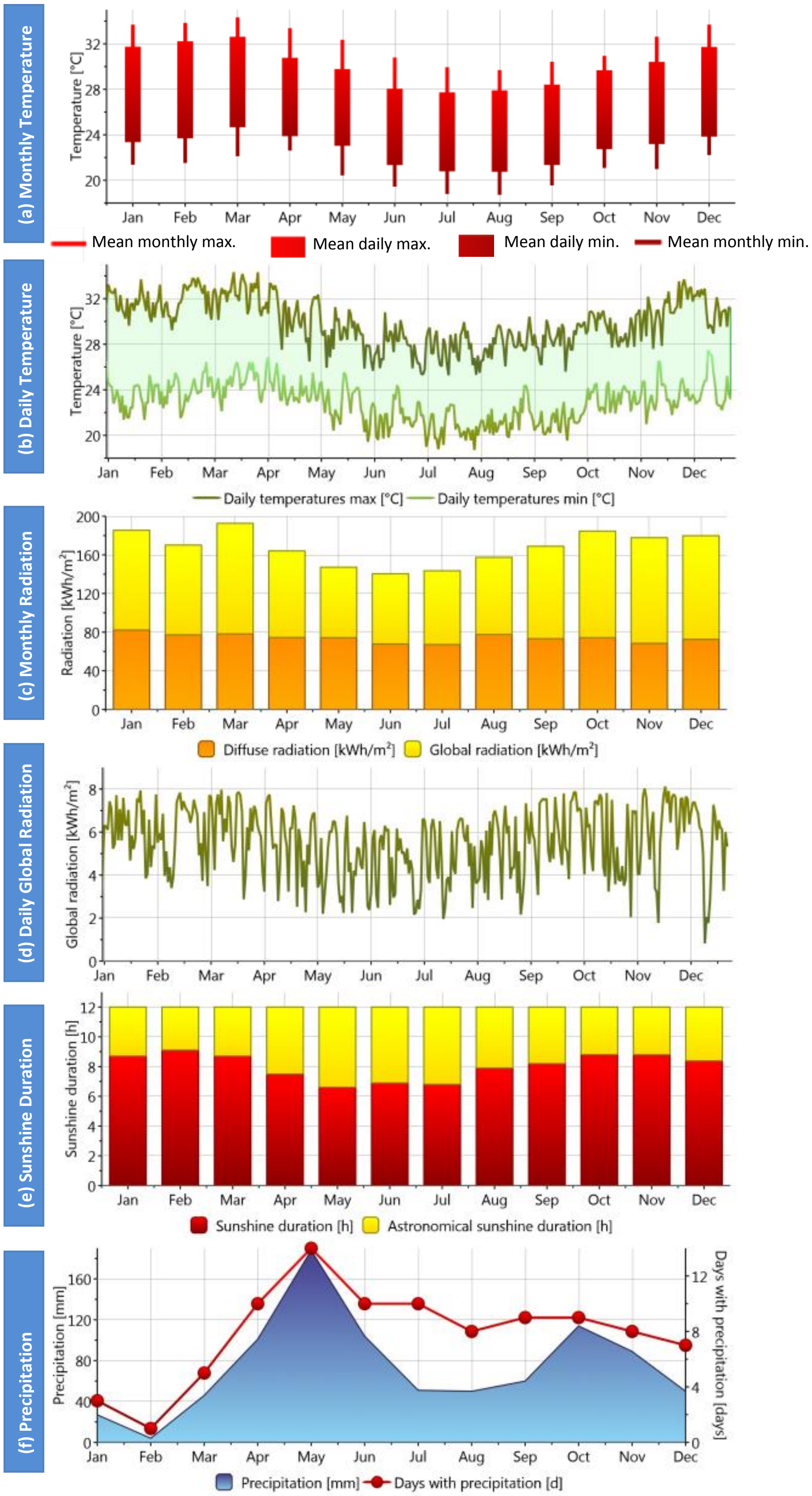


Figure 1-11 (a) to (f) Climate graphs for the warm humid city of Mombasa, Kenya (author-generated with Meteonorm Version 7 using weather data from U.S Department of Energy (2013).

Following this, the thermal comfort limits for Mombasa were extracted based on the findings of section 1.2. Using Equation 1-3 and Equation 1-4, the predicted comfort limits for the warm humid city of Mombasa were calculated and the results presented in Table 1-4, Figure 1-12 and Figure 1-13.

Table 1-4 Calculated comfort limits for Mombasa.

Month	Ta/To	Tn	LTc01	UTc01	Tc	LTc02	UTc02
Jan	27.4	26.1	23.6	28.6	28.3	26.3	30.3
Feb	27.8	26.2	23.7	28.7	28.5	26.5	30.5
Mar	28.5	26.4	23.9	28.9	28.9	26.9	30.9
Apr	27.5	26.1	23.6	28.6	28.4	26.4	30.4
May	26.1	25.7	23.2	28.2	27.6	25.6	29.6
Jun	25.0	25.4	22.9	27.9	27.0	25.0	29.0
Jul	23.9	25.0	22.5	27.5	26.4	24.4	28.4
Aug	24.0	25.0	22.5	27.5	26.5	24.5	28.5
Sep	25.0	25.4	22.9	27.9	27.0	25.0	29.0
Oct	25.8	25.6	23.1	28.1	27.4	25.4	29.4
Nov	26.9	25.9	23.4	28.4	28.0	26.0	30.0
Dec	27.4	26.1	23.6	28.6	28.3	26.3	30.3

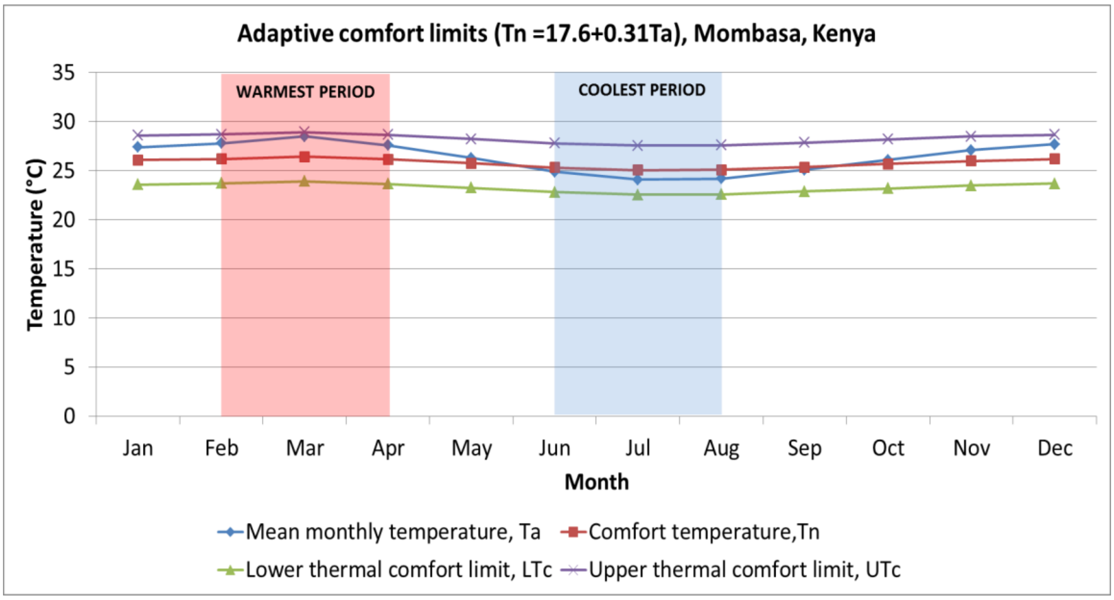


Figure 1-12 Comfort limits for Mombasa based on Szokolay's T_n equation.

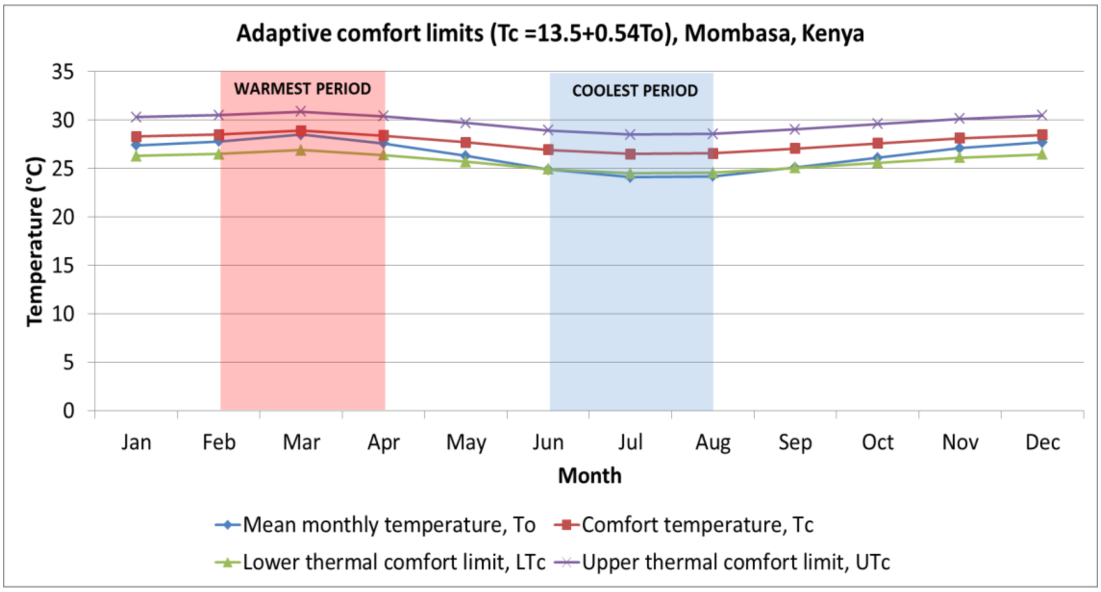


Figure 1-13 Comfort limits for Mombasa based on Nicol and Humprey's T_c equation.

The choice to compare both comfort limit equations was informed by a similar study conducted by Nicol et al. (1999) where they aimed to derive the thermal comfort limits of office buildings in various climatic regions of Pakistan. Their study findings for the warm humid region indicated that the temperature limits derived from both equations were fairly similar with the temperatures extracted from the T_c equation being slightly higher than those derived from the T_n equation. In addition, they reported that subjects were generally comfortable at temperatures of between 20° to 30°C when using fans. When temperatures became unbearable, mechanical fans would be employed to enhance air movement.

A similar approach was adopted for this study. Using both the T_n and T_c equations, it was predicted that the upper comfort limits for Mombasa could be extended to 29°C and 31°C, respectively (both based on results extracted for the month of March). It is noted that, although the local climate conditions are fairly constant all year round, March is the warmest month of the year and therefore the most prone to overheating. Consequently, it was suggested that the predicted upper comfort limits of March could be used to define the comfort extreme for the entire year. It was suggested that if the ambient temperatures exceeded these limits, there would be the need to restore the indoor comfort conditions. To help maintain the comfort conditions indoors, it would be necessary to apply design strategies for regulation purposes. These measures could either be passive methods (preferable) or mechanical/active methods (last resort). To help determine the passive methods that might be considered, a psychrometric chart analysis was conducted for Mombasa using the climate analysis software Climate Consultant 4.0 and presented in Figure 1-14. A psychrometric chart is a graphical representation of the psychrometric processes of air which include physical and thermodynamic properties such as dry bulb temperature, wet bulb temperature, humidity, enthalpy and air density (Aulicems and Szokolay, 2007). These charts provide a rapid overview of air conditions as they relate to the selected climate and occupant comfort. Further, they can be used to chart the environmental design strategies that can be used to extend comfort and the period for which this can be effective.

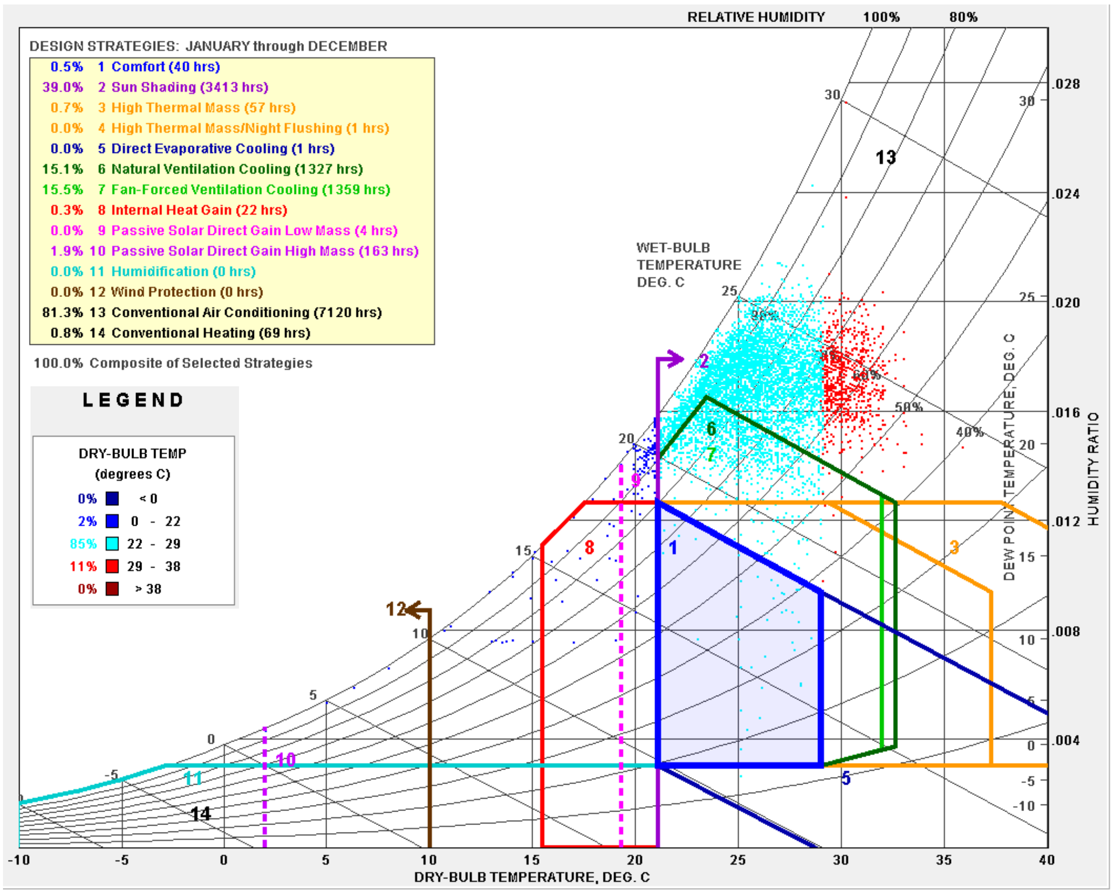


Figure 1-14 Psychrometric chart with environmental strategies overlays for Mombasa.

The analysis indicated that if passive strategies were considered, it would be possible to meet thermal comfort requirements for 85% of the entire year by keeping ambient temperatures within the predicted comfort range of 22°C to 29°C (based on the T_n equation results). It was also predicted that, even if passive methods were applied, ambient temperatures would lie above 29°C for 11% of the year – signalling potential for occupant discomfort during this period. This analysis was deemed to be particularly significant as it indicated the amount of time that a building could be run in Mombasa without the input of mechanical or active measures.

The following is a checklist of passive design guidelines recommended for the extension of comfort as derived from this analysis:

- Sun-shading designed for the specific latitude to reduce or eliminate the need for air conditioning.
- Minimise or eliminate west facing glazing to reduce heat gain in warmer periods and in the afternoons.
- Use of natural ventilation, where windows are well shaded and oriented to prevailing breezes.
- Use of light coloured materials for walls and roofs (with high emissivity) to reduce heat gain through conduction.
- Use of high thermal mass indoor walls to provide coolth and provide time-lag.
- Use of passive design strategies developed by vernacular type architecture (where suitable).
- On particularly warm days (applies to the period when temperatures are above 29°C – 11% of the hours in the year) air conditioning may be required where fan-forced ventilation does not make conditions suitable for occupants.

Of the guidelines recommended, both sun shading (39% hours of the year) and natural ventilation (15.1% hours of the year) were found to be the most beneficial passive interventions in the extension of the comfort range. Specifically, sun shading is particularly suitable for mitigating solar heat gain whereas natural ventilation is suitable for removing warm air build up and providing psychological cooling (Koenigsberger et al., 1973, Olgyay and Olgyay, 1963). Thermal mass and fan-forced ventilation were recommended for 0.7% and 15.5% hours of the year, respectively. The suitability and application of these strategies was examined in greater detail in

Chapter 2. It was also recommended that a review of local vernacular architecture (which has inherently tried and tested over long periods of time) might be worth considering when seeking solutions for local buildings. Similarly, a review of the local vernacular types was examined in greater detail later in section 1.4 and Chapter 3.

Further to determining the period of time when passive strategies could facilitate comfort all year round (85%), Climate Consultant version 5.4 software was used to derive the proportion of this period that falls within typical working hours (set from 8am to 6pm as would mainly be the case in office buildings). The results of this review were illustrated in Figure 1-15. The findings indicated that ambient temperatures would lie between 22°C and 29°C for 74% of the year and greater than 29°C for 26% of the year if passive design strategies were applied during working hours.

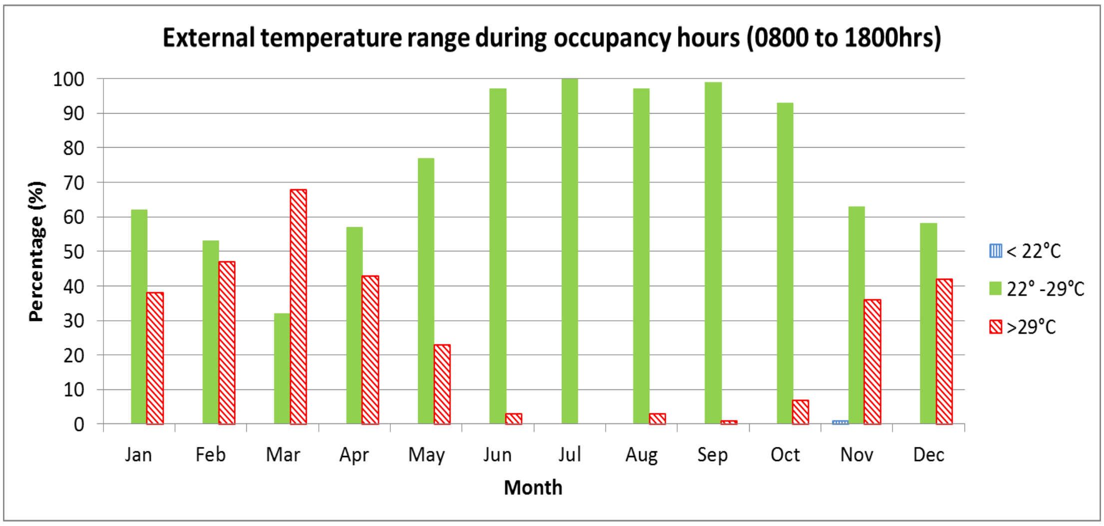


Figure 1-15 External temperature range during working hours (8am to 6pm).

For comparison purposes, psychrometric chart analysis using the PMV model (ASHRAE Standard 55-2004) was conducted using Climate Consultant version 5.4. In this method, an experimentally derived algorithm considers dry bulb temperature, humidity, air velocity and metabolic activity. It has two comfort zones for summer and winter clothing and the slightly sloped temperature limits account for the fact that in dryer air people are more comfortable at slightly higher temperatures. With this model the mean radiant temperature (MRT) is assumed to be roughly equal to dry bulb temperature.

From this, it was determined that the PMV comfort limits lay between 20.3°C and 26.7°C for 90% percentage people satisfied, PPS (PPS = 100 – PPD). A review of the ambient temperatures with respect to these limits indicated that the passive measures would only be able to restore thermal comfort for 67% of the year, leaving 38% of the year reliant on active measures. This was significantly decreased to 34% (comfort facilitated by passive means) and 66% (comfort facilitated by mechanical or active means) when considering working hours only.

A comparison of these findings indicated that the adaptive comfort model offered a suitably higher upper comfort limit that predicted the provision of comfort via passive means for 40% more time than the PMV method. Similarly, a 40% reduction in the use of active means was also recorded. Currently, the emission factor for the Kenyan electricity grid is 0.33kgCO_2 per kWh generated (Ecometrica, 2011, IEA, 2015). Considering the impact of applying adaptive comfort measures to commercial buildings such as offices in Kenya, this would translate into significant annual cooling energy cost savings of approximately KShs.10bn ($107m at the current rate of Ksh.1 to $0.009), and significant carbon emission reductions of 17,902,269kgCO2 (representative of a 15% cut in current national emissions).

1.4 Local Architectural Responses

In this section an initial review of the vernacular and contemporary architectural responses in the warm humid region of Kenya was undertaken. This included an introduction to vernacular Swahili architecture (a typology identified to be predominant/ typical of the local precedent) and a comparative analysis of the environmental responses of the local Swahili vernacular and typical contemporary office buildings.

1.4.1 Vernacular Architecture

The East African coastal region is steeped in a history that is said to go back as far as 100 A.D (Ghaidan, 1975). Settlements in this region, including the key city of Mombasa, emerged from a period that was heavily influenced by transoceanic trade and an amalgamation of diverse cultures (Kiamba et al., 2014, Mombasa Municipal

Council and National Museums of Kenya, 1990). With this came the development of a distinct architectural type which is now referred to as 'vernacular Swahili architecture'. Consisting mainly of two to three storey coral stone buildings reminiscent of the hot dry Arab world, this predominant type is distinguished by buildings with thick walls that are punctuated by relatively heavily shaded fenestration openings and ornate timber balconies (Table 1-5).

In addition to the seemingly heavyweight Swahili coral stone buildings, other common typologies included the lightweight Swahili mud and wattle houses with corrugated iron sheet roofs, Mijikenda 'Kayas' made of a wattle frames covered with palm leaf fronds and Mijikenda mud and wattle houses with palm frond roofs (Table 1-5). These lightweight typologies were more common with the local indigenous population consisting mainly of a collection of nine ethnic groups collectively referred to as the Mijikenda people; and later among those who could not afford to build coral stone houses (Ghaidan, 1975, Mombasa Municipal Council and National Museums of Kenya, 1990).

Table 1-5 Predominant vernacular architecture in the coastal region of Kenya.

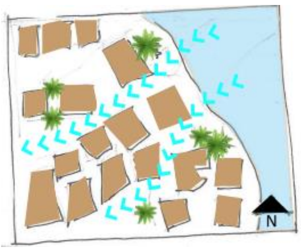
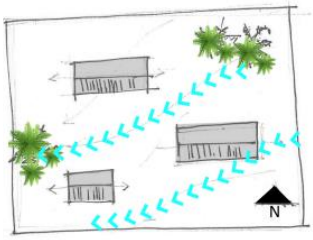
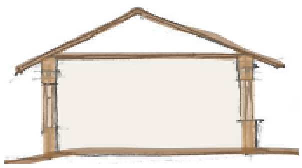
Type	Main characteristics
a) Swahili coral stone building (vernacular Swahili architecture) 	• Laid out in dense urban layouts. • Two to three storey buildings with thick coral rag walls, flat coral rag ceilings and a palm frond pitched roof - replaced by corrugated iron sheet roofing. • Heavily shaded by balconies, screens and neighbouring buildings. • Typically mixed-use building in the Mombasa region; ground floor - commercial, first floor - residential.
b) Swahili mud and wattle house 	• Layouts were similar in concept to the residential floor of the stone houses (built for occupation by those considered to be of lower class/slaves). • Single storey buildings with wattle frames and mud and coral aggregate infill. Roofs were pitched and made of palm frond thatch with open gable ends - replaced by corrugated iron sheet roofing.

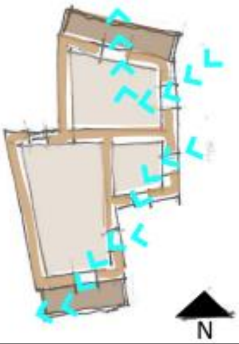
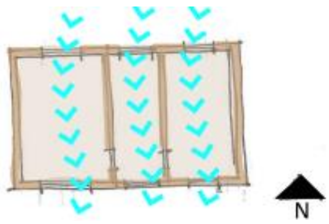
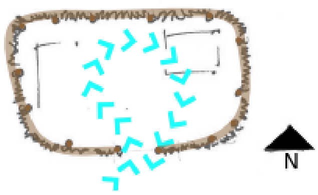
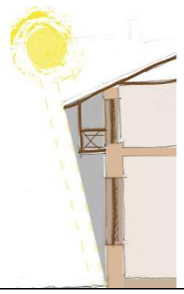
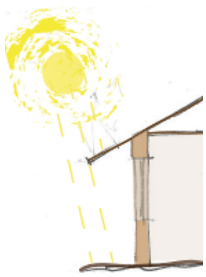
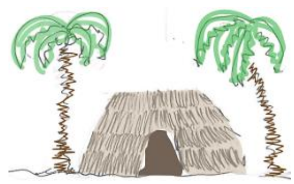
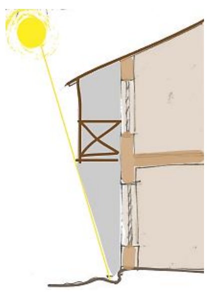
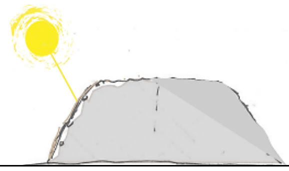
c) Mijikenda 'Kaya' house 	• Entirely made of wattle frame and palm frond thatch. • Open-plan layout. • In the mid-19th century, most of these settlements were abandoned for various reasons (mainly migration to more 'permanent' settlements due to increased social and economic empowerment).
d) Mijikenda mud and wattle house 	• Single storey buildings with wattle framed walls of mud and coral aggregate infill and palm frond thatch roofs with open gable ends. • Layouts typically consisted of two rooms for living and sleeping areas.

The review of the vernacular architectural types found that they tended to be strictly for residential use or mixed residential and commercial use (Kiamba et al., 2014, Hoyle, 2001). Despite the fact that this study is focused on solutions suitable for office buildings, it was suggested that an examination of the local precedent (irrespective of their primary use) presented the opportunity to identify and examine local design solutions with the aim of identifying suitable transferable design strategies.

It has been noted that Mombasa is located in a primarily warm humid climate zone, where heat and humidity are the main environmental issues of concern for building designers. With this in mind, an initial review of the environmental design strategies of the selected vernacular types - taking into account the potential causes of climatic stress on indoor conditions including relatively high temperatures, direct solar radiation, humidity and glare – was undertaken and presented in Table 1-6. For purposes of clarity, the review was divided into two sections, 'heavyweight' and 'lightweight', as per the main construction materials employed in each architectural type.

Table 1-6 Comparison of the environmental design principles of the vernacular architectural types found in the coastal region of Kenya.

	Heavyweight	Lightweight		
(a) House types	a) Swahili coral stone building 	b) Swahili mud and wattle house (SM) 	c) Mijikenda 'Kaya' house (MK) 	d) Mijikenda mud and wattle house (MM) 
(b) Orientation & Layout	• Are laid out to fit into dense urban layouts and to channel incoming breezes. 	• Tend to be oriented along the east-west axis (to avoid solar gain through the east and west facades). • Open layouts to encourage breezes around all buildings within residential compounds. 		
(c) Construction and materials	• Thick coral rag walls with potentially high thermal capacity (increased time lag). • Ventilated attic space (to reduce the conduction of heat into lower floors). • Screened timber window shutters and balconies for shading 	• SM and MM: Permeable roof with open gable ends (to reduce the conduction of heat into lower floors).  • MK: Thin permeable walls to encourage cross ventilation. 		

(d) Ventilation	• Compact plans with window placement to encourage cross ventilation. • Ventilation at full body level is encouraged by windows of up to 1.8m height with a cill level of 0.3m. 	• SM and MM: A central corridor with rooms on either side to encourage cross ventilation. This is sometimes replaced by an internal courtyard which serves the same role.  • MK: One main opening and the permeable walls area used to ventilate the entire space. 
(e) Shading	• Mutual shading of buildings • Use of sun shading elements including balconies, screens and shutters. 	• SM and MM: Relatively deep roof overhangs and surrounding vegetation offers an element of shading. • Window shutters control solar/ daylight infiltration indoors. • MK: With only one opening, little other than the thatch surface is left exposed to solar gain.  
(f) Daylighting	• Lighting and glare is controlled using window shutter systems. 	• SM and MM: Shaded window openings provide adequate lighting with little risk from glare. • MK: With only one opening, lighting levels are expectedly low. However, given that many domestic tasks were conducted outdoors during at daytime and under shade, it was not a major concern. 

The comparison of the local vernacular responses showed distinct physical differences in both form and structure. Nonetheless, it was suggested that both typologies responded to climatic influences, albeit in slightly different ways.

The lightweight options were found to be reminiscent of past building trends in warm humid climates for a significant period of the 20th century where the widely accepted house type was lightweight and elevated on stilts so as to enhance the effect of cross ventilation – much like the traditional Malay house type (see Figure 1-16 and Figure 1-17). These lightweight houses worked the premise that: since the temperature differences between the outside and inside show little variation, the only substantial relief that can be gained by users is from air movement for physiological cooling. Therefore, during the day they would exploit breezes to offer relief to occupants and after sunset they would cool down rapidly thereby reducing unwanted heat retention (Koenigsberger et al., 1973, Szokolay, 1996).

(a)

(b)

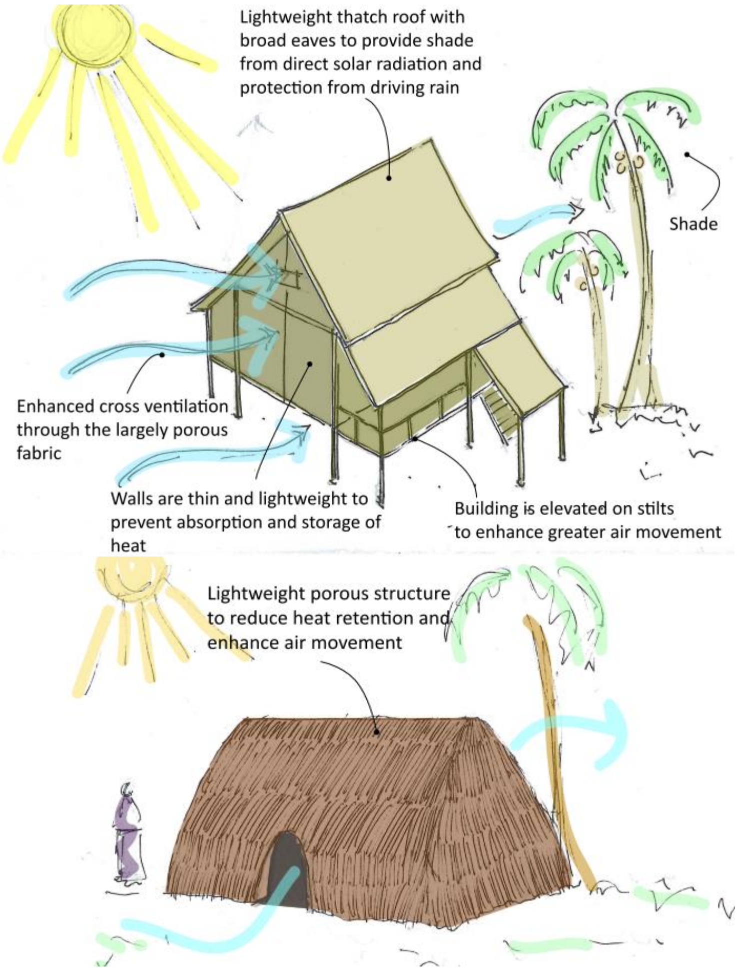


Figure 1-16 (a) Typical lightweight Malay house. (b) Lightweight Mijikenda 'Kaya' house.

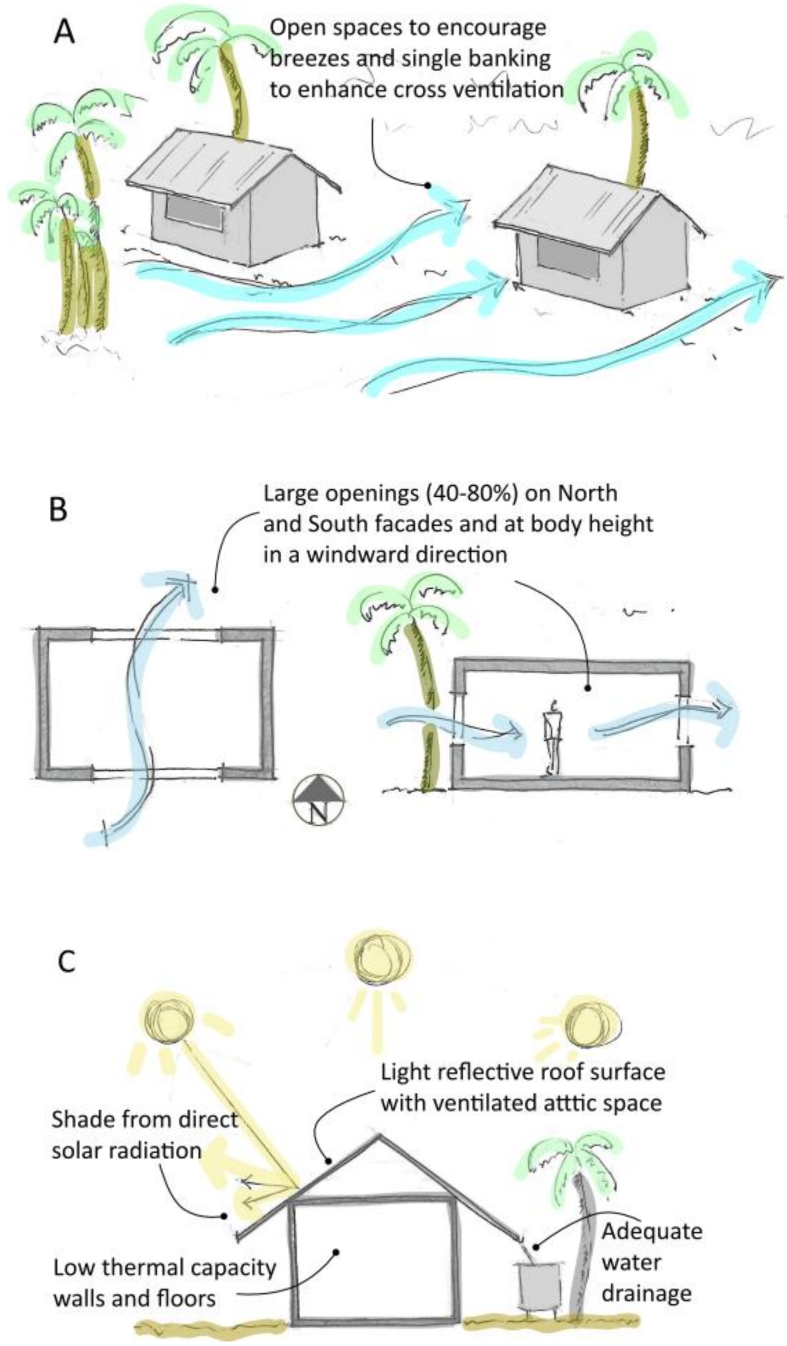


Figure 1-17 A, B and C: Recommended environmental strategies for warm humid climates.

Unlike the aforementioned lightweight typologies, the predominant Swahili coral stone building was characterised by seemingly heavyweight structures made of thick coral rag walls, timber framed doors and windows, timber balconies and similarly thick coral rag ceilings with pitched palm leaf frond roofs (more recently, these were replaced with corrugated iron roofing sheets) – see Figure 1-18.

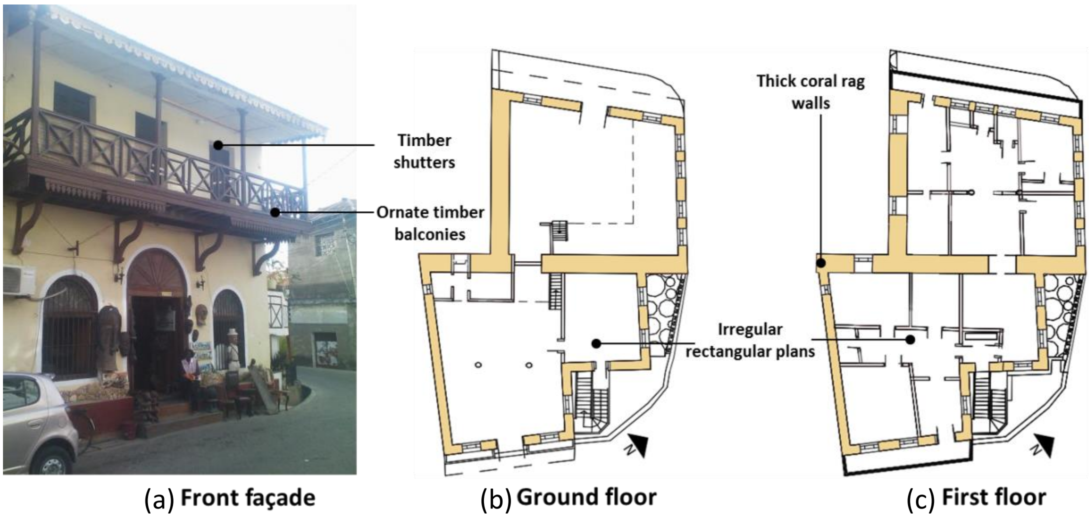


Figure 1-18 Typical two storey Swahili building (The Old Post Office) in Mombasa, Kenya.

In a paper entitled 'Climate-responsive Vernacular Swahili Housing' written as part of this research study, it was determined that this distinct typology was not established merely as a result of physical constraints or individual factors, but rather due to the effect of an entire range of socio-cultural factors, modifications by climate and the availability of materials and technology (Kiamba et al., 2014). One of the significant factors in the cultural determination of space was seen to be the impact of Islamic heritage where aspects of privacy are highly significant and evident in use of screens and the 'inward' organisation of space (Ghaidan, 1975, Mombasa Municipal Council and National Museums of Kenya, 1995). Owing to the strict social requirements for visual and acoustic privacy it was considered highly unlikely that the usually prescribed lightweight solution (prescribed for warm humid regions according to Koenigsberger et al. (1973) and Szokolay (2008)) would have been deemed socially acceptable. This might explain the prominence of architectural elements such as screened balconies, window shutters and enclosed courtyards which not only enhance privacy but also meet the climatic obligations of shading and cross ventilation. Also evident was the use of decorative architectural elements for aesthetic purposes. This was apparent in the use of ornately carved doors, highly decorated balconies and decorative frieze motifs (Figure 1-19). It was suggested that figurative representations in these Swahili settlements was rare due to the discouragement of imagery in art by sections of Islam ideology (Allen, 1988).

(a) (b)

Figure 1-19 (a) Decorative timber carved balcony balustrades in Old Town, Mombasa. (b) Indoor frieze motifs in a house in Lamu. Both are typical decorative features of vernacular Swahili architecture.

In addition to socio-cultural influences, climate modifications were also evident at various levels of the Swahili settlements. Earlier in this chapter, the local climate analysis revealed that the air temperature in warm humid climates is almost always very near to that of skin temperature. This leaves sensible air movement as the main means of relief for occupants. Typically, it was found that a Swahili town consists of an irregular maze of buildings arranged in dense clusters with streets measuring an average of 1.5 to 6 metres (m) wide and punctuated by a series of open spaces (Figure 1-20). The streets are considered to be public ‘living rooms’ and are constantly abuzz with activity. To ease conditions in the humid heat, the streets are laid out to channel cooling sea breezes (Ghaidan, 1975). Subsequent field studies by the researcher (presented in Chapter 3) revealed this to be a logical assumption (Kiamba et al., 2014).

Figure 1-20 (a) Sectional plan of Old Town, Mombasa. (b) Children play within one of the typical open spaces. (c) Ndia Kuu, a characteristic narrow street in Old Town, Mombasa.

Similarly, for semi-enclosed and indoor spaces, the application of architectural elements including screened balconies, shuttered windows and courtyards was suggested to facilitate effective cross ventilation indoors that enabled occupants to cope with the somewhat muggy conditions.

Even more noticeable than the use of natural ventilation for air movement and heat expulsion was the application of a combination of sun shading strategies. Together, the narrow streets and alleyways, balconies, shutters and small enclosed courtyards played a significant role in mitigating solar radiation as illustrated in Figure 1-21. By closely aligning the buildings, mutual shading was expected to decrease the impact of solar insolation on the external wall surfaces. Similarly, balconies and window shutters worked by screening direct sunlight from glazing and wall surfaces and in the prevention of glare. For enclosed courtyards and open spaces, vegetation such as trees was often used to shield direct solar radiation.

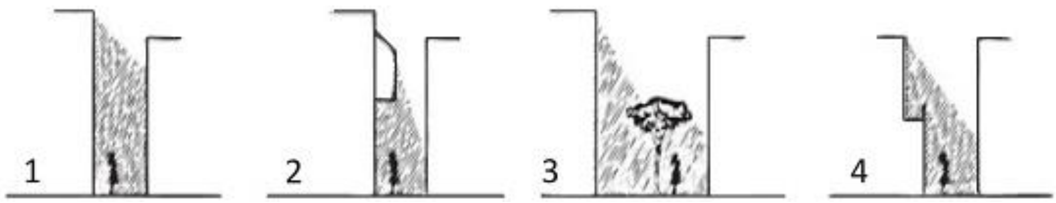


Figure 1-21 Shading configurations (1 to 4) found in a vernacular Swahili setting.

The local climate analysis findings in section 1.3 revealed that it was advisable for buildings to be laid out with their shorter sides facing east and west and to minimise or eliminate west facing glazing for solar control purposes. However, mainly due to the need to channel breeze or due pre-existing street layout constraints, this was not always possible in Swahili settlements. Instead, the walls were shaded to minimise direct solar insolation. In addition to this, the reflective qualities on the outer surface of the mostly light coloured lime washed walls (high emissivity values) were suggested be useful in reducing heat gain through conduction.

In hot dry climates, the use of a heavyweight walls and roofs is valid as the warmth accumulated in the thick fabric is dissipated during the significantly colder nights. Despite the slightly warmer night temperatures in Mombasa (average daily temperature range of 6°C) compared to those in hot dry climates, it was suggested that the heat that builds up in the heavy fabric during the day is also dissipated by facilitating air movement during the night - done mainly by opening of windows. The windows were found to have integrated shutter systems that could be operated by occupants as necessary to allow for air movement and heat dissipation (see Figure 1-22). Further to this, the roofs were found to have attic spaces and open/ventilated gable ends. These were thought to temper the effect of direct solar radiation at the zenith by flushing out unwanted warm air from the attic thereby reducing conductive heat gain in lower floor spaces. Similarly, the screened balconies provided zones where one could enjoy the benefit of the sea breeze while being sufficiently screened from the sun.

Figure 1-22 A typical vernacular Swahili building (the Old Post Office) showing A: a screened balcony and B: shuttered window C: Sketch of shutter window in use.

Records indicate that earlier settlements had houses made of palm fronds, mangrove poles, wattle and mud brick, similar to those of the lightweight type. With the onset of immigration, there was a shift towards the building 'stone' coral houses. In fact, one was held in higher esteem if they owned such a house (Ghaidan, 1975). Correspondingly, as benefitted by its readiness of availability and usability, coral became a major building material on the East African coast. It is available in two varieties: hard terrestrial coral and soft reef coral, used for structural and non-structural purposes, respectively. As is still done in some places today, the coral was burnt to provide the lime for mortar and plaster. The coral walls were made notably thick, and ranged between 440 to 560mm thick (Ghaidan, 1975, p.24). Field studies by the researcher has found evidence of walls of up to 700mm thick in the Old Post Office building that would be able to provide a time-lag of up to 8.5 hours (Kiamba, 2010b). This facilitated a delay of peak indoor temperatures thus extending periods of thermal comfort indoors. Further analysis investigating the thermal mass properties of coral (main vernacular construction material) and concrete (main modern construction material - other than glass) are covered in Chapter 5.

As mentioned earlier, roofs in more recent Swahili settlements were clad with recently available corrugated iron sheet roofing (CIS) with room left for an attic below. This was common to both heavyweight and lightweight typologies there was a notable shift from the use of palm frond leaves roofing to CIS. As with the shift to the use of coral, this was suggested to have been propagated by both socio-cultural factors (seen to denote higher social status) and material factors (ready availability and relatively low maintenance) (Ghaidan, 1975, Mombasa Municipal Council and National Museums of Kenya, 1990).

Of the main traditional roofing covers found across the world, thatch is well known for its good insulation properties (Pickles, 2016). In this case, it was suggested that the use of thatch would have been advantageous in providing increased insulation to the attic spaces. It was suggested that the shift to CIS would have resulted in increased solar gain which would possibly be reduced to some extent by the provision of open gable ends (examined in greater detail in section 3.2.6 and Chapter 5).

Despite the fact that the Swahili structure is a deviation from the lightweight norm, recent research has indicated that closely packed heavyweight buildings are feasible for warm humid climates. The basis behind this premise is that the heavyweight buildings which are mostly ‘protected’ during the day would allow for significantly lower solar heat gains. At night, they would then be opened up to allow for sufficient cross ventilation that would in effect get rid of stored heat (see Figure 1-23).

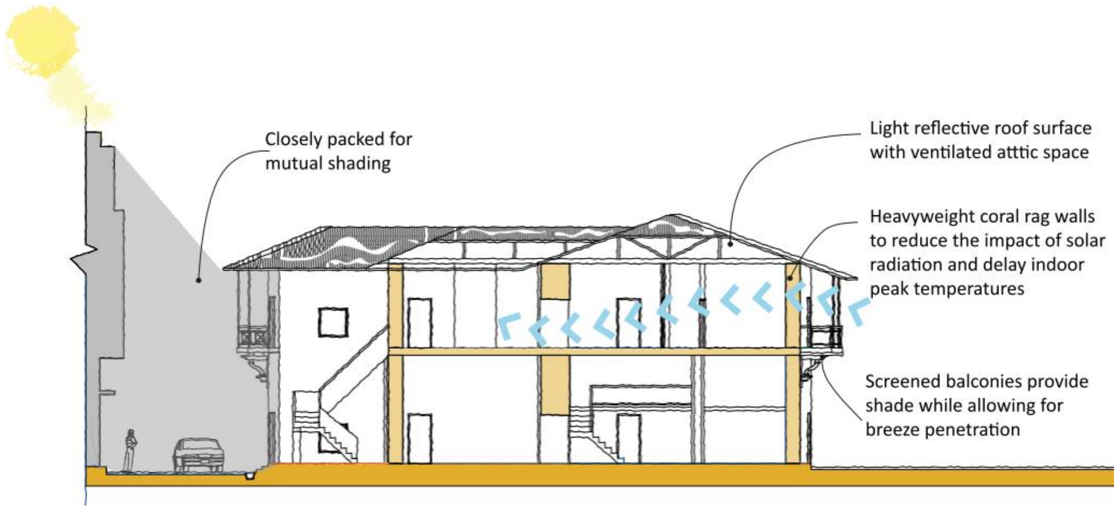


Figure 1-23: How a typical vernacular Swahili house (Old Post Office) works.

Indeed, in a separate study examining the potential of heavyweight buildings in warm humid climates, Szokolay (1996) suggested that the inherent thermal capacity of the heavyweight structure facilitates heat storage, release and dissipation as opposed to a lightweight structure that closely follow outdoor temperature variations. Related studies by Tenorio (2002) reached a similar conclusion.

Design guidelines for warm humid climates typically recommend a lightweight solution that capitalises on low thermal capacity and the physiological cooling effect of sensible air movement to make higher temperatures acceptable to users. On observation, vernacular Swahili architecture was found to be the antithesis of this strategy as it is densely packed, seemingly heavyweight and with comparatively fewer and smaller openings. Nonetheless, it was suggested that the vernacular Swahili type still worked to suit the prevailing warm humid climate as described. This might explain why the Swahili architype seemed to be particularly predominant in the local region despite seeming alien to the local climate at first glance.

Although this initial analysis suggested that the heavyweight typology is suitable for moderating the impact of the external climate on indoor conditions, further detailed analysis was conducted and presented in Chapter 3 to determine the suitability of this approach to office buildings in warm humid climates.

1.4.2 Modern Architecture Influences

In section 1.4.1, it was highlighted that immigration and the ensuing cultural fusion on the East African coast had led to the creation of Swahili culture which in turn gave rise to a distinct vernacular Swahili architecture. Similarly, the advent of the colonial period in the 19th century brought with it European architectural influences (Hoyle, 2001, Jewell, 1976, Kiamba et al., 2014, Mombasa Municipal Council and National Museums of Kenya, 1990). In Kenya, this carried through into the post-colonial period (post 1963) when increasingly rapid urbanisation and influence from 20th century modern architecture gave rise to the introduction of 'newer' and mainly lightweight architecture typified by highly glazed facades.

Examples of typical commercial and office buildings in Mombasa that represent this progression were presented in Table 1-7 with details of their construction materials and their potentially effective environmental design strategies (passive and active).

Table 1-7 Progression of architectural types.

Building	**Details**
a) Old Law Court Gallery (1902) 	**Construction materials:** 300mm thick masonry walls and 150 mm thick slabs, timber framed windows with shutters and a clay tiled roof. **Environmental controls:** • Sun shading elements including shutters and recessed walls. • Placement of windows to enhance cross ventilation. • Thick masonry walls for thermal mass. • Ventilated attic to reduce the conduction of heat gains to floors below. • Light coloured walls with high emissivity to reduce heat conduction.

b) Bousted & Clark Importers (1940s) 	**Construction materials:** 300mm thick masonry walls and 150 mm thick slabs, steel framed windows with glass panels and a clay tiled roof. **Environmental controls:** • Canopy shading over windows on the western facade. • Thick masonry walls for thermal mass.
c) City House (late 1950s) 	**Construction Materials:** Reinforced concrete structural frame with steel framed glass panelled window strips with and a clay tiled roof. **Environmental controls:** • Shading overhangs of varying depth. • Interior shades. • Mechanical fans.
d) First Mansion Building (1980s) 	**Construction materials:** Reinforced concrete structural frame with concrete block infill. Steel framed windows and flat concrete roof. **Environmental controls:** • Use of partially recessed windows/ balconies for sun shading. • Air conditioning.
e) Lotus Building (1990s) 	**Construction materials:** 150mm thick concrete walls and 150 mm thick concrete slabs, steel framed windows and flat concrete roof. **Environmental controls:** • Air conditioning. • Tinted glass
f) Furaha Plaza (Late 1990s) 	**Construction materials:** 150mm thick concrete walls and 150 mm thick concrete slabs, aluminium framed windows and flat concrete roof. **Environmental controls:** • Air conditioning. • Tinted glass. • Shallow overhangs.

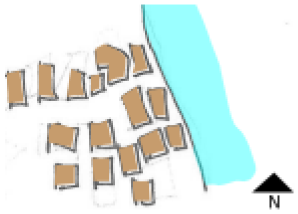
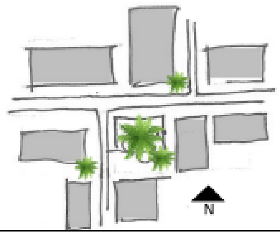
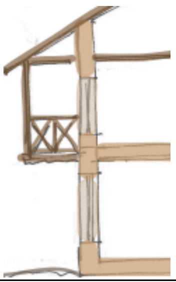
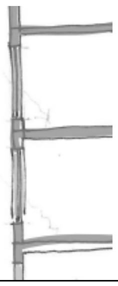
g) TSS building (Early 2000s) 	**Construction materials:** Reinforced concrete frame with expansive aluminium framed reflective glass infill with a flat concrete roof. **Environmental controls:** • Air conditioning. • Reflective glass.
h) The Avenue (2014) 	**Construction materials:** Reinforced concrete frame with aluminium framed reflective glass infill with flat concrete roof. **Environmental controls:** • Air conditioning. • Reflective glass.
i) KK Building (2014) 	**Construction materials:** Reinforced concrete frame with aluminium framed reflective glass infill with flat concrete roof. **Environmental controls:** • Air conditioning. • Reflective glass.
j) Links Plaza (2014) 	**Construction materials:** Reinforced concrete frame with aluminium framed reflective glass infill with flat concrete roof. **Environmental controls:** • Air conditioning. • Reflective glass.

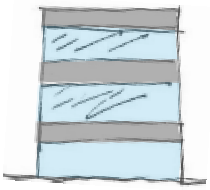
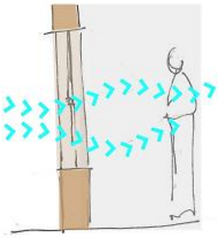
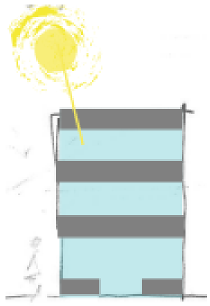
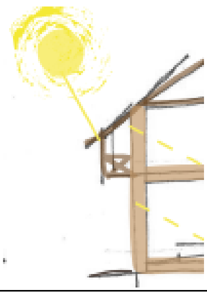
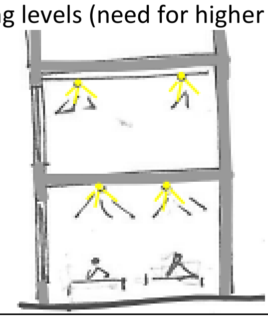
The findings indicated a shift in the use of masonry and a subsequent increase in the glazing area of the facades, especially after the 1980s. Gone were the days of closely packed buildings mutually shading one another; in their stead were modern buildings which typically 'need' to be seen in isolation (Uhlfelder, 1998). These newer buildings are generally tall and do not engage their urban form to mutually shade other buildings.

Typically, the newer construction materials used in these modern buildings included concrete, glass, steel and aluminium. In contrast to the recommended lightweight type for warm humid climates that is dependent on high levels of permeability, these newer types are often sealed up and have few adaptable opportunities for occupants. This has necessitated the introduction of mechanical and active methods for ventilation and cooling to curb overheating.

A brief comparison of the vernacular Swahili type and the local contemporary office buildings identified significant differences in environmental design responses as shown in Table 1-8.

Table 1-8 A comparison of local vernacular and contemporary environmental responses.

	Vernacular Swahili architecture	**Contemporary Office Buildings**
(a) Orientation/Layout	• Narrow streets with closely packed buildings orientated to channel breezes. 	• Orientation and layout likely informed by existing road network and plot boundaries. 
(b) Construction Materials	• Coral rag and timber. • Materials are of suitably low thermal conductivity. 	• Concrete, glass, aluminium and steel. • Abundance of glass resulting in increased solar control issues. 

(c) Facades	• Relatively few openings with heavy screening and shading. 	• Significantly large glazing areas with use of special glass, *E.g.* tinted and reflective glass. 
(d) Ventilation	• Naturally ventilated spaces with focus on user control. • Minimum internal divisions to improve cross ventilation performance. • Shallow plans encourage cross ventilation. 	• Active ventilation systems for air conditioning. • Deep plans hinder adequate cross ventilation. 
(e) Shading	• Mutual shading of buildings and use of sun shading elements including balconies and window shutters. 	• Few instances of shading, if used tend to consist of overhangs of small depth. 
(f) Daylighting	• Mainly daylighting, with use of screens to filter in light and reduce glare. Lighting levels suitable for current use but would be unsuitable for offices due to low lux levels. 	• Mix of daylighting and artificial lighting. Higher proportion of artificial lighting due to use of special glass that reduces indoor lighting levels (need for higher illuminance). 

A comparison of the two building typologies revealed a clear shift from passive to active methods for environmental controls. One of the outcomes of this has been an increase in energy dependency. This is a matter of concern given that the latest available statistics indicate that electricity usage in non-domestic buildings is responsible for 30% of the total annual consumption. Further, annual growth in electricity demand is forecasted to be 8%, compared to an annual increase of electricity supply capacity of 3 to 4% (KPLC, 2013, p.115-120). With these kinds of figures, it is not surprising that the Kenyan government realises that buildings need to embrace more passive measures for energy efficiency. Indeed, the review of the local climate has established that it is possible to run buildings under passive controls for a significant amount of time. This implies that if climate-responsive measures are embraced by local designers, they can facilitate a significant reduction in energy use without compromising on the thermal comfort of occupants.

1.5 Conclusions

An overview of warm humid climate has described the rationale behind the classification of the climate type as informed by the environmental parameters of air temperature and humidity. Both are main factors considered in the analysis of comfort conditions useful in building design. In addition, a review of the typical climatic conditions of Mombasa established that the relatively high temperatures and high relative humidity levels coupled by strong solar radiation are the main environmental issues of concern when designing buildings for this climate.

A review of thermal comfort for warm humid climates compared two common methods: the PMV model and the adaptive comfort model. From this, it was determined that whereas the PMV model incorporated a significant number of variables pertinent to the human heat balance model, it ignored the equally important thermal adaptability variables. As a result, it underestimated the upper comfort limits for occupants of buildings in warm climates. Consequently, it was determined that the adaptive model offered a more suitable model for free running buildings in warm humid climates as it gave a better description of comfort. As actively ventilated buildings allow for greater control of indoor conditions, it was suggested that the PMV model would be more suitable for them.

Further, comfort limits of 22°C to 29°C (adaptive comfort model) and 20.3°C to 26.7°C (PMV model) were predicted using climate data for Mombasa. Using the adaptive model, it was determined that the ambient temperatures would lie within the comfort band for 74% of the year (working hours only). This implied that passive design strategies could be used to restore comfort during this period. This percentage fell to 34% when considering the PMV model, signalling a significant reduction of 40%. Outside of this period, mechanical or active methods would be required to restore comfort.

A review of the local vernacular types revealed the predominance of vernacular Swahili architecture which was suggested to have developed from a mix of socio-cultural influences, climatic modifications and material availability. Unlike the often recommended lightweight solution that capitalise on low thermal capacity and the physiological cooling effect of sensible air movement to make higher temperatures acceptable to users; the seemingly heavyweight vernacular Swahili architecture was heavily shaded during the day to mitigate solar heat gains and opened up to allow for sufficient cross ventilation to expel stored heat. Having been established for a significant period of time, it was suggested that it provided useful insights into suitable design strategies for office buildings in Mombasa.

On the other hand, a review of modern architectural influences with respect to office buildings revealed the shift towards highly glazed lightweight buildings. As most of these buildings did not factor in permeability for air movement, necessary for similarly lightweight buildings in the warm humid region, they were prone to overheating which necessitated the use of active air conditioning (for cooling and ventilation) and artificial lighting (owing to a reduction of natural lighting levels due to the use of special glass).

Given the current situation, it is not surprising that annual energy demand in buildings in Kenya has continued to grow at an unsustainable rate. Without proper guidance for designers, it is anticipated that this trend will continue escalate.

However, the initial review of vernacular Swahili architecture suggests that it offers transferrable design alternatives for office buildings. Should this be found to be the case in further analysis, it will have considerable impact in the discussion of the improvement of thermal comfort and energy efficiency in office buildings in the warm humid region of Kenya.

2 DESIGN STRATEGIES FOR HOT AND WARM HUMID CLIMATES

In this chapter, a review of passive design strategies recommended for warm humid climates is undertaken with the aim of developing an analytical framework for empirical data interpretation in the succeeding chapters. Further to this, energy efficiency building regulations in selected hot and warm humid climate regions are examined to establish the commonly-recommended approaches and their underlying objectives.

2 DESIGN STRATEGIES IN HOT AND WARM HUMID CLIMATES

When taking a climate-responsive approach to design, the first step involves reviewing the given climate and establishing the nature of the problem as relates to human requirements. In Chapter 1, it was determined that the main design problems in warm humid zones would arise from relatively high temperatures and high humidity levels coupled by solar radiation. Naturally, given that heat and humidity are the main issues of concern and based on the recommendations given by the previous psychrometric chart analysis (Chapter 1), passive cooling design strategies were suggested to be suitable in meeting environmental design objectives in office buildings in the warm humid region of Kenya.

Passive cooling design strategies are defined as the means by which a designer can either prevent or modulate heat gain and make provision for cooling (Krishan, 2001). In so doing, one can effectively bridge the difference between desirable targets of indoor environmental conditions and outdoor conditions which fall outside those targets. The magnitude of this difference varies with:

a) Geographic location of a building, site topography and microclimate: This variation is specific to a given site. Even within warm humid climates, there are local influences that would warrant a building response to be different from another within a similar climate. For instance, a building located within a dense neighbourhood will be expected to be less exposed to the effect of prevailing wind as compared to those within more rural settings.

b) Changes in outdoor conditions (seasonal and daily): Seasonal variations in warm humid climates are relatively small, with major differences mainly being classified in terms of precipitation as periods of heavy rainfall or light rainfall. Although diurnal temperature variations are not usually large in warm humid regions, significant diurnal temperature differences of 6°C in Mombasa reveal the suitability of cooling strategies such as night ventilation (explained later in section 2.2.3).

c) Building type, occupancy patterns and activities, and thermal comfort criteria: Various buildings have different uses and thus different occupancy patterns and thermal comfort criteria. For instance, office buildings tend to be used and occupied in a manner different to a domestic building. This may impact on the suitability of the design strategy applied. For example, in office buildings, occupancy patterns may mean the difference between the hindering or promoting night ventilation. In addition, depending on the occupant densities and activities taking place in the building, higher or lower internal gains can in turn increase or reduce the cooling loads. Further, the thermal comfort criteria will determine the extent to which comfort will need to be restored. Oftentimes this differs in domestic situations where occupants tend to have more access to modes of adaptation in comparison to more formal scenarios; this also varies for passive and actively ventilated buildings (section 1.2).

d) Building design: Various basic aspects of the building design can be modified so as to minimise the need for cooling. Detailed aspects of the building may be varied so as to provide a variety of thermal responses. For instance the use of materials with high insulation properties can cut down on solar gains by a considerable amount.

Of these influences, the designer has the most control over the building design. By proposing and effecting appropriate building design strategies, the designer can promote desirable indoor conditions with little or no need for active solutions. In this instance, a building can be defined as a thermal system. Quite similar to the need for the human body to maintain equilibrium in terms of metabolic heat gains and losses, a building can be examined in terms of heat inputs and outputs. This system is depicted by Equation 2-1:

$$Q_i + Q_c + Q_s + \ Q_v + \ Q_e = \Delta S$$

Equation 2-1 Building thermal heat balance equation (Szokolay, 2008, p.35).

Where:

Q_i = internal heat gains

Q_c = conduction heat gain or loss

Q_s = solar heat gain

Q_v = ventilation heat gain or loss

Q_e = evaporative heat loss

ΔS = change in heat stored in the building

In this case, thermal balance occurs when ΔS is equal to zero. Where ΔS is greater than zero, the indoor temperature is increasing, or if it less than zero, the indoor temperature is reducing and cooling is taking place. It is possible to manipulate this equation using of heat gain prevention and modulation methods so as to augment cooling in warm climates.

2.1 Heat Gain Control

Heat gain control strategies work by preventing the build-up of heat indoors. In so doing, these strategies effectively reduce the cooling load and promote comfortable indoor conditions. The most significant cause of heat gain in a building is solar radiation (Szokolay, 2008). Consequently, the attenuation of solar radiation or solar control forms one of the main heat gain prevention methods. The next section examines the control of solar heat gain and other potential gains highlighted in Equation 2-1.

2.1.1 Solar heat gain control

When considering solar control measures, the initial step involves determining when solar radiation would be a welcome input or when it should be excluded. This is followed by the specification of suitable shading devices and detailed design based on the glazing orientation of a particular building (Koenigsberger et al., 1973, Szokolay, 2008, Olgyay and Olgyay, 1963). Using the climate data presented in Chapter 1, the critical shading times for the city of Mombasa were determined. Climate analysis for Mombasa revealed March and July to be the warmest and coolest months, respectively. Although the climate conditions were found to be relatively constant (showing little variation), March was found to experience the highest external temperatures and solar radiation levels recorded during a typical year. Further, thermal comfort analysis showed that the external temperatures exceeded the upper comfort limits during this month, signalling the greater potential discomfort from heat (Figure 2-1).

This being the case, March was determined to be the most critical month of the year when solar radiation would need to be excluded to prevent overheating. Further, considering the mean monthly average temperatures in relation to comfort limits of the other months of the year and the potential overheating impact of internal gains (from occupants and equipment), it was determined that solar input would not be required at any time of the year. Therefore, it was deduced that solar heat gain would be unnecessary in office buildings in Mombasa all year round.

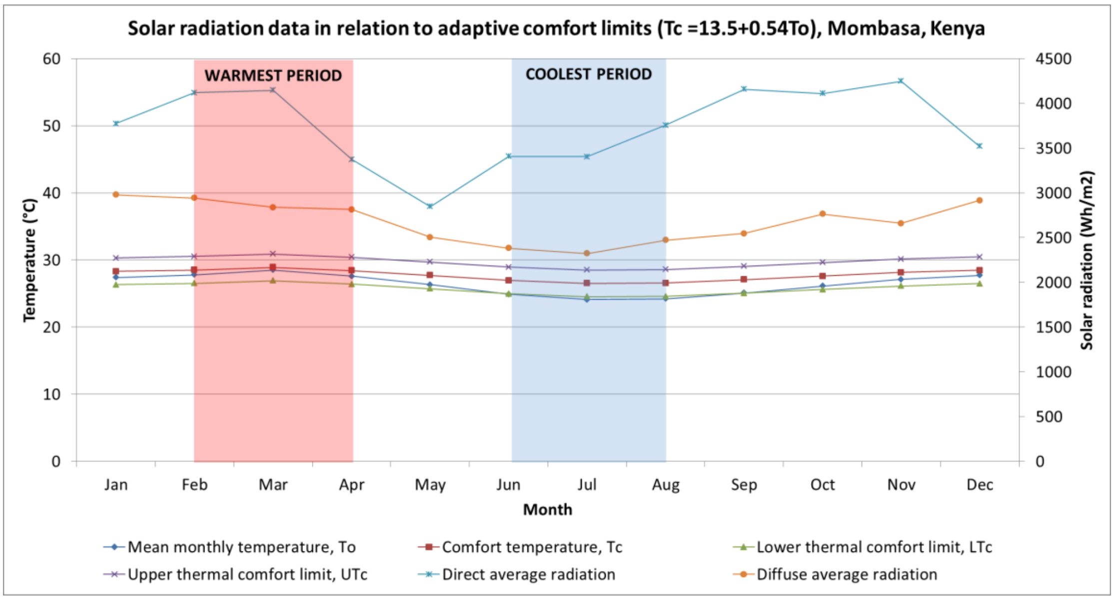


Figure 2-1 Mombasa annual temperature and solar radiation profiles in relation to adaptive thermal comfort limits.

Where solar overheating is problematic, as it can be in warm humid climates, there are methods under the control of the designer which are available to reduce solar heat gain through glazing and opaque surfaces of the building fabric. The two main methods are often broken down into orientation and shading controls.

Usually, the building orientation is determined during the early stages of the design process. When considering the environmental impact of solar heat gain with respect to building orientation, it is useful to compare the variations of solar radiation intensities on horizontal surfaces (relatable to the roof) and vertical surfaces (walls) as is illustrated in Figure 2-2. In regions near the equator, as the sun is almost always overhead, the horizontal surface receives the greatest intensity from solar radiation. Similarly, due to the apparent movement of the sun (rising in the east and setting in the west), the east and west orientations receive the second greatest solar intensities. On the other hand, the north and south orientations receive the least intensity of solar radiation and for only a short duration of the year.

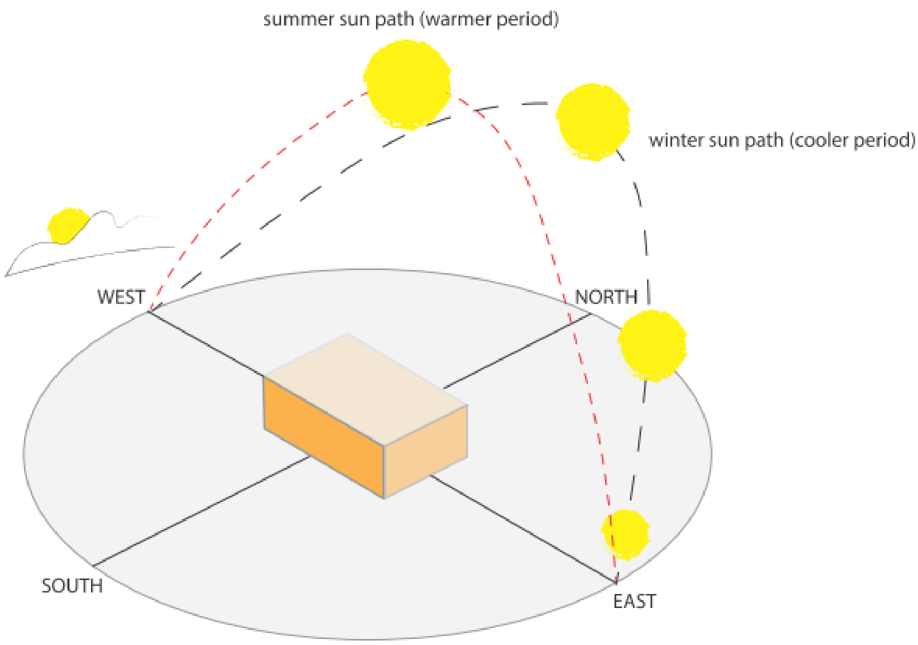


Figure 2-2 Recommended building orientation in equatorial regions.

All this considered, it is advisable to orient the building with the longer sides exposed to the north-south axis to reduce solar heat gain. This exposure is defined by the term 'aspect ratio' which denotes the ratio of the longer dimension of an oblong plan to the shorter (Szokolay, 2008). Given the potential for greater solar heat gain through glazing surfaces (Olgyay and Olgyay, 1963) as opposed to opaque surfaces, it is also advisable to position window openings on the north and south orientations so as to reduce further heat gain from the east and west facades. In addition to solar control, building orientation can be influenced by a variety of factors including plot location, road layout, view requirements, prevailing winds, among others. Oftentimes, these requirements can override those of solar control – thereby making the use of sun shading necessary.

As with the determination of building orientation, the design of shading devices is better undertaken during the initial design stages. Shading devices can be located on the inside (blinds, rollers or curtains) or outside of the building (overhangs or fins). Internal shades are not known to be very effective. As internal shades are ideally placed behind the glazing, they can only reflect part of the radiation while most of the remaining radiation is absorbed by the blind and convected and re-radiated indoors. As this re-radiation is in long wave form, it will be stopped by the glazing and retained in the building. This may result in a rise of indoor MRT, thereby causing discomfort.

On the other hand, external shading devices are considered to be very effective as they actually shade the glazing area from direct radiation and prevent a significant amount of heat getting indoors. Generally, external shades take on the form of horizontal, vertical and egg-crate elements (Figure 2-3). For all the external types of shading, it is necessary to establish the time of the year and for which hours in a day shading is necessary (previously covered when determining the period for which solar gains would be required). To promote efficient design for shading, the calculation of shadow angles to indicate the limits beyond which the sun would be excluded is also required. Shadow angles and their respective shadow masks can be manually calculated using sun-path diagrams and shadow protractors as described by Olgyay and Olgyay (1963) or using simulation software such as Ecotect.

External horizontal shading devices are characterised by a vertical shadow angle (VSA). The VSA is measured on a vertical plane normal to the elevation considered. One large horizontal shading element may be broken down into several smaller horizontal shades to give the same performance (based on the VSA). These shades are considered most effective when the sun is near opposite to the window considered. External vertical shading devices are characterised by horizontal shadow angles (HSA). The HSA indicates the difference between the solar and wall azimuth angles; it cannot be greater or smaller than 90° as that would indicate the sun is behind the selected facade. Vertical shades are considered most effective when the sun is towards one side of the direction that the window is facing. Blades of shallow depth with close spacing can be used to give a HSA similar to that given by blades of deeper depth and wider spacing. External egg crate devices consist of a combination of both horizontal and vertical shades where both the VSA and HSA are considered.

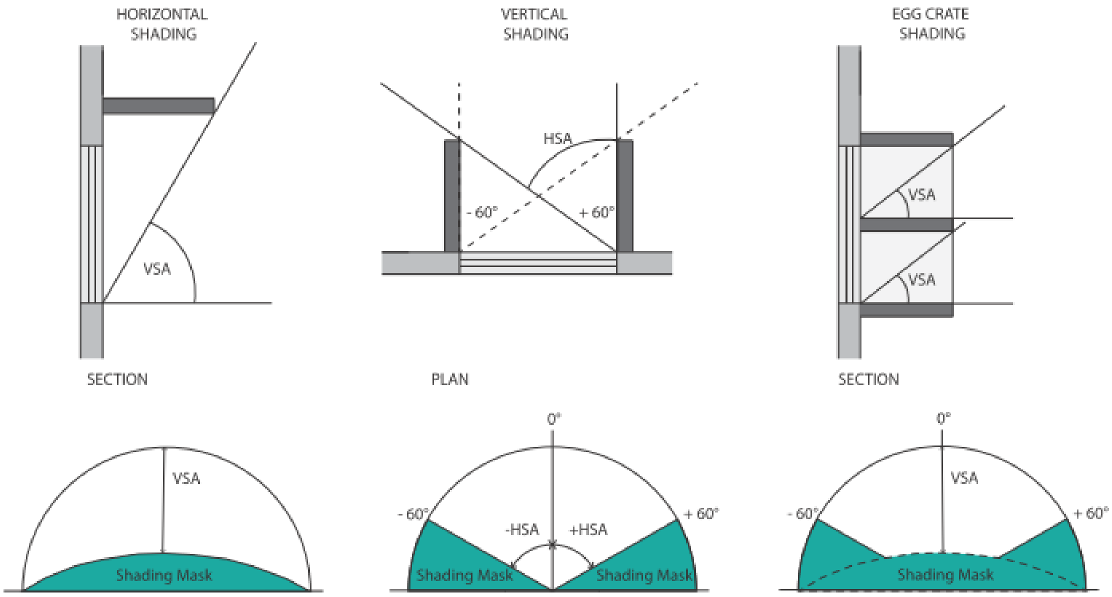


Figure 2-3 External shading types and their shadow angles and shading masks.

2.1.2 Conduction gains control

Conduction gains are dependent on the conduction heat flow rate through a wall of a given area; it can be described by Equation 2-2:

$$Q_C = A \times U \times \Delta T$$

Equation 2-2 Conduction heat flow rate (Koenigsberger et al., 1973, p.76).

Where:

Q_c = conduction heat flow rate in W.

A = surface area in m^2

U = transmittance, u-value in W/m^2 degC

ΔT = temperature difference (outdoor and indoor temperatures)

Equation 2-2 reveals that conduction gains are directly influenced by the shape and surface to volume ratio of the building, and by the thermal insulating properties of the building envelope (Aste et al., 2009, Koenigsberger et al., 1973, Szokolay, 2008). As heat gain is dependent on the envelope area, it is often advisable to present the least surface area for a given volume. In this case, a more compact plan will experience less heat gain than one that is more spread out in arrangement (Figure 2-4). In warm humid climates, it is necessary to consider the impact of providing a compact plan to conduction gains with respect to the provision of spread out layouts that are more suitable to enhanced cross ventilation.

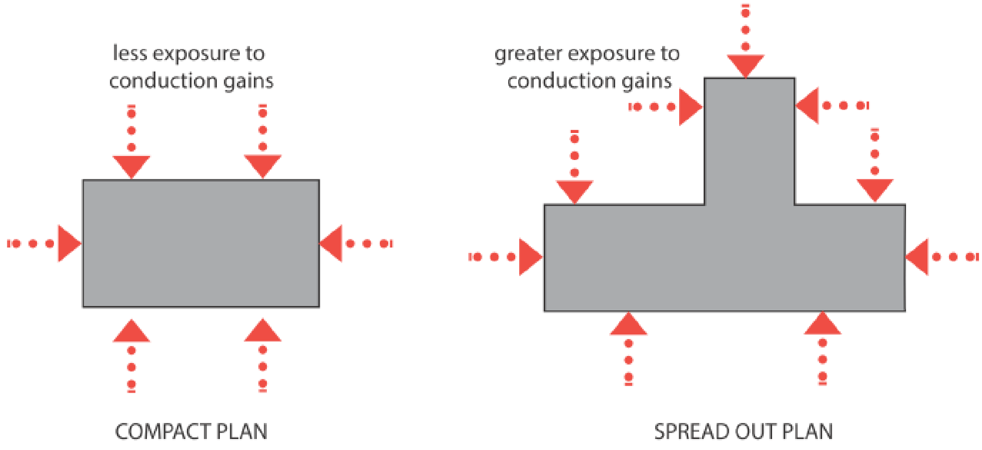


Figure 2-4 Conduction gains control.

The use of insulation may also be considered for conduction gains control. The selected insulation may be resistive, reflective or capacitive in nature. Both resistive and reflective insulation tend to work by reducing the heat flow magnitude. Whereas capacitive insulation can be used to absorb heat and delay its flow indoors. It has the added advantage of affecting the timing of the heat input (ASHRAE, 2013a). This delay in heat flow can be designed to ensure that heat gain is hindered when occupants are more likely to be using the space, thereby reducing the need for cooling.

When considering a multi-layer building element, it is important to examine the effect of the placement of the insulation layer. For instance, placing of the insulation layer outside and exposed thermal mass on the inside will result in the creation of a stable heavyweight material with considerably less heat gain. Conversely, where insulation is placed on the inside surface, the space will take on a lightweight nature and behave as such (Szokolay, 2008).

2.1.3 Ventilation and infiltration gains control

Generally, ventilation and infiltration gains are directly influenced by building openings, closing mechanisms and the airtightness of the building envelope (ASHRAE, 2013a, CIBSE, 2015). Depending on where building openings are located, they can enhance ventilation - especially if they are in positions where air entry would be relatively easy. In addition, the size and location of the opening will determine the rate and size of the ventilation air flow. Similarly, the closing mechanism will also determine how and when the building is open to ventilation that may or may not result in gains. Further, where a building is not airtight, it may lead to high infiltration gains that could significantly increase heat build-up and reduce cooling system efficiency.

It is important to consider both ventilation and infiltration gains to prevent unwanted gains when outdoor temperatures are greater than indoor temperatures. When external temperatures are higher than those indoors, ventilation and infiltration gains can raise indoor temperatures in passively ventilated buildings (Figure 2-5). On the other hand, in mixed mode or air conditioned buildings, the cooling load can be significantly increased if the building does not have a high level of airtightness to prevent ventilation and infiltration gain. For purposes of this study, air conditioning is defined as the efficient cooling of room air, supply of constant and adequate ventilation while maintaining suitable humidity levels (ASHRAE, 2013a).

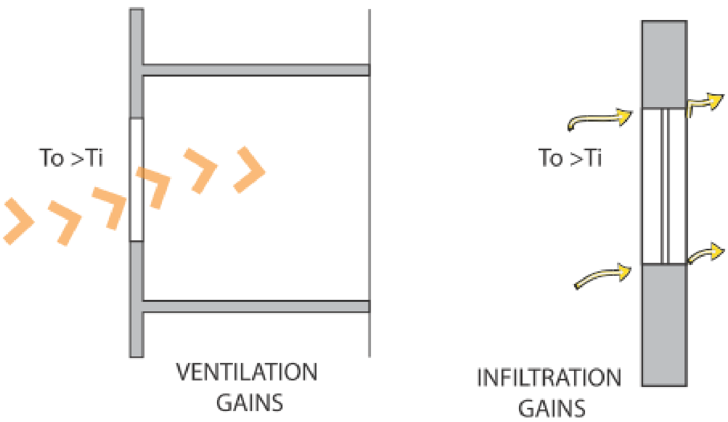


Figure 2-5 Ventilation and infiltration gains when T_o is greater than T_i.

Typically, ventilation in buildings is used for three purposes: the supply of fresh air, removal of internal heat build-up when outdoor temperature (T_o) is lower than indoor temperature (T_i) and physiological cooling (Szokolay, 2008). In the first two cases, the rate at which ventilation occurs depends on the ventilation rate (V) usually given in m^3/s as shown by Equation 2-3:

$$Q_v = 1300 \times V \times \Delta T$$

Equation 2-3 Volume flow rate (VR) (Koenigsberger et al., 1973, p.76).

Where:

Q_v = ventilation heat flow

1300 = volumetric specific heat of air, J/m^3 degC

V = ventilation rate in m^3/s

T = temperature difference in degC.

If the number of air changes per hour (N) is known, then the ventilation rate (V) can be derived from Equation 2-4 shown below:

$$V = \frac{N \times room\ volume}{3600(which\ is\ the\ number\ of\ seconds\ in\ an\ hour)}$$

Equation 2-4 Ventilation flow rate (Szokolay, 2008, p.15).

In the case of physiological cooling, the rate of ventilation is directly related to the air velocity and is measured in metres per second (m/s). This effect is examined in greater detail in section 2.2.1.

2.1.4 Internal gains control

Internal gains refer to gains caused by sources of heat within a building including occupants, lighting and equipment (Szokolay, 2008). If not controlled, internal gains can lead to uncomfortably high internal temperatures, especially during an overheating period (CIBSE, 2015). Mainly, internal gains regulation measures involve the control of space and occupancy patterns. The control of space patterns can involve the isolation of heat emitting functions from occupied spaces; this prevents heat build-up in occupied spaces that would potentially cause discomfort (Yannas, 2004). Typically, these spaces will have different ventilation systems to avoid having warmer air seep into occupied zones (Figure 2-6). For example, in office buildings, IT server areas (which are prone to significant heat generation) are usually situated in separate zones.

In addition, one may also consider the option of using energy efficient equipment which is less likely to emit less heat, or the dissipation of any heat generated at or near the source. This would require the placement of the zone in an area that would allow for adequate natural ventilation (Figure 2-6). Where passive means are deemed inadequate, the use of an extract fan near heat-generating machinery or passive cross-ventilation may be considered.

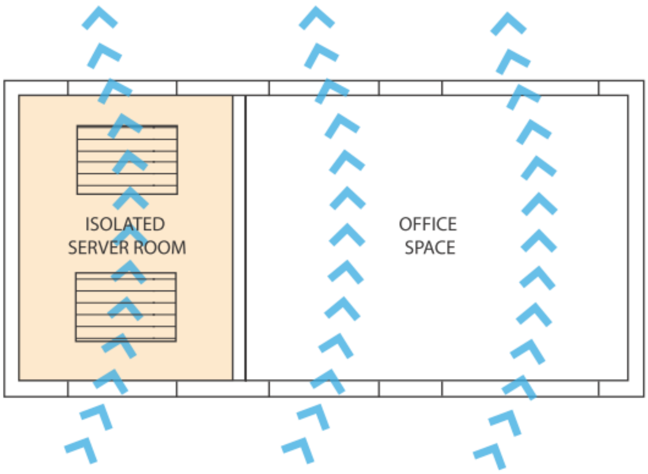


Figure 2-6 Internal gains control.

In office buildings, the effect of artificial lighting on the cooling load can be significantly high, especially in cases of deep plan offices which have increased lighting needs (CIBSE, 2015). To avoid this, it is essential to look for alternative passive solutions in order to increase natural lighting and consequently reduce the needs for artificial lighting (CLEAR, 2004, Rennie and Parand, 1998).

2.2 Provision for cooling

Having considered and applied suitable heat gain control measures, the next step taken by a designer would involve the provision of cooling controls. The main aim of providing cooling is to counter heat gain and to create a thermal balance that would enable thermal comfort. In warm climates, the main passive method of providing cooling is natural ventilation. This is because it can be used to create volumetric flow for the transfer of heat resulting from the outdoor wind speed or stack effect and the renewal of indoor air qualities (Santamouris, 1994). It can also be used in combination with other cooling strategies to further enhance the cooling effect. The following section examines typical cooling methods that may be considered suitable for warm humid climate regions.

2.2.1 Air Movement

The movement of air can be used in two ways to provide cooling. First, by ventilating a space when the outdoor temperature (T_o) is cooler than the indoor temperature (T_i), warm air can be expelled leaving the building cooler (CIBSE, 2015, Rennie and Parand, 1998). Secondly, as mentioned earlier in the comfort analysis in section 1.3, sensible air movement can be relied on to provide physiological cooling for occupants. This is especially important in warm humid climates as air movement will enhance convection, reduce surface resistance on skin and clothing, and increase evaporation from the skin; leaving occupants more likely to experience thermal comfort.

To encourage air movement for ventilation and physiological cooling, air-movement may be enhanced by the provision of cross ventilation relying either on wind or stack effect. For cross ventilation to work adequately, there should be an inlet and an outlet opening to create positive and negative pressure differences that will drive the movement of air across the selected space (Figure 2-7). The inlet opening will define the direction of the air stream entering. To get the maximum localized air velocity, the inlet opening should be much smaller than the outlet. Positioning the inlet opening, its accessories (for example, louvres or other shading devices) as well as the aerodynamic effects outside (before the air enters) will determine the direction of the indoor air stream (CIBSE, 2015, Thomas, 2006).

For body cooling, the best location for windows is at or below body level. For office spaces, this needs to be considered at sitting level to be effective (Royle and Terry, 1990). In extreme cases, low powered fans may be relied on to enhance air movement further.

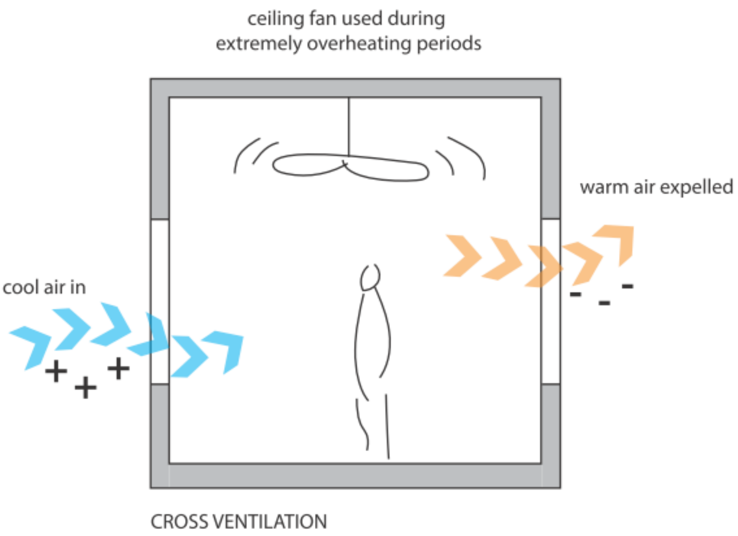


Figure 2-7 How cross ventilation works.

Air flow by means of the stack effect is driven by the difference in density between indoor and outdoor air *i.e.* thermal buoyancy (Figure 2-8). Due to the temperature difference of indoor and outdoor air, then the air indoors will either be more or less dense than that outside. If there is a low inlet and a high outlet in the building, then a natural flow of air will be caused where warm air will float out of the top opening, being replaced with cool air from outside (CIBSE, 2015, Szokolay, 2008). In warm humid climates, stack effect might not be heavily relied upon for sensible air movement as it would need a significant difference in indoor and outdoor temperature to work (Szokolay, 2008, Rennie and Parand, 1998). Even where this happens, it is unlikely it would happen in such a way that it would be noticeable.

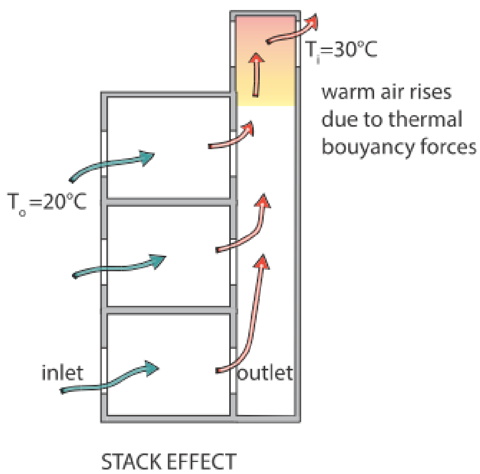


Figure 2-8 How stack effect works.

Under everyday normal conditions, the average subjective reactions to the various air velocities in are indicated as shown in Table 2-1 (Cowan, 1991, p. 334).

Table 2-1 Subjective reactions to various velocities.

Velocity	Reaction
Less than 0.25m/s	Unnoticed
0.25 to 0.5m/s	Pleasant
0.5 to 1.0m/s	Awareness of air movement
1.0 to 1.5m/s	Draughty
Greater than 1.5m/s	Annoyingly draughty

These reactions have been found to be dependent on the local air temperature. For instance, under hot conditions, 1m/s is pleasant and indoor air velocities up to 1.5m/s are acceptable (Auliciems et al., 1997). In cool conditions, air movement would more likely create an unwanted chill effect instead (Cowan, 1991).

The apparent cooling effect of the air movement (dT) can be approximated using Equation 2-5:

$$dT = 6 \times V_e - 1.6 \times V_e^2$$

Equation 2-5 The apparent cooling effect of air movement (Szokolay, 2008, p.42).

Where V_e is the effective air velocity, which is equal to V – 0.2 and V is air velocity (m/s) at the body surface. This equation is only valid for air velocities of up to 2 m/s.

The potential cooling effect in Mombasa was estimated as follows using Equation 2-5 and the results superimposed on a psychrometric chart illustrated in Figure 2-9 (Modified from Carrier Corporation (1975)):

For 1m/s air velocity: $dT = 6 \times 0.8 - 1.6 \times 0.8^2 = 3.8K$

For 1.5m/s air velocity: $dT = 6 \times 1.3 - 1.6 \times 1.3^2 = 5.1K$

Using these results, it was possible to define the control potential zone (range of outdoor conditions for which air movement has the potential to ensure indoor comfort) for air movement as determined by the dT values. Referring to the comfort limits derived for Mombasa in Chapter 1 for the warmest month of March, the corresponding upper comfort limit was found to be 29.0°C. The corresponding upper limits of the air movement control potential zone would thus be:

For 1m/s air velocity: 29 + 3.8 = 32.9°C

For 1.5m/s air velocity: 29 + 5.1 = 34.2°C

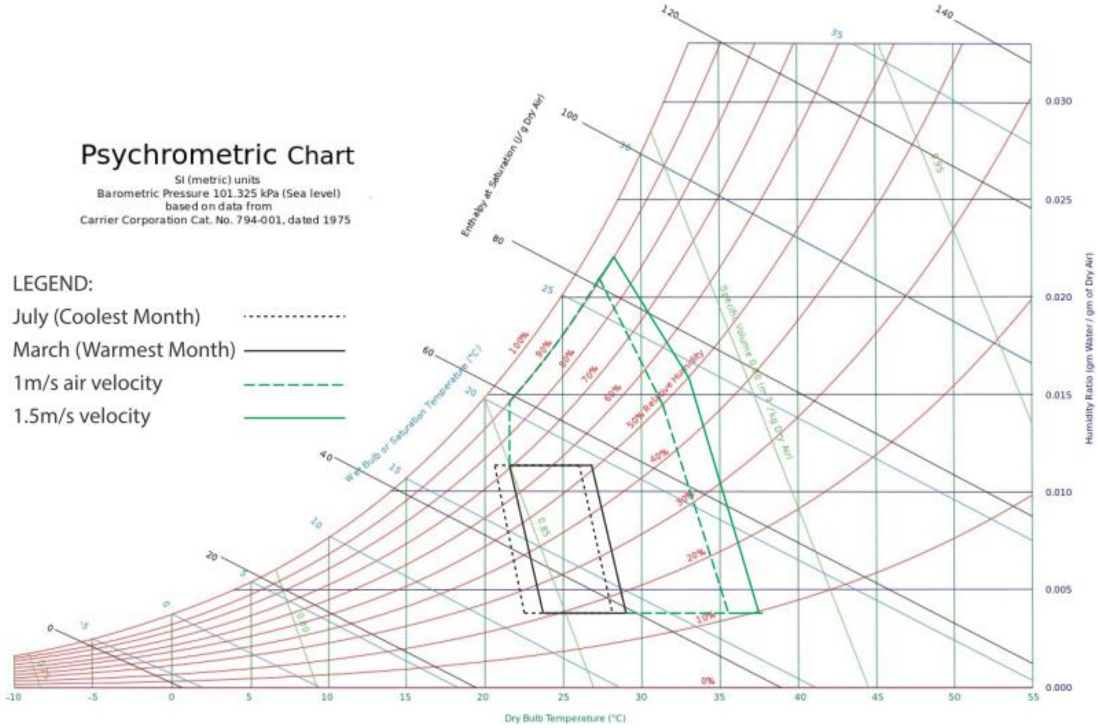


Figure 2-9 Cooling effect of air movement in Mombasa superimposed on a psychrometric chart.

The boundaries outlined on the psychrometric chart defined the range of outdoor conditions under which air movement has the potential to render indoor conditions comfortable in naturally ventilated buildings in Mombasa.

2.2.2 Thermal mass

In many offices today, typical finishes such as false floors, false ceilings and lightweight wall coverings (which may also have insulating air spaces) tend to render them more lightweight in nature. These lightweight buildings tend to respond quickly to outdoor temperature fluctuations and are more likely to result in overheating in office buildings. It is suggested that this can potentially be avoided by the introduction of thermal mass.

Thermal mass may be created (or increased) in naturally ventilated buildings by using dense materials for the internal surfaces of external walls, limiting glazing areas or changing the profile of internal surfaces to increase surface areas (Braham, 2001). Typically heavyweight or dense materials have high admittance properties. Admittance quantifies the thermal mass properties of construction materials; it is described as the rate at which a square metre of surface area can absorb heat from the air at a temperature difference of 1°C, expressed in W/m^2K (CIBSE, 2015).

When thermal mass is applied to a building, it can alter the thermal response and performance of indoor spaces. Typically, the inclusion of thermal mass helps buildings 'respond' slowly to heat gain sources. By incorporating thermal mass into the building fabric, designers can stabilise fluctuating temperatures across their diurnal cycle (Shaviv et al., 2001). This is done in three ways: providing heat source and heat sink surfaces for radiative, conductive and convective heat processes, providing time-lag in the equalisation of outdoor and indoor temperature, and providing temperature reduction across an external wall (decrement factor) (Koenigsberger et al., 1973).

In warm humid climates, the thermal mass of a building may be used to reduce heat flow into the interior of a building to allow for the indoor space to be free of outdoor influence during the warmer day time period. Where there is a significant diurnal variation in temperature values, materials with high heat storage capacity, such as concrete, heat up and cool down relatively slowly. When outside temperatures fall, heat from the inside can then be re–radiated outwards through the building element leaving the space cooler for the next occupancy period (Figure 2-10) (Braham, 2001, Shaviv et al., 2001, Szokolay, 2000). This is especially useful for office buildings as in most cases, the buildings remain unoccupied at night. In such a situation, it is possible to reduce the effect of peak outdoor temperatures by delaying the indoor peak temperature until after occupancy periods.

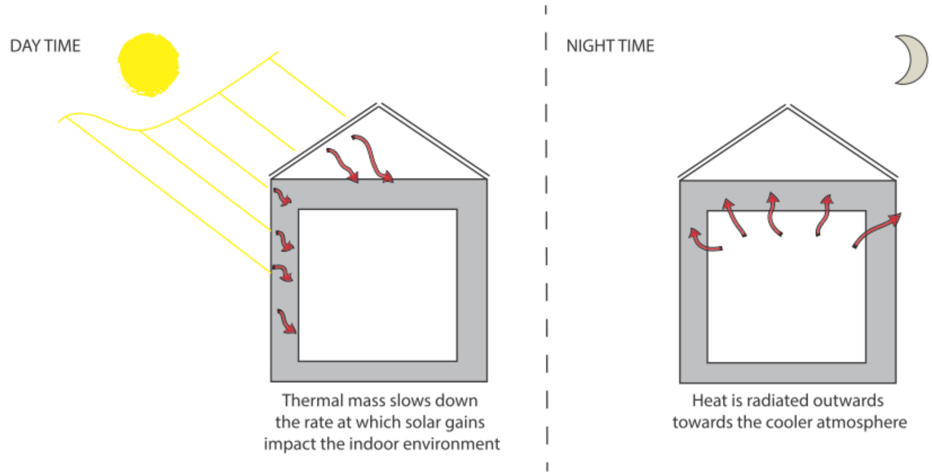


Figure 2-10 How thermal mass works.

The increase of thermal mass when considering porous materials such as coral has the ability to create a breathable wall which readily absorbs and releases moisture in response to changes in relative humidity in their surroundings. These hygroscopic characteristics involve thermal processes including the effects of latent heat to the extent that moisture condenses (releasing heat) and evaporates (absorbing heat) on the surface of the material and within its pores (Lawrence et al., 2013). This phenomenon increases their effective thermal mass, allowing the material to act as a thermal buffer in conjunction with their hygric buffering properties. Importantly, this has the potential to reduce the energy requirements of air conditioning in similar hot and humid regions (Mendes, 2000).

2.2.3 Night ventilation

Typically, night ventilation works by reducing the internal peak temperatures and cooling loads (La Roche and Milne, 2004, Santamouris and Asimakopoulos, 1996, Givoni, 1994). This may be through natural ventilation or can be assisted by mechanical ventilation such as low power extract fans. The building or space should be set out such that air is drawn in, circulates through the space and hot air expelled. The desired effect would be to reduce the indoor temperature and dissipate heat (Figure 2-11).

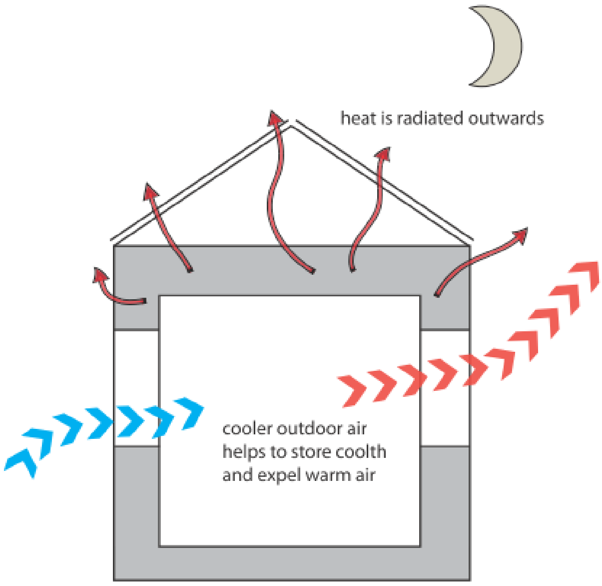


Figure 2-11 Combined thermal mass and night ventilation.

In the early morning period, the building is closed and kept sealed throughout the day. This prevents warmer outdoor air from seeping in. Night ventilation can be used in combination with thermal mass where the day's average temperature is higher than the comfort limit so as to enhance the heat dissipation process. During the day, the cool mass will absorb heat from external and internal loads. This heat is later dispelled when cooling the space during the night ventilation period leaving the temperature of the thermal mass lower and ready for the next day.

Night ventilation for cooling is particularly effective in climates with a large diurnal temperature range (an absolute minimum of 5°C), where external air temperatures are too high to provide adequate natural cooling during the day, but where night-time temperatures are low enough to 'pre-cool' the building ready for the next day (Designing Buildings, 2015). This strategy is not often considered for warm humid climates due to the small diurnal range common to cities that lie within this climate zone. However, research by Tenorio (2002) and (Szokolay, 2000) has shown this to be a potentially viable design strategy in warm humid climates. Further, diurnal temperatures of approximately 6°C in Mombasa show that this method might be suitable (Kiamba et al., 2014, Kiamba, 2010a).

2.2.4 Ground cooling

Where methods of avoiding unwanted heat gains have been applied and indoor temperatures within the space are still high, the ground can often be used as a heat sink to provide cooling. Throughout the year, temperatures below ground are more constant and significantly cooler than air temperatures above ground (Goulding et al., 1992). Increasing the building's contact with the ground can provide additional cooling. This can be done via direct contact with the ground or the introduction of ground cooling pipes that transfer the coolth from the ground to air that is distributed in the space.

There appears to be a consensus that ground cooling is not very effective in humid climates (Zaki et al., 2007). This is primarily due to the fact that underground temperatures are found to be fairly similar to ambient conditions (thereby reducing the potential cooling effect) and high humidity levels (moisture reaches dew point and often remains in the tubes). Further, evidence indicates that vernacular buildings in the warm humid region are often raised off the ground to enhance air movement (Koenigsberger et al., 1973, Oliver, 1997a, Szokolay, 2008). However, this also exposes a larger surface area of the building fabric to heat gains via conduction and prevents contact with the ground (Figure 2-12). Recent studies have shown that ground cooling might be a useful strategy (Sanusi et al., 2013, Yusof et al., 2014), especially if dehumidification processes are integrated to get rid of excess moisture in underground pipes (Zaki et al., 2007).

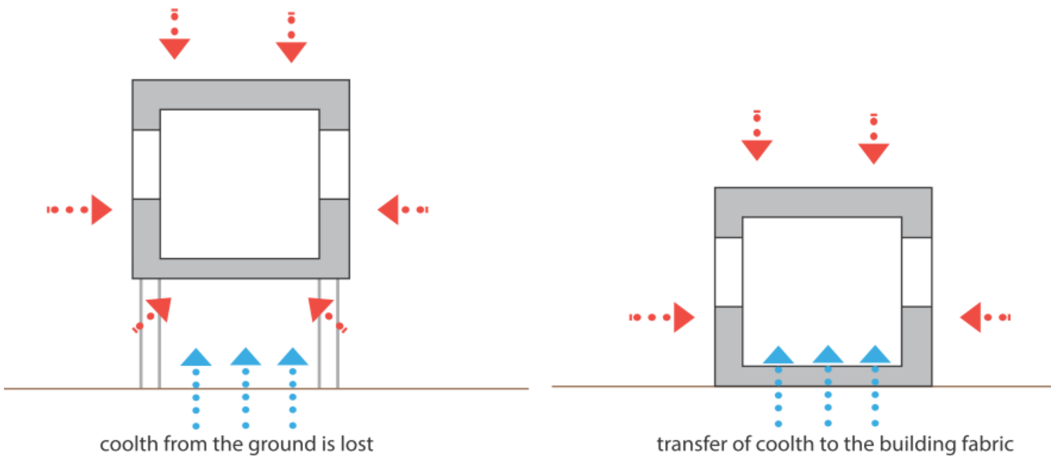


Figure 2-12 Transfer of coolth in ground cooling.

2.2.5 Evaporative cooling and Dehumidification

Evaporative cooling is mainly provided by mechanical means for greater control, or less so by purely passive means. Two types of evaporative cooling exist; direct and indirect evaporative cooling. Direct evaporative cooling works by passing warmer outside air through a surface or pipe with water and then introducing the cooler air into the space. This system works by using high latent heat of water to absorb a considerable amount of the heat in the air. As the water evaporates, it absorbs a significant amount of heat, and humidifies the air (Koenigsberger et al., 1973, Szokolay, 2008). For humid climates this would result in an undesirable increase in humidity (Cuce and Riffat, 2016). As such, one may consider employing indirect evaporative cooling instead (Chavez and Givoni, 2011).

Similar to direct cooling for the first part of the process, for indirect evaporative cooling, the air would need to be dehumidified before the cooled air is introduced into the space (Chen et al., 2014, El Hourani et al., 2014). Conventional solutions for the indirect method involve the use of roof ponds, sprays and porous walls. The application of these systems may result in high implementation and running costs that may not justify their sometimes negligible effect. Dehumidification works by cooling air to condense it and forcing the moisture out. Its advantage lies in its ability to improve thermal conditions by lowering relative humidity. However, its main disadvantage is that it can only be used effectively if it is carried out by mechanical means, which consumes vast amounts of energy to cool air below its dew point. Its application in warm humid climates is usually limited to the use of desiccants (El Hourani et al., 2014).

2.3 Learning from energy efficiency regulations in hot and warm humid climates

The term 'energy efficiency' is generally used to refer to the use of less energy to achieve the same service or output (Patterson, 1996, p.337). Over the last few decades, energy efficiency has garnered a fair amount of interest across the world. This awareness has been largely attributed to the energy crisis of the 1970s (Biswas, 1986, International Energy Agency, 2008b, Pérez-Lombard et al., 2011, Schipper and

Meyers, 1983, UN-HABITAT, 2010). More recently, concerns of climate change resulting from increasing greenhouse gas emission levels have led to a review of the role that the buildings have in promoting energy efficiency and tempering degradation of the environment (UN-HABITAT, 2010).

There is a general acceptance that the building industry has a prime role to play in increasing energy savings and simultaneously improving indoor conditions (Bodach and Hamhaber, 2010, Denton et al., 2014). Usually, energy efficiency measures are applied as a result of regulatory measures or voluntary choices (Australian Building Codes Board, 2010b, p.7). The introduction of these measures has been considered essential in the reduction of energy dependence in the built environment (Chua and Chou, 2011, International Energy Agency, 2008a). To date, a significant number of countries have embarked on the development of energy efficiency regulations to reap the potential benefits (Biswas, 1986, International Energy Agency, 2008b, Pérez-Lombard et al., 2011, Schipper and Meyers, 1983, UN-HABITAT, 2010).

A review of current energy efficiency regulations for buildings in the hot and warm humid region carried out as part of this study revealed that efforts are at a relatively early stage in most countries. Nonetheless, substantial headway has been made in a few countries. For instance, regulations in Singapore and Australia were found to be quite advanced; a factor that could be attributed to high government resolve, enforcement of mandatory legislation, and provision of economic incentives for building developers/owners (Building and Construction Authority, 2004, Australian Building Codes Board, 2010b). Similarly, although lacking in mandatory regulation (Lamberts et al., 2007), Brazil was found to have made significant strides through investment in energy efficiency in buildings research as part its development of building energy efficiency regulations. In the Caribbean region, no clear guidelines were identified. Instead, most countries were found to be in the process of developing their national energy policies (The Caribbean Renewable Energy Development Programme - CREDP, 2009).

Closer to the study region of Mombasa, Kenya, policy frameworks were found to be in place in countries in the East African region. In Kenya, an advanced National

Energy Policy was found to be clear on the need to develop energy efficiency regulations for the building industry (Ministry of Energy, 2012). However, a review of current Kenyan building regulations revealed the need for specific and more informative guidelines as opposed to generalised recommendations (Kiamba and Rodrigues, 2016 - expected). More recently, a programme labelled 'Promoting Energy Efficiency in Buildings' led by the United Nations Human Settlements Programme (UN-HABITAT) in collaboration with the respective East African governments aimed to carry out energy audits of commercial and office buildings to initiate energy consumption benchmarks, organise stakeholder education sessions and develop and publish design guidelines for the local region (Kitio, 2010, UN-HABITAT, 2011). At the conclusion of this project in Kenya (2015), it was found that a significant amount of effort had gone into raising energy efficiency awareness, particularly amongst design professionals. However, as highlighted in Chapter 1, more in terms of specific design guidelines coupled by mandatory regulation will be required to meet the energy efficiency goals set out by the Kenyan government.

2.3.1 Energy efficiency regulations in Singapore, Australia and Brazil

For purposes of this thesis, the building regulations of three countries – Singapore, Australia and Brazil were selected for investigation. Selection of the countries was based on the following criteria:

a) Each country is located within the hot and warm humid climate zone. In larger countries such as Australia and Brazil, where a range of climate types are experienced, regulation applicable to a city located in a warm humid region is examined.
b) Building energy efficiency regulations have been tried and tested and would be considered to be fairly well-advanced.
c) Building energy efficiency regulations recommendations show the potential for transferability.

The energy efficiency regulations of these countries were examined with focus on building thermal regulations developed to encourage reduced energy use for space cooling in commercial and office buildings. These regulations and their underlying objectives were identified, and those that were found to be commonly recommended and considered transferable to the Kenyan situation were highlighted.

a) Singapore

Buildings in Singapore account for about one-third of the total national energy consumption and 16% of greenhouse gas emissions; this amounts to a significant amount of building electricity usage for air conditioning (40 to 50%) and mechanical ventilation (20%) (Chua and Chou, 2010, NCCS, 2008, p.27). In response to these high energy and electricity usage rates, the main building standards authority, the Building and Construction Authority (BCA), made the provision of energy efficiency measures a priority. In 2004, energy efficiency regulations were introduced to provide guidelines on envelope thermal performance as determined by the performance index requirements defined by the Envelope Thermal Transfer Value (ETTV), and the energy efficiency of building services and equipment (Building and Construction Authority, 2010b).

Currently, Singapore's building regulations require the submission of ETTV calculations for new buildings that integrate active means of ventilation and cooling. The ETTV index accounts for the thermal contributions of the building envelope including conventional external shading devices, such as overhangs or fins. This index was based on the now disused Overall Thermal Transfer Value (OTTV) which was originally developed by the American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE) in 1975 as a thermal performance index for the envelope of air conditioned buildings (ASHRAE 90.1, 1975). Later, it was discovered that OTTV did not accurately represent the distinct performance of different elements of an envelope system; this resulted in the solar radiation gain through fenestrations being underestimated (Building and Construction Authority, 2010b, Chua and Chou, 2010, Yik and Wan, 2005). Considering the high potential for solar gain in the hot humid Singapore (highlighted in Chapter 1), it is clear to see why this was a critical flaw of OTTV use.

In 2000, the BCA set about a major overhaul of OTTV to derive a more accurate thermal performance index suitable for the Singaporean climate. In addition to the development of the ETTV (envelope) index, the RTTV (roof) index was introduced to differentiate the roof thermal transfer value of a building provided with a skylight (Building and Construction Authority, 2010b, Building and Construction Authority, 2008b). Similar in structure to the OTTV index, ETTV considers three aspects of heat gain through the building envelope including: heat conduction through opaque walls, heat conduction through glazing and solar radiation through glazing.

An average of all three heat gain sources over the entire building envelope gives a value that represents the predicted thermal performance of the envelope. The value for the ETTV (W/m^2) is calculated as show in Equation 2-6:

$$ETTV = 12(1 - WWR)U_w + 3.4(WWR)U_f + 211(WWR)(CF)(SC)$$

Equation 2-6 ETTV equation (Building and Construction Authority, 2008b, p.7).

Where: WWR is the window to wall ratio, U_w is the thermal transmittance of an opaque wall, U_f is the thermal transmittance of fenestration, CF is the correction factor for solar heat gain through fenestration and SC is the shading coefficients of fenestration. Currently, the maximum permissible ETTV value for new buildings is set at $50W/m^2$ (Building and Construction Authority, 2008b, p.7). Chua and Chou (2010, p.496) proposed that a further reduction of the ETTV maximum value to $45W/m^2$ from $50W/m^2$ could lead to a reduction of cooling energy by 2.5%. Further, they suggested that the ETTV value could be reduced to 30 W/m^2 if wall cladding was incorporated into building facades.

In addition to the aforementioned prescriptive type solutions more typical to older building regulations, a performance-based approach was also introduced to encourage the generation of alternative innovative solutions that would meet the objectives of the performance criteria of energy efficiency. This was defined in the Code for Environmental Sustainability of Buildings, which was introduced to enhance the existing regulations (Building and Construction Authority, 2008a). The main component of this code is the environmental assessment method Green Mark which sets a 'minimum' environmental sustainability standard for buildings (Building and Construction Authority, 2012b). Currently, the code is mandatory for all new construction or retrofits of over 2000m² gross floor area. Each must meet the minimum Green Mark assessment score of 50 points as determined on a points-basis (of which a minimum of 30 points is required for energy efficiency criteria).

Initially, to encourage the shift towards use of Green Mark and the attainment of high ratings, the BCA set up a series of incentives. This included the Green Mark Incentive Scheme which advocated for the use of an integrated energy modelling approach. In this case, in addition to meeting the minimum Green Mark requirements, the energy consumption of a proposed building was compared to that of a reference building of similar shape, size and orientation. Further, for existing AC buildings, the BCA also developed an Energy Efficiency Index (EEI) (kWh/m^2/yr), a building performance indicator that measures the buildings unit area energy consumption for monitoring and future improvement purposes in existing AC buildings. EEI is derived using Equation 2-7.

$$EEI = (TBEC - DCEC)/(GFA_{excluding\ car\ park} - DCA - GLA \times VCR) \times (55/OH)$$

Equation 2-7 (Building and Construction Authority, 2010a, Appendix B, Sustainable Earth Office, 2011, p. 6).

Where:

TBEC is total building energy consumption (kWh/year), DCEC is data centre energy consumption (kWh/year), GFA is gross floor area (exclusive of car park area)(m^2), DCA is data centre area (m^2), GLA is the gross lettable area (m^2), VCR is weighted floor vacancy rate of gross lettable area (%), 55 is number of typical weekly operating hours of office buildings in Singapore, *i.e.* 55 hours/week and OH is the weighted weekly operating hours of the GLA exclusive of data centre area (hours/week). Calculation of EEI assumes an occupancy rate of 100% and energy consumption of all main building equipment. For those buildings with established benchmarks, such as office buildings, the maximum current Energy Efficiency Index

(EEI) is set to 215kWh/m^2/yr (Building and Construction Authority, 2010a, Appendix B, Sustainable Earth Office, 2011, p. 6).

A review of the Singaporean regulations revealed that majority of the regulatory measures was focused on artificially ventilated buildings. However, some basic design strategies were also provided for naturally ventilated buildings as stipulated in the Code on Envelope Thermal Performance for Buildings and illustrated in Figure 2-13 (Building and Construction Authority, 2012b, Section NRB 1-3).

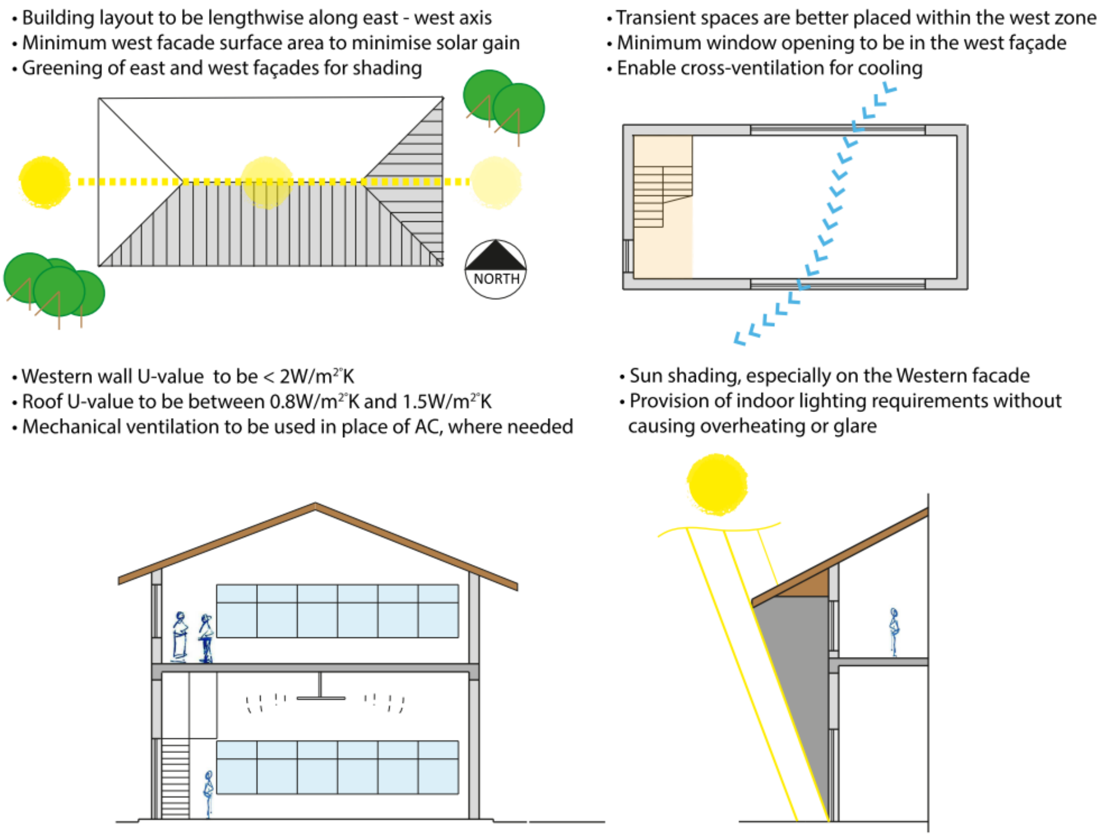


Figure 2-13 BCA design recommendations for naturally ventilated buildings.

Primarily, as is recommended for hot and warm humid climates, these design guidelines for passive buildings aim to mitigate heat gain by solar and conduction gains control and to provide cooling by enhancing natural ventilation. In addition to these strategies, the use of simulation software was recommended to aid in designing an efficient building layout for adequate cross ventilation for ventilation and cooling.

Other general design strategies recommended for both passive and AC buildings in include: the use of innovative design methods (for the performance-based approach), design for effective daylighting, use of renewable energy sources, energy waste prevention, monitoring of building energy consumption and the maintenance of acceptable energy use during building life cycle (Building and Construction Authority, 2013b).

b) Australia

The introduction of building energy efficiency regulations in Australia was driven by the Australian government's need to reduce the greenhouse gas emissions caused by the operation of buildings. This was motivated by the fact that buildings in Australia are responsible for up to 27% of the country's energy related greenhouse gas emissions (Australian Building Codes Board, 2010b, p.4). Falling under the custody of the Australian Building Codes Board (ABCB), these regulations are integrated into the Building Code of Australia (usually abbreviated to BCA but referred to in this thesis as BCA-A for clarity purposes due to the aforementioned Building and Construction Authority, Singapore).

Generally, the BCA-A energy efficiency regulations cover aspects related to the building envelope, building services and equipment. Whereas these regulations were developed for nationwide adoption, their implementation is subject to the omission or addition of provisions deemed necessary by state and territorial governments (Australian Building Codes Board, 2011). Nonetheless, general energy efficiency goals tend to be fairly similar across the country (Council of Australian Governments, 2009).

Due to its territorial expanse, climate conditions in Australia range from warm in the North to the cool in the South. To address this, the BCA-A regulations stipulate that the climate type should be identified to ensure that suitable design strategies applied to buildings (Australian Building Codes Board, 2010b). The first method recommended by the ABCB involves the identification of the proposed site location on a country map that outlines the eight climate zones based on climate data and local government boundaries (Figure 2-14). For each of these eight climate zones, accompanying prescriptive recommendations are provided for implementation purposes. As an alternative to this method, the ABCB recommends the use of the National Australian Built Environment Ratings System (NABERS) software. NABERS is a performance-based environmental impact rating system for existing buildings that measures the environmental performance of buildings (Office of Environment and Heritage, 2013). NABERS lists 69 distinct climate types based on climate data and postal locations in Australia. On selection of the climate type, the software can be used to evaluate ranging solutions for improved predicted thermal performance and energy use suitable to the given climate type.

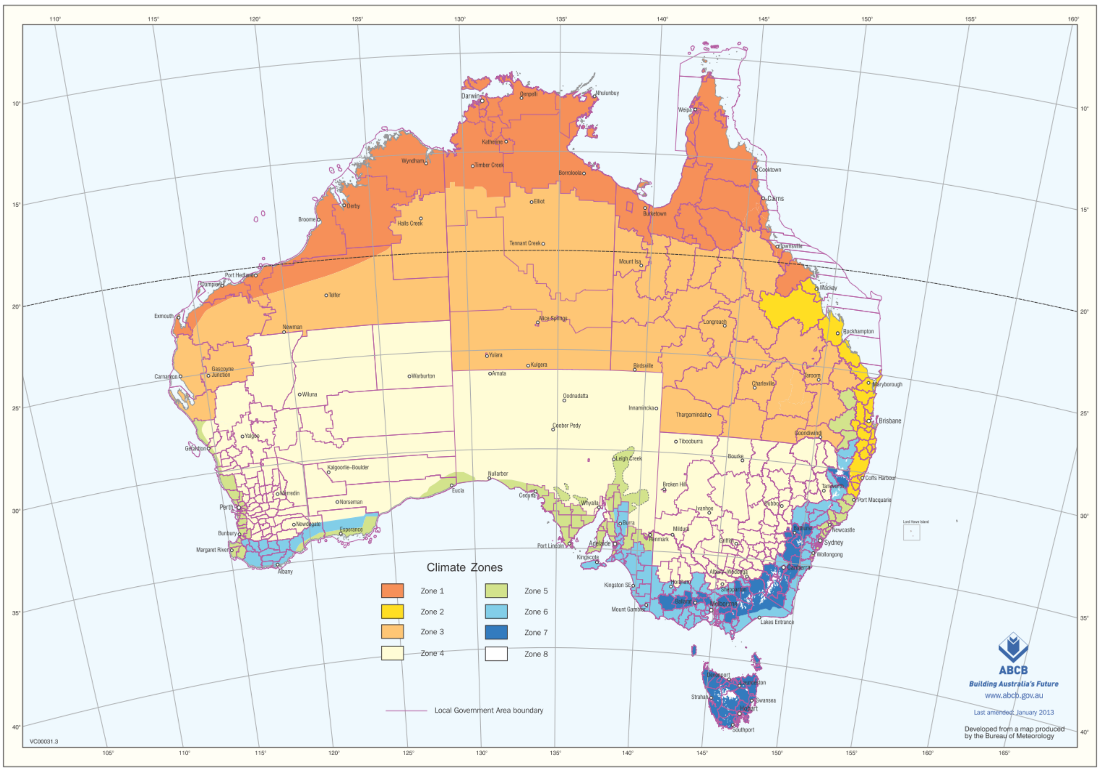


Figure 2-14 BCA-A climate classification map (Australian Building Codes Board, 2013).

For purposes of this study, the recommendations and guidelines applicable to the warm humid region of Northern Australia, also identified as Zone 1 in the BCA-A climate classification map was considered. The BCA-A regulations reveal that this zone is more likely to require cooling over most of the year and propose 'deemed to satisfy' (DTS) solutions that aim to reduce heat gain that would warrant the need for increased cooling (Australian Building Codes Board, 2010b). These DTS performance standards address aspects of building thermal insulation, suitable building orientation, sun shading for glazing and infiltration control in an effort to mitigate overheating problems (Australian Building Codes Board, 2010b).

The ABCB approach towards energy efficiency in buildings aims to reduce energy consumption by controlling heat flow through the building fabric to maintain suitable indoor conditions and improving the performance of building services (Australian Building Codes Board, 2010b). This involves examining fuel-use in the operation of energy consuming building services such as cooling, heating or lighting as well as specifying performance standards for building fabric. The regulations have a format similar to the Singaporean case in that they outline performance standards with the option of implementing a choice of the DTS standards or alternative solutions based on current or innovative design that meet performance requirements. Mandatory DTS performance requirements are outlined in Section J of the BCA in reference to all non-residential buildings where all sections must be satisfied as outlined in Table 2-2 (Australian Building Codes Board, 2010b, Kearsley, 2007).

Table 2-2 BCA Section J 2010 Structure (Australian Building Codes Board, 2010a).

Energy Efficiency Target	**Performance requirements for Class 2 to 9* (Multi-residential, Commercial and Public Buildings).**
Part J1 Building Fabric	Set minimum acceptable levels for suitable thermal performance of the building fabric.
Part J2 Glazing	Minimum energy performance for glazing elements as calculated for each geographic direction is provided as per climatic region; sun shading component requirements are also addressed.
Part J3 Building Sealing	Control of undesirable air movement and air leakages throughout the building to minimise unwanted air movement (AC buildings only).
Part J4 Air Movement	Use of air-movement as a cooling strategy.
Part J5 Air conditioning and Ventilation Systems	Provision of systems to meet building requirement as efficiently as possible.
Part J6 Artificial Lighting and Power	Provision of suitable lighting for given space use in an efficient manner.
Part J7 Hot Water Supply	Reduction in energy used for provision of hot water supply.
Part J8 Access for Maintenance and Monitoring	Provision of access to the building for maintenance and monitoring purposes to ensure the building continues to run in an efficient manner.
*An office building used for professional or commercial purposes falls within Class 5.	

Where one chooses to use alternative methods over DTS, they are obliged to verify that the method meets performance standards as stipulated by the BCA-A. A list of these DTS provisions as applies to the warm humid region of Darwin is illustrated in Figure 2-15 (Australian Building Codes Board, 2010b).

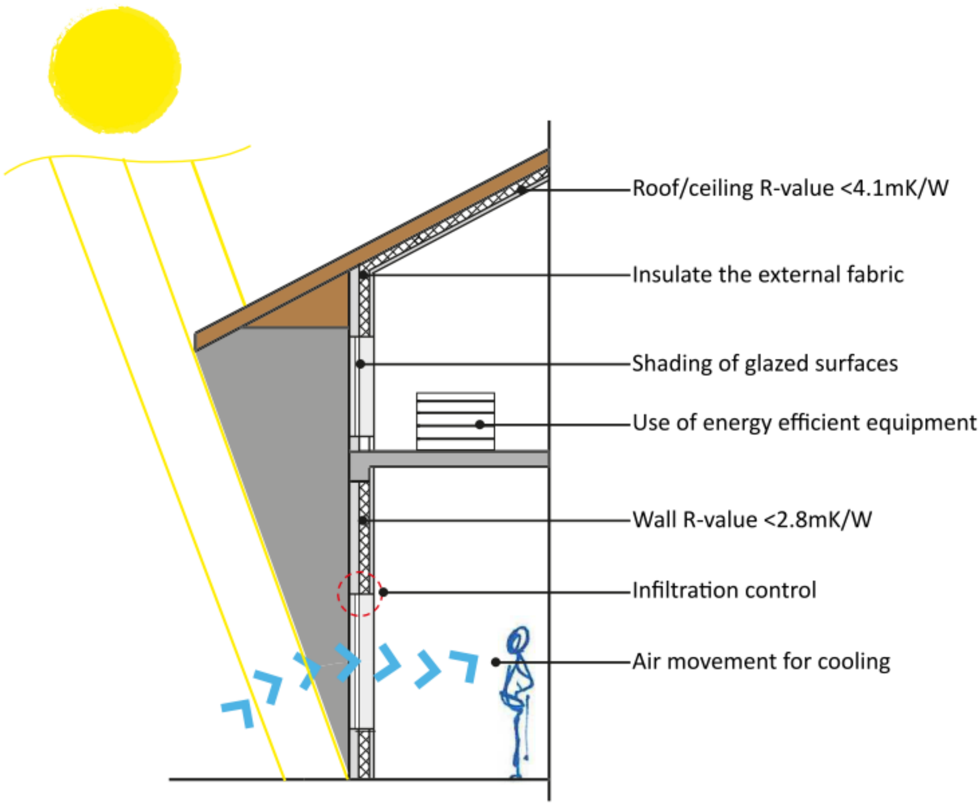


Figure 2-15 DTS solutions for Darwin (Zone 1).

In contrast to Singapore, energy efficiency regulation efforts in Australia have been largely focused on residential buildings (originally initiated in 2000 and covered in class 1 to 4 of BCA-A Section J). In comparison, regulation for office buildings (Class 5) were only catered for with the introduction of provisions into BCA-A national regulation in 2006, and with increased stringency effected by means of mandatory regulation in 2010 (Australian Building Codes Board, 2011). Even so, this was only at national level leaving adoption of regulation at state and territory level up to the local governments. Nonetheless, with the advent of initiatives such as NABERS, energy efficiency regulations continue to gain ground nationwide.

In addition to the compulsory NABERS rating system, Green Star (a voluntary accreditation scheme run by Green Building Council of Australia) can also be used to provide ratings for new and retrofitted commercial buildings (Department of the Environment - Australian Government, 2011). As with NABERS, the scheme examines aspects related to energy efficiency, indoor environment quality, water and waste. Further, Green Star also examines aspects related to management, transport, materials, land use and ecology, emissions and innovation.

A significant difference between NABERS and Green Star is that the former rates the actual performance of a building when in use whereas the later rates predicted performance of the proposed or an 'as-built' building. NABERS gives the building a star rating that represents its actual operational performance, using 12 months of measured performance information, such as energy or water bills. In addition, it takes into consideration local climatic conditions, building size and occupancy, hours of usage, services provided and energy used. The software works by comparing the performance of a select building or tenancy to benchmarks that represent the performance of other similar buildings in the same location. The ratings are valid for twelve months when another assessment is required to keep the rating up to date. The frequency with which they are undertaken suggests that the rating accurately represents the building or workplace's current operational performance.

As of 2010, all owners of commercial buildings with a floor area of more than 2000m^2 were required to disclose a NABERS rating when renting or selling their spaces thereby raising the profile of energy efficiency to market participants (Australian Building Codes Board, 2011). This was set up under the Commercial Building Disclosure (CBD) scheme supported by all the state and territorial governments in Australia. As from 2011, commercial building owners are also required to obtain a Building Energy Efficiency Certificate (BEEC), which requires owners to obtain a NABERS rating, a lighting energy efficiency assessment and general energy efficiency guidance.

c) Brazil

Building energy usage is responsible for approximately 45% of Brazil's electricity consumption (PROCEL EDIFICA, 2006). In addition, it has been found that increased electricity usage in commercial type buildings is as a result of air conditioning and lighting use (Lamberts and Westphal, 2000). Following the Brazilian electricity crisis in 2001, it was noted that whereas Brazil has vast energy potential in the form of hydro-power sources, the lack of continued development of these sources and growing energy demand no longer renders the country's energy situation comfortable (Carlo and Lamberts, 2008, Cândido et al., 2011b, Batista et al., 2011). This electricity crisis led to the declaration of the first law of energy efficiency in buildings and equipment (Law no. 10.295) and resulted in the establishment of the National Policy of Conservation and Rational Use of Energy (Lamberts et al., 2007, p. 603).

Further, to target the advancement of legislation for energy efficiency including building certification and regulations, the development of a National Energy Efficiency in Buildings action plan, labelled the 'PROCEL Edifica' program was launched in 2003 (Batista et al., 2011, Cândido et al., 2011a, Carlo and Lamberts, 2008). According to Lamberts et al. (2007), PROCEL Edifica was initially challenged with developing bioclimatic architectural recommendations, establishing performance minimums, building materials and appliance certification and stakeholder education. However, instead of attempting to establish minimum compulsory requirements, focus was later shifted to the introduction of regulation for voluntary labelling. This was explained to be due to a lack of stringency in the prevailing construction industry, lack of supporting documentation and an insufficient number of trained professionals in the field - all of which would result in poor implementation (Lamberts et al., 2007). Nonetheless, it is anticipated that over time, it will be possible to improve competence and allow for testing of typologies for more complex energy efficiency regulations.

In Brazil, the ABNT - Associação Brasileira de Normas Técnicas (Brazilian Standards Association) develops the 'technical' standards that are implementable at a national level; building codes that refer to these national standards are developed at municipal and state levels (Bodach and Hamhaber, 2010). Currently, the main national energy efficiency regulation for buildings is covered in NRB 15220, which examines the thermal performance of buildings (ABNT, 2003). This regulation divides Brazil into eight different bioclimatic regions and recommends bioclimatic design strategies and guidelines for low-cost houses. This is quite similar to the prescriptive approach encountered in Australia's regulations.

In 2006, voluntary labelling for commercial buildings was introduced. This was defined under the Federal Regulation for Voluntary Labelling of Energy Efficiency Levels in Commercial, Public and Service buildings referred to as The Quality Technical Regulation for Energy Efficiency in Public, Commercial and Service Buildings (RTQ-C) (Carlo and Lamberts, 2008). Currently, the attainment of a performance rating is recommended for commercial buildings of over 500 m² or for those whose energy demand is equal to or more than 2.3kV (Lamberts et al., 2007, p.606).

The voluntary labelling process comprises of two stages, the first takes place during the design stage whereas the second is undertaken on completion of the building (to confirm the efficiency levels obtained). The first stage considers one of two evaluation methods: the prescriptive method where various electricity consumption equations, table requirements and limit parameters are set for application in buildings or the trade-off approach or simulation method which compares the performance of a proposed building with that of a reference building (Pollis, 2013, Carlo and Lamberts, 2008).

The initial prescriptive method outlines the parameters for envelope materials and components and building services equipment (Amorim et al., 2010, Carlo and Lamberts, 2008) as highlighted in Table 2-3.

Table 2-3 RTQ-C prescriptions breakdown (ABNT, 2006, Carlo and Lamberts, 2008).

i. Lighting	Based on lighting power density limits that are compared to those calculated according to Brazilian illuminance level standards (ABNT, NBR 5413)
ii. HVAC	Based on the classification for systems as outlined by the National Institute of Metrology (INMETRO) and ASHRAE Standard 90.1-2004
iii. Envelope	Based on electricity consumption equations/performance indices derived from simulations to assess envelope efficiency.

The envelope section (Table 2-3, part iii) of the prescriptive method limits some physical aspects including thermal transmittance of roofs and walls, solar coefficients of glazing and sun shading elements according to various indices. The main prerequisites for the warm humid zone (Z8) are highlighted in Figure 2-16.

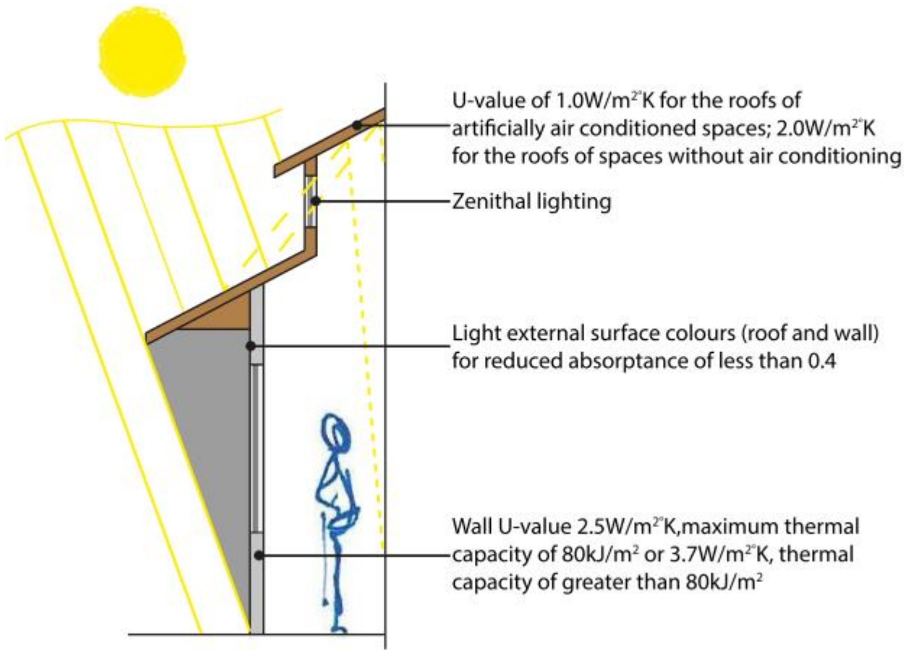


Figure 2-16 Pre-requisites for higher efficiency ratings in typical warm humid zone (Z8).

On meeting the aforementioned prerequisites, the envelope compliance is calculated depending on building area and compared with limits set for the different building rating levels. Use of energy saving measures such as renewable energy sources or other innovative measures can earn one an extra point if justified and confirmed to be saving energy. Envelope compliance is determined using a multi-variable regression equation, the envelope consumption index (IC), which takes into account the building area and provides an electricity consumption indicator. The IC was developed from the simulation of six basic generic building types and their variations. These simulations were conducted for each bio-climatic zone in Brazil to come up with two equations for each zone for buildings with floor area of either under 500m^2 or over 500m^2 (Carlo and Lamberts, 2008, p.2005). IC takes into account the following variables: window to wall ratio (WWR), solar heat gain coefficient (SHGC), solar protection angles, building volume indicators and roof U-value (Carlo and Lamberts, 2008, Amorim et al., 2010, Batista et al., 2011, Lopes et al., 2011). The IC equations are presented in Equation 2-8 and Equation 2-9, respectively:

$$IC = -175.30\left(\frac{A_p}{A_{tot}}\right) - 212.79\left(\frac{A_{env}}{V_{tot}}\right) + 21.86WWR + 5.59SHGC - 0.19VSA + 0.15HSA + 2.34U_{roof} + 0.19ILD.Sch\left(\frac{A_{proof}}{A_{tot}}\right)\left(\frac{A_{env}}{V_{tot}}\right) + 213.35\left(\frac{A_{proof}}{A_{tot}}\right)\left(\frac{A_{env}}{V_{tot}}\right) - 0.04WWR.SHGC.VSA - 0.45WWR.HSA$$

Equation 2-8 IC equation for buildings with a floor area of under 500m^2 (Carlo and Lamberts, 2008, p.2005).

$$IC = -14.14\left(\frac{A_p}{A_{tot}}\right) - 113.94\left(\frac{A_{env}}{V_{tot}}\right) + 50.82WWR + 4.86SHGC - 0.32VSA + 0.26HSA + 1.76U_{roof} - 0.13ILD.Sch\left(\frac{V_{tot}}{A_{env}}\right) - 0.54WWR.HSA - 0.45WWR.HSA + 0.925ILD + 1.74Sch + 0.81ILD.Sch$$

Equation 2-9 IC equation for buildings with a floor area of over 500m^2 (Carlo and Lamberts, 2008, p.2005).

Where the variables for Equation 2-8 and Equation 2-9 are:

A_{proof} is the area of the horizontal projection of the building (m^2); A_{tot} is the total floor area (m^2); A_{env} is the envelope area (m^2); V_{tot} is the building volume (m^3); WWR is the window to wall ratio; VSA is the vertical shading angle (8); HSA is the horizontal shading angle (8); Sch is the lighting, equipment and occupation schedule (h); ILD is the internal load density (W/m^2).

Interestingly enough, the U-value of the external walls was excluded from these IC equations as it was deemed too complex for the IC's linear regression equation (Carlo and Lamberts, 2008). Nonetheless, it is suggested that the aforementioned pre-requisites (including set U-values, surface colours and zenithal lighting) are thought to complement the IC equations. The IC value allows for comparative analysis against the benchmarks where buildings are rated from 'A' (most efficient) to 'E' (least efficient). As the equations were developed for average generic buildings, they do not properly represent those with relatively smaller or larger areas.

Instead of the aforementioned prescriptive method, one may choose to use the simulation method. This requires the use of computer simulations to verify that the energy consumption of a proposed building is better than or similar to that of a similar type reference building (one which meets the requirements of the prescriptive method) (Amorim et al., 2010). The software used must be able to facilitate the modelling of building energy consumption. Lopes et al. (2011) explains that there are various requirements that are essential to adequately validate the energy consumption levels of the proposed building. This includes use of suitable simulation for energy consumption to ensure comfort for 80% of the year, use of suitable weather files and inputting of valid building characteristics (occupancy times, number of levels and building fabric).

Whereas the prescriptive method is faster and easier than the simulation method, it is exclusively recommended for use in air conditioned buildings (Amorim et al., 2010). Where natural ventilation is considered, the simulation method is the mandatory and is used to verify that the space will be thermally comfortable all year round (for at least 80% for highest RTQ-C rating level 'A').

While RTQ-C labelling is currently voluntary, it is anticipated that the transformation of the overall construction sector will result in the regulation eventually becoming mandatory and resulting in energy savings of up to 30% and 50% in existing and new buildings respectively (Pollis, 2013, p.13).

2.3.2 Discussion

The review of energy efficiency building regulations in Singapore, Australia and Brazil provided useful insights into their overall structure and underlying objectives. Primarily, the regulations aimed to address the following objectives:

- improvement of building fabric or envelope (for heat gain control)
- reduction of cooling loads (provision for cooling)
- integration of renewable sources of energy
- use of 'intelligent' energy management systems

- improvement of indoor conditions while minimizing energy requirements
- use of energy saving equipment

Overall, it was apparent that the focus of regulation lay in the first two objectives which were directly related to the aforementioned design strategies for hot and warm humid climates *i.e.* heat gain control and provision for cooling. This was suggested to be due to the fact that they would possibly produce the greatest effect in building's energy efficiency and that they directly affect the need or extent of the subsequent objectives.

Generally, the development of the energy efficiency regulations in the three countries has revealed their increased uptake, albeit at different rates (Institute for Building Efficiency, 2013). Of the three countries, Singapore appears to have made the most significant strides. The latest available figures indicate that the number of energy efficient building projects grew from 17 in 2005 (mandatory energy efficiency regulation was introduced in 2004) to about 1,600 in eight years. This translates to 47,000,000m^2 of Gross Floor Area (GFA), or 20% of Singapore's total GFA. Singapore aims to increase this figure to 80% of its building stock by 2030 (Building and Construction Authority, 2013c). A study of the impact of mandatory regulation on a sample of 36 retrofitted buildings found that the annual total building energy savings per square metre improved by 16% per annum (58kWh/m^2/year). These energy savings translated into 85 GWh energy savings per annum, or $22,700,000 in cost savings (Building and Construction Authority, 2013a).

In Australia, a memorandum of understanding between the various states led to the development of the National Strategy on Energy Efficiency (2009-2020) which aimed to maximise energy efficiency measures across the country. As a result, higher energy efficiency standards are applied to an estimated 26,500 commercial building projects constructed each year, as well as the significant number of major building renovations (Council of Australian Governments, 2009, p.3). It was suggested that the introduction of the mandatory Commercial Building Disclosure (CBD) scheme in 2010 requiring all commercial building owners to obtain a Building Energy Efficiency Certificate (BEEC) in 2011 should signal even more significant improvements.

Further, the adoption of mandatory approaches to energy efficiency regulations in Singapore and Australia is suggested to have been the prime reason why the development of the energy efficiency regulations has shown increasing growth or uptake.

In Brazil, the implementation of regulations was found to be at a relatively early stage, this made it difficult to judge the impact of energy efficiency regulation to date. However, a recent energy efficiency indicator survey revealed that more building stakeholders in Brazil were keen on incorporating energy efficiency measures (Institute for Building Efficiency, 2012). Given the parallels that can be drawn between Brazil and Kenya, including the lack of stringency in the prevailing construction industry, lack of supporting documentation and the small number of trained professionals in the field, the Brazilian model offers significantly useful insights. For instance, as Kenyan energy efficiency regulations are at a relatively early stage of development, a similar transition from voluntary and to mandatory regulations can provide opportunities to fine tune regulations and time for stakeholders to gain experience.

In the context of energy efficiency and with reference to the inherent nature of building regulations, the reviewed regulations were found to consist of one or two approaches as outlined in Table 2-4.

Table 2-4 Typical energy efficiency regulatory approaches (Australian Building Codes Board, 2010b, Gann et al., 1998, Inter-jurisdictional Regulatory Collaboration Committee, 2010, Lamberts et al., 2007).

Type	**Prescriptive**	**Performance-based**	**Trade-off approach**
Definition	Offer a detailed set of prescriptions that outline how to go about reaching a certain solution.	Specify the required goal of the regulation so as to bring about a desired function.	Compares a proposed building to a reference building that meets the anticipated requirements of a prescriptive nature.
Main Characteristic	Describes the 'what' and the 'how' of a required standard or code and are deemed mandatory.	Describes the 'what' but leaves the 'how' open to interpretation thereby allowing for innovative solutions.	Allows for trade-off on building envelope properties. For example, the U-values of different building elements.

Historically, the prescriptive approach has formed the basis of majority of building regulations (Bell and Lowe, 2000, Inter-jurisdictional Regulatory Collaboration Committee, 2010, May, 2007, Pérez-Lombard et al., 2011). However, the rapid rise in the number of regulated areas and the difficulty involved in attempting to capture all requirements within individual building regulation, as well as the rigid nature of the prescriptive approach, has resulted in the shift towards performance based regulations that allow for greater flexibility of solutions (Inter-jurisdictional Regulatory Collaboration Committee, 2010, Chua and Chou, 2011). In this case, it was suggested that the relatively recent introduction of energy efficiency regulations deemed it reasonable to anticipate evolved or new solutions. This trend is evidenced by the adoption of this approach by numerous building regulatory bodies (Gann et al., 1998, May, 2007), including the BCA in Singapore and ABCB in Australia.

Generally, the reviewed prescriptive regulations consisted of performance indices that were mainly addressed towards AC buildings. These indices offer guidelines on the optimisation of the building envelope performance (such as ETTV) or reduction in energy or electricity consumption (such as EEI and IC). Despite the apparent restriction of prescriptive regulations to AC buildings, it was suggested that they might also be beneficial to employ a similar method to naturally ventilated buildings to serve as a 'first approach' method for the optimisation of the building envelope. It was suggested that this might be particularly useful in Kenya; given that such indices are usually relatively easy to use, in contrast to use of modelling software that requires skilled personnel which is currently in short supply.

On the other hand, the performance-based approach tended to be recommended for naturally ventilated buildings. This was attributed to its flexible nature which allowed for greater variation in solutions. With current developments in modelling software solutions, it is possible to run various strategies that would simulate building service systems allowing for greater accuracy in prediction of indoor comfort and energy use. Using modelling software, performance could be predicted and improved upon as required during the early design stages. Whereas this method is not usually recommended for AC buildings, it is suggested that it would also serve to benefit designers who employ it in any type of building, irrespective of ventilation mode.

The choice of regulatory approach was also determined by the local conditions. Brazil, which changed course from the development of fixed prescriptive minimums to the use of a trade-off approach, is one example. This shift was made owing to the foreseen difficulties in ensuring quality of construction and implementation of regulation. This situation bears close similarities to Kenya which has had enforcement issues of its own (Mathenge, 2012); similar issues have been reported in other developing countries (Ofori, 2012, International Council for Research and Innovation in Building and Construction (CIB) and United Nations Environment Programme International Environmental Technology Centre (UNEP-IETC), 2002).

It has been established that the main thermal comfort concern in buildings in hot and warm humid regions arises from relatively high temperatures coupled by high relative humidity (Chapter 1). In Kenya, the effect of these climatic factors combined by poor building design is often overheating in buildings and an increase in cooling load. To address this, energy efficiency regulations need to apply the necessary adjustments to accommodate local climate conditions. For instance, in Singapore, Australia and Brazil, suitable climate-responsive strategies key in achieving suitable indoor conditions were considered (including natural ventilation and sun shading). To further improve the effectiveness of regulation, specifications for building envelope efficiency were found to recommend heat gain control and the provision for cooling.

In addition, it was found that energy efficiency regulations are largely guided by requirements for the given climate, even more so those relevant to naturally ventilated buildings. This was done to increase their accuracy for local use. For instance, prescriptive equations such as IC were developed for each of the eight bio-climatic zones of Brazil, as was ETTV in the case of Singapore. Similarly, by using the simulation approach, one is able to test solutions for specific site locations by running climate specific weather files. This would be especially useful in Kenya where the existing wide range of climate zones necessitates the need for climate-specific guidelines.

Numerous thermal comfort field studies have indicated that adaptive opportunities can increase the range of thermal acceptability levels (Cândido et al., 2011b). Similarly, evidence has shown that the more thermally comfortable the occupants of a building are, the less likely they are to resort to active means as a way of meeting their comfort requirements, hence reducing the need for energy expenditure (Bodach and Hamhaber, 2010). However, of the regulations reviewed, thermal comfort was revealed to be more of a potential outcome of energy efficiency rather than as a main objective. Little is mentioned of the improvement of indoor conditions to minimise energy requirements. Given the range of predicted comfort presented in Chapter 1, it is thought that the regulation provided in the three select countries is rather limiting – and especially for naturally ventilated commercial buildings.

In Singaporean regulations, where naturally ventilated buildings are considered, no clear definitions of thermal comfort are made, instead thermal comfort is considered a possible result of building envelope design strategies (shown in Figure 2-13). For AC buildings, comfort is alluded to in relation to indoor air quality and the installation of AC systems; in this case it is recommended that temperature levels of between 24°C to 26°C with corresponding relative humidity of 65% be maintained consistently (Building and Construction Authority, 2012b, p.30).

In Australia, the ABCB categorically state that whereas thermal comfort is desirable, it is neither defined nor are optimum levels provided but rather it is anticipated as a result of improved energy efficiency (Australian Building Codes Board, 2010b). Instead, the ABCB stress that the main drive of energy efficiency regulation is to reduce greenhouse gas emissions and argue that if the building envelope is constructed efficiently then the consequent effect will be occupants being more comfortable than they would be otherwise.

Correspondingly, no specific comfort definition or standard has been developed for the Brazilian climate zones for purposes of labelling of naturally ventilated buildings;

instead guidelines recommend use of ASHRAE 55, ISO 7730 or any other adaptive comfort standard, without going into any specifics (INMETRO, 2010). Cândido et al. (2011b) suggests that whereas it would be difficult to provide a unique standard that is suitable for all regions in Brazil (owing to the bioclimatic differences), a more valid approach to indoor thermal acceptance would be through development of a standard that focuses on air movement and thermal comfort. It is suggested that the provision of such a regulation could encourage a shift towards natural ventilation during suitable times of the year and in so doing, reduce energy requirements.

Whereas one may argue that building energy efficiency regulations are, as the term suggests, concerned primarily with energy consumption, the role that provision thermal comfort can play in increasing energy efficiency cannot be ignored. Traditionally, air conditioning strategies have emphasized the management of indoor temperature and humidity conditions through active systems to provide thermal comfort for occupants (as with the case in Singapore). As such, owners or building designers may not typically understand or utilize the broader range of means at their disposal to support thermal comfort, or look to incorporate them into their designs or operation.

Thoughtful building design that makes use of the wider array of available thermal comfort mechanisms and opportunities can be leveraged to result in significant energy savings, whether when evaluating options for a new build or retrofit; or through operational improvements on an existing air conditioning system. It is further suggested that thermal comfort regulations need not be 'static figures' leaving little room for manoeuvre but rather guidelines that allow the designer to improve potential for thermal acceptability and comfort as guided by results from local field study recommendations.

Owing to the revival of energy efficiency measures in the 1990s, various assessment methods arose to help improve energy efficiency and minimise energy consumption. These assessment methods are now considered instrumental in driving sustainability within the construction industry from design to post occupancy stages (Haapio and Viitaniemi, 2008, Pérez-Lombard et al., 2009). A review of energy efficiency regulation in the selected countries has revealed the prevalence of these environmental assessment methods. Typically, they are used to measure and rate the environmental performance of buildings. Similarly, they outline the criteria through which the performance of a building can be gauged; in most cases this criterion is relative to established benchmarks in the form of guidelines or databases.

Different building rating systems give varying labels and certificates dependant on specific end user needs (Ding, 2008) with many having been developed to apply specifically to the country in which they have been developed, or localised to fit climate and government policies and regulations (Kubba, 2012, Alyami and Rezgui, 2012). Nonetheless, in as much as different criteria have been developed in the aforementioned regulations, the basic themes are recurrent. Table 2-5 presents an overview of the main environmental assessment tools that are recommended as part of building regulation in Singapore, Australia and Brazil. The tools include Green Mark - developed by BCA; NABERS - originally referred to as Australian Building Greenhouse Rating; and RTQ-C which was a product of the PROCEL-Edifica initiative in Brazil.

Table 2-5 Environmental Assessment Tools Comparison (Building and Construction Authority, 2012a, Green Building Council Australia, 2013, Kubba, 2012, NSW Department of Environment Climate Change and Water, 2013, Pollis, 2013).

Tool	**GREEN MARK**	**NABERS**	**RTQ-C**
Year formed	2005	1998	2006
Climate suitability	Tailor-made for the humid Singaporean climate	Australian climate zones (including warm humid)	Brazil's bioclimatic zones (including warm humid)
Status	Mandatory under the Code of Practice for Energy Efficiency Standard for Building Services and Equipment	Mandatory under the CBD scheme and also by law in Government buildings in States and territories (varies)	Voluntary, to be made mandatory
Building type	Commercial and residential	Commercial and residential	Commercial
Assessment criteria	• Energy efficiency • Indoor Environmental Quality • Water efficiency • Environmental protection • Other Green Features and Innovation	• Energy • Indoor environment • Water • Waste	• Prescriptive method (Building envelope pre-requisites and electricity efficiency) • Simulation method (to compare the proposal with a reference building or to gauge comfort)
Rating Scales	Certified (lowest rating), Gold, Gold Plus or Platinum (highest rating)	6 stars (Market-leading performance), 5 (excellent), 4 (good), 3 (average), 2 (below average), 1 (poor)	Rating from 'A' to 'E' from most efficient to least efficient.
Post occupancy evaluation provisions	Re-assessment required every three years	Ratings reviewed annually	Currently labelling is done in just two phases: in the design stage and on building completion to confirm rating

Besides providing a useful framework within which designers can checklist energy efficiency requirements, these assessment tools also promote the certification or labelling of buildings which has encouraged integration into the market sector. A valid example is the CBD scheme in Australia that is designed to improve energy efficiency in commercial buildings by requiring all building owners to obtain and disclose a NABERS rating before selling or renting space. Similarly, in Singapore, commercial buildings are required to obtain a minimum Green Mark rating for which energy efficiency comprises of up to 60% of the score. Of the regulations reviewed, it was established that these tools provide a comparatively concise approach within which regulations can be outlined and easily followed through by designers.

The role of environmental assessment tools has grown over the years with more established methods such as BREEAM and LEED having had a significantly wider reach spanning into the developing world. In Kenya, the recent formation of the Kenya Green Building Council has seen the introduction of the Greenstar rating tool which assesses the environmental attributes of new and existing facilities in building industry in Kenya. Where energy efficiency regulations are yet to be fully developed or accepted, it is suggested that these tools could work fairly well in introducing the concept to stake holders without being too overwhelming (owing to their concise approach). Although it is early days yet, the development of a localised tool in Kenya has the added advantage of benchmarking similar type buildings within a local climatic region for comparison purposes that could lead to further improvements in energy efficiency.

2.4 Conclusions

Passive design for climate in hot and warm humid regions requires that buildings are designed to ensure that occupants remain thermally comfortable with minimal need for supplementary cooling. To do so, suitable passive design strategies that address the relatively high temperatures, high relative humidity and solar radiation common to hot and warm humid climates should be applied. In this chapter, it was noted that these passive design strategies can be divided into two groups: heat gain control measures and provision for cooling. In particular, heat gain control measures were deemed to form the basis of passive design in hot and warm humid climate; this is because they work to restrict or minimise heat gain that has the potential to cause discomfort indoors. On the other hand, cooling control measures were suggested to be more remedial in nature; this is because they work to expel heat build-up and provide cooling for occupants.

The prime contributor of heat gain to a building is usually from solar gain. Consequently, where heat gain is undesirable, as would be the case in occupied office buildings in warm humid climates, solar control forms one of the main heat alleviation strategies applied to buildings. This would appear to justify the focus on solar control in a substantial number of design guidelines for warm and hot humid climates and indeed in the limitation of this study to the application of external shading devices for the improvement of thermal comfort and energy efficiency. In addition to solar control, the regulation of conduction gains, ventilation and infiltration gains and internal gains were found to be useful in curbing heat gain in buildings. The extent to which these controls impact heat gain and subsequent comfort is explored in succeeding chapters examining the thermal performance of selected case study buildings.

In addition to solar control, the mitigation of conduction gains, ventilation and infiltration gains and internal gains was also examined. The performance of conduction gains was found to be highly dependent on the exposure and performance of the building envelope. A smaller building surface area led to reduced gains, whereas increased insulation reduced the influx of gains through the fabric. On the other hand, ventilation gains were found to depend on the difference between the outdoor and indoor temperature; this necessitates the control of ventilation when the outdoor temperature is higher than that indoors. On the other hand, infiltration gains were found to be dependent of the airtightness of the building. This is particularly important when designing for AC buildings to prevent a reduction in cooling system efficiency. Internal gains control was attributed to occupants, artificial lighting and equipment. These could be tackled using space and occupancy controls as per the building design requirements.

Following the implementation of heat gain controls, where ambient temperatures are still too high for thermal comfort, the next logical step was suggested to be the provision of cooling. These cooling strategies offer opportunities to improve indoor ambient comfort conditions for occupants while reducing energy consumption during overheating periods. The strategies reviewed as part of this study included air movement, thermal mass, night ventilation, ground cooling, evaporative cooling and dehumidification. Of these strategies, air movement was deemed to be the most effective; this is because it worked to expel heat build-up and to provide physiological cooling for occupants. To enable adequate air movement, the provision of cross ventilation, driven by local winds and in some cases temperature buoyancy forces, is required. With this in mind, suitable placement of fenestration openings should be made to ensure adequate cross ventilation.

In addition to air movement, the role of thermal mass and night ventilation was also highlighted. Although not usually recommended for warm humid climates (due to small diurnal temperatures), recent studies have shown that there is the potential to apply them; and especially in office buildings (owing to occupancy patterns). The performance of thermal mass in warm humid climates in particularly interesting considering that the predominant local vernacular Swahili architecture (introduced in Chapter 1 and covered in greater detail in Chapter 3) appears to be significantly heavyweight. Further, diurnal temperatures of 6°C in Mombasa (as revealed by previous analysis of climate data in Chapter 1) indicates that both thermal mass and night cooling strategies are potentially suitable for local office buildings.

The suitability of ground cooling, evaporative cooling and dehumidification in hot and warm humid climates does not appear to be high. Additionally, evidence has shown that these strategies would potentially require the input of mechanical or active means to work adequately. It is suggested that their application in office buildings in Kenya would require further in depth review and testing which is out of the scope of this thesis.

Further, a review of energy efficiency regulation in Singapore, Australia and Brazil, showed a similarity of approach to some extent. Normally, these energy efficiency guidelines were inclined to a local context and in some instances, direct comparison was not feasible. For instance, solar correction factors or solar heat gain coefficients are dependent on location and are therefore not transferable. A common factor was that energy efficiency regulations generally aimed to provide guidelines that target the alleviation of heat gain, provision of cooling and result in a reduction in energy consumption. Other objectives included the integration of renewable energy sources and the use of energy efficient equipment.

In addition, it was found that energy efficiency regulation tended to be either prescriptive, performance based or trade-off/simulation in nature. It was noted that rigid prescriptive regulations (*e.g.* ETTV, EEI and IC) were more the preserve of AC buildings where indoor conditions are usually maintained within small temperature ranges irrespective of fluctuations outdoors. On the other hand, performance based regulation and simulations allow for greater flexibility and therefore endear themselves more towards naturally ventilated buildings.

One aspect that appeared to be unduly ignored was the role of thermal comfort in energy efficiency regulations. This is in spite of the fact that thermally comfortable buildings translate into improved indoor thermal conditions. In turn, this would reduce the need for energy consuming climate control measures used to improve indoor conditions. Given the increased acceptance of adaptive comfort, it is suggested that localised studies would go a long way in informing standards that target energy efficiency in Kenya. Generally, these energy efficiency regulations gave an indication of the feasibility of energy efficiency regulations in other developing countries within the hot and warm humid region. In as much as the effect of regulation cannot be isolated from other factors, particularly economic ones, it is acknowledged that their implementation does result in significant improvements to energy efficiency in buildings, as has been the case in Singapore, Australia and Brazil.

Also, the integration of environmental assessment methods was determined to be a useful framework within which designers could checklist aspects related to energy efficiency. A similar method was adopted for guidance recommendations prepared later in this study. Similarly, these assessment tools also promote certification or labelling of buildings that has had the effect of further encouraging integration into the market sector.

Overall, the introduction of energy efficiency regulation in these countries has been shown to facilitate the improved performance of buildings (by promoting suitable design strategies) with the aim to achieve reduced energy consumption. Similarly, all the countries reviewed display the potential to meet goals set out to improve energy efficiency by way of voluntary regulation (to begin with) and mandatory regulation (for greater enforcement). These indicated the potential feasibility of developing energy efficiency regulations in other developing countries such as Kenya.

3 VERNACULAR CASE STUDY: THE OLD POST OFFICE

Swahili architecture forms one of the distinct typologies found in the warm humid region of Kenya. In this chapter, a critical appraisal of the Old Post Office - a typical mixed-use vernacular Swahili building located in Mombasa, Kenya - is presented. Following an intensive field study including a post-occupancy evaluation, subsequent analysis of monitoring data is conducted and conclusions are drawn regarding the environmental performance of the building. From this, Swahili-inspired design strategies are identified and proposed to be potentially suitable for application in typical office buildings in Mombasa.

3 VERNACULAR CASE STUDY: THE OLD POST OFFICE

The Old Post Office building is located along Sir Mbarak Hinawy Road and adjacent to the Government Square in Old Town, Mombasa (Figure 3-1). Encapsulated in an irregular rectangular plan form, the Old Post Office building comprises of two main levels as shown in Figure 3-2, Figure 3-3 and Figure 3-4. Originally, the building had a small bridge spanning over Mbarak Hinawy road on its eastern side that connected it at first floor level to a neighbouring building that housed the postmaster's office (Mombasa Municipal Council and National Museums of Kenya, 1990). This was found to be common in old Swahili settlements where houses had bridges or annexes connecting to adjacent houses owned by extended family members (Ghaidan, 1975, Donley, 1982). The other building has since been demolished, as have any remnants of the bridge.

Figure 3-1 Part urban plan of the Old Town in Mombasa highlighting the location of the Old Post Office building (author-modified from Google Maps).

Figure 3-2 Old Post Office front facade.

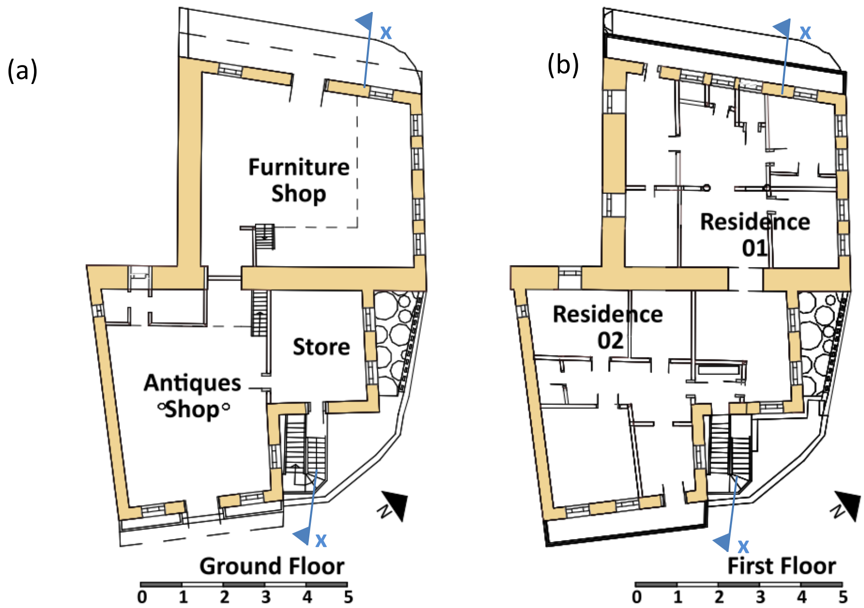


Figure 3-3 Old Post Office (a) ground and (b) first floor layouts.

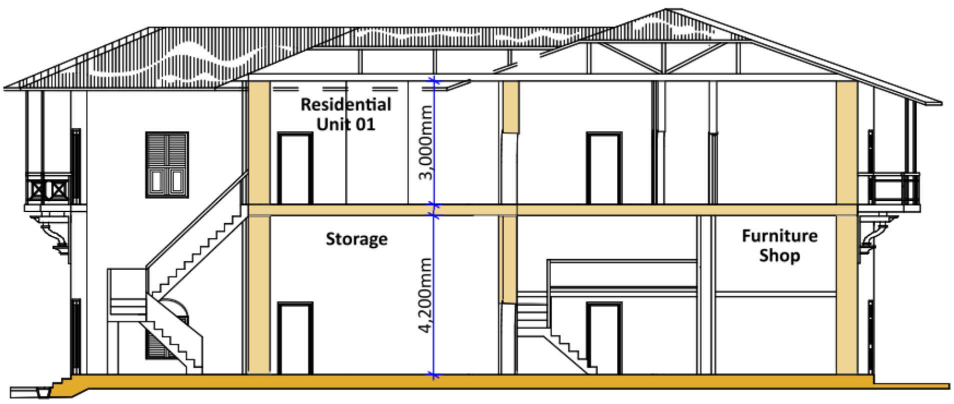


Figure 3-4 Longitudinal section of the Old Post Office building (section x-x in Figure 3-3).

In 1899, the building was officially opened to the public to accommodate a post office, later it also served as a trolley terminal station. The building also served as a temporary immigration office during the First World War period. In 1941, the postal services were relocated to another building in the Treasury Square and use of the trolley service discontinued. Today, the Old Post Office houses an antiques and furniture shop on the ground floor level and two residential flats on the first floor (Figure 3-3).

The Old Post Office has been identified by the National Museums of Kenya (NMK) as a key building of interest within the Old Town conservation area; a factor which is attributed to its typical Swahili architectural style, historic use and central location (overlooking the Government Square and next to the Old Port). Although the building has seen better days, it is in relatively good condition in comparison to a significant number of Swahili buildings in Old Town that have either been extensively modified or are in a great state of disrepair. Recent efforts led by the Mombasa Old Town Conservation Office (MOTCO), under the NMK, and in collaboration with the Old Town community are working towards rehabilitating houses in the Old Town conservation zone.

3.1 The Building Design

Due to the lack of availability of suitable building information all the layouts, detail drawings, sketches and other illustrations of the Old Post Office building presented as part of this study were prepared by the researcher based on site measurements and observations.

3.1.1 Building Use, Form and Layouts

Architectural features typical to vernacular Swahili architecture, as highlighted in Chapter 1, were evident in the Old Post Office building and its immediate surroundings (Figure 3-5). To begin with, an examination of the general street fabric indicated that the irregular rectilinear form of the Old Post Office fit in well within the existing dense urban fabric. Typically, streets in Old Town are narrow with irregularly shaped buildings tending to be closely packed; as a result they often provide mutual shading too.

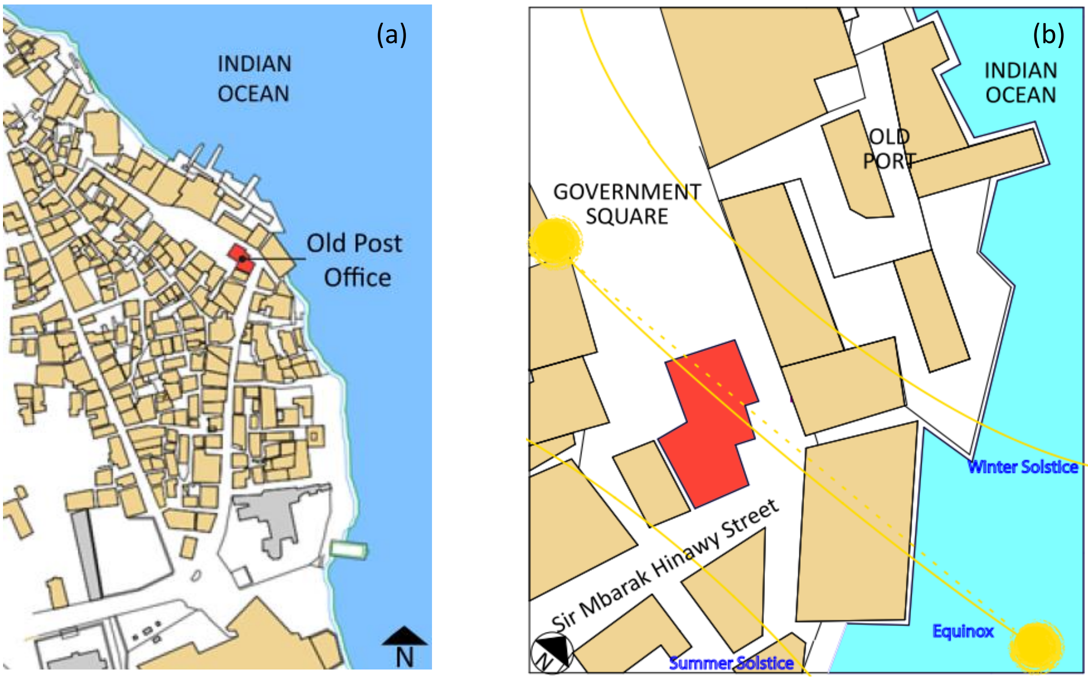


Figure 3-5 (a) Partial urban layout of the Old Town Conservation area. Note the tightly packed and irregular-shaped buildings. (b) Location of Old Post Office building highlighted within the sectional plan with superimposed sun-path (author-modified from Google Maps).

The ground floor zones of a significant number of vernacular Swahili buildings situated along the main streets of the Old Town conservation area are considered semi-public in nature and are often used to accommodate commercial activities (Mombasa Municipal Council and National Museums of Kenya, 1990). This ground floor space use often 'spills out' into the street where the shaded streets and outdoor spaces become a public 'living room'.

In the Old Post Office building, all of the ground floor area is allocated to commercial activity (see Figure 3-6). An antiques shop fronts Sir Mbarak Hinawy Road on one side and a furniture workshop and shop (unoccupied during the study period) opens into the Government Square on the other. With a ground floor to ceiling height of approximately 4.2m on the ground floor, both shops each have a small mezzanine area at approximately 2.1m floor level that is used to accommodate administrative activities and provide extra storage space. The only access to the first floor is through an external staircase, on this floor rooms have a floor to ceiling height of approximately 3.3m. The first floor is divided into two residential flats; one of which is occupied by the current building manager and owner (Residence 01) and one which was unoccupied at the time of the study (Residence 02). It was noted that the unoccupied sections of the building were empty due to ongoing changes in tenancy.

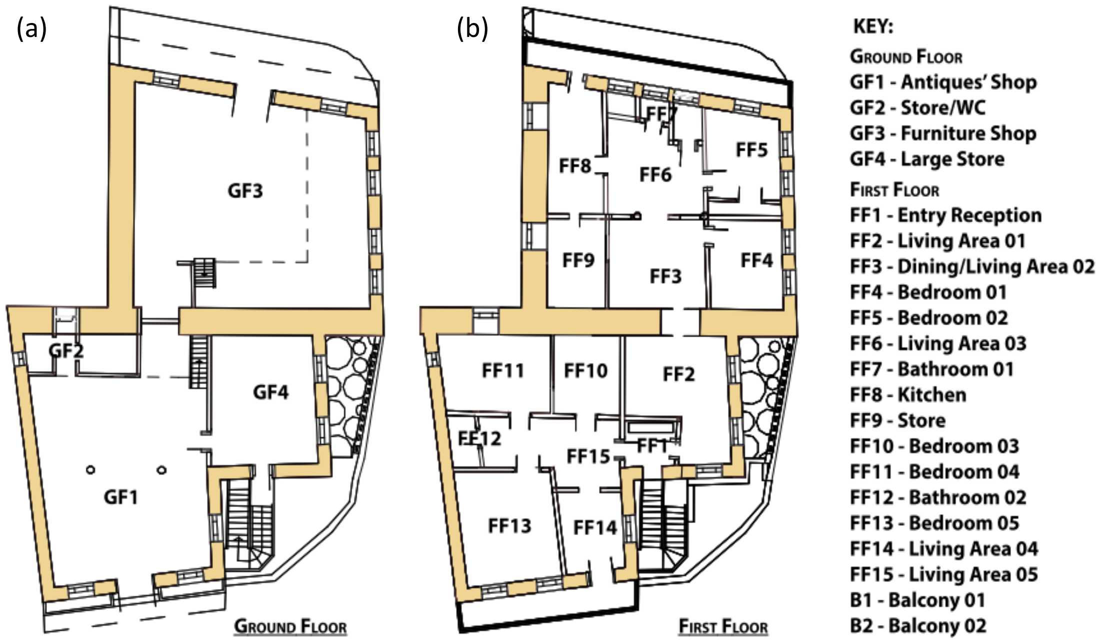


Figure 3-6 Space use on the (a) ground and (b) first floor of the Old Post Office building.

In addition, a pattern of the building usage including information on occupancy and operation times was identified during the study period and illustrated in Table 3-1.

Table 3-1 Space Use in the Old Post Office

Floor	Space allocation	Number of occupants	Occupancy times
Ground Floor	Antiques Shop	6 'permanent' occupants during the weekdays and 3 'permanent' occupants during the weekends (varies depending on number of customers)	0800hrs to 1800hrs (7 days a week)
Ground Floor	Furniture Shop	Unoccupied during the study period	Not applicable
First Floor	Residence 01	5 occupants (varies during the day)	24hrs (7 days a week)
First Floor	Residence 02	Unoccupied during the study period	Not applicable

One of the most prominent architectural features identified in the Old Post Office building were the ornate timber balconies that enriched the main facades. Made entirely of timber, these balconies were found to feature carved balustrades and brackets that serve to enhance their decorative nature (Figure 3-7 and Figure 3-8). Later in this chapter, balconies and their screens are explained to play a significant role in cutting down solar radiation. Other notable features included the use of frieze plaster work, heavy carved solid timber doors and timber window shutters, all of which served to animate the facades (Figure 3-8).

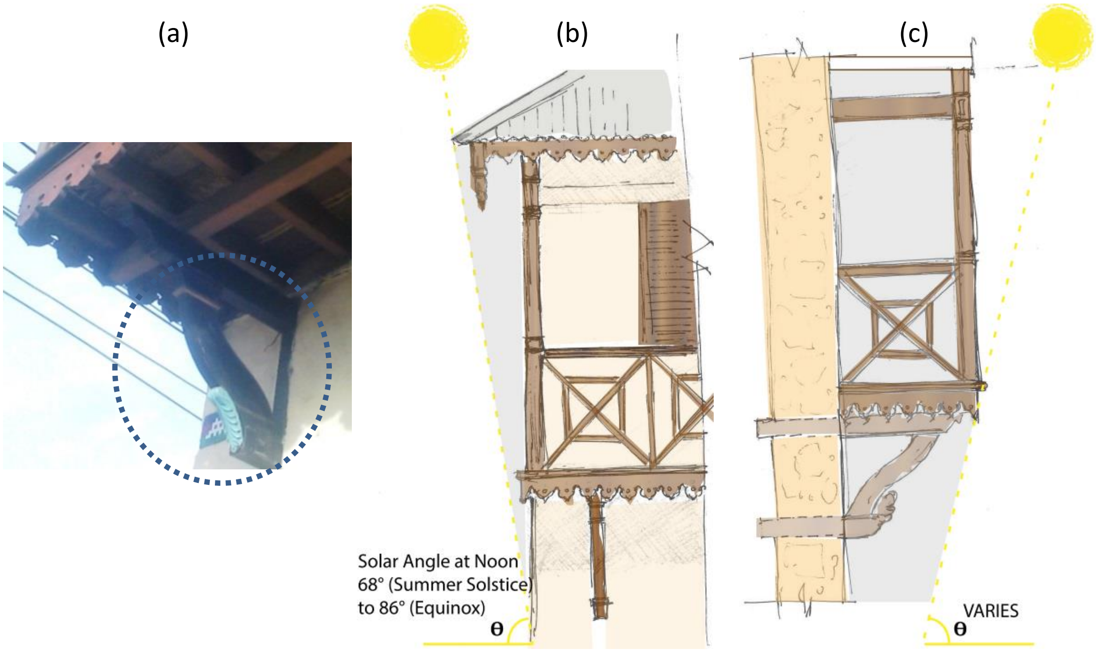


Figure 3-7 (a) Underside of one the balconies showing the attention to detail in the design of the highly decorative balcony elements. (b) and (c) Sketches showing detailing to balconies.

Figure 3-8 a) View from Mbarak Hinawy Road showing the entrance into the antiques shop. b) View from Government Square showing the entrance into the furniture shop.

3.1.2 Materials and Construction Methods

Coral happens to be one of the most prolific building materials found on the East African coast (Ghaidan, 1975). Thick coral rag walls make up one of the main defining characteristics of vernacular Swahili architecture. Usually, uncoursed coral stone blocks (derived from hard terrestrial coral) would be packed into timber formwork and bonded with the lime mortar to help bind the stones together to form the typically thick walls. These walls are then finished off with lime plaster and lime wash (Figure 3-9). Typically, these walls were constructed to be between 400mm to 560mm thick (Ghaidan, 1975, p.24); in the case of the Old Post Office building, external walls were up to 730mm thick. Coral was also used in the embellishment of walls, where soft reef coral is used to create decorative friezes externally and internally (Figure 3-10).

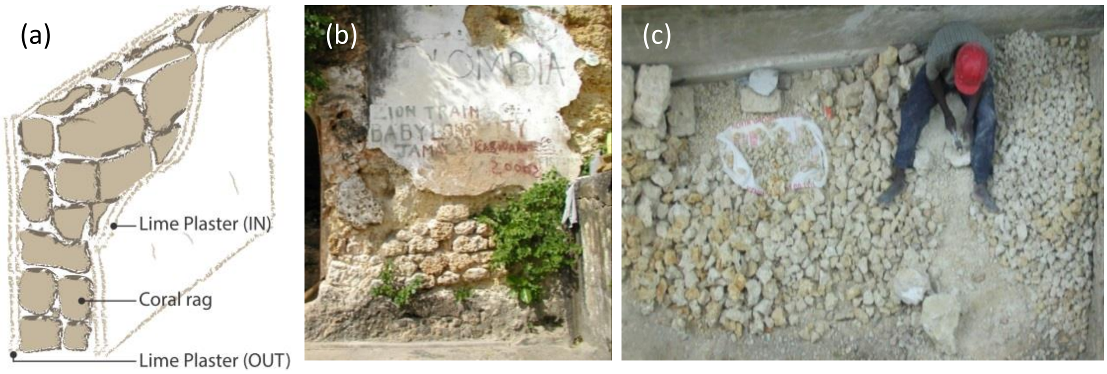


Figure 3-9 (a) Sketch profile of a typical coral rag wall. (b) Exposed coral stone work. (c) A local mason breaking down coral blocks into smaller blocks for a plaster repair job.

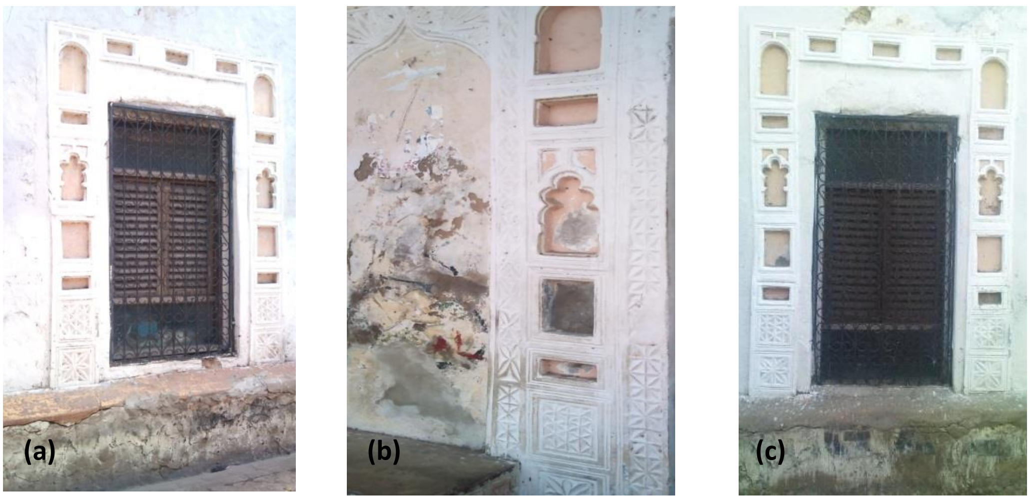


Figure 3-10 (a, b and c) Decorative friezes frame window and door openings on ground floor level.

The ground and first floor slabs consist of coral rag with a lime screed and coral stone tile finish; the first floor also has an additional layer of timber slats and beams underneath (exposed into the ground floor) (Figure 3-11). Given the insulation properties of timber, it is suggested that the addition of this exposed timber layer serves to provide added insulation to the ground floor spaces against conduction gains from the top floor.

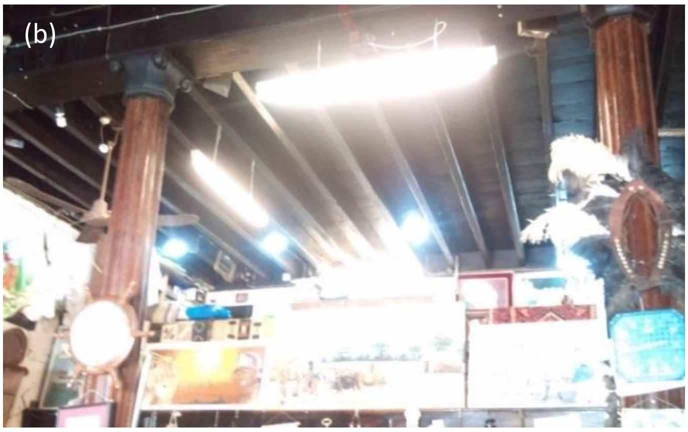


Figure 3-11 (a) View of the first floor ceiling exposed timber layer. (b) Timber column supports on the ground floor.

As with coral, timber was used quite extensively in the construction of individual structural and non-structural elements found at the Old Post Office. They include the aforementioned ceiling beams and slats, balconies, window shutters, doors and staircases. The type of timber used consists mainly of teak, a hardy hardwood which is readily available locally (Mombasa Municipal Council and National Museums of Kenya, 1990).

Although not found to be a common architectural feature in typical vernacular Swahili buildings, the ground floor antiques shop features two internal timber columns that support the main central beam. It was suggested that the use of the timber columns allowed for a larger open floor span which was not entirely typical in vernacular Swahili buildings. Indeed, Ghaidan (1975, p.50) reveals that older houses in Lamu (an older Swahili settlement found on the Kenyan coast) had characteristic room spans of 2.7 to 3.0m. Ghaidan explains that these room sizes were restrained by the spanning limitations of mangrove poles. Mangrove poles are a readily available structural reinforcement material commonly used in the coastal region of Kenya (Chapter 1).

Given the resemblance of the timber columns used in the Old Post Office to the typical ionic style column, albeit in timber, it is possible that this approach may have been as a result of influence from British colonialists who settled in the region in the late 1800s during the establishment of what was then referred to as British East Africa (Jewell, 1976). Similar to the interactions of the local people with immigrants from the Middle East and Asia (Chapter 1), the architectural influence of the British is prominently displayed in a number of buildings in Mombasa (Figure 3-12).

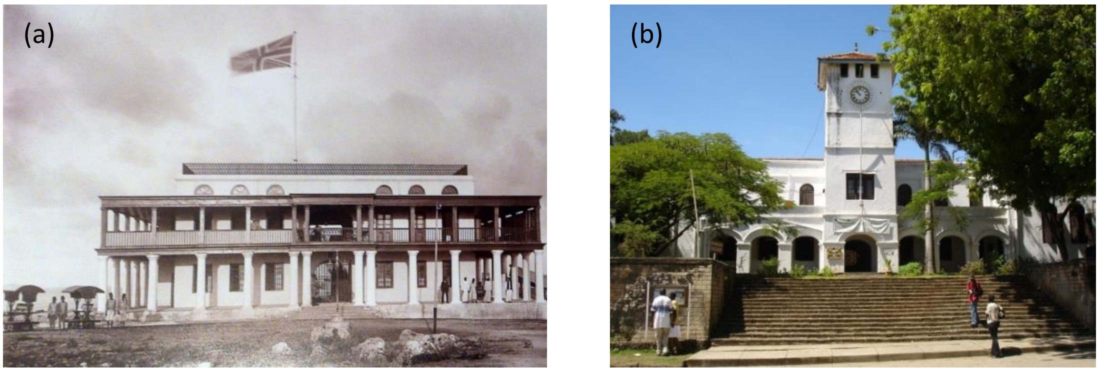


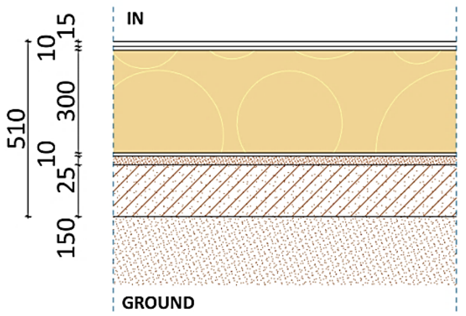
Figure 3-12 (a) The Provincial Commissioner's house, built in the early 1900s (image courtesy of Kenya Railways Authority). (b) The Old Law Courts (opened in 1902) showcasing influence of British occupation on local architecture.

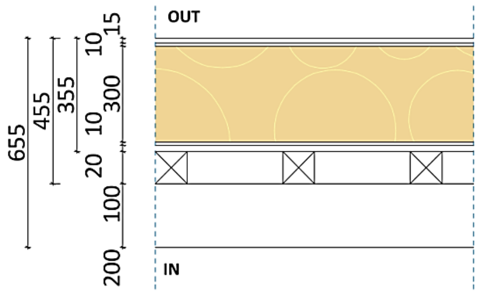
The Old Post Office roof is made of corrugated iron roofing sheets on a timber frame. Like most other buildings in Old Town with similar roofs, evidence of some corrosion is visible. This is understandable given high salt content in the atmosphere of coastal regions (Koenigsberger et al., 1973). The ceiling of the first floor level below is made up of soft board or timber board ceiling (zone FF2 only, reference Figure 3-6). Unlike the ground floor level ceiling which has significantly more insulation by virtue of its combined coral and timber construction, the first floor spaces appear significantly less protected from the impact of heat transfer from the roof attic. Originally, the attic was ventilated via open gable ends; however, these openings have now been partially sealed up on both ends thereby compromising ventilation. The combination of these two factors brings into question the potential impact on indoor temperature levels and particularly on the first floor level. This question, among others, was posed later in this chapter on the review of monitoring data.

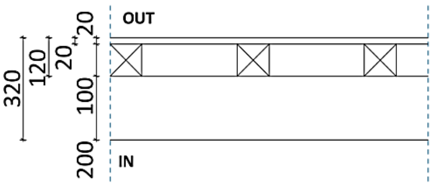
Table 3-2 presents an illustrated overview of the aforementioned Old Post Office building materials. It is noted that these construction details were prepared by the researcher as part of this study based on site observations. Using Thermal Analysis Software (TAS) by EDSL (EDSL Tas, No date) and Dynamic Thermal Properties Calculator (a free Microsoft Excel tool used for calculating the thermal properties of construction elements) developed by Arup for The Concrete Centre (The Concrete Centre, 2010), the u-values of the different constructions were calculated. Majority of the constructions were found to have relatively low u-values and high admittance values; this was an indication of significant thermal mass, and suggested that conduction heat transfer through the building envelope would be reduced.

As the main construction had significant decrement delay periods, it was expected that this ensured that peak heat gains passing from the outer to inner surfaces would not get through until late evening or night periods. Having moderated the risk of overheating during the day time hours, night cooling could be used to offset the effect of the warmer surface and flush out conducted heat. This is of particular interest given the prevalence of strong solar radiation in Mombasa. It is noted that although indoor and outdoor temperatures may sometimes show small differences, the impact of sol-air temperature might actually cause a significantly higher temperature (Koenigsberger et al., 1973).

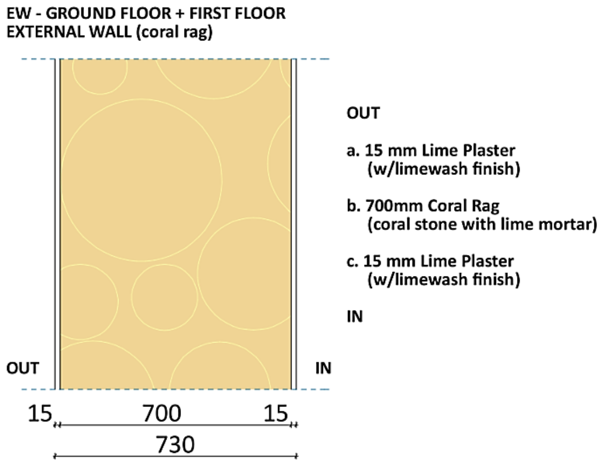
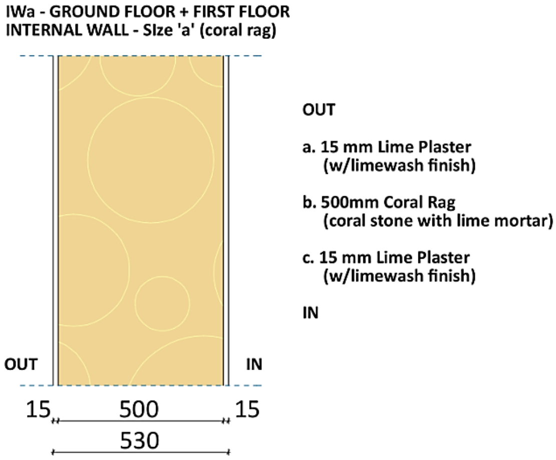
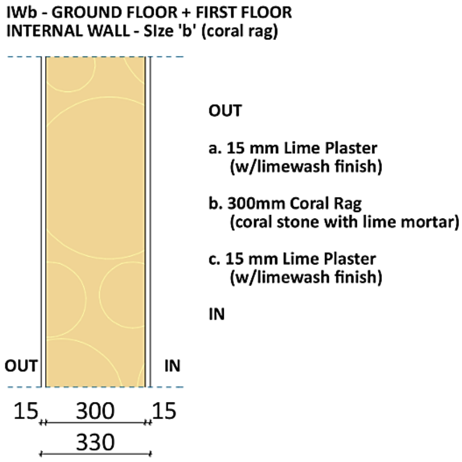
Table 3-2 Old Post Office construction element table (author-generated during field study).

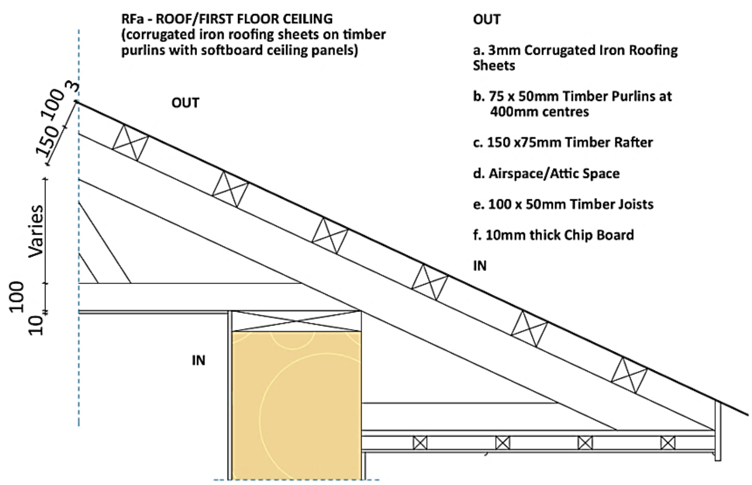
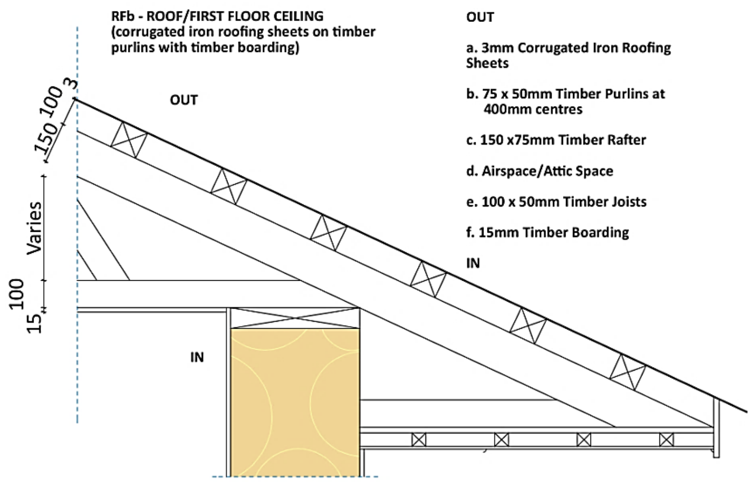
<table>
<tr><th colspan="3">Floor Slabs</th></tr>
<tr><td rowspan="5">GF - GROUND FLOOR (coral rag)


IN
a. 15mm Coral Stone Tile
b. 10mm Lime Screed
c. 300mm Coral Rag (coral stone with lime mortar)
d. Hessian Cloth
e. 25mm Sand Blinding
f. 150mm Hardcore
g. Ground
GROUND</td><td>Thickness (mm)</td><td>510</td></tr>
<tr><td>U-value (W/m^2K)</td><td>0.92</td></tr>
<tr><td>Admittance (W/m^2K)</td><td>3.93</td></tr>
<tr><td>Time lag (Decrement delay in hours)</td><td>14.45</td></tr>
<tr><td>Decrement Factor</td><td>0.12</td></tr>
<tr><td rowspan="5">FF - FIRST FLOOR/GROUND FLOOR CEILING (coral rag with timber boarding underside)


OUT
a. 15mm Coral Stone Tile
b. 10mm Lime Screed
c. 300mm Coral Rag (coral stone with lime mortar)
d. Hessian Cloth
e. 20mm Timber Boarding
f. 100 x 50mm Timber Joists at 400mm centres
g. 300 x100mm Timber Beam
IN</td><td>Thickness (mm)</td><td>Varies (see image)</td></tr>
<tr><td>U-value (W/m^2K)</td><td>0.74 (at 355mm)</td></tr>
<tr><td>Admittance (W/m^2K)</td><td>3.93</td></tr>
<tr><td>Time lag (Decrement delay in hours)</td><td>Not Applicable (indoors)</td></tr>
<tr><td>Decrement Factor</td><td>Not Applicable (indoors)</td></tr>
<tr><td rowspan="5">MF - MEZZANINE FLOOR (timber deck)


OUT
a. 20mm thick Timber Floor Board
b. 100 x 50mm Timber Joists at 400mm centres
c. 300 x100mm Timber Beam
IN</td><td>Thickness (mm)</td><td>Varies (see image)</td></tr>
<tr><td>U-value (W/m^2K)</td><td>2.42 (at 355mm)</td></tr>
<tr><td>Admittance (W/m^2K)</td><td>0.58</td></tr>
<tr><td>Time lag (Decrement delay in hours)</td><td>Not Applicable (indoors)</td></tr>
<tr><td>Decrement Factor</td><td>Not Applicable (indoors)</td></tr>
</table>

<table>
<tr><th colspan="4">Walls</th></tr>
<tr><td rowspan="5">
</td><td>Thickness (mm)</td><td>730</td><td>530</td></tr>
<tr><td>U-value (W/m^2K)</td><td>0.45</td><td>0.61</td></tr>
<tr><td>Admittance (W/m^2K)</td><td>4.01</td><td>3.89</td></tr>
<tr><td>Time lag (Decrement delay in hours)</td><td>9.37</td><td>23.8</td></tr>
<tr><td>Decrement Factor</td><td>0.00</td><td>0.02</td></tr>
<tr><td rowspan="5">
</td><td>Thickness (mm)</td><td colspan="2">530</td></tr>
<tr><td>U-value (W/m^2K)</td><td colspan="2">0.58</td></tr>
<tr><td>Admittance (W/m^2K)</td><td colspan="2">3.89</td></tr>
<tr><td>Time lag (Decrement delay in hours)</td><td colspan="2">Not Applicable (indoors)</td></tr>
<tr><td>Decrement Factor</td><td colspan="2">Not Applicable (indoors)</td></tr>
<tr><td rowspan="5">
</td><td>Thickness (mm)</td><td colspan="2">330</td></tr>
<tr><td>U-value (W/m^2K)</td><td colspan="2">0.86</td></tr>
<tr><td>Admittance (W/m^2K)</td><td colspan="2">3.92</td></tr>
<tr><td>Time lag (Decrement delay in hours)</td><td colspan="2">Not Applicable (indoors)</td></tr>
<tr><td>Decrement Factor</td><td colspan="2">Not Applicable (indoors)</td></tr>
</table>

<table>
<tr><th colspan="3">Roof</th></tr>
<tr><td rowspan="5">
</td><td>Thickness (mm)</td><td>Varies</td></tr>
<tr><td>U-value (W/m^2K)</td><td>3.18*</td></tr>
<tr><td>Admittance (W/m^2K)</td><td>-</td></tr>
<tr><td>Time lag (Decrement delay in hours)</td><td>-</td></tr>
<tr><td>Decrement Factor</td><td>-</td></tr>
<tr><td rowspan="5">
</td><td>Thickness (mm)</td><td>Varies</td></tr>
<tr><td>U-value (W/m^2K)</td><td>3.18*</td></tr>
<tr><td>Admittance (W/m^2K)</td><td>-</td></tr>
<tr><td>Time lag (Decrement delay in hours)</td><td>-</td></tr>
<tr><td>Decrement Factor</td><td>-</td></tr>
<tr><td colspan="3">* As heat gain is anticipated from the zenith, the U-value is calculated downwards.</td></tr>
</table>

3.2 Environmental Design Strategies

It has been suggested in previous sections of this chapter that different aspects of the Old Post Office building appear to lend themselves to solutions that promote climate-responsive design. This was also highlighted in a paper written as part of this study where the analysis of vernacular Swahili architecture revealed its suitability of plan, form and fabric characteristics (Kiamba et al., 2014). In this section, these environmental design elements and the design strategies to which they apply as identified during the field study period are highlighted (Figure 3-13). Later in this chapter, data collected during this study period was also examined to give an indication of effectiveness of the identified strategies.

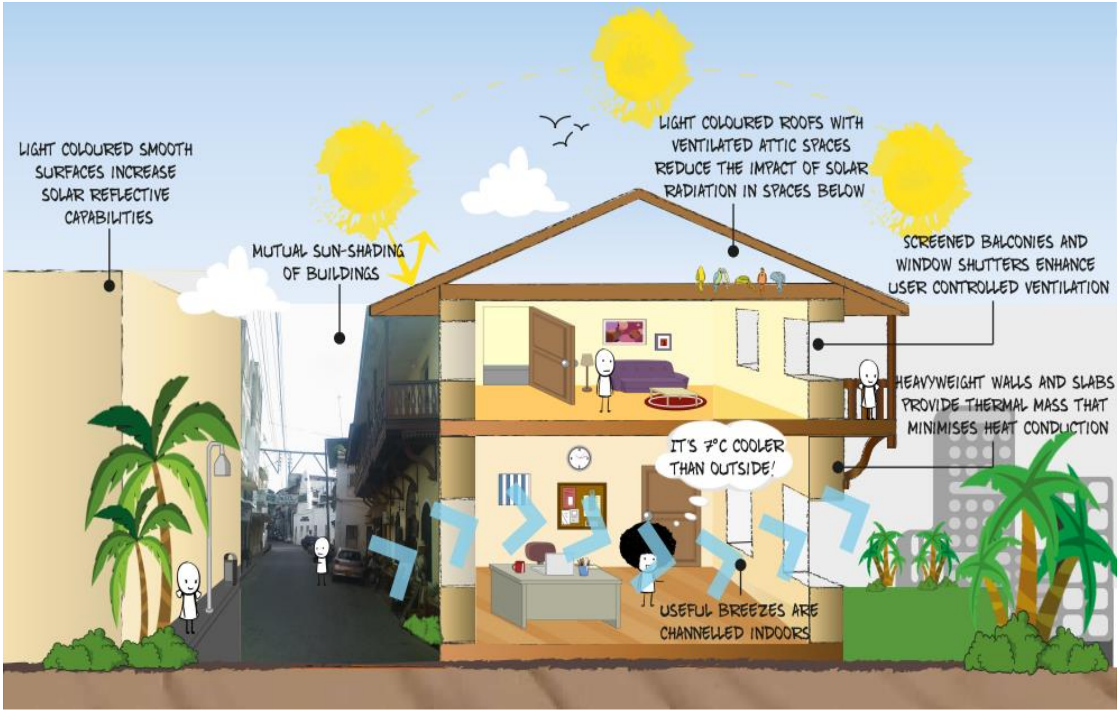


Figure 3-13 Environmental design strategies applied to the Old Post Office.

3.2.1 Building Orientation/Positioning and Mutual Shading

In warm humid climates, the thermal environment of buildings is significantly influenced by the combination of localised wind direction and sun path with respect to the building orientation. This is because the building orientation may be used to accentuate or attenuate the impact of localised winds or sun path, respectively. If possible, it is recommended for buildings within this climatic region to have elongated plan shapes, with the longer sides open to the prevailing wind direction to admit cooling winds (Chapter 2).

The response to the requirement for wind channelling is evident in the vernacular Swahili settlements of Mombasa and Lamu, where streets are laid out to channel incoming sea breezes along the streets and through the buildings (Ghaidan, 1975).

Subsequent work by Deogun et al. (2013) and field studies conducted as part of this study have revealed this to be a logical assumption.

The Old Post Office building has its longer axis running along the north-west and the south-east (Figure 3-14). The longer side of the Old Post Office building was found to be laid out almost perpendicular to the predominant winds (localised winds blow from the north-east and the south-east) (Figure 3-14). Correspondingly, majority of the windows were found to be positioned on the eastern side of the building. Naturally, this positioning would enhance the channelling of cooling breezes indoors. Further to this, the main living spaces on the residential first floor were found to be strategically placed to take advantage of this positioning of window openings and the general building orientation. This was found to work particularly well in March (warmest month) when the majority of the strongest winds were from the south-east.

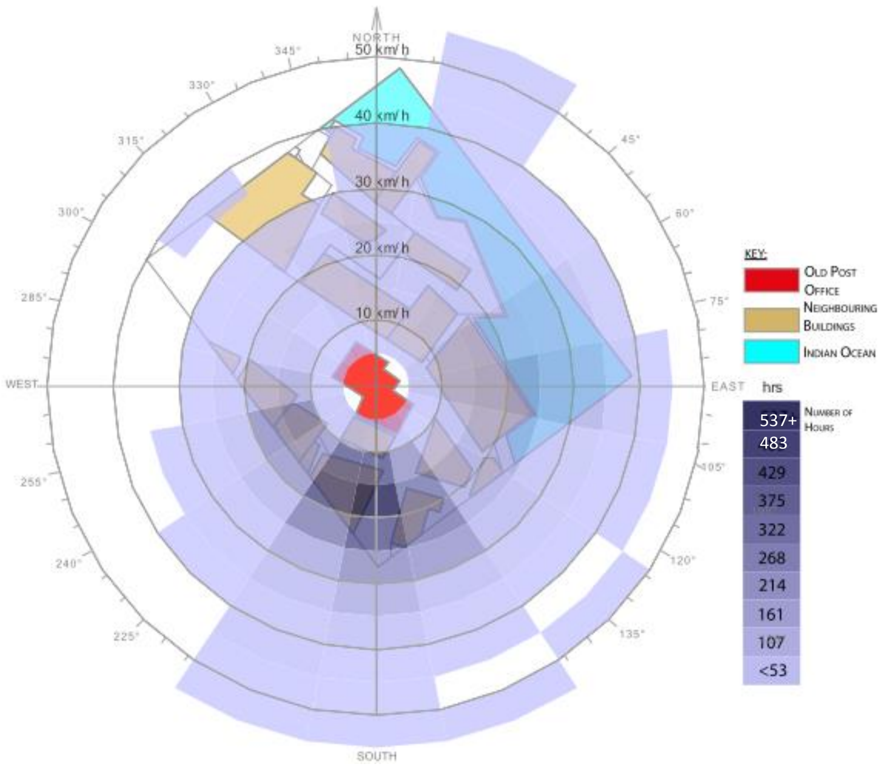


Figure 3-14 Location plan of the Old Post Office with a superimposed annual wind rose analysis diagram.

To reduce the impact of direct solar radiation, it is advisable for buildings along or near the equator to be laid out with the shorter sides facing east and west, and longer facades facing the north and south (Koenigsberger et al., 1973). The superimposition of the Old Post Office building on a sun-path diagram for the given latitude of -4.05° (for Mombasa, Kenya) reveals this to not to be the case (Figure 3-15). From this, it appears that the need to channel ocean breezes and to conform to existing street layouts may have overridden a 'true' east-west alignment. Nonetheless, it is also known that if effective shading is provided for the western and eastern facades, then it is possible to minimise the effect of direct insolation without compromising the channelling of winds. The extent of where and how much shading would be desirable may be determined using suitable analysis methods.

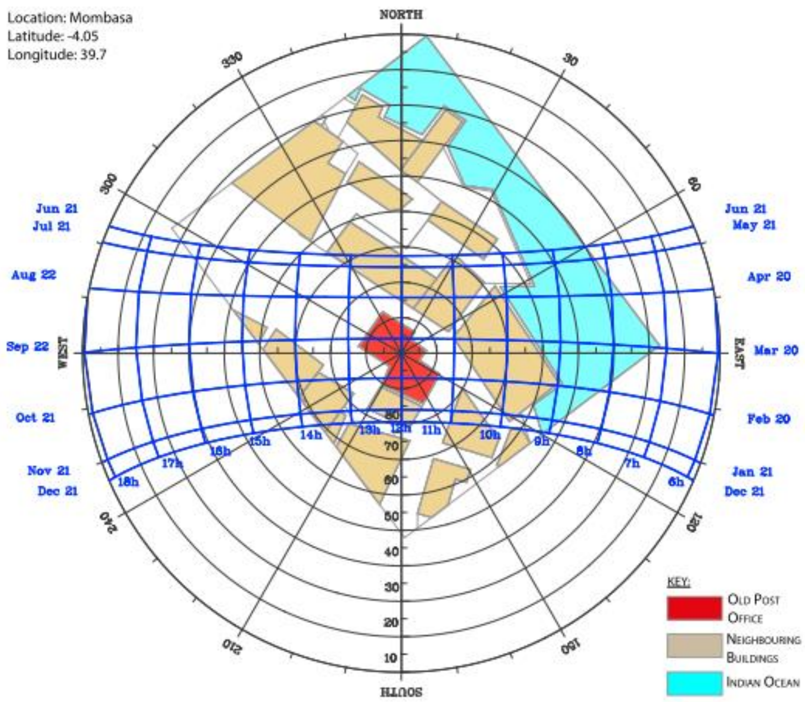
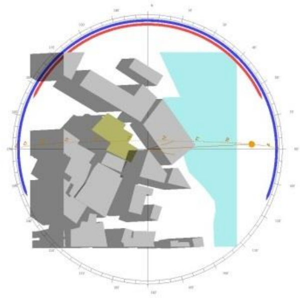
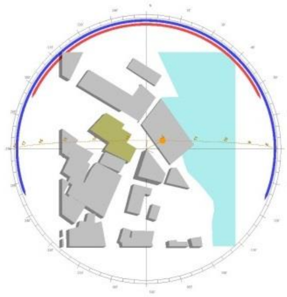
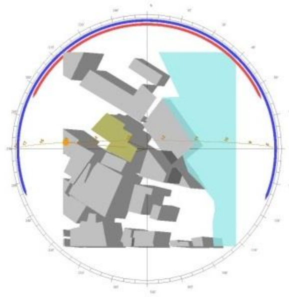
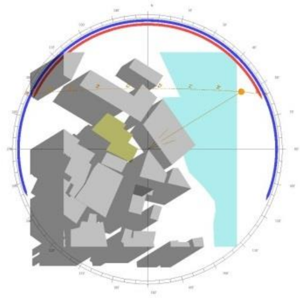
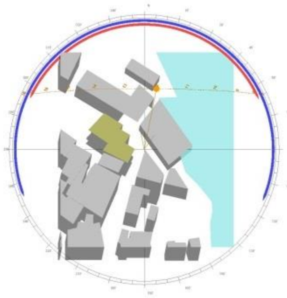
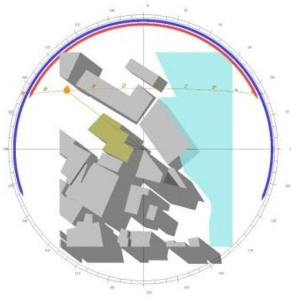
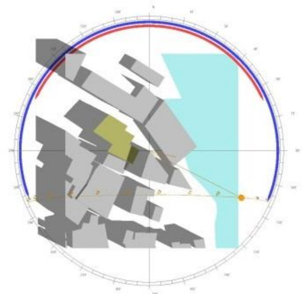
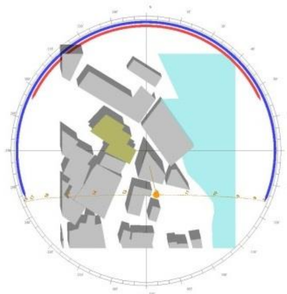
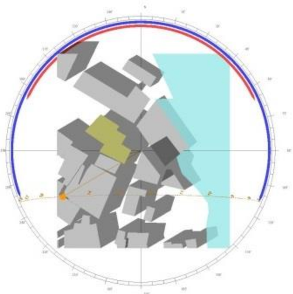


Figure 3-15 Location plan of the Old Post Office with a sun path diagram.

Using Ecotect software, it was possible to track the apparent sun movement over the Old Post Office building based on existing building orientation and reveal the anticipated exposure and the impact of solar radiation faced by the building during various times of the year. An illustration of part of this exercise is presented in Table 3-3 with further analysis conducted in section 3.3.2.

Table 3-3 Old Post Office shadow analysis showing solar altitude angles (SAA) at key times of the year in relation to the Old Post Office building.

	9am	12pm	3pm
Equinox – March 21st	 SAA= 45°	 SAA= 86°	 SAA= 45°
Summer Solstice – June 21st	 SAA= 38°	 SAA= 68°	 SAA= 38°
Winter Solstice – December 21st	 SAA= 43°	 SAA= 70°	 SAA= 43°

Due to the fact that the sun is almost always overheard for a significant portion of the year, the roof surface of the Old Post Office was the most susceptible to solar heat gain. Little in terms of building orientation can be done to control the effect of solar radiation at the zenith. However, structural controls such as the use of a parasol roof or increased insulation can be integrated in the roof design to counter the effect of direct solar radiation on the roof. Further, the ventilation of the attic roof space can be used to 'flush' out warm air build-up as a result of solar gains and prevent the transfer of heat into the spaces below (Koenigsberger and Lynn, 1965).

Next to the roof plane, the most susceptible orientation to solar gain is the western facade (section 1.3). In the Old Post Office, solar gain via the western facade was countered by the building's minimal exposure to the west orientation. This was mainly attributed to close proximity to a neighbouring building and the provision of significantly fewer highly shaded openings. Effectively, this resulted in the provision of shading and minimal solar gain through glazing, respectively. In addition, measuring up to 730mm (almost 200mm thicker than other facades in the building), the western facing wall was significantly thick. Although it was not possible to establish if this was intended solely for solar control purposes, it was acknowledged that the particularly thick wall would work well to curb conduction gains on the critical facade. This might have been particularly useful if the neighbouring building (responsible for a significant amount of shading on the west facade) was non-existent at the time of construction.

Where the aforementioned western facing window or door openings were not shaded by the neighbouring building, a higher percentage of screening was visible (Figure 3-16). It was noted that the habitable spaces of the Old Post Office building were mainly located on the eastern side to channel incoming breezes. Similarly, by placing these habitable spaces in the eastern side, they were less prone to significantly higher solar gain that would be admitted through the western facing walls. Majority of the indoor spaces within the more vulnerable western zone of the Old Post Office housed secondary uses including wet areas and storage.

Figure 3-16 Comparison between the level of balcony screening on the north-eastern facade (a) and the north-western facade (b).

Further, the Old Post Office appeared to be laid out in a nature typical to the densely packed urban layout. This was suggested to play a significant role in enabling neighbouring buildings to partially shade one another, and especially the western sides of the building (see Table 3-3). This shading strategy coupled by fewer fenestration openings on the western sides indicates that there appears to have a been a conscious decision to temper the effect of solar heat gain. Similarly, although solar radiation tends to be less of an issue in the morning periods, the windows on the eastern side also benefit from the mutual shading effect, albeit to a lesser extent.

As has been suggested by various researchers including Givoni (1994) and as was explained earlier in this section, building orientation can be used to control solar gain. However, where enhanced air movement is also required, building orientation is more likely to be designed to meet these requirements. Nonetheless other site and structural characteristics (see Figure 3-17) may be capitalised on to counter the effect of direct solar radiation and allow for adequate channelling of winds for increased air movement.

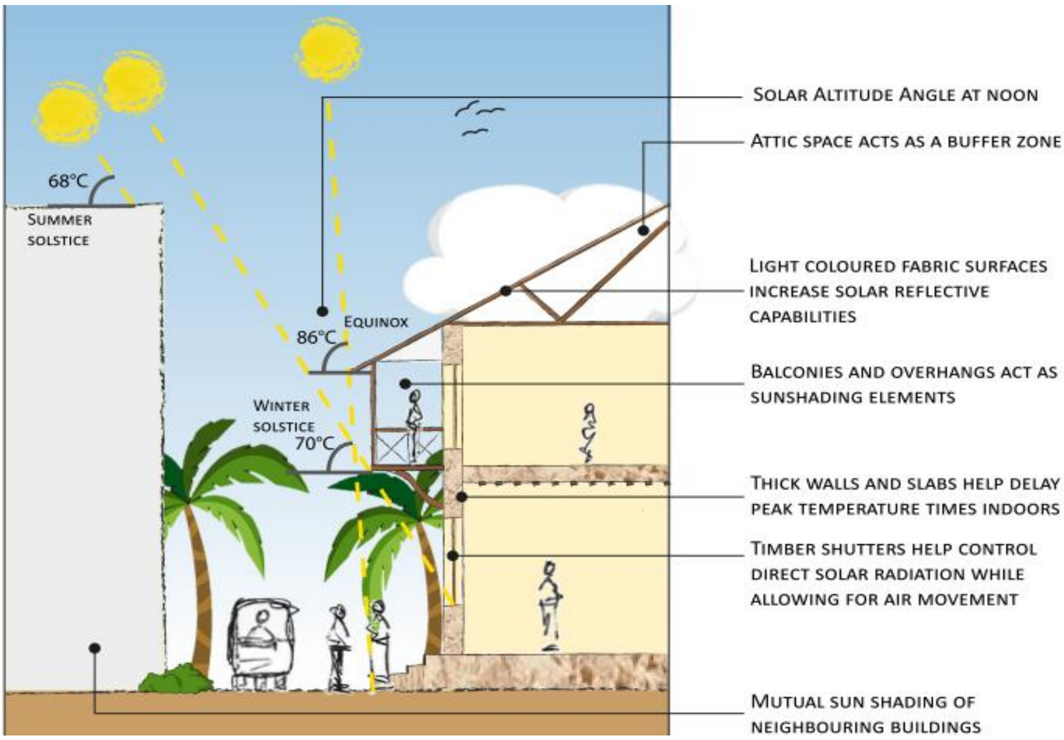


Figure 3-17 Site and structural characteristics for solar control as relates to building orientation.

3.2.2 Outdoor 'living rooms'

The typical Swahili town consists of an irregular maze of buildings arranged in dense clusters with streets measuring an average of 1.5m to 6m wide and punctuated by a series of open spaces, as is shown in Figure 3-18. In most warm climates, a significant number of daily activities take place in these outdoor or semi-outdoor spaces. In the case of Old Town, the streets are often treated as living and working areas, with numerous domestic or commercial activities being conducted within them.

Occupants of the ground floor often sat by the shop front and especially during the afternoons (Figure 3-19), shown later in this chapter to be when outdoor temperatures were at their peak and when local air speed showed a marked increase. Similarly, during a previous field study conducted by the researcher (at a time when the furniture shop was occupied), it was found that their occupants also tended to extend their workspace into the Government Square area to take full advantage of increased air movement.

Figure 3-18 Sectional plan of Old Town, Mombasa.

Figure 3-19 Occupants tend to sit in locations of shade and increased air movement.

Previous climate analysis revealed that the air temperature in warm humid climates is almost always very near to that of skin temperature; therefore, for physical comfort to be achieved then there must be an ample amount of air movement to allow the body to relieve itself through heat dissipation. In section 3.2.1, it was highlighted that streets within Old Town tended to be laid out to capture and channel cooling ocean breezes. Besides being channelled into indoor spaces, this strategy was also found to work to improve outdoor comfort conditions for users of external spaces (Figure 3-20).

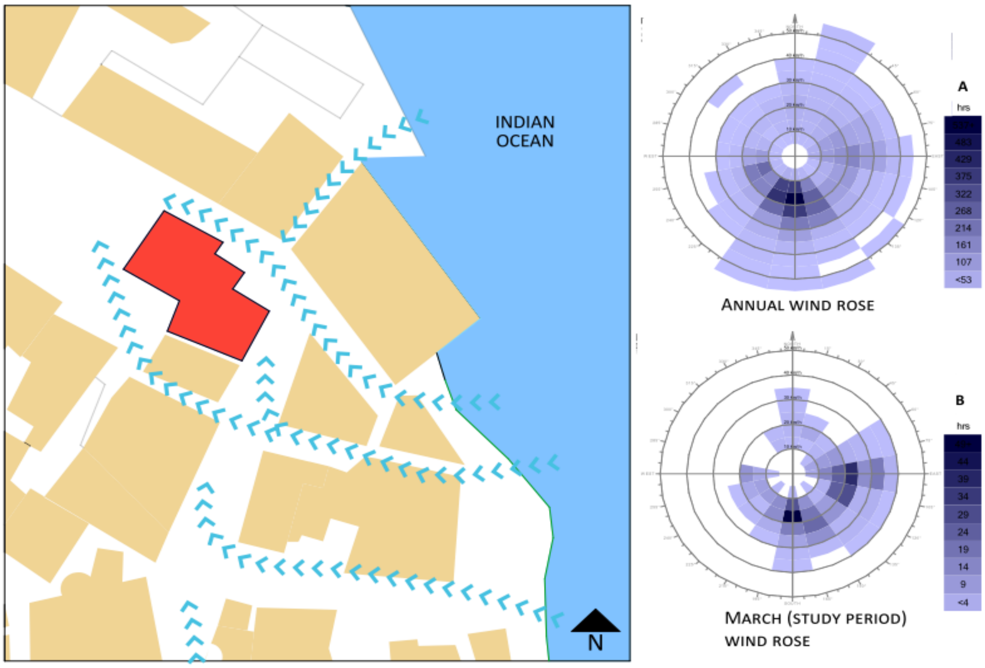


Figure 3-20 General wind direction in the external spaces during the afternoons in March.

In addition to provision for enhanced air movement, shading was found to play a significant role in the design of the outdoor spaces surrounding the Old Post Office building. The provision of shade from the balconies and the neighbouring buildings gave an added advantage to occupants using the immediate external spaces. The extent to which this shading was effective in these external spaces was dependant of the depth of the balconies, the proximity of neighbouring buildings and the size of outdoor space. An illustration of the shading configurations present in the study area are shown in Figure 3-21. With streets of approximately 6m width, the high walls of the neighbouring buildings cut down on the directional solar radiation at certain times of the day thereby allowing the neighbouring buildings to provide providing mutual shading (configuration 1). Similarly, the use of balconies was found to be quite useful in cutting out direct sunlight in the external spaces, and particularly when the sun's position was high in the sky. While using the outdoor spaces, occupants would tend to shift depending on where the shade fell; in some cases this led to them sitting in locations opposite to their buildings.

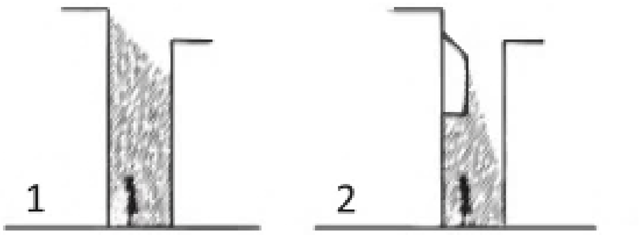


Figure 3-21 Shading configurations found in the general study area.

As with the roof, horizontal paving surfaces are prone to receiving a significant amount of direct solar radiation. More recently, outdoor spaces within the Old Town conservation area were paved using concrete paving blocks. Within the proximity of the Old Post Office building, the hard paving in the square poses a problem to surrounding buildings given its significant size and the fact that little has been done to 'soften' the space by way of using permeable paving or planting to reduce the impact of direct solar radiation (Figure 3-22).

Figure 3-22 The Government Square has extensive hard paving. Before (a) and after (b) pictures reveal softening attempts in the late 1990s to the early 2000s.

Hard paving materials like concrete have the tendency to absorb solar energy and heat generated during the day and re-radiate this at night. As a result of this, the night-time air temperature could remain high (NHBC Foundation, 2012). This has the potential to hamper the effect of night ventilation. Although no detailed measurements were taken to investigate this further, it was suggested that the extensive use of hard paving may result in slightly higher sol air temperature that could negatively affect the performance of surrounding buildings including the Old Post Office.

3.2.3 Balconies

Balconies form one of the main identifiable features of vernacular Swahili architecture. Besides their aesthetic appeal, they were also found to play a significant role in the environmental performance of the typical Swahili building. Generally, balconies in the Old Town conservation area can be grouped into two types based on their screening levels - open and enclosed - both of which were found in the Old Post Office building (Figure 3-23).

Typically, enclosed balconies are heavily screened – allowing for enhanced visual privacy in the balcony space. In Swahili culture, privacy plays a significant role in space making, and especially in domestic zones (Kiamba et al., 2014, Mombasa Municipal Council and National Museums of Kenya, 1990). On the other hand, the typical open balcony lacks the shutter or screen construction. Instead, they tend to have just the decorative fretwork at the top (below fascia board and balcony ceiling level). Typically, the balconies are supported using ornately carved timber brackets, whereas their roofs are made of timber ceiling with a pitched corrugated iron sheet (CIS) cover.

Figure 3-23 (a) Open balcony type (Balcony A). (b) Enclosed balcony types (Balcony B).

The Old Post Office building has two balconies on both main facades. Balcony A (Mbarak Hinawy Road) is an open balcony and does not have any shutters or screens whereas Balcony B (Government Square) is an enclosed balcony and has a variety of screens on the top half of the balcony. In a previous field study, when residence 02 was occupied, it was noted that the occupants had attached fabric screens on the top of Balcony A, a factor that was attributed to the need for visual privacy. Indeed, both the balconies give the users of the top floor spaces visually private or semi-private ‘rooms’ where various domestic activities are conducted (Figure 3-24 and Figure 3-25).

The porous nature of the balconies encourages unrestricted air movement in and around the balcony space as well as into the building. In the Old Post Office, this gives the occupants the benefit of a protected outdoor space without largely compromising the need for air movement in indoor spaces too. The balconies also play an important role of shading the wall and windows of the building. Due to their positioning and their porous nature, the balconies shade the walls immediately behind them but also those below on the ground floor. This is especially useful for cutting down on direct sunlight and glare on the walls and in the indoor spaces.

Overall, balconies were determined to be quite useful elements as they not only enabled large percentage of the wall facades to be shaded but they also did not appear to hinder air movement. Further, balconies were suggested to enable further adaptive opportunity by providing a space when occupants could carry out various activities or just relaxed as they enjoyed the cooling breezes.

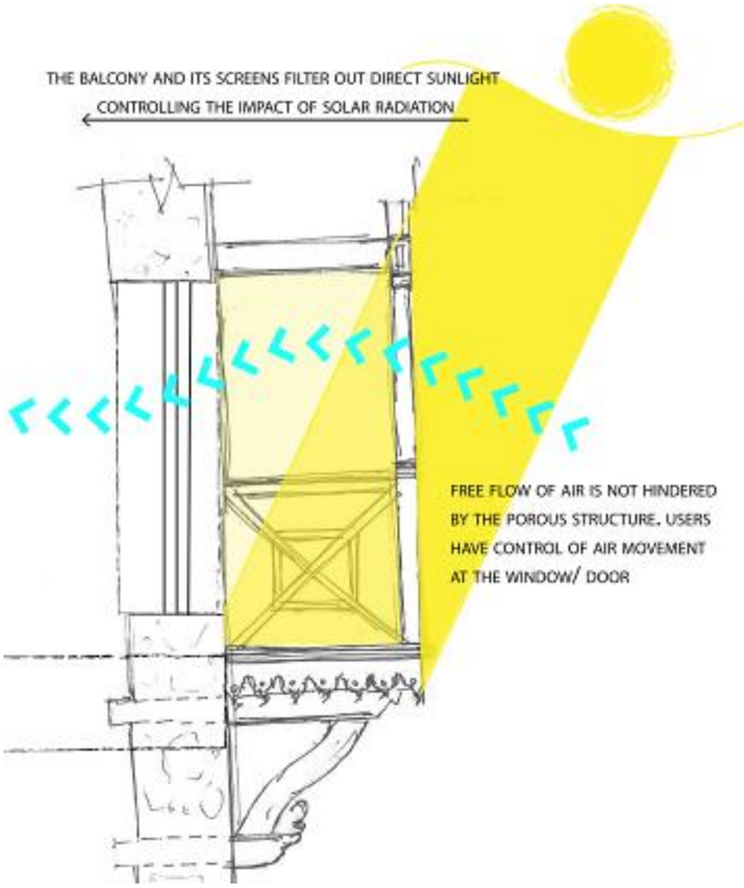


Figure 3-24 Balconies help to reduce solar heat gain without hindering free air flow.

Figure 3-25 View of the outdoor space in Balcony A.

3.2.4 Doors and Screened Windows

Natural ventilation is the prime means of the supply of fresh air and the cooling of the Old Post Office building and its occupants. The manual opening of doors and windows was identified to be the main 'control' method employed by occupants to ventilate the indoor spaces. The periods for which the openings were left open or shut varied as illustrated in Figure 3-26. For doors, 'open' refers to when the door is left ajar. In windows, 'open' may also refer to when the outer panel is shut but windows shutters and the inner panel window are left open with little restriction to air movement.

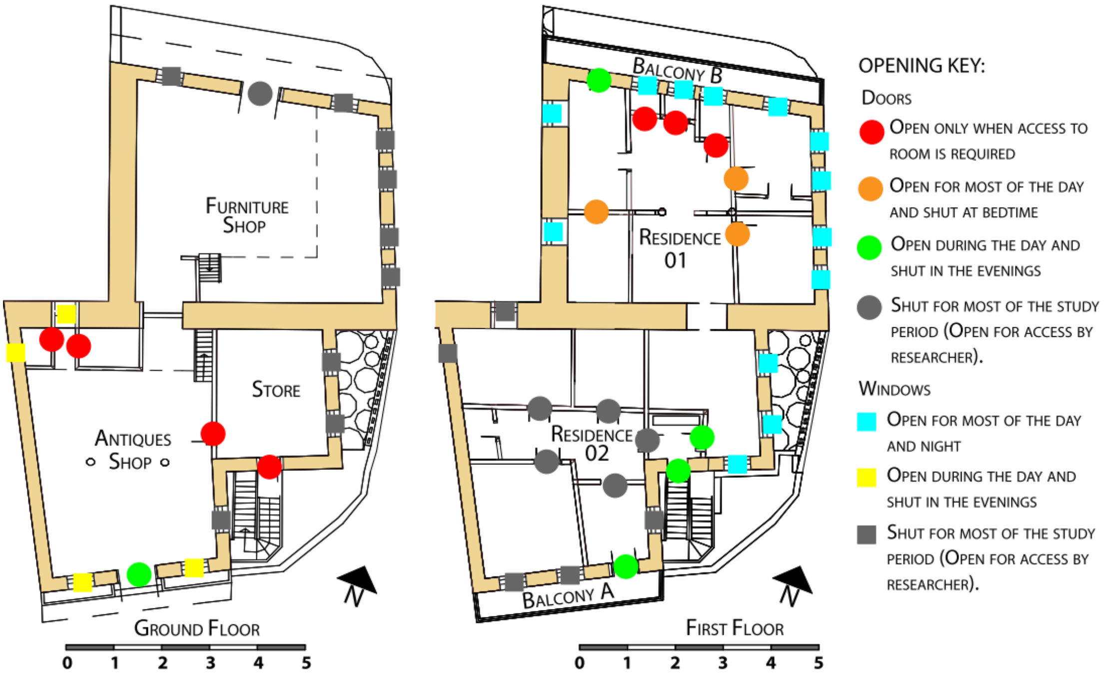


Figure 3-26 Door and window opening schedules (occupant-controlled).

External doors and windows were mostly often left open during the daytime to allow for unrestricted air movement in and out of indoor spaces, with many occupants preferring to sit by them (Figure 3-27). On the ground floor, the external door to the antiques shop (occupied zone) remained open during working hours (0800hrs to 1800hrs). On the other hand, internal doors on the ground floor were usually kept shut; this is understandable as these spaces are non-habitable.

Figure 3-27 Occupants seated by the main door of the antiques store.

On the first floor, the external doors from Residence 01 (occupied zone) to the external staircase and the balcony (balcony B) remained open during the daytime. After dusk, the door to the staircase was shut whereas the door to the balcony B (leading from the kitchen) was usually left open until all the domestic chores were finished (usually until 9pm, and later if the family had guests). For most of the daytime, doors to the bedrooms in Residence 01 remained open, only to be closed after 10pm when occupants often retired to bed.

As mentioned in section 3.2.1, majority of the windows on the Old Post Office building are positioned on the eastern side of the building. This was suggested to be in response to the direction of localised winds. Further, the placement of the main habitable areas within this zone indicated that this was done to take full advantage of natural ventilation. Cross ventilation and single sided ventilation were identified as the main natural ventilation strategies used in the Old Post Office building (Figure 3-28). In the antiques store, cross ventilation was restricted due to the obstruction of one of the main window opening (Figure 3-26). This was suggested to have compromised the effect of natural ventilation in the antiques shop. Nonetheless, the potential effectiveness of cross ventilation and single sided ventilation, assuming all openings were accessible and open able as designed for, was calculated for the Old Post Office building using existing rules of thumb and based on room height and depth dimensions.

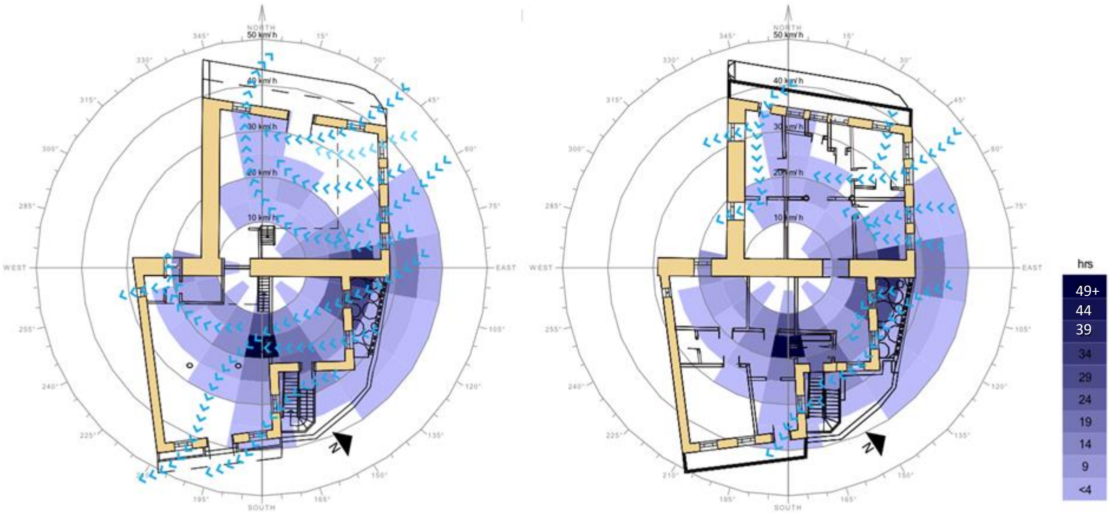


Figure 3-28 Potential for cross ventilation and single sided ventilation on the (a) ground and (b) first floor in the most extreme month, March.

For cross ventilation, a maximum room depth of five times the room height is recommended. This requirement is halved to a maximum room depth of two and a half times the room height for single sided ventilation (Rennie and Parand, 1998), as illustrated in Figure 3-29. Using this calculation method, it was found that the existing ground floor room height of 4.2m would allow for maximum room depths of 21.0m and 10.5m for cross and single sided ventilation, respectively. Similarly, the first floor room height of 3.3m would allow for maximum room depths of 16.5m and 8.3m for cross and single sided ventilation, respectively. With measured room depths ranging from 2.5m to 8m, room dimensions in the Old Post Office were found to fit within the aforementioned rule of thumb requirements. This indicated that the room depths and heights with respect to the given openings were suitable for both cross-ventilation and single sided ventilation as provided.

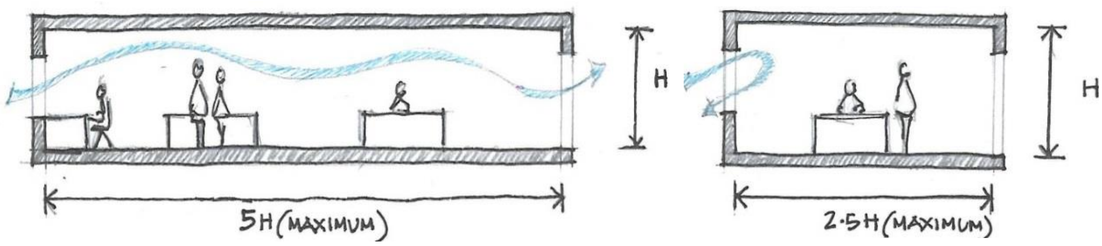


Figure 3-29 Rules of thumb for cross (left) and single sided (right) ventilation.

All habitable rooms in the Old Post Office have one or more windows to facilitate natural ventilation through the spaces. Typically, these windows consist of a double leaf side hung window system that can be adjusted by occupants to regulate indoor conditions for comfort (Figure 3-30). Much like the balconies, the windows give users the opportunity to control both ventilation and shading under different conditions. For instance, to counter driving rain, occupants may open the inner top leaf of a window while leaving the permeable outer shutter leaf shut and the shutters open to allow air permeability. The same strategy may be used to counter potential instances of glare or to provide shading (Figure 3-31). Unlike windows on the first floor that have a half sized decorative and protective grille on the inside of the window system, select windows on the ground floor were found to have a full length external iron grille for security purposes. This being the case, both top and lower window shutters were designed to swing inwards (Figure 3-32).

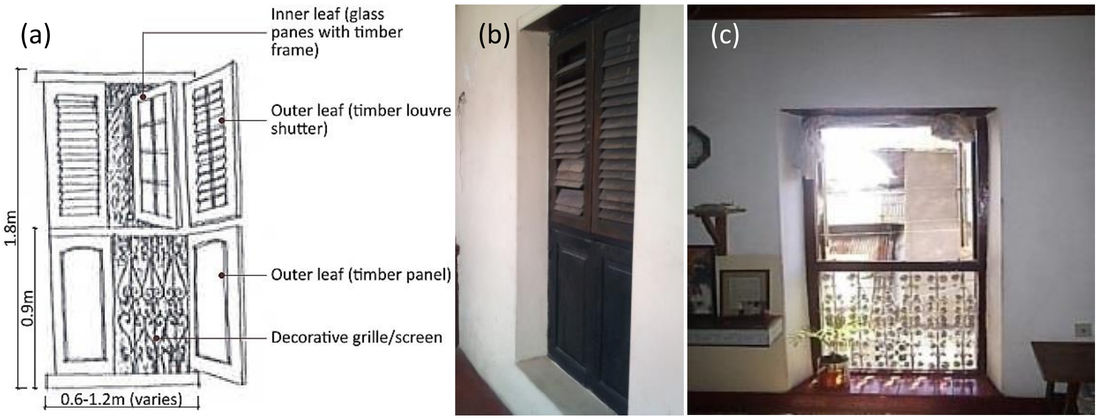


Figure 3-30 (a) Typical window type and components (ground and first floor). (b) External view of a typical window. (c) Internal view of a typical window.

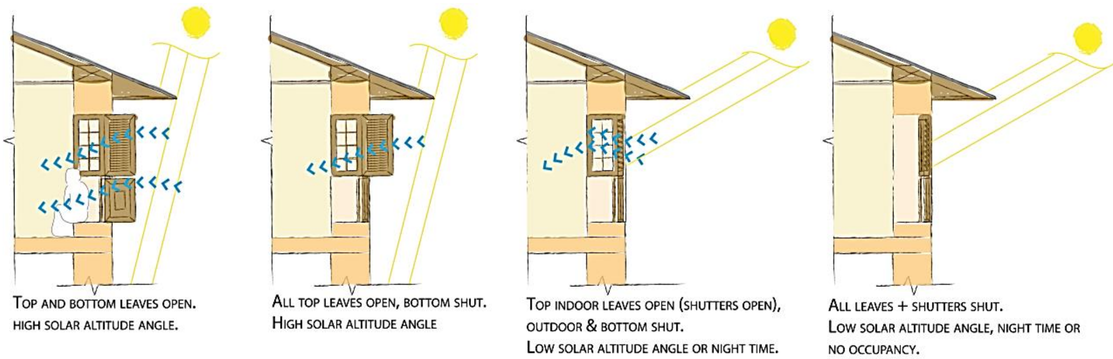


Figure 3-31 Typical window profiles used by occupants to control the impact of air movement and sun shading indoors.

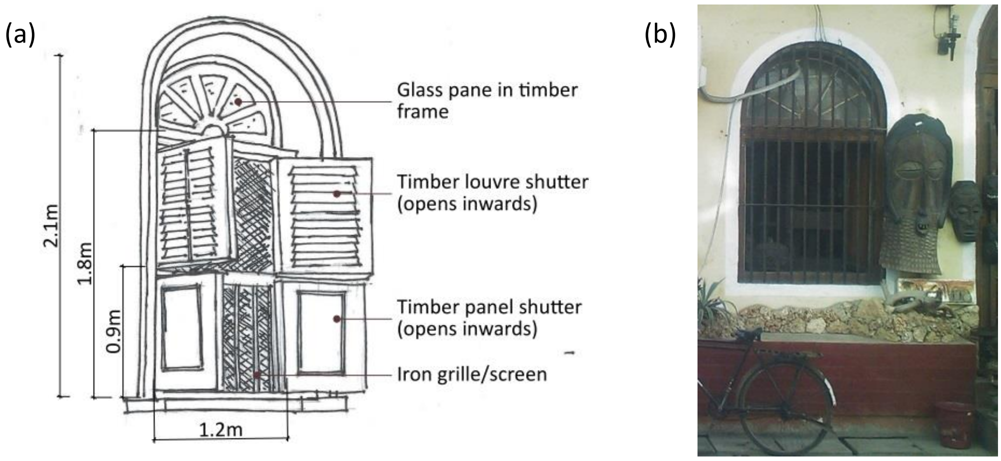


Figure 3-32 (a) Select ground floor window type and components (ground floor only). (b) View of one of the main ground floor windows. Note the raised stone seating area by the window.

The presence of inbuilt door and window seats is fairly common in Swahili buildings (Mombasa Municipal Council and National Museums of Kenya, 1990). Observations of occupant behaviour in the Old Post Office revealed that occupants tended to sit by door and window openings to maximise the effect of the incoming sea breeze on individual comfort during different times of the day. This was more frequent during the afternoon periods when temperatures peaked. The presence of the in-built window and door seats were suggested to offer more adaptive opportunities to occupants by encouraging them to exploit the effect of direct air inflow thereby enhancing physiological cooling (Figure 3-33).

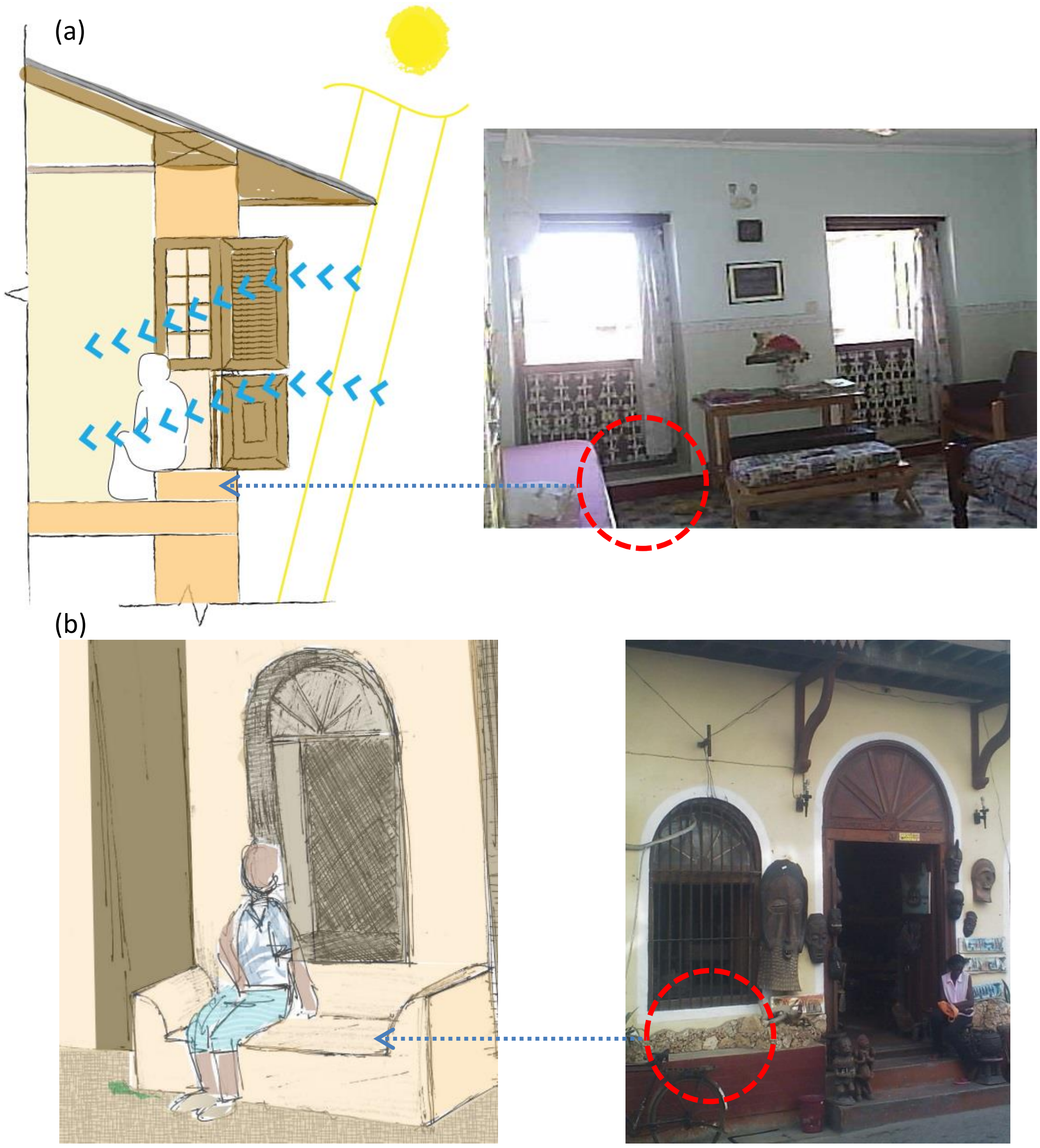
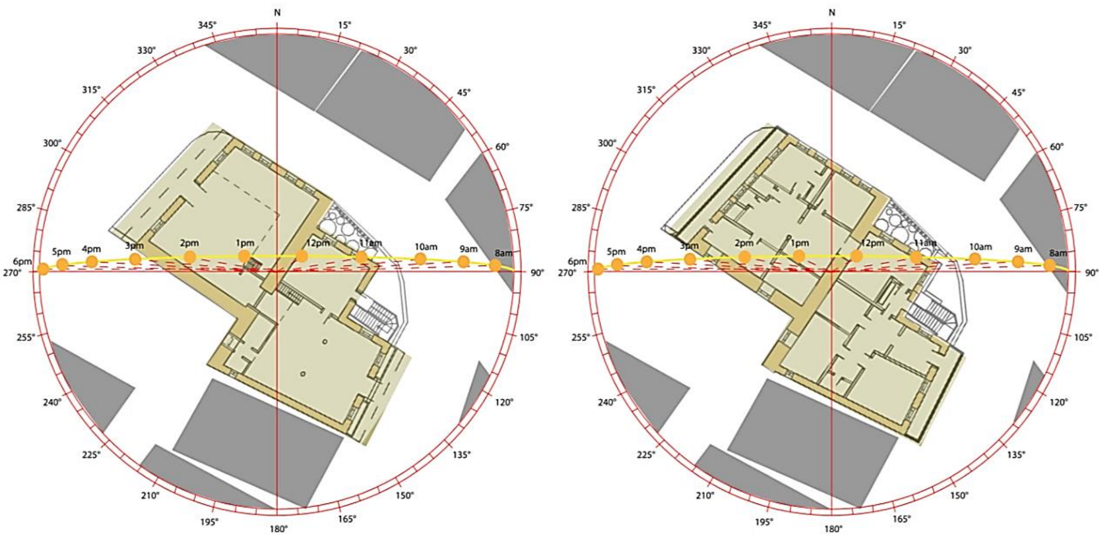


Figure 3-33 Internal and external window seats located at selected first floor (a) and ground floor (b) windows.

All of the habitable rooms were found to have access to natural lighting. In the evenings, low energy fluorescent lighting (provided via a mixture of compact bulbs and tubes) is used. As has been revealed in Chapter 2, suitable building strategies for warm humid climates focus on eliminating direct solar radiation for thermal reasons. In response to this climate requirement, the Old Post Office building bears a high amount of shading (from shading elements and neighbouring buildings). This being the case, it was expected that there would be a chance of reduced direct illumination indoors. Even so, it was suggested that the bright sky experienced in the region would still be adequate in providing satisfactory illumination to indoor spaces

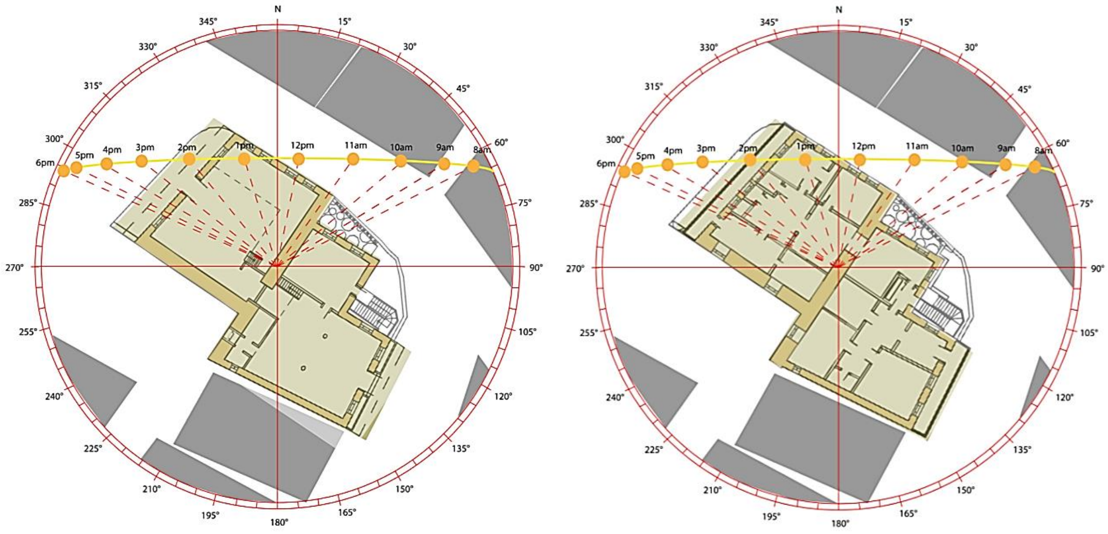
- with consideration for glare. Apart from observations made during the field study process, illumination levels were not quantified during the field study as it was not the main focus of the study. Even so, to get a clearer understanding of the performance of the building, solar ingress analysis was carried out for the Old Post Office building.

From this, illumination levels for spaces within the Old Post Office were found to vary with time of the year, time of the day, room orientation and window operation. A trail of solar ingress was mapped with respect to significant dates of the year for the fenestration openings (Figure 3-34, Figure 3-35 and Figure 3-36). It appeared that for majority of the spaces, few instances of direct illumination via fenestration are possible. This is mainly due to the relative position of the sun for most of the year (almost overhead). Even when the sun is at lower angles, that is during the early morning and later afternoon periods, the effect of shading elements and shading from neighbouring buildings would be expected to restrict the instances of direct sunlight within the selected spaces.



(a) GROUND FLOOR (b) FIRST FLOOR

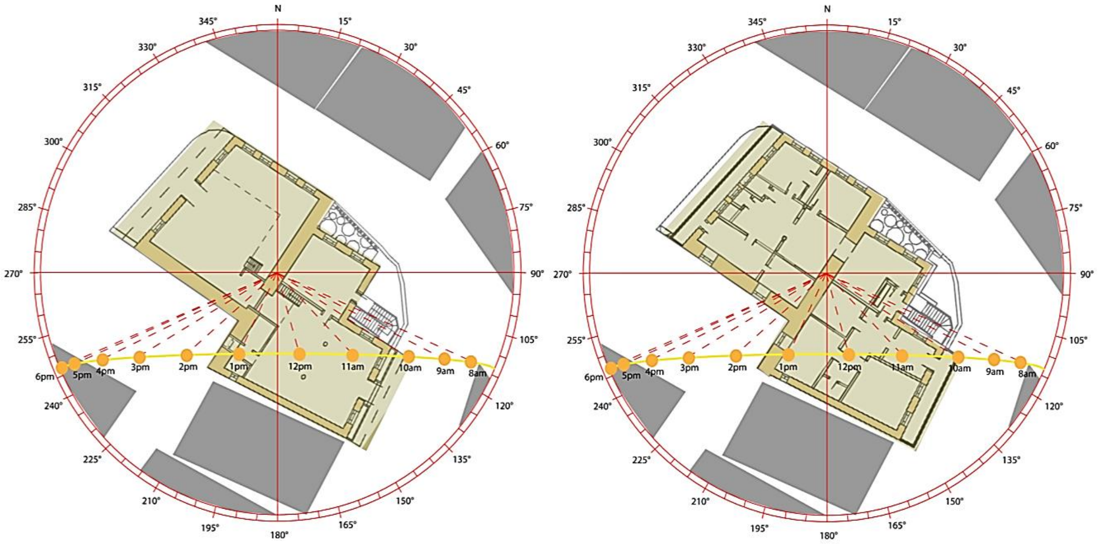
Figure 3-34 Solar ingress into the building during the equinox (a) ground floor and (b) first floor.



(a) GROUND FLOOR

(b) FIRST FLOOR

Figure 3-35 Solar ingress into the building during the summer solstice (a) ground floor and (b) first floor.



(a) GROUND FLOOR

(b) FIRST FLOOR

Figure 3-36 Solar ingress into the building during the winter solstice (a) ground floor and (b) first floor.

The control of the window shutter system also affected the illumination levels. When closed, one could adjust the louvres to allow for the filtering in of diffuse sunlight. As the louvre system consited of dark timber elements, levels of reflection were quite low thereby reducing potential instances of glare. On the other hand, due to the low reflectivity levels, light levels could be greately compromised when windows panels remained shut, even when louvres are open and the sky was overcast.

On the first floor, patches of direct sunlight were notable mainly on the top floor of the eastern zone when the windows panels were fully open during the morning period. This solar ingress was not suggested to cause uncomfortable instances of glare. On the ground floor, it was found that the indoor daylight illumination levels were also affected by the dark timber ceiling and shutters which further reduced the level of reflectivity within the indoor spaces. Nonetheless, whitewashed indoor walls tended to counter this effect leaving the rooms appearing adequately illuminated. Similarly, the white coloured walls and ceiling on the first floor played a similar illuminating role.

Although this was not quantified by site monitoring data, the majority of occupants noted that natural lighting was adequate for day to day activities undertaken within the various spaces. Occupant response with regards to lighting is covered further in section 3.4. Overall, the indoor spaces reveal a drama of sorts with light from the few windows serving to wash the spaces with daylight that reveals shapes and shadows that instantly animate the space. Given the nature of the businesses on the ground floor, the need to supplement daylighting was found unnecessary by the occupants who preferred to showcase their products in a soft lit environment (Figure 3-37). It was suggested that similar illumination levels would possibly be unsuitable for office environments which require greater illumination levels for occupants to carry out day to day tasks adequately.

Figure 3-37 (a) Supplementary lighting effect in the antiques shop. (b) The same space with daylighting.

3.2.5 Thick Walls with Significant Thermal Mass

In section 3.1.2, it was noted that the walls in the Old Post Office building were constructed from coral (Figure 3-38) bonded with lime mortar and finished with lime plaster. The external walls were found to be notably thick with sizes of up to 730mm thick measured during the field study. Internally, walls were less thick and measured between 230mm to 530mm thick. Judging by their seemingly heavyweight nature, it was suggested that the very thick walls might have the potential to minimise heat conduction potential thereby resulting in lower indoor temperatures when peak outdoor temperature occurs. Previous research has suggested that heavyweight buildings, would allow for significantly lower solar heat gains (refer to section 1.4 and 2.2.2). At night, they would then be opened up to allow for sufficient cross ventilation that would in effect get rid of stored heat.

Figure 3-38 Sample of hard terrestrial coral, similar to what was used to build the walls.

A previous field study undertaken by the researcher found indoor temperature in the antiques shop location (GF1, refer to Figure 3-6) to be up to 7°C lower when peak outdoor temperature occurred (Kiamba et al., 2014, Kiamba, 2009). This is despite the low diurnal temperature range that is common in the local warm humid climate. This significant drop in temperature was suggested to be attributed, in part, to the significantly thick walls. The extent to which this is actually due to the thick walls is examined later in this chapter and also in Chapter 5.

It is also important to note that the walls are significantly shaded from direct solar radiation for most of the day. This implies that shading of the thick walls also plays a substantial role in the overall performance of the building. As with the shading, wall surface qualities are expected to influence the solar heat input. It has been found that white or light coloured surfaces often work well in reducing solar heat gain (Koenigsberger et al., 1973). All the external walls of the Old Post Office building are painted white with lime wash on smooth lime plaster finish. White plaster finish can have a relatively high albedo of up to 0.93 (Santamouris, 2013, p.112). The smooth surface and the light colour imply that heat reflectance and dissipation properties of the external wall finishes could contribute to improving overall building thermal performance.

In addition, it was observed that occupants often chose to sit leaning back against wall surfaces. Besides the obvious support benefits, closer investigation revealed that the walls often felt cool to touch. It is suggested that this might imply that the wall surface gave off a radiant cooling effect that was pleasing to occupants. No heat flux measurements were collected during the period of study to quantify this. However, parametric studies presented in Chapter 5 were used to examine the potential impact of 'heavyweight' Swahili thermal mass on the indoor thermal conditions.

3.2.6 Ventilated Roof Attic

In section 3.1.2, the roof profile was revealed to be made up of corrugated iron roofing sheets (CIS), an attic space and a soft board or timber board ceiling below. The function of the roof in this climate context is twofold: to keep out rain and to prevent or reduce solar heat build-up indoors. Rain protection appeared adequate during the field study period, although minor leakages attributed to corrosion were noted. By virtue of its location at the zenith and its lightweight nature, the roof was suggested to be particularly prone to the impact of solar radiation and the resultant heat gain.

As with many other buildings within the Old Town area (Figure 3-39), the lightweight roof in the Old Post Office building is different from what was more common in older Swahili buildings. Oliver (1997b) notes that, originally, flat coral rag roofs in old Swahili towns were covered with pitched palm frond thatched roofs; leaving open gable ends. The resultant attic space (then sometimes used for various domestic activities such as cooking, sleeping, *etc*.) was freely ventilated to effectively reduce the impact of direct solar radiation (Figure 3-40).

Figure 3-39 Aerial view showing the proliferation of CIS roofs across the neighbourhood.

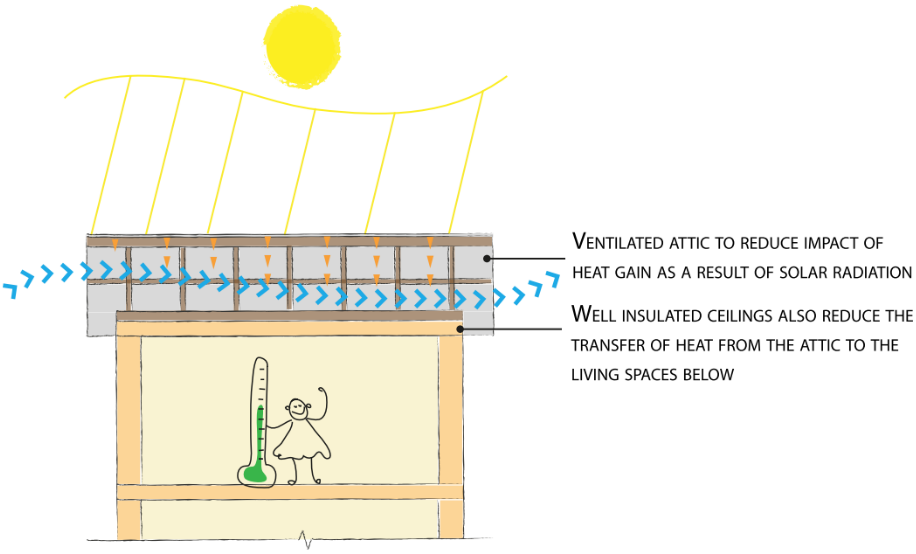


Figure 3-40 Ventilated attic spaces reduce the impact of solar heat gain in the living spaces below.

In hot dry climates, the use of a heavyweight roof is valid as the warmth accumulated in the thick mass can be dissipated during the significantly colder nights. There is the potential to use a similar strategy in warm humid climates and especially when night ventilation is integrated. Koenigsberger et al. (1973) states that the principle of thermal storage cannot be fully relied upon and instead recommends that a well-designed lightweight roof can prevent the indoor temperature from rising above that of outdoors and keep the ceiling surface at the same level as others. Szokolay (2008) suggests that undue increase in the ceiling temperature can be prevented by using a reflective roof surface, forming an attic space to have a separate ceiling, ensuring adequate ventilation of the attic, using a reflective surface on the underside of the roof and resistive insulation on the ceiling.

Of these recommendations, the Old Post Office only meets the requirement of having an attic space. Whereas the roofing may have been highly reflective on installation, years of corrosion have compromised its reflectivity. Similarly, although the building was originally built with open gable ends, these have now been partially sealed up, thereby restricting ventilation of the attic. On further investigation, the building owner explained that the sealing up of the attic was done to prevent birds from accessing the attic. Further, a review of the u-value of the ceiling u-value revealed a relatively high u-value of 4.14 W/m^{2}K (for 10mm thick chipboard); this gave an indication of poor resistivity and a high potential for solar gain.

In an initial field study, the impact of the roof construction on the spaces below was investigated by measuring and comparing indoor temperatures of the spaces below (Figure 3-41). This study found that temperatures in the attic were significantly higher than those on the first floor (up to 4°C) and even more on the ground floor spaces (up to 6.8°C) (Kiamba, 2010b). Also, the attic temperature was almost always as high as or higher (up to 3.1°C) than the corresponding outdoor temperature.

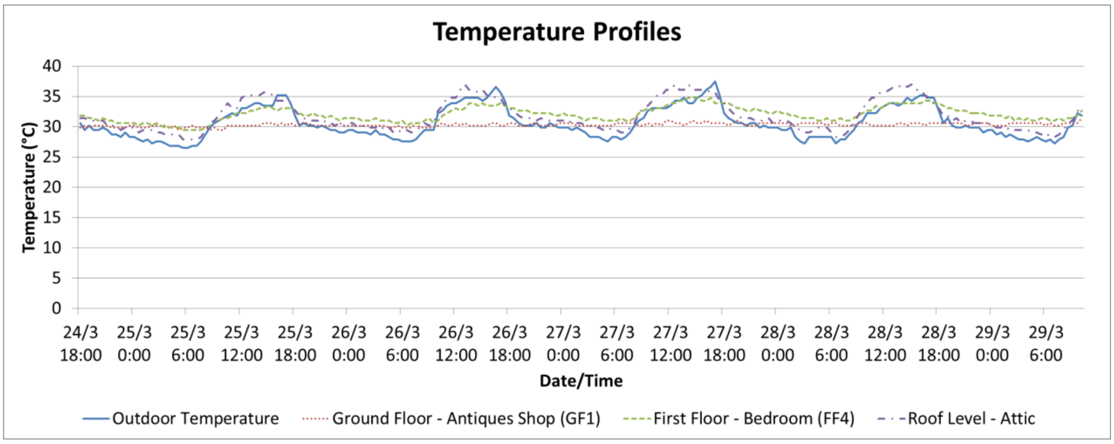


Figure 3-41 Temperature profiles for the Old Post Office building showing temperature stratification across various floors in relation to the roof.

Similar results were found during this field study where temperatures on the first floor remained very close to those outdoors - even where rooms remained unoccupied and windows shut. Besides the orientation and location of the roof that makes it particularly prone to the risk of solar heat gain, it was suggested that this stratification was also due both the lack of adequate ventilation of the attic and poor insulation of the ceiling below. The impact of the thermal performance of the roof element was examined at greater detail in Chapter 5.

3.3 Environmental Data Analysis

A review of the main environmental design elements in the previous section revealed that these design elements mainly fall within the scope of heat gain prevention (solar control and thermal mass) and cooling (natural ventilation) design strategies. Given their similarity to design strategies recommended for warm humid climates (Chapter 2), it was suggested that the vernacular Swahili architecture design strategies could offer useful insights into design for local climate-responsive office buildings. To get a better understanding of how effective these Swahili-inspired design strategies were in contributing to a suitable indoor thermal performance, analysis of site monitoring data was conducted and the results presented.

An intensive site monitoring exercise was conducted during the warmest month of the year (March, 2014). During this period, on-site recordings of selected environmental variables were undertaken to analyse the thermal performance of the Old Post Office building. The main bulk of this data consisted of indoor and outdoor temperature and relative humidity - values which were recorded every fifteen minutes for a period of up to four weeks. Primarily, this data was recorded to analyse the indoor conditions in response to building envelope characteristics and impact on occupant comfort. In addition to this, spot measurements of temperature, relative humidity and air speed were recorded at selected indoor and outdoor locations. This spot data was mainly used to analyse the potential impact of air movement on building thermal performance and indoor thermal comfort.

The choice of data recording instruments (*i.e.* Tinytag data loggers) was largely informed by their ability to provide a continuous record of the environmental variables to give a representation of prevailing environmental conditions. Tinytag data loggers accurately and reliably monitor temperature, humidity, power usage, CO_2 and other environmental parameters (see APPENDIX A part 'i' and part 'ii' for Tinytag technical data sheets). Tinytags include compact units for indoor use and rugged devices for outdoor applications. They monitor a wide range of parameters, and include dual channel loggers are available which simultaneously monitor two parameters such as temperature and humidity. The Tinytag loggers have a large memory size which is useful for long term or intensive recording. The Tinytag data logger range has been manufactured in the UK by Gemini Data Loggers since 1992, and has an established reputation for accuracy and reliability (Tinytag, 2016).

To facilitate the environmental data collection process, five locations within the building were identified for the positioning of temperature and humidity data loggers (Figure 3-42). The loggers were either suspended from the ceiling or placed on surfaces at a height of between 0.9m to 1.5m from the floor surface level. Care was taken to ensure that the loggers were placed in locations with free air movement and away from direct solar radiation and other heat sources. All the selected indoor spaces were naturally ventilated and each had window openings at various orientations. The room sizes ranged between 4.7m^2 (T4a – Residence 02 bedroom) and 19.1m^2 (T1a – antiques shop), approximately.

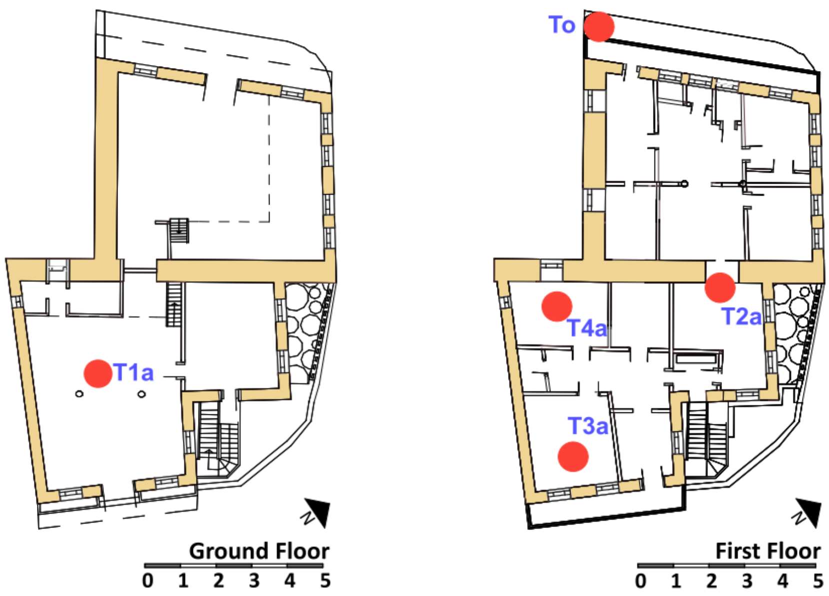


Figure 3-42 Location of temperature and humidity data loggers set up in the Old Post Office.

Locations T1a and T2a were selected as they were the main habitable spaces on each floor of the Old Post Office. A series of spot measurements taken on the first floor level (at a height of approximately 1.2m to 1.5m from floor surface level) indicated that the data collected at T2a was similar to data recorded in the habitable zones of Residence 01. This was possibly due to the occupants of that flat leaving all the adjacent doors to habitable areas open for most of the day.

3.3.1 Air temperature and Relative Humidity

High temperatures typically experienced in warm humid climates can often lead to overheating in poorly designed buildings resulting in the thermal discomfort of occupants. Similarly, relatively high relative humidity levels also experienced in warm humid climates are known to compromise the rate at which one can resort comfort through evaporative cooling (refer to Chapters 1 and 2). As such, the need for air movement for physiological cooling was identified to be especially useful in restoring comfort. In this section, an analysis of air temperature and relative humidity monitored data is presented with respect to the indoor thermal conditions of the Old Post Office. A summary of the main recorded data is presented in Figure 3-43 (dry bulb temperature – DBT) and Figure 3-44 (relative humidity - RH).

The recorded DBT and RH values were found to be fairly representative of those experienced in March in a typical year in Mombasa. A review of the recorded data indicated that the outdoor temperature (T_o) ranged between 26.8°C and 34.3°C. Typically, T_o peaked in the afternoon (approximately 1200hrs to 1500hrs), with the lower extremes recorded during the early morning period (approximately 0500hrs to 0700hrs). Generally, outdoor DBT remained higher than indoor DBT for a significant period of the time during working hours (0800hrs to 1800hrs).

Further, diurnal outdoor DBT ranges were found to be up to 8.4°C. This range was similar to that recorded at previous other field studies carried out by the researcher in March of 2006 and later in March of 2010 (6°C to 7°C) (Kiamba, 2010b). Given that a temperature diurnal range of over 5°C was considered suitable for night ventilation cooling strategy (section 2.2.3), it was suggested that these recorded levels gave an indication of suitability for night cooling.

Indoors, the temperatures ranged between 28.3°C and 34.1°C. The lowest indoor temperature (T_i) was recorded in location T4a in the early morning period whereas the highest T_i was recorded in location T3a during the late afternoon period. Unlike the significant temperature fluctuations recorded outdoors, especially steady conditions were observed in the ground floor location of T1a which had diurnal temperature swings of less than 1°C. There was comparatively less fluctuation of the temperatures recorded in other indoor spaces which had diurnal temperature swings of less than 4°C.

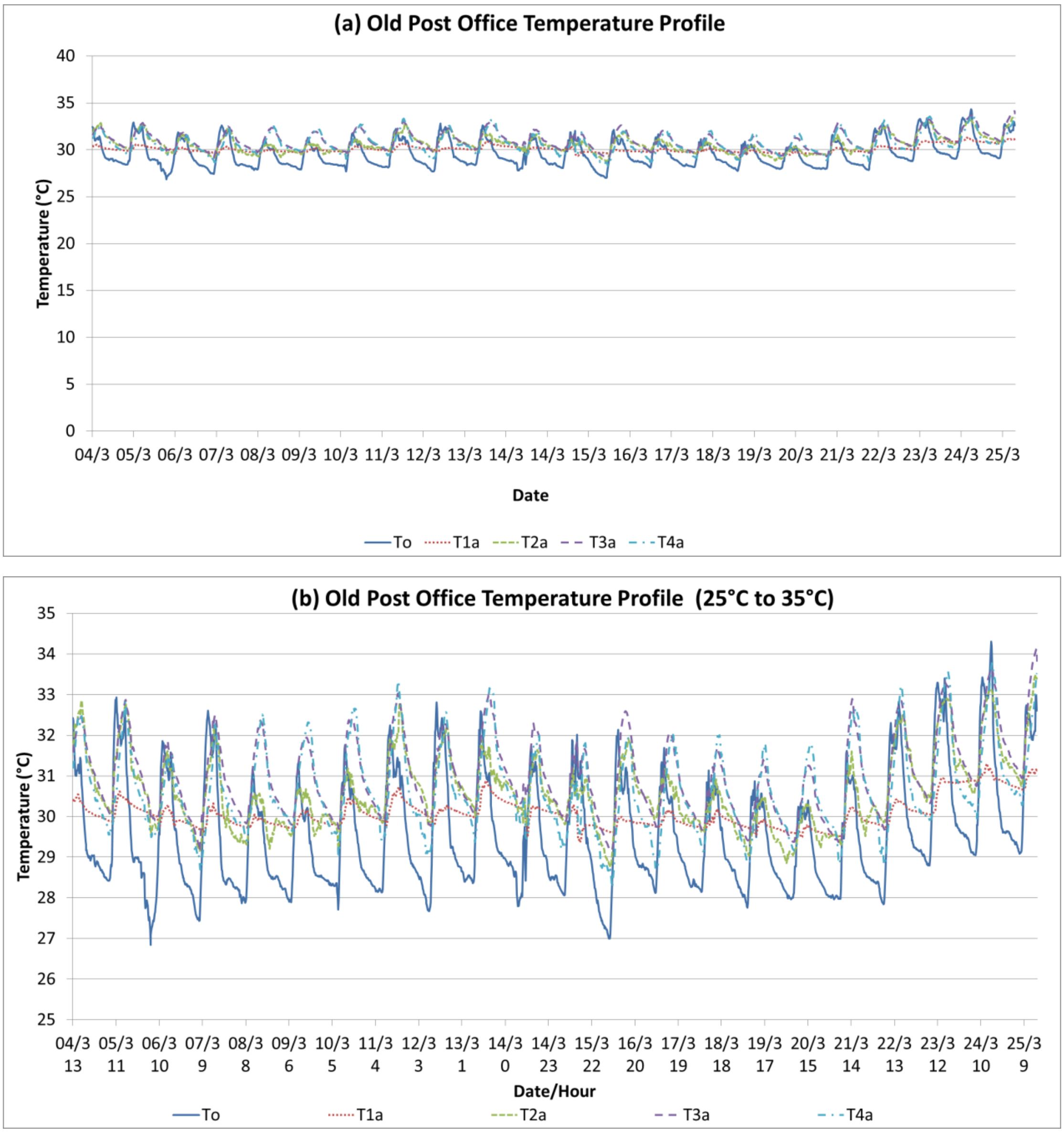


Figure 3-43 a) Representation of outdoor and indoor temperature profiles for the Old Post Office building during the field study period. b) A truncated graph gives a clearer indication of the same.

As is typical of warm humid regions, relative humidity (RH) recorded during the field study period was characterized by a relatively high RH levels (see Figure 3-44). Outdoor RH (RH_o) ranged between a minimum of 55.5% and a maximum of 90.6% with corresponding T_o values of 30.8°C and 26.8°C, respectively. This worked out to an average RH_o of 73.8%, which compares well with the typical average RH_o of 75% for warm humid climates (as identified in the climate analysis in section 1.1). Higher RH_o values were recorded during the early morning period (usually between 0545 and 0630hrs) whereas lower RH_o values were recorded in the evenings (after 1700hrs).

Indoor RH (RH_i) was only recorded on the first floor level location of T2a. Here, RH_i was found to range between 59.7% and 78.3% with corresponding temperatures of 30.6°C and 29.2°C, respectively. Higher RH_i values were recorded during the early morning period at about 0500hrs to 0600hrs whereas lower RH_i levels were recorded during the afternoons, after 1500hrs. RH_i fluctuations tended to be relatively similar to RH_o with diurnal swings of up to 16%. Relative humidity is dependent on the amount of water vapour present in the atmosphere and the given air temperature (Thomas, 2006, Szokolay, 2008). In this case, the fluctuation of RH_i values was attributed to the rise and fall of temperature. If the water vapour remained the same and the temperature dropped, the relative humidity would increase. Conversely, if the water vapour content stayed the same and the temperature rose, the relative humidity would decrease. This is because colder air does not require as much moisture to become saturated as warmer air.

During the study, it was noted that occupants were largely instrumental in the performance of the building (see sections 3.3.3 and 3.4.2). Typically, occupants opened the building up for ventilation purposes thereby allowing for the provision of cooling breezes during the day and the flushing out of warm air during the night. It was suggested that this had the positive effect of reducing indoor temperatures at the Old Post Office building.

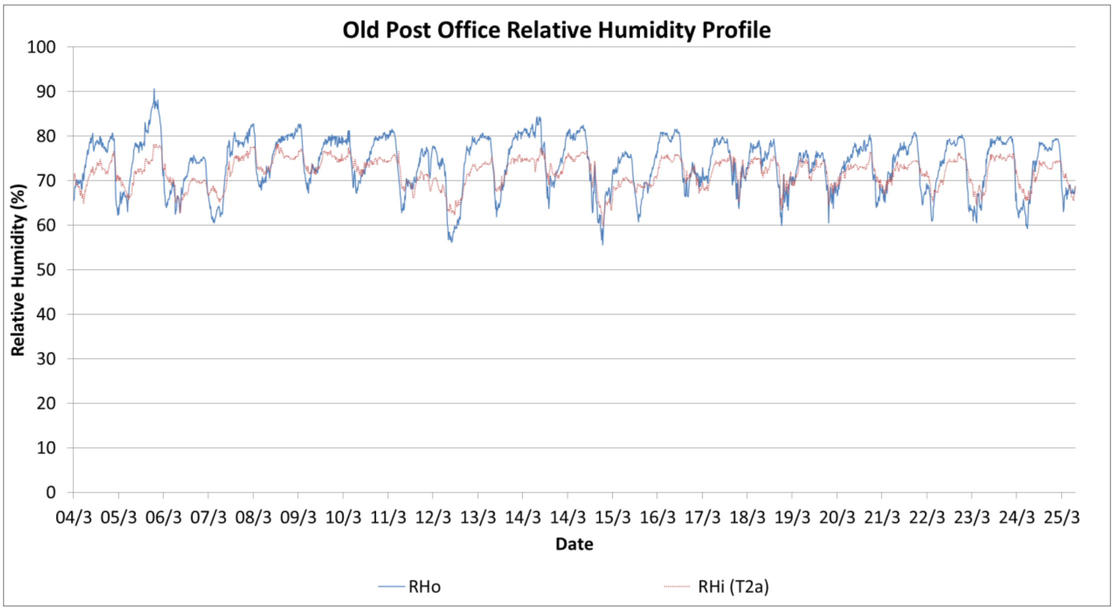


Figure 3-44 Representation of outdoor and indoor relative humidity profiles for the Old Post Office building during the field study period.

Next, the potential for adaptive comfort in the Old Post Office was calculated based on data collected during the field study period. Previously in section 1.2, thermal comfort limits were determined to be relative to the neutral temperature (T_n) or comfort temperature (T_c) and could be extended by up to ±2.5°C for 90% acceptability. In this case, the comfort limits were similarly derived albeit with the outdoor temperature data collected on site and the results presented in Table 3-4.

Table 3-4 Calculated comfort limits for Mombasa (Based on Equation 1-3 and Equation 1-4).

	T_n equation results			**T_c equation results**		
T_a/T_o	T_n	LT_c01	UT_c01	T_c	LT_c02	UT_c02
29.6	27.0	24.5	29.5	29.5	27.5	31.5
UT_c: Upper Thermal Comfort Limit, $UT_c01 = (T_n + 2.5)$°C, $UT_c02 = (T_c + 2.0)$°C LT_c: Lower Thermal Comfort Limit, $LT_c01 = (T_n - 2.5)$°C, $LT_c02 = (T_c - 2.0)$°C						

Following a review of these results, the T_c comfort limits of 27.5°C to 31.5°C were adopted for purposes of this study. In part, this was due to the fact that the T_c comfort limits derived for Mombasa were fairly similar to limits that had been proved comfortable in similar warm climate regions (as highlighted in section 1.2). Further, it was noted that the field study average outdoor temperature (T_a/T_o) of 29.6°C did not vary considerably from the earlier figure of 28.5°C (derived from the climate data file used to calculate the comfort limits for Mombasa in section 1.2); therefore large variations were not anticipated. In addition, given that these comfort limits were based on actual site data, it was suggested that the higher comfort limit value of 31.5°C would be an ideal representation of worst-case scenario conditions where overheating is considered.

Following the derivation of comfort limits, the frequencies of the recorded field study temperatures in relation to the aforementioned predicted adaptive thermal comfort limits were derived and illustrated in Figure 3-45.

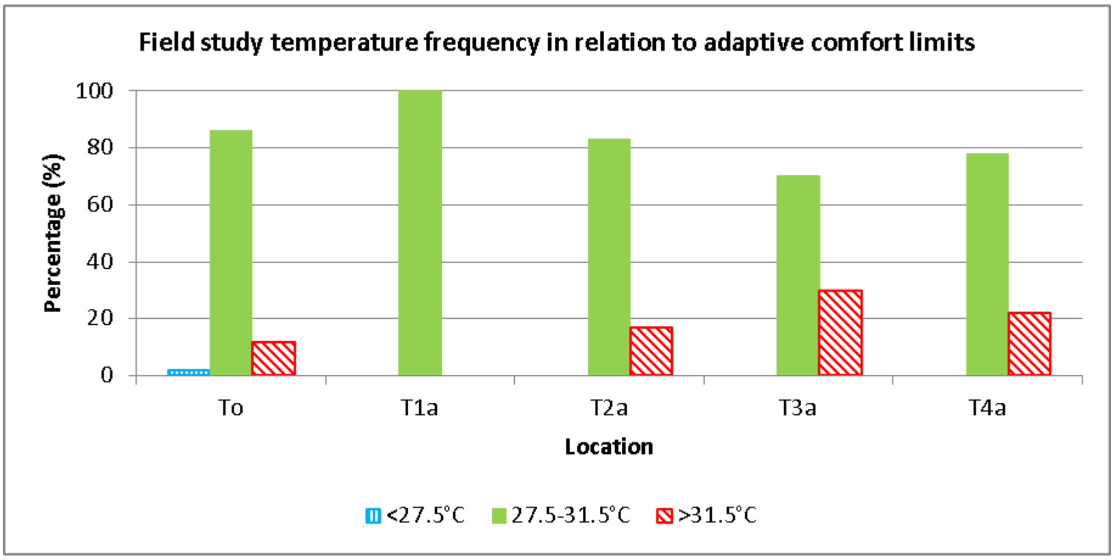


Figure 3-45 Field study temperature data range in relation to predicted adaptive comfort limits.

The findings indicated that for up to 86% of the entire study period (March), the outdoor DBT fell within the adaptive comfort range. This finding was quite interesting as it indicated that the indoor conditions in the Old Post Office building could be kept within March's comfort limits using passive methods for a significant amount of time. Indeed, a review of indoor DBT confirmed this to be a valid assumption. Results for the ground floor location T1a indicated that for 100% of the monitoring period, indoor temperatures were within comfort limits. Similarly, a review of indoor temperatures recorded in the first floor indicated that temperatures lay within comfort limits for majority of the time. In location T2a, T4a and T3a, indoor temperatures fell within comfort limits for 83%, 78% and 70% of the time, respectively. Overall, these results indicated that the Old Post Office building appeared to perform relatively well in relation to the predicted comfort requirements. These results were also considered in the post occupancy evaluation covered in section 3.4 where the thermal comfort of occupants was revisited.

3.3.2 Sun Shading for Solar Control

In section 3.2, it was revealed that the Old Post Office building shows evidence of environmental design elements that contribute to solar heat gain control. These design elements included balconies, screens, window louvres, close proximity of neighbouring building for mutual shading, previously ventilated attic space, thermal mass and light coloured finishes. The effectivity of these strategies in relation to solar heat gain control was analysed further and the findings presented in this section.

Previous analysis revealed that in regions which are close to the equator, the sun is almost always overhead, therefore the majority of incident solar radiation falls on roofs and other horizontally inclined planes (section 3.2.6). In Mombasa, fairly high solar altitude angles are experienced and can range between 68° (summer solstice) and 86° (equinox) at noon. As a result, it would be expected that the roof plane would be a significant source of solar heat gain. A review of recorded temperature data collected on all levels of the Old Post Office building revealed the stratification of temperatures where the ground floor measurements were significantly lower and steadier than those on the top floor. Generally, the indoor temperatures in rooms on the top floor (T2a-T4a) were often up to 3°C higher than those on the ground floor space (T1a) as revealed in Figure 3-46. In addition, temperatures of the top floor spaces were also found to be relatively similar those recorded outdoors – and in some cases were higher than peak outdoor temperatures.

Correlation analysis conducted for the recorded temperatures and average hourly radiation levels for the month of March in Mombasa shows that the outdoor temperatures tended to peak in response to the radiation peak. This was the same case for the indoor temperatures, albeit to a lesser extent, and even less so for the ground floor. The stratification of the indoor temperatures, with top floor temperatures being consistently higher, and especially during peak times suggests that solar radiation may have contributed to this rise in indoor temperature (Figure 3-46 and Figure 3-47).

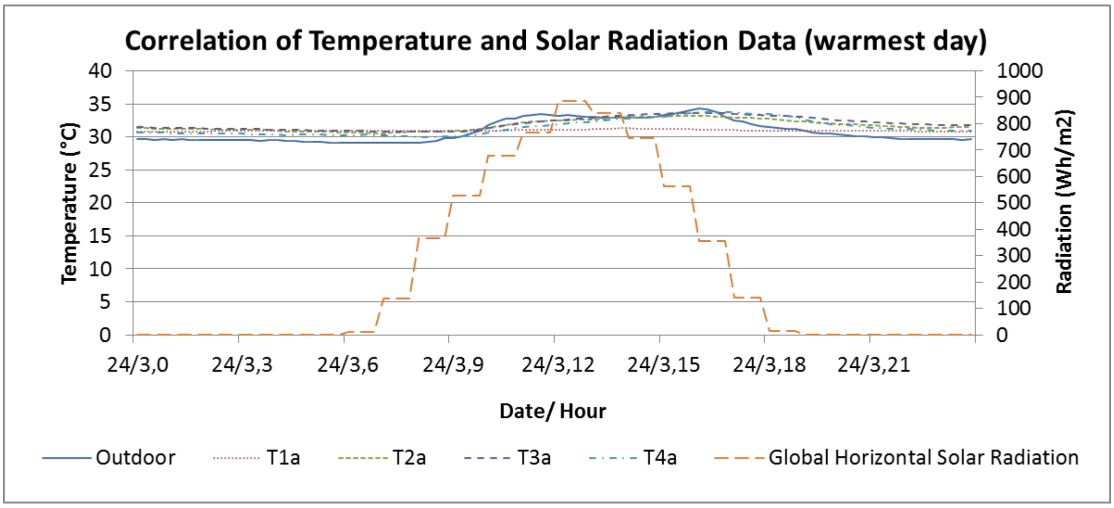


Figure 3-46 Correlation of outdoor temperature and solar radiation data on the warmest day.

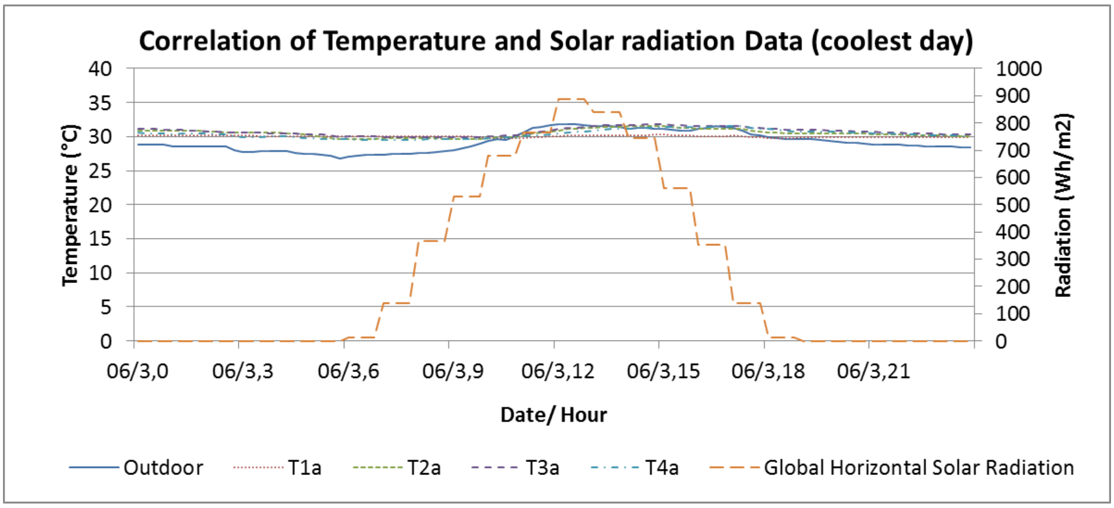


Figure 3-47 Correlation of outdoor temperature and solar radiation data on the coolest day.

In addition, the study findings suggest that the thermal mass and insulation properties of the building fabric significantly influenced the indoor thermal balance by regulating the rate of radiant heat gain and losses from the building fabric. This was evident in a three to nine hour delay in peak temperatures times (Figure 3-43). The delay in peak indoor temperature (after 1500hrs) is desirable for indoor spaces as recorded temperatures remain lower than those outdoors. This is especially significant for the commercial space on the ground floor as lower indoor temperatures are maintained for a significantly longer period of time when the space is occupied.

It is possible that this effect was compromised on the top floor owing to the use of corrugated iron roofing sheets with a soft board ceiling. As is revealed in section 3.1.2, the poor insulation properties of the roof element did little to reduce the impact of solar radiation on indoor temperatures. Further, as a result of part of the open gable ends being sealed up, the ability to ventilate the roof space was compromised. As a result, solar heat gain was more likely to radiate into the immediate first floor level. Given that the first floor slab and ground floor ceiling was significantly insulated, the effect of radiation from the zenith was determined to be significantly lower on the ground floor.

In the Old Post Office building, the glazing percentages/ fenestration areas were significantly low. This is in contrast to the high percentages of between 40 to 80% that are recommended for increased permeability in warm humid regions (Koenigsberger et al., 1973). A review of the fenestration areas indicated that the greatest areas were found on the north-east (36.32%), and the south-east (13.24%) facades. Earlier, it was suggested that the eastern orientations showcased a higher fenestration area owing to the need to channel localised breezes for cooling. On the other hand, the western facing facades had significantly fewer openings with the north-west (11.03%) having a greater fenestration area than the south-west (0.59%). It was suggested that the fairly low glazing percentages contributed to a reduction of solar heat gain indoors.

In addition to the significantly low glazing percentages, it was proposed that the use of balconies and timber louvres and screens significantly reduced the impact of solar radiation on the building fabric of the Old Post Office (Figure 3-48). The balconies were up to 1.2m deep, and provided substantial coverage on their respective facades, and especially in response to a high angle sun. On the other hand, the screens found on the balcony on the Government Square facade and the louvre system on the windows was found to work well by cutting off solar ingress and filtering of daylight during periods of especially low angle sun. Images taken during the study period (March - Equinox), shown in Figure 3-49 reveal that the balconies do work to as previously illustrated in Figure 3-48.

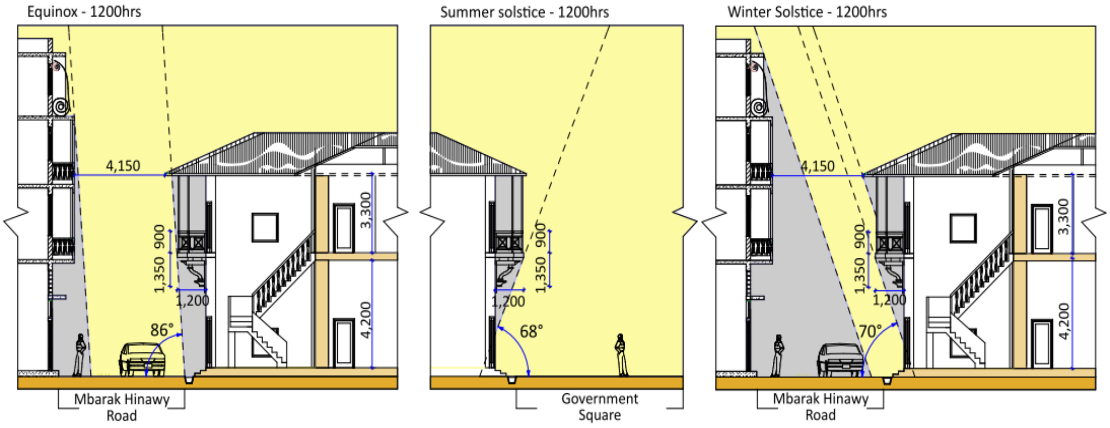


Figure 3-48 Impact of direct solar radition on the prominent facades at key times of the year.

Figure 3-49 (a) Impact of balcony shading effect on the Mbarak Hinawy Road facade at 1200hrs, March 21st (Equinox). (b) Image of the same location at 1500hrs on the same day showing the effect of mutual shading. (c) Shading screen impact on the balcony fronting Government Square.

Further shadow range analysis was conducted using Ecotect software and the results presented in Figure 3-50, Figure 3-51 and Figure 3-52. The findings confirmed that the mutual shading of buildings played a significant role in sun shading of the Old Post Office building. Annual shadow range analysis representing the hours ranging between 0800hrs and 1800hrs revealed that the buildings tend to shade each other. The impact of this on the Old Post Office was that the building remained in the shadow range of neighbouring buildings for a significant portion of the day. This confirmed an earlier assumption that suggested that buildings within the neighbourhood are laid out in a way to provide mutual shading. Further, average solar insolation analysis indicated that the total solar radiation incident around the Old Post Office building was significantly lowered by a third of the initial value due to the presence of neighbouring buildings (Figure 3-53).

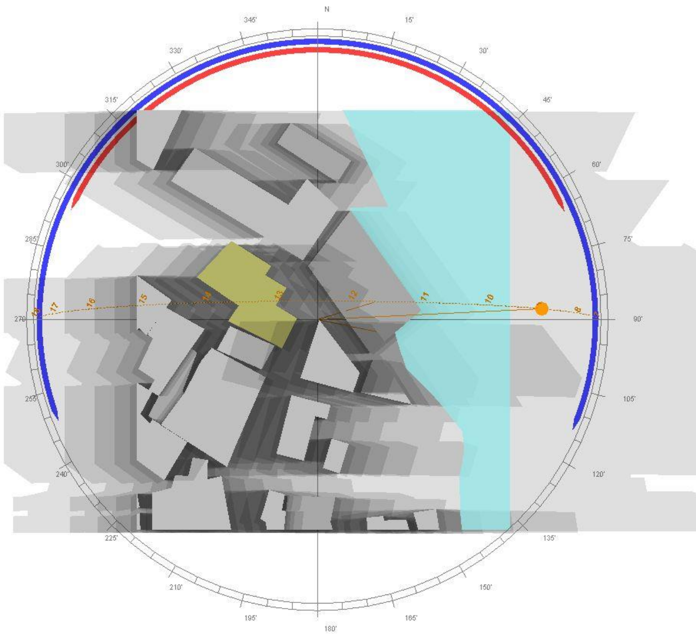


Figure 3-50 Old Post Office building equinox shadow range analysis (0800hrs to 1800hrs).

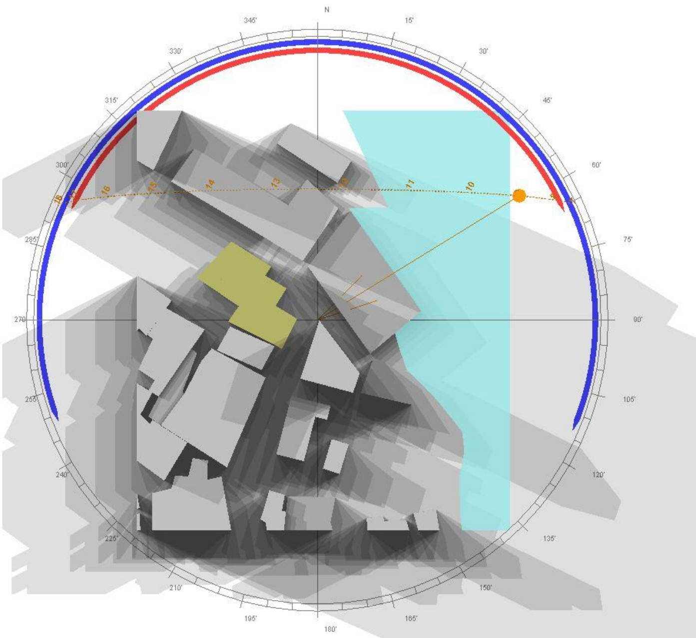


Figure 3-51 Old Post Office building summer solstice shadow range analysis (0800hrs to 1800hrs).

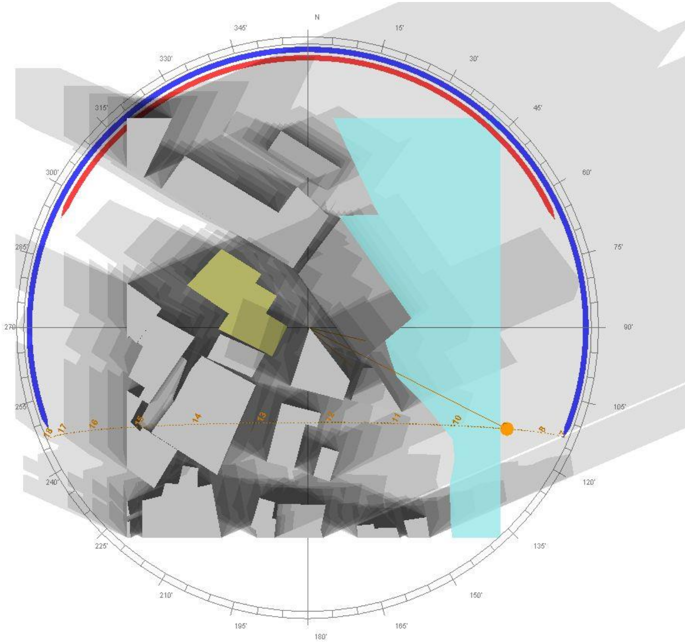


Figure 3-52 Old Post Office building winter solstice shadow range analysis (0800hrs to 1800hrs).

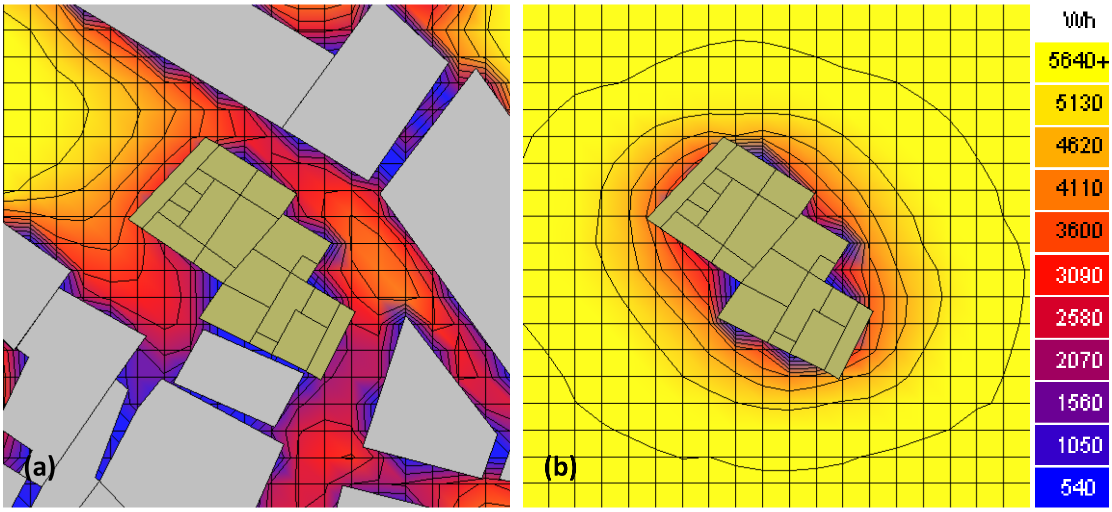
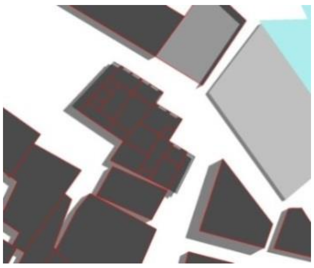
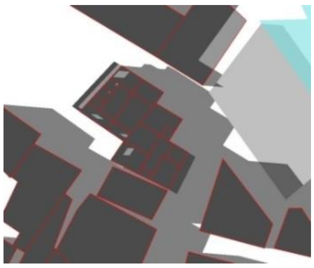


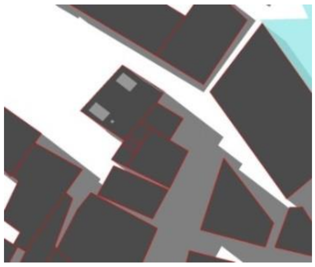
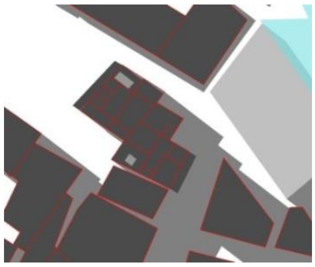
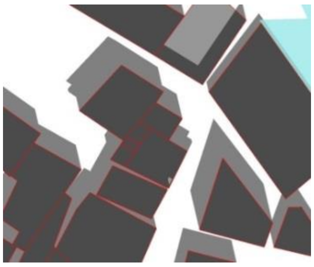
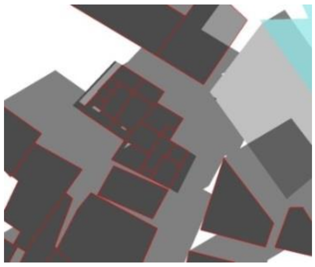
Figure 3-53 Illustration of the average daily solar insolation in March with (a) and without (b) the impact of mutual shading from neighbouring buildings.

Previous studies have indicated that a high albedo, typical in highly reflective surfaces can help cut down on indoor solar gains by reflecting part of the incident solar radiation (section 3.2.5). In the Old Post Office, lime plaster with a lime wash finish was used on all the external walls giving the walls a relatively smooth finish and enhancing the walls heat reflecting capabilities. In addition, although no mean radiant temperature or heat flux measurements were recorded, it was noted that the walls remained cool to touch during the field study period. It was also noted that occupants tended to sit with their backs in contact with the wall surfaces as the surfaces felt cool. It was suggested that the combined effect of material properties and shading resulted in the reduced impact of solar radiation on these surfaces. Consequently, it is possible that the cooler temperatures on the wall surfaces helped maintain lower DBT indoors.

Further, solar penetration analysis was conducted for key times of the year and the findings illustrated in Table 3-5. From this it was found that of all the orientations of the Old Post Office building, the rooms on the north-eastern side had the greatest potential for the direct infiltration of sunlight. Besides having the greatest number of fenestration openings, this region was on the ‘path’ of the low angle sun in the mornings. Also the neighbouring buildings on that side offered less protection by way of mutual shading as they had shorter overall building heights (under 4m high). Nonetheless, given that the window had an integrated louvre system it was possible for occupants to manipulate solar penetration if they choose to. Even so, it was noted that occupants did not seem to mind the less intensive ‘morning sun’.

Table 3-5 Old Post Office solar penetration analysis.

	9am	**12pm**	**3pm**
Equinox - March 21st (Ground Floor)			
Equinox - March 21st (First Floor)			

Summer Solstice - June 21st (Ground Floor)			
Summer Solstice - June 21st (First Floor)			
Winter Solstice - December 21st (Ground Floor)			
Winter Solstice - December 21st (First Floor)			

The findings revealed that the highest potential of sunlight infiltration was during the summer solstice period (June 21st) - due to having the lowest sun angles of the year. On the other hand, the winter solstice period (December 21st) offered the lowest potential for sunlight penetration for rooms of all orientations (due to having the highest sun angles of the year). Quite significantly, rooms with western orientation were found to show fewer instances of sun penetration in comparison to those on the eastern orientation. This is due to the fact that the zone had fewer fenestration openings; and that it was significantly shaded. Thus, it was anticipated that this helped to reduce the amount of solar heat gain into the building.

Often, the suitability of lighting in informal settings tends to be subjective. Although not forming the focus of this study, indoor light distribution was briefly examined to determine if the sun shading elements had a major impact on indoor lighting levels of the Old Post Office. Visually, the heavy use of shading in the Old Post Office had the impact of reducing indoor lighting levels. Even so, the use of artificial lighting was not common during daylight hours. It is possible that the use of light coloured walls generally improved overall indoor illuminance levels. Occupant satisfaction with regards to lighting was briefly addressed further in the post occupancy evaluation (section 3.4).

3.3.3 Air Movement

In Mombasa, winds are predominantly from the north-east and the south-east. During the field study, it was noted that winds were mainly from the south-east as is expected during the month of March (see Figure 3-54). Mainly, the Old Post Office building was naturally ventilated all year round; a strategy that was dependent on the channelling of breezes through fenestration openings. The general building layout was revealed to be strategically aligned to channel local winds into the main habitable spaces.

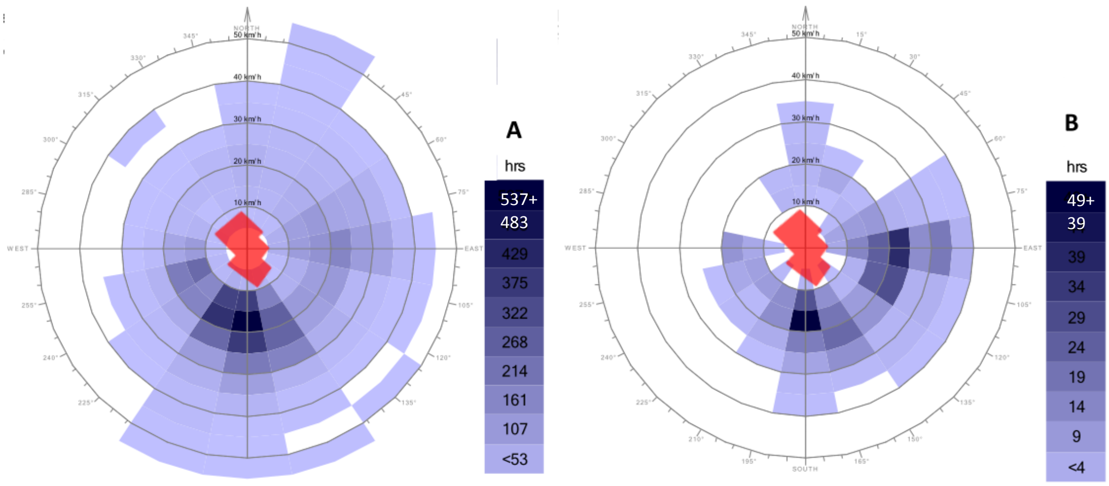


Figure 3-54 Annual wind rose (A) and March wind rose (B) superimposed on the Old Post Office.

In addition to the supply of fresh air and the cooling of the building, natural ventilation is particularly important in warm humid regions as it provides air movement for physiological cooling. Typically, occupants manipulated window louvres systems to adjust airflow to desired levels, and preferred locations with notable sensible air movement (such as balconies, doorways and windows). Respondents of the POE study (section 3.4) reported that it was quite pleasant to sit by these locations as one would experience refreshing incoming sea breezes, especially in the afternoon periods when high temperatures were more likely to cause discomfort. Additionally, mechanical fans were used to boost air movement during warmer periods of the year. Occupants noted that although the incoming sea breeze was adequate, they sometimes opted to use fans to boost cooling; especially if there was an increase in the number of occupants, and mainly in warm afternoons.

During the field study, a number of air movement spot measurements were recorded at various window and door locations and heights of the Old Post Office building at the set times of 9am, 12pm and 3pm and for a series of consecutive days (Figure 3-55 and Figure 3-56). Similarly, corresponding spot temperature and relative humidity readings were recorded for correlation purposes (See APPENDIX A part 'iii' for anemometer data sheet). The main aim of this was to establish the impact of air movement on the variation of temperature indoors and thermal comfort.

Figure 3-55 Air velocity spot measurement locations on the ground and first floor levels.

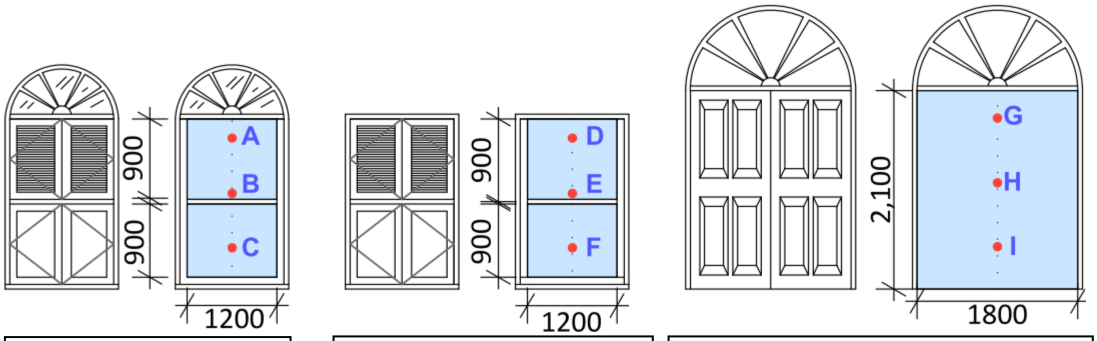


Figure 3-56 Openings configurations and spot measure points (measurements given in millimetres).

On the ground floor, the windows and doors in the antiques shop were opened at 0800hrs (opening time) and left open until 1800hrs (closing time). Even then, only the openings on the front facade were ever opened (W1a-W3a) leaving single sided ventilation as the main ventilation strategy. One other window in the main habitable space remained shut as it was inaccessible due to an existing display; this compromised the potential for cross ventilation within the shop. On the first floor, both windows and doors were left open for most of the daytime period whenever an occupant was indoors – which in this case happened to be for all of the study period. During the evenings or when it rained, window shutters remained shut with the louvres left open to channel breezes indoors.

Generally, air speed spot measurements recorded at the ground floor locations (W1a-W4a) and first floor locations (W5a-W6a) were found to vary between 0.3m/s to 4.5m/s. From this, it was revealed that daily air velocity averaged between 0.9m/s to 1.9m/s (for periods between 9am and 3pm). As indicated in Figure 3-57, air velocities recorded during the morning period were found to be consistently lower than those recorded in the afternoon periods; with differences of between 0.5m/s to 1.2m/s recorded on both floors. This is quite significant given that peak temperature times tend to be during the afternoon hours – potentially when increased air velocity would be most required for ventilation and physiological cooling purposes. This may also explain why occupants felt that the afternoon breeze was more sensible.

Additionally, air velocities on the first floor (W5a and W6a) were found to be consistently higher than those on the ground floor by up to 1m/s, irrespective of time of the day. The increase in air speed may be attributed to the presence of fewer obstructions from the surroundings (such as with the neighbouring buildings fronting the Indian Ocean which were of lower height than the Old Post Office). It is also possible that a greater number of openings within the first floor locations encouraged increased cross ventilation thereby increasing the air flow rates.

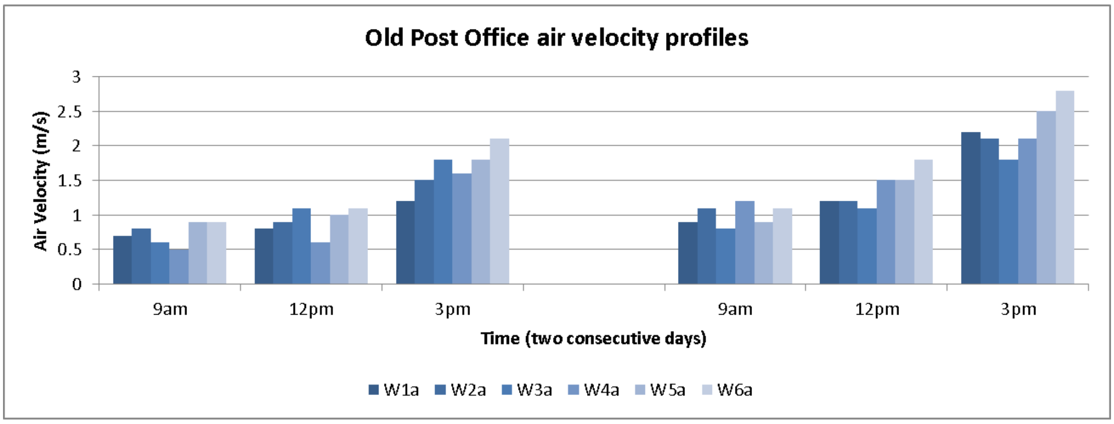


Figure 3-57 Representative air velocity profiles showing data recorded at 9am, 12pm and 3pm on two consecutive days in locations W1a to W4a (ground floor) and W5a to W6a (first floor).

A review of corresponding DBT measurements indicated that temperatures at the selected locations tended to increase slightly during the daytime (Figure 3-58). Previous air temperature analysis in section 3.3.1 gave an indication of the same, and especially on the first floor level. Given that the indoor spaces were dependant on natural ventilation for cooling it was suggested that the potential for ventilation gains was significant when T_o was greater than T_i. On the first floor, an increase in indoor temperatures was partly attributed to the fact that the windows and doors were left open for most of the day, leading to ventilation gains.

The scale of this increase in indoor temperatures was found to be lower on the ground floor; this could have been due to restricted cross ventilation (which hampered ventilation gains) or high levels of shading and insulation (reducing the impact of solar gain in raising indoor temperatures). Despite the increase in daytime temperatures, occupants still preferred to keep external windows and doors open. This suggested that occupants found the effect of air movement more effective in providing comfort.

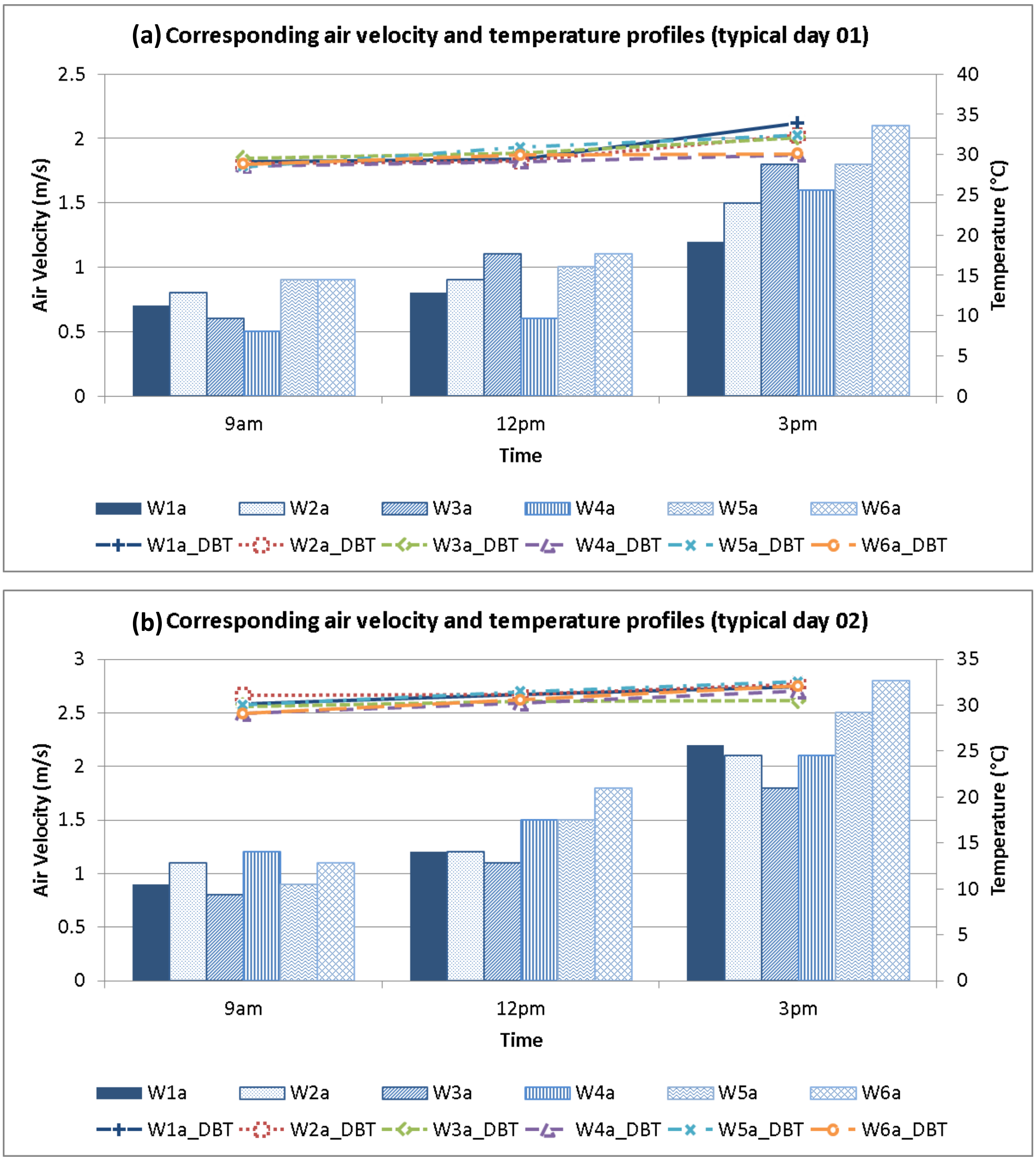


Figure 3-58 (a) and (b) A comparison of corresponding air velocity and temperature profiles on two typical consecutive days.

In section 2.2.1, it was revealed that it is possible to estimate the apparent cooling effect of air movement for air speeds of up to 2m/s using Equation 2-5. Given that the recorded air speeds at the Old Post Office ranged between 0.3m/s to 4.5m/s, and considering the formula's 2m/s maximum value, the apparent cooling effect for the minimum and maximum recorded air velocity was calculated as follows:

For 0.3m/s air velocity (minimum allowable): $dT = 6 \times 0.1 - 1.6 \times 0.1^2 = 0.6°C$

For 2.0m/s air velocity (maximum allowable): $dT = 6 \times 1.8 - 1.6 \times 1.8^2 = 5.6°C$

Using these results, it was possible to define the control potential zone (range of outdoor conditions for which air movement has the potential to ensure indoor comfort) for air movement as determined by the dT values. These results indicated that the adaptive comfort limit based on outdoor DBT can be increased by up to 5.6°C for air velocity of up to 2m/s. Given that higher velocities were recorded during the afternoon period, this perceived reduction in indoor temperatures explained to some extent how it was that occupants felt comfortable in the fairly warm indoor temperatures. Indeed, it has already been highlighted that occupants tended to prefer locations where they could maximise the effect of the incoming cooling breezes.

Additional measurements taken at opening locations sought to give an indication of air velocity levels along the height of the typical openings (Figure 3-59). Data collected revealed that air velocity tended to increase with an increase in height. This may be due to fewer obstructions at higher levels.

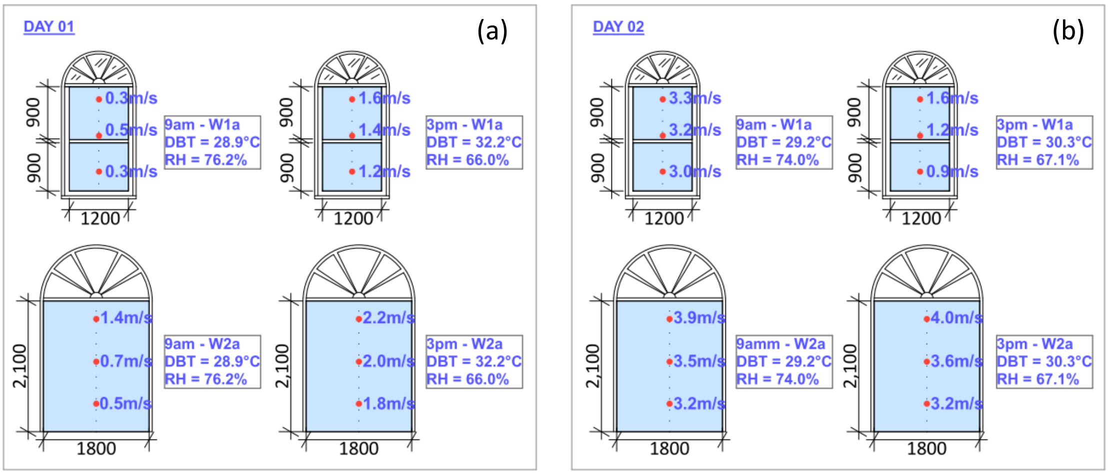


Figure 3-59 (a) and (b) Spot measures of air speed at W1a and W3a, at 9am and 3pm, carried out for two consecutive days.

Spot RH measures for the two floors were lower in the afternoon period. In addition, the findings revealed that RH levels reduced with increase of air movement (Figure 3-60). As was explained in section 3.3.1, this was attributed to higher air temperatures which reduced the ability of the air to hold water vapour. Additionally, little variation was noted in RH values on locations on individual floors. However, when comparing the RH on the two floors, it was noted that the first floor locations had slightly lower RH compared to the ground floor locations. This difference was attributed to the higher indoor temperatures recorded in first floor locations.

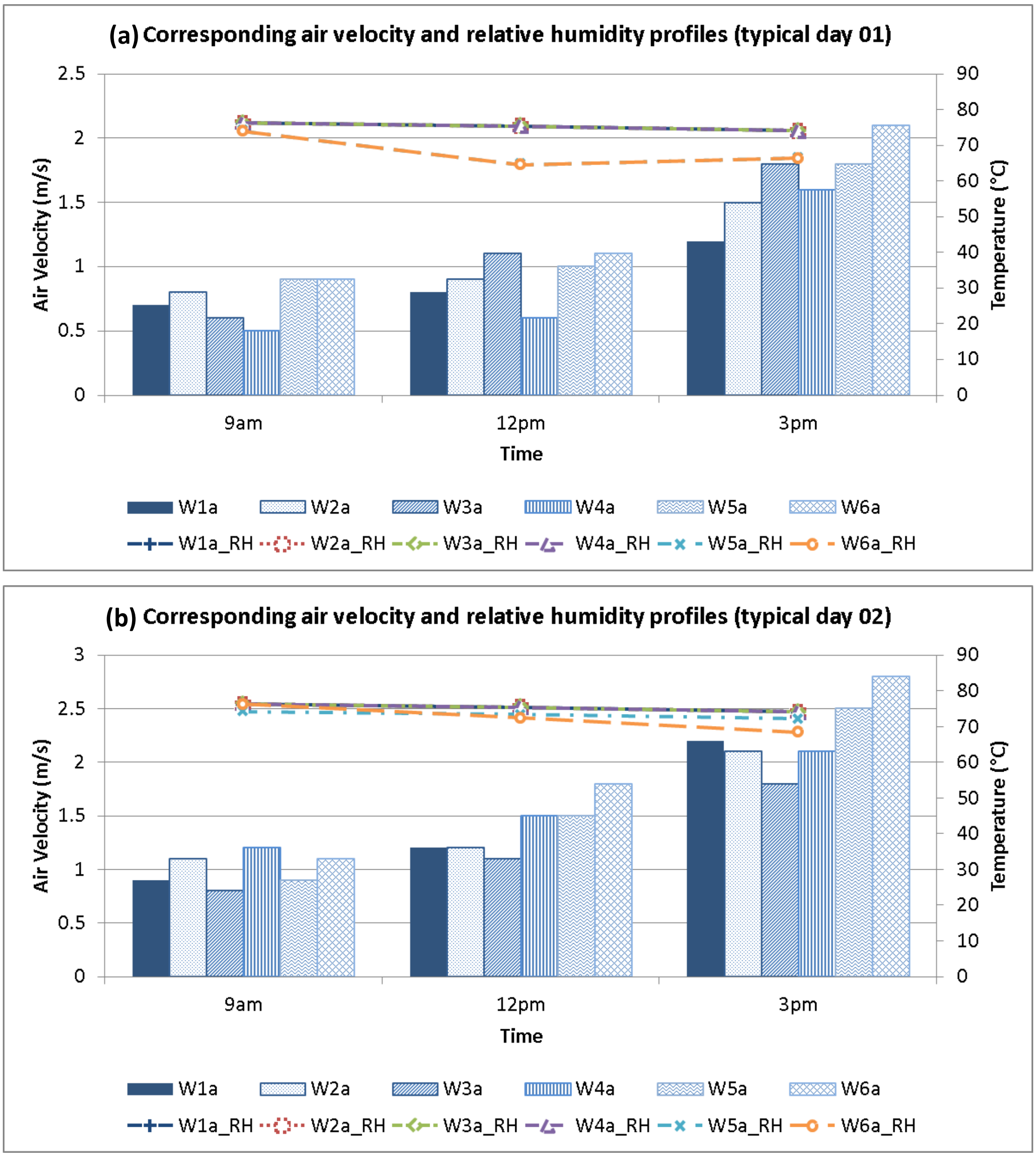


Figure 3-60 (a) and (b): A comparison of corresponding air velocity and relative humidity profiles on two typical consecutive days.

During the field study, it was established that the Old Post Office building, and indeed the street layout, seemed to have been laid out with the intention of driving ocean breezes inland (Figure 3-61). A review of spot air velocity measurements recorded outdoors (at 9am, 12pm and 3pm) indicated that outdoor air velocity values were almost always greater than 0.25m/s with an average of approximately 3.7m/s.

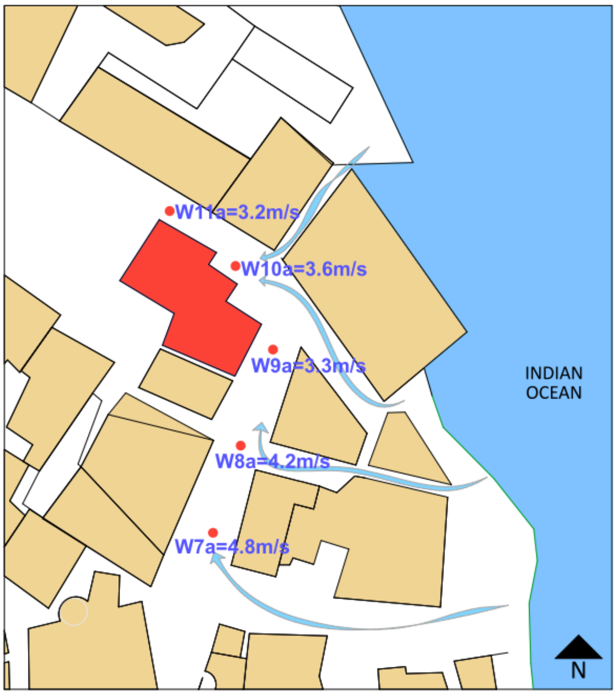


Figure 3-61 Spot street air velocities recorded during the field study period.

As with the indoor air velocities, outdoor air velocities increased during the afternoon periods – thereby explaining a similar increase indoors. At times, these velocities could get quite high. During the study, air velocities of up to 7m/s (between 12pm to 3pm) were recorded on the street level surrounding the Old Post Office building. Overall, air movement experienced in and around the Old Post Office building was found to play a significant role in enhancing comfort through physiological cooling and possibly to a smaller extent, providing ventilation cooling when the outdoor temperature was cooler than the indoor temperature (at night and in the early morning periods).

3.3.4 Thermal Mass

The amount of thermal mass in a building and its distribution in the envelope can play an important role in the effectiveness of heat prevention and cooling in warm climates. To assess the potential effectiveness of indoor thermal mass, the degree swing in temperatures was examined.

Generally, indoor DBT values were found to be relatively steadier than those recorded outdoors. Specifically, DBT values recorded on the ground floor location of T1a were found to be the steadiest and the lowest for most of the study period with 100% of DBT recorded found to be less than 31.5°C (within the comfort limits). It was suggested that this performance may be attributed to the provision of thermal mass from the highly insulated coral ceiling slab (ground floor only) and the relatively thick coral walls.

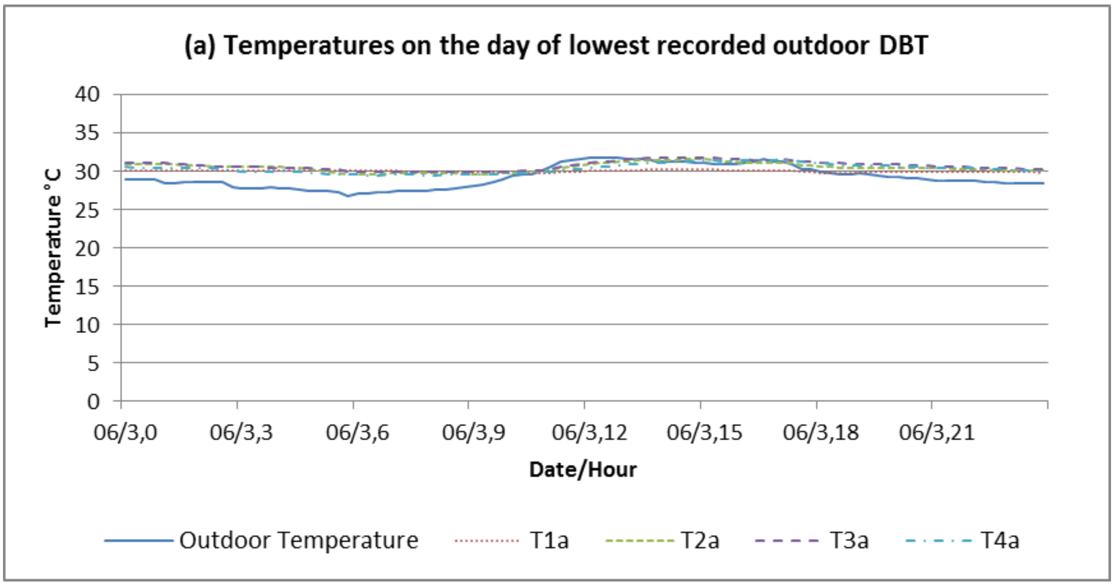
The highest indoor DBT was recorded on the first floor. Of the three locations on the first floor, the highest indoor temperatures were recorded at location of T3a. It was suggested that the significant temperature difference between location T3a (including other top floor spaces) and the ground floor location T1a could have been as a result of reduced protection from the impact of solar radiation on the zenith. Unlike the ground floor space which has the benefit of an insulated ceiling, the lightweight roof and ceiling construction on the first floor offered significantly less protection from solar radiation heat gain in comparison to the exposed thermal mass common to the ground floor. It is also worth noting that, as location T3a was hardly inhabited (and therefore closed up) during the study period, it was less likely for heat to be expelled via ventilation driven cooling thereby allowing for higher temperatures to be maintained. As with location T3a, T4a was also hardly occupied thus ventilation opportunities were infrequent.

Both locations T2a and T4a had lower DBT than T3a during the duration of the study. Overall, T2a was found to be the best performing space on the first floor level. This is emphasized by the fact that T2a had lower peak DBT than the two other locations and also had a significant majority of temperatures lying below 31.5°C. Unlike locations T3a and T4a, this space was occupied during the study period. As a result, occupants tended to keep windows open for most of the day to enhance ventilation and air movement for cooling. Window placement within this space was earlier suggested to improve cross ventilation performance driven by incoming cooling sea breezes. Also, as T2a has a north-east orientation, it is anticipated that the impact of solar radiation was further moderated. This is in addition to the effect of mutual shading from neighbouring buildings.

A further review of the temperature data revealed that the outdoor temperatures were generally between 1 to 3°C lower than recorded indoor temperatures during the early to mid-morning period ranging from 0000hrs to 0900hrs, approximately. Outdoor peak temperatures were attained after 1200hrs and tended to be up to 4°C (maximum) higher than selected indoor spaces – after which they tended to fall gradually. Further analysis of the field study data for the warmest and the coolest days (as per outdoor DBT) illustrates this trend in Figure 3-62 and Figure 3-63.

Indoor temperatures showed smaller and fewer fluctuations than outdoor temperatures throughout the day. During the daytime, indoor peak temperatures were attained between 1500hrs and 1600hrs. Conversely, the lowest temperatures were recorded mainly between 0400hrs and 0900hrs. Also, it was noted that DBT fluctuations on the top floor were more similar to those outdoors unlike the lower floor which was found to have a significantly lower temperature swing; and were therefore more prone to attaining peak temperatures similar to those outdoors and in a shorter period of time. On the other hand, smaller fluctuations in the ground floor location, T1a meant that the DBT remained fairly constant. This resulted in the DBT in T1a remaining significantly lower during the 'critical' period; that is from 0800hrs to 1800hrs when occupants were more likely to be using the space.

The indoor DBT fluctuations translated into a delay of indoor peaks by about 3 to 9 hours; with a significantly longer peak delay recorded on the ground floor (Figure 3-62 and Figure 3-63). It is suggested that this delay may have been partially attributed to exposure of these spaces to the building mass provided by the thick coral rag walls. The thermal properties of the thick coral walls presented in section 3.1.2 shows this to be a logical assumption.



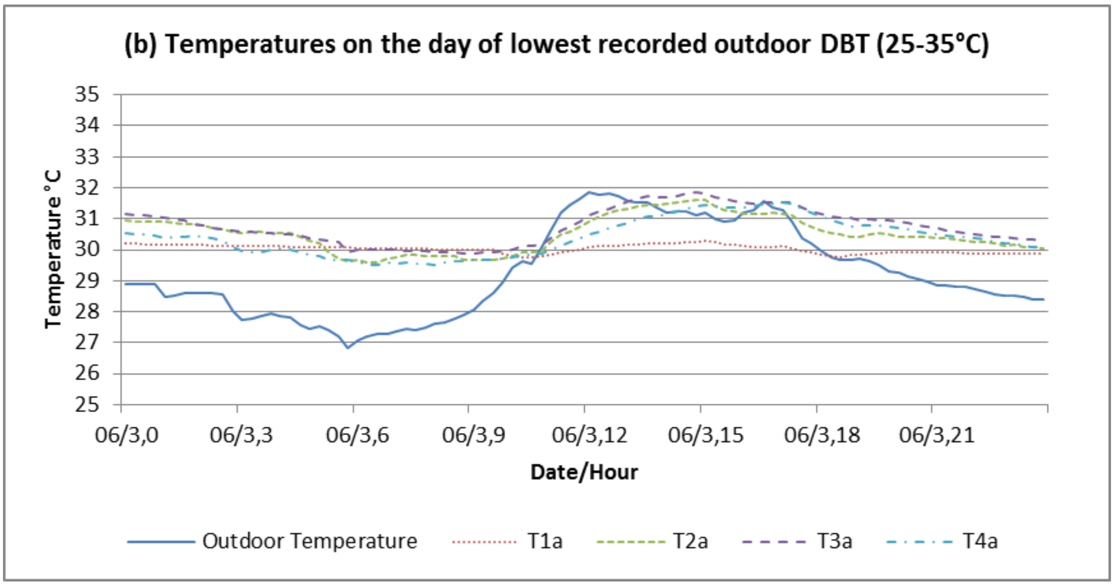


Figure 3-62 (a) Temperature profiles of all locations during the day with the lowest recorded outdoor temperature. (b) A truncated graph gives a clearer indication of the same.

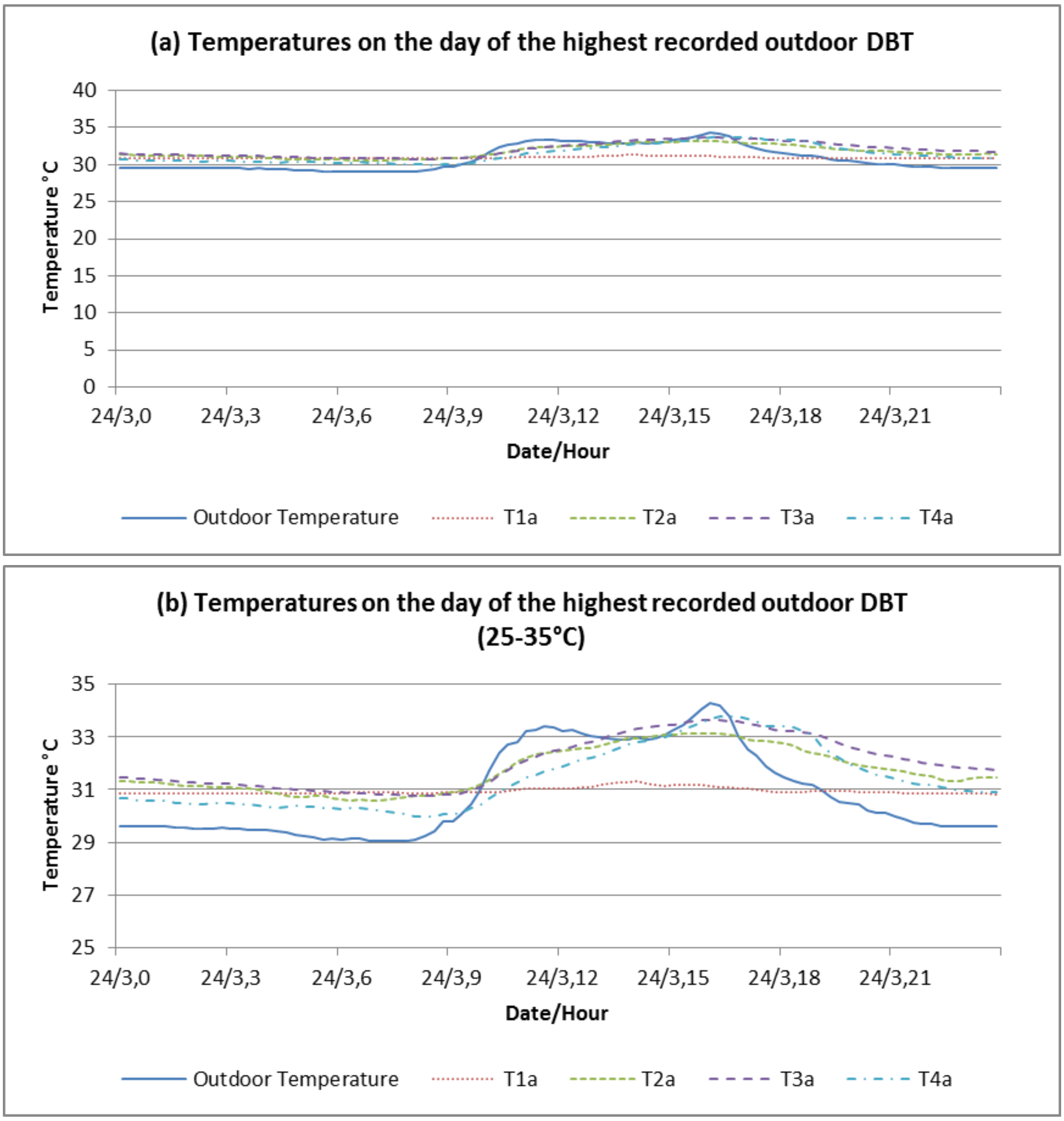
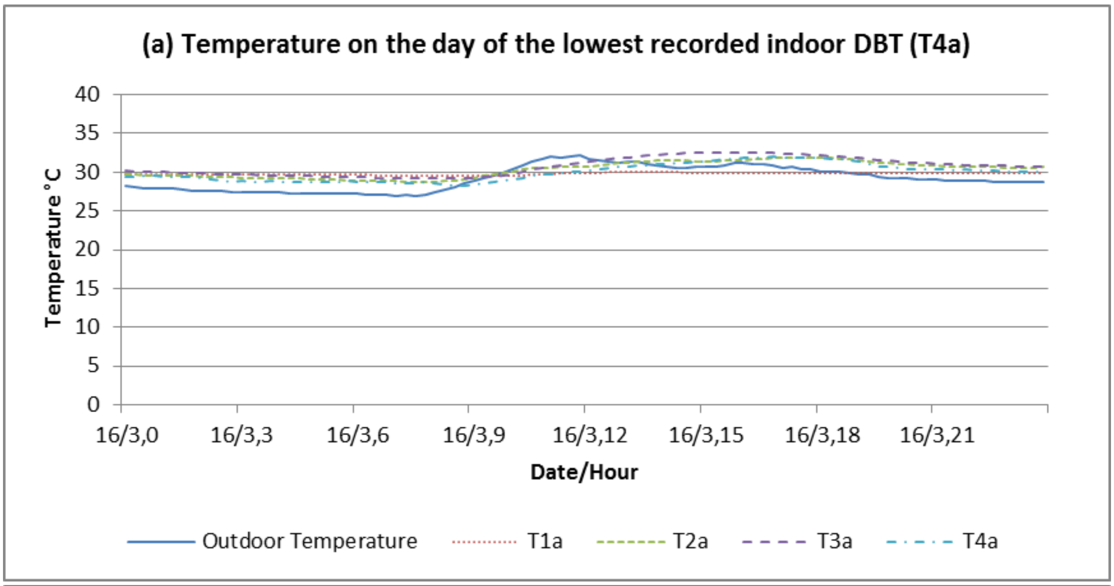


Figure 3-63 (a) Temperature profiles of all locations during the day with the highest outdoor temperature. (b) A truncated graph gives a clearer indication of the same.

An examination of temperature profiles during the coolest and warmest recorded temperature days reveals temperature differences between indoor DBT and the outdoor DBT peak temperature is lower (by up to 2.2°C) on the cooler day and higher (by up to 3.3°C) on the warmer day. On the other hand, differences between indoor temperatures during indoor peaks reveals that temperature differences remain the same on both the coolest and warmest days with a temperature difference of up to 2.8°C (Figure 3-64, Figure 3-65 and Figure 3-66).



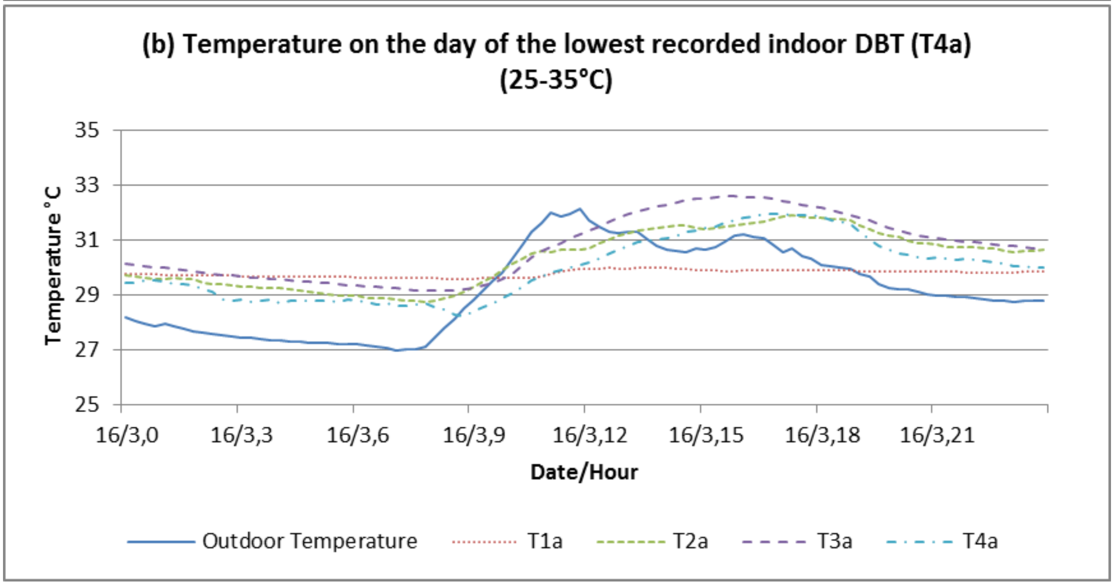
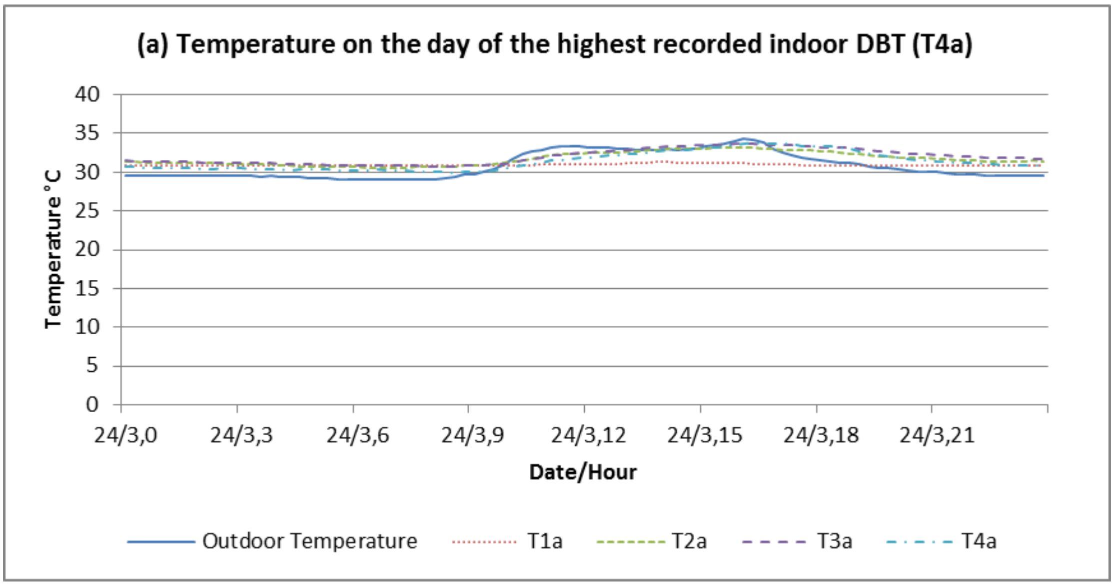


Figure 3-64 (a) Day with coolest recorded indoor temperature, T4a. (b) A truncated graph gives a clearer indication of the same.



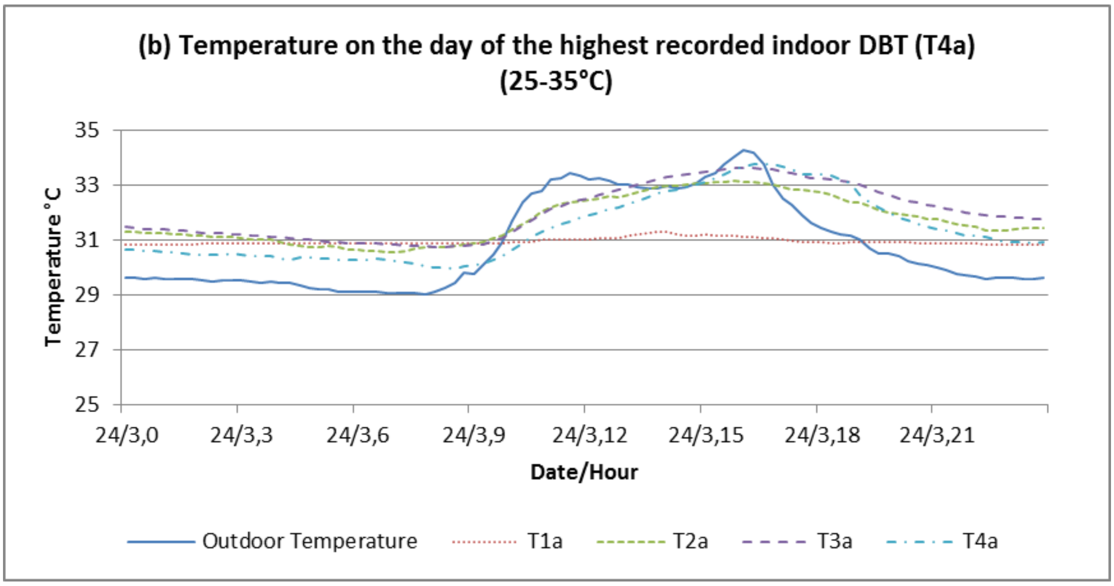


Figure 3-65 (a) Day with warmest temperature, T4a (full day recorded). (b) A truncated graph gives a clearer indication of the same.

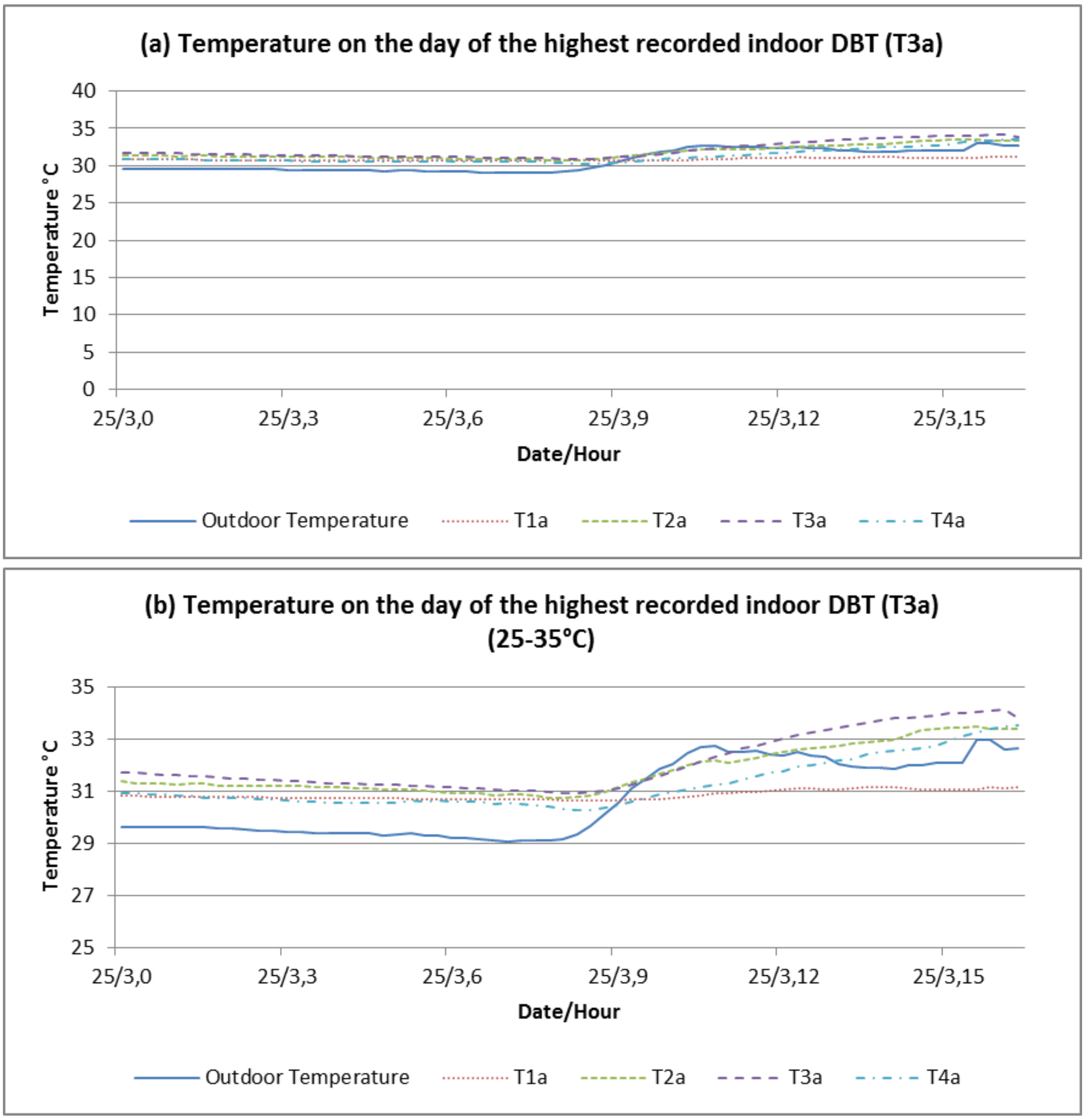


Figure 3-66 (a) Day with warmest temperatures, T3a (part day record available. (b) A truncated graph gives a clearer indication of the same.

Although the data collected on site was not conclusive, the findings strongly suggested that the significant thermal mass present in the Old Post Office building contributed to improved thermal conditions and occupant comfort. Computer simulation studies presented in Chapter 5 are used to further quantify the effect of this design strategy.

3.4 Post Occupancy Evaluation

As part of this field study, a post occupancy evaluation (POE) was conducted to provide further insights into the building thermal performance of the Old Post Office building. The collection of this data served to augment the measured findings by relating the observed and measured building thermal performance with user satisfaction. Opinion was sought from occupants regarding the best and worst aspects of the user experience in the building, their level of understanding of aspects related to user comfort as well as any other issues relevant to their interaction with the building. Additionally, the building manager was interviewed on matters regarding building operation and usage patterns, maintenance and energy consumption. Willing occupants were asked to fill in structured questionnaires (based on the Building Use Studies, BUS methodology – see section 3.4.2) whereas the building manager was interviewed. The following section aims to give an outline of this evaluation process and its outcome.

3.4.1 Semi-structured Interview

Following a walkthrough of the Old Post Office building with the building manager (and owner), a semi-structured interview was conducted to get further insight into factors that directly affect the building's thermal performance and resultant user comfort. The aspects covered during the interview included: building operation and usage patterns, maintenance, energy consumption amongst other points of interest (see APPENDIX B for semi-structured interview guidance).

a) Building Operation and Usage Patterns

Generally, it was reported that the building occupants had not raised any issues regarding the building performance and their comfort as relates to building operations and usage patterns. In section 3.1.1, the Old Post Office building was identified to be a mixed-use building with commercial and residential activity restricted to the ground and first floor level, respectively. A variety of both occupied and unoccupied spaces were identified as was highlighted in Table 3-1.

Generally, the ground floor antiques shop had opening hours ranging from 0800hrs to 1800hrs, for 7 days a week. During this period, the shop usually had 6 occupants (permanent shop staff) present. Usually, one to two occupants would be located on the mezzanine level of the shop carrying out administrative activities whereas the others tended to be on the shop floor level. Quite often, the staff members would be found positioned by the two front windows or the door. The occupancy levels would increase for relatively short periods depending on the number of customers. During the weekends the occupancy was halved to 3 occupants. Outside of these hours the shop remained shut and unoccupied.

On the other hand, Residence 01 had varying occupancy levels at different times of the day, with a minimum of 5 occupants present after 1800hrs for 7 days a week. During weekdays, the space was mainly occupied by 3 occupants between 0800hrs and 1800hrs. Higher occupancies of up to 5 occupants were common all day during the weekend when occupants had no social, work or school commitments. In addition, it was reported that occupants were more likely to receive guests in the afternoon to late evening periods during weekends – this was later found to coincide with when the occupants tended to turn on the mechanical fans during significantly warmer periods.

b) System Operation

Overall, issues regarding system operation were not reported to be a major factor. Majority of the building systems and the means of their operation were identified to be easily accessible and user controlled with no identifiable levels of automation. This is highlighted in section 3.2 where the main environmental design elements are identified as passive in nature. The only passive control 'system' operable by occupants consisted of openings which could be adjusted to encourage air movement for ventilation and cooling or provide shade and vary daylighting levels. It was also reported that ventilation could be augmented by use of mechanical fans during extreme conditions. In addition, artificial lighting via low-energy lighting fixtures was provided.

Ventilation and cooling controls consisted of fenestration systems and fan switches. On the ground floor, the staff member tasked with opening and shutting the shop premises would ensure that all windows and the main door were opened at the start of the day and shut at closing time. Although other occupants in the antiques shop were not restricted from operating the window louvre system, there appeared to be a general consensus to leave the windows fully open all day to allow for adequate ventilation and daylighting. In addition, given the exhibitory nature of business in the antiques shop and its interaction with the street level, it was suggested that it would probably not be in their best interest to shut the windows or indeed the heavy timber door!

On the first floor, residents of the occupied flat also tended to have windows in habitable rooms open for most of the day. Further, the window louvre systems were manipulated more often, and especially during the evening periods when the occupants still wanted the benefit of cooling breezes without compromising on visual privacy. Similarly, in cases of driving rain, the louvres were used to maintain air flow while preventing water infiltration indoors.

As with the window louvre system, the mechanical ceiling fan switches on the ground floor were positioned for easy accessibility by occupants. It was reported that these fans were sometimes turned on during extremely warm afternoons. Usually, occupants would tend to inquire from each other before turning on the fan. In other cases, such as when the shop had an increased number of customers, the staff member closest to the fan switches would turn them on. The Old Town conservation area is a rather busy tourist attraction; it is fairly common to see large groups of tourists from mainly temperate regions (Kenya National Bureau of Statistics, 2010) often wandering into many of the shops that line the main streets of Old Town. The Old Post Office antiques shop was no exception. It was suggested that when they turned on the fans during extremely warmer periods, chances were that the potential customers in the shop would be more likely to spend a longer time browsing in the cooler space, thereby increasing the chance that they would buy something! This revealed that the occupants were conscious of the fact that people who were not acclimatised might find indoor conditions warmer than desired. On the first floor, each habitable room had a ceiling fan. Nonetheless, it was noted that the occupants rarely turned on the fans unless it was an exceptionally warm day or when there were higher than normal occupancy levels (such as when they had guests).

It was reported that access to daylight was found adequate by occupants. Additionally, it was noted that there was provision for supplementary energy efficient lighting. Supplementary lighting was operated using switches placed at strategic locations of the various spaces and within reach of occupants. Artificial lighting was regarded as one of the main sources of electricity consumption in the building. Although electricity-use data was not readily available, the building manager revealed that the cost was minimal. This was attributed to the fact that supplementary lighting was hardly ever used apart from by occupants in Residence 01 after dark.

c) Maintenance

Maintenance and repairs of the building were reported to be the sole responsibility of the owner. Usually, maintenance and repair work was carried out on breakdown rather than as a result of programmed work. However, it was also revealed that preventative work was in the process of being planned for with focus on the repair of the aesthetic features of the Old Post Office building. Under ordinary circumstances, if the occupants on the ground floor had any concern, they would take it up with the shop owner who would then ask the building owner to plan for repairs. It was noted that the speed at with which repairs were carried out was dependant on the urgency and scope of the work and more importantly, the financial cost.

A series of walkthroughs conducted during the field study revealed that the building showed indications of needing repair work on its roof, balconies and the timber window panels. The corrugated iron roof showed signs of corrosion which could lead to water ingress. Further, part of the decorative trimming to the balconies appeared to have been weathered, as were the timber panels on select window shutters. It was suggested that these elements could do with repair to prevent irreversible damage caused by warping resulting from water damage.

Indoors, the shop space appeared to be in good condition with little need for any repairs or maintenance. Similarly, on the first floor, the general condition of the various spaces appeared to be in good condition. The only exception was noted to be some sections of the soft board ceiling where it appears there might be leakage from the aforementioned roof. During the study period, none of these pending repairs were seen to have significantly affected building use and operation.

d) *Other Control and Interfaces*

It was noted that the ground floor antiques shop had a disused air conditioning (AC) unit and control switch. It was revealed that, with permission from the building owner, the shop owner had installed an AC unit to temper indoor conditions in anticipation of the arrival of relatives visiting from the UK who would be helping organise the antiques shop for a three month period. After this period, the use of the AC was discontinued as none of the 'usual' occupants felt the need for it. Further, it was noted that the cost implication of running the AC would have been unsustainable - especially considering that the shop relies on having its doors wide open to showcase wares and lure potential customers off the street. It was further noted that the shop owner was planning to sell off the existing AC unit. No other active controls and interfaces were identified.

e) *Energy Consumption*

Given that the Old Post Office building employed mainly passive controls, energy use for climate control was not found to be a major concern. It was reported that, as building occupants appeared to find indoor conditions tolerable, there was no apparent need to boost the existing systems other than by the provision of mechanical fans for cooling in extreme conditions or supplementary lighting. Even so, it was reported that the use of both mechanical fans and the supplementary lighting had a relatively low impact on running costs. Instead, it was noted that the greatest electricity use was from the use of personal equipment (such as phones and computers) and kitchen appliances. Although no bills were available for study comparison purposes, the building manager indicated that the average monthly cost of electricity in the Old Post Office building was quite manageable. In addition, although no rigid plan had been developed for consumption management in the building, it was noted that occupants had been asked to be 'sensible' in their usage patterns. This included doing things such as turning off lighting, fans, and equipment when not required.

f) Other Points of Interest

The building owner was very obliging to have the building analysed and its performance determined as part of this study. Of the issues discussed during this interview, the owner noted that conservation was high on the agenda. Given that the Old Post Office building is located within the gazetted Old Town Conservation area, significant changes or maintenance to buildings within this zone are subject to approval by MOTCO under NMK. The main aim of this regulation is to ensure that the building heritage of Old Town is well conserved. This process can be quite costly; as such owners tend to find it financially taxing to meet the prescriptive requirements. MOTCO is currently working on providing financial incentives to building owners. Nonetheless, the owner of Old Post Office remains committed to ensuring that the building does not fall into a state of disrepair and is quite keen to commence with restoration efforts.

3.4.2 BUS Occupant Study

The occupant study presented in this section is based on the BUS methodology which has been created from thirty years of continuous development in building use studies for post occupancy evaluation. The BUS method was first developed and refined when it was used for a seminal series of UK government funded PROBE (Post-occupancy Review Of Buildings and their Engineering) building performance evaluation studies (AUDE, 2006, Bordass and Leaman, 2005, Bordass et al., 2006). Having been tried and tested in the benchmarking of levels of occupant satisfaction within buildings against a large database of results for similar buildings, the BUS method is considered to be a well-established and straightforward system. Prime examples of its use include the Carbon Trust's Low Carbon Accelerator and Low Carbon Building Programme and the Technology Strategy Board's Building Performance Evaluation programme (Leaman, 2008).

The main element of the BUS methodology is a structured questionnaire which is administered to willing participants of a selected building as a means of rating various aspects of occupant satisfaction in relation to building performance on a rating scale of 1 to 7. Respondents can also provide comments on these aspects, allowing for the collection of both quantitative and qualitative feedback (BUS Methodology Brochure, n.d.). Over 45 variables are evaluated to provide a building satisfaction score covering aspects that include thermal comfort, ventilation, indoor air quality, lighting, user control, among others.

Currently, the non-domestic BUS database has around 650 buildings from 17 countries whereas the domestic database has around 50 projects from the UK (BUS Methodology Brochure, n.d.). The results of the BUS occupant study can be used to provide insights into occupant experience and building performance as well as propose solutions to improve the same. The results of the survey undertaken in the Old Post Office building are discussed next. A copy of the questionnaire administered to occupants of both the Old Post Office building and the Mombasa Uni Plaza building (reviewed in Chapter 4) is presented in APPENDIX C.

The Old Post Office BUS survey received a good response rate with 100% of the questionnaires that were handed out being returned. Generally, the respondents consisted of 10 occupants, both male and female, ranging from 55 to 21 years of age, of generally good health and who were accustomed to warm humid climatic conditions (Figure 3-67). Typically, the subjects had a metabolic rate ranging from 0.7 to 1.6 met (depending on the task at hand) and a clothing insulating value of less than 0.6 clo at any given period.

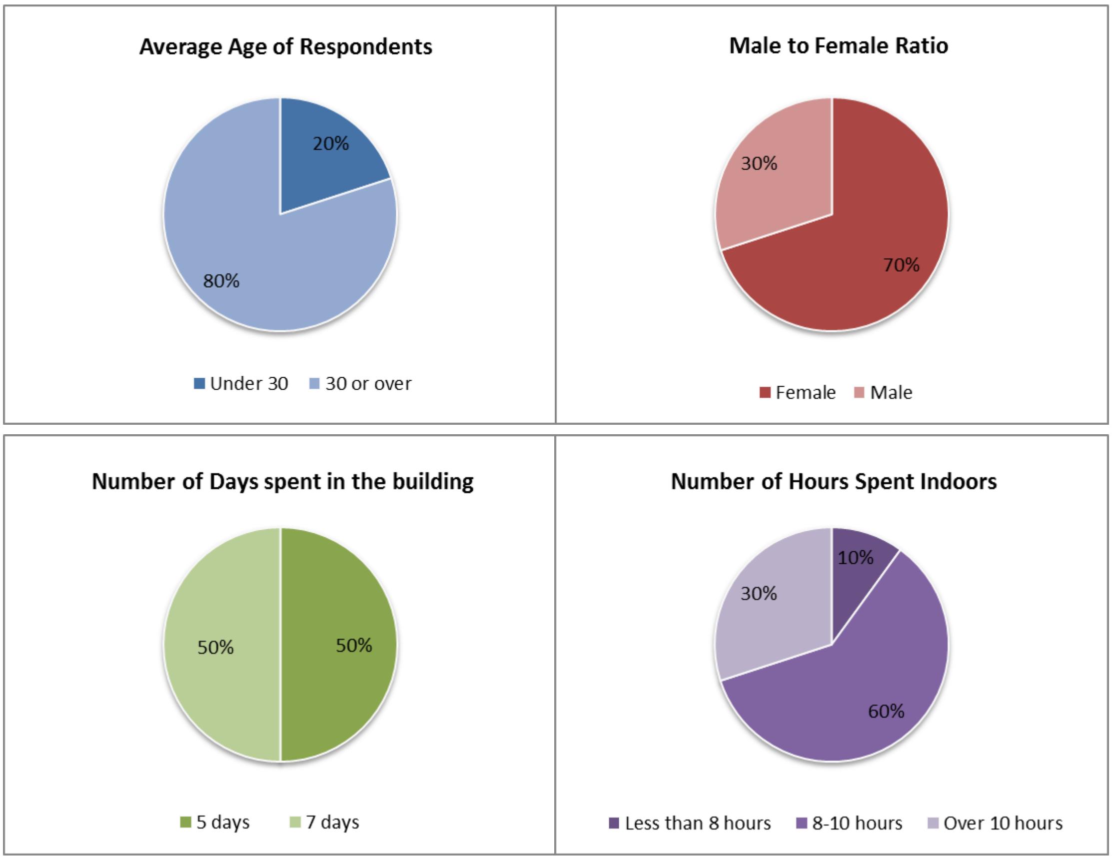


Figure 3-67 General statistics of the Old Post Office BUS study respondents.

Although the BUS methodology covers a wide array of variables, as this study is focused primarily on occupant thermal comfort and building thermal performance, efforts were made to elaborate the findings derived from responses related to those variables. To prevent ambiguity of the analysis of responses, the BUS slider scale which ranges from 1 to 7 was interpreted for the selected variables so as to explain better what the scales between 4 (neutral/scale midpoint) and the top (7) and bottom (1) scales indicate as illustrated in Figure 3-68. Further, Figure 3-69 presents the percentile graphic details which are used to represent data in this section.

All the BUS slider graphics and percentile graphic details presented in Chapters 3 and 4 were derived from the BUS methodology reports prepared following the occupant surveys conducted at the Old Post Office (BUS Methodology, 2014b) and Mombasa Uni Plaza buildings (BUS Methodology, 2014a).

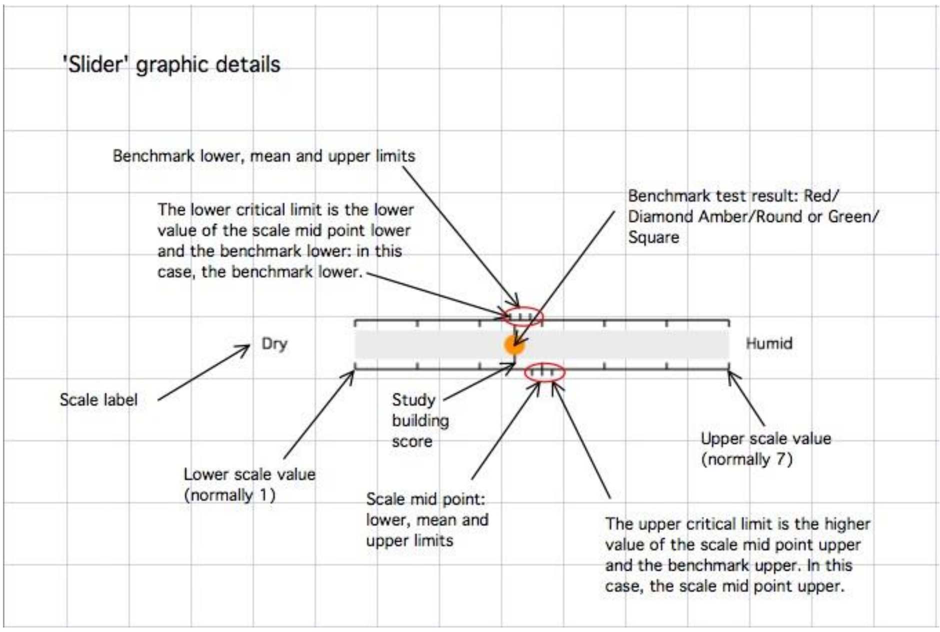


Figure 3-68 BUS slider graphic details (BUS Methodology, 2014b).

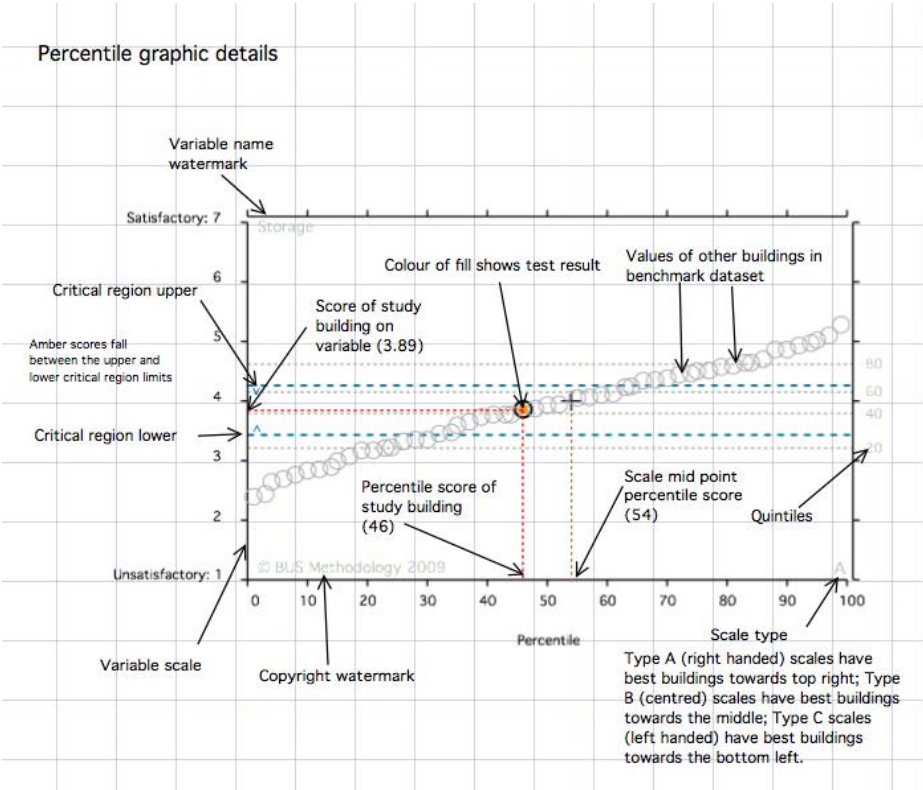


Figure 3-69 BUS percentile graphics details (BUS Methodology, 2014b).

Although the BUS data analysis output refers to 'summer' and 'winter' periods, these terms should not be taken to mean the respective seasons as would be referred to in more temperate climates. Instead, given that the study was conducted in a warm humid region (which is well known for having significantly less climatic variation), adjustments were made and these terms were re-interpreted and explained to all study respondents. In this study, 'summer' refers to the warmest period of the year and ranges between the months of January to March whereas 'winter' refers to the cooler period of the year and ranges between the months of June to August.

A summary of the overall variables of the Old Post Office BUS analysis results was presented in Figure 3-70. It shows the main variables that were investigated and the scale at which the occupants rated them. The BUS 2012 international benchmark (based on benchmarking of 45 variables of similar type buildings) was considered for purposes of this analysis. On the given slider scales, the green squares represent mean values that are significantly better than both the benchmark and the scale midpoint, amber circles are mean values that do not differ from the benchmark and red diamonds are mean values worse or lower than benchmark and scale midpoint.

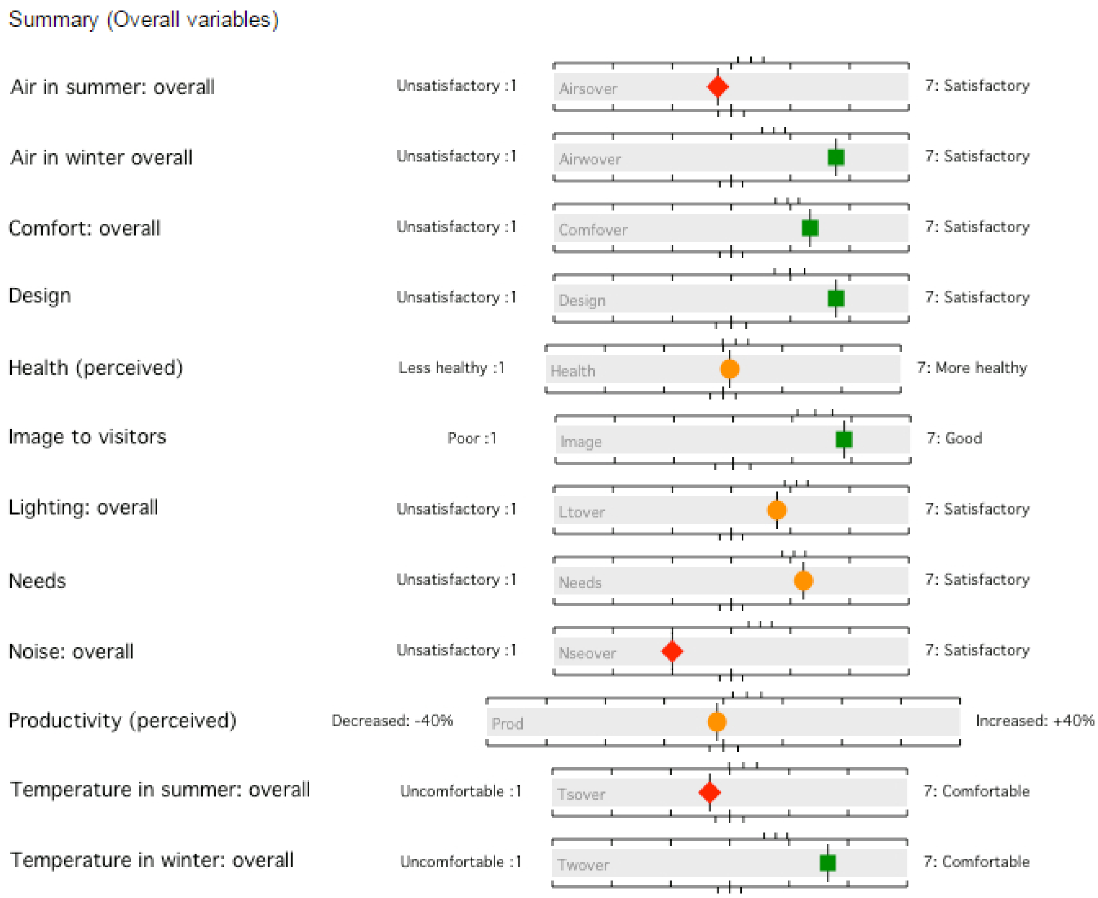


Figure 3-70 Overview of BUS results for the Old Post Office building (BUS Methodology, 2014b).

When all the variables were considered, the overall comfort performance of the Old Post Office building was rated highly on the satisfaction scale by occupants. This was represented by a score of 5.33 on the 7 point scale compared to a benchmark mean value of 4.95. Further, the overall comfort percentile score of the Old Post Office building was rated at 70, indicating that the building performed significantly better than other benchmark and scale midpoint (Figure 3-71). One of the recurring comments given by occupants regarding this rating was that they often got pleasant cooling breezes form the sea. This indicated that access to physiological cooling had a significant role in improving the occupant perception of comfort in the building.

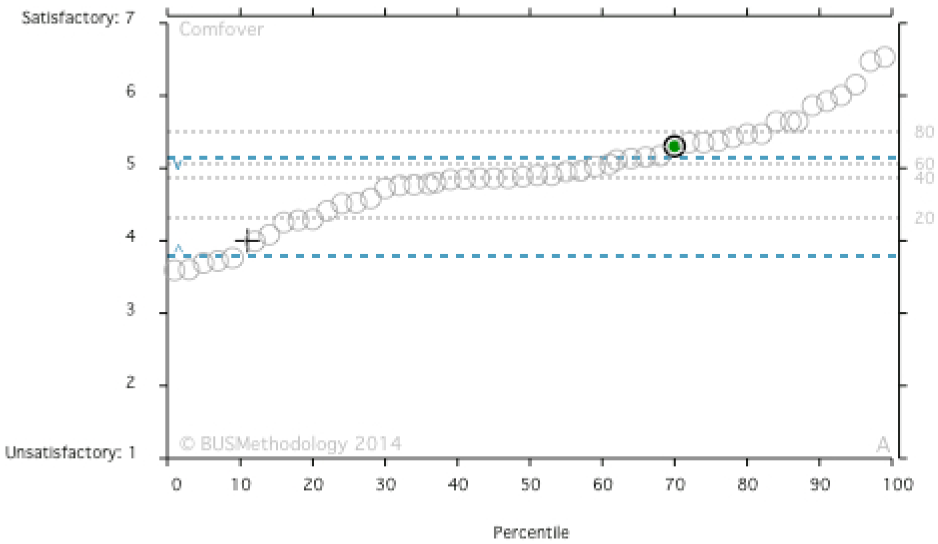


Figure 3-71 Old Post Office overall comfort BUS rating (BUS Methodology, 2014b).

Further, the survey indicated that up to 87% of study respondents changed their behaviour due to conditions in the building. Comments from respondents revealed that changes in behaviour ranged from opening windows or turning on fans if the air was too still or wearing lighter clothing when it was too warm. This indicated that occupants of the Old Post Office building were highly proactive in restoring comfort as far as possible as was indicated in previous studies of adaptive thermal comfort (refer to section 1.2).

The best performing variable was identified to be ‘image to visitors’ where 100% of the occupants indicated that the Old Post Office building presented itself well to visitors. In this case, the respondents rated the building at 5.88 on the 7 point scale compared to the benchmark mean value of 5.39, and a percentile score of 68 indicating that the building performed significantly better than the benchmark and scale midpoint.

On the other hand, the worst scoring variable was identified as 'noise' from a combination of sources, where 100% of respondents indicated that noise levels from outside were either substantial or too much. This was identified to be partly as a result of the fact that the building windows and doors remained open to the busy streets that surround it. Considering that the area in which the Old Post Office is located was found to have high levels of human and vehicular traffic, it was clear to see why this might be a problem. Similarly, it was noted that, because the road width around the building is quite tight (Sir Mbarak Hinawy Road leading into the Government Square), only one way motorised vehicular traffic in either direction can pass at any given time. Consequently, drivers tend to hoot when approaching the bend so as to alert any oncoming pedestrian and vehicular traffic. Unfortunately, owing to the existing street layout, little other than expanding the road network, using timed barriers or banning vehicular movement can be done to ease noise levels.

a) Temperature

To enable a comparison of field study data findings and respondent's responses, the 'temperature in summer' variable was considered first. This is because this variable covered occupant responses to temperatures experienced in the warmer period of the year *i.e.* also when the field study was conducted and the period for which the predicted adaptive comfort was determined. The occupant survey results for overall temperature in summer revealed that occupants found the indoor temperature in summer slightly uncomfortable (33%) or gave a neutral response (66%). This worked out to a score of 3.66 on the 7 point scale which was revealed to be slightly worse than the benchmark mean of 4.23 (Figure 3-72).

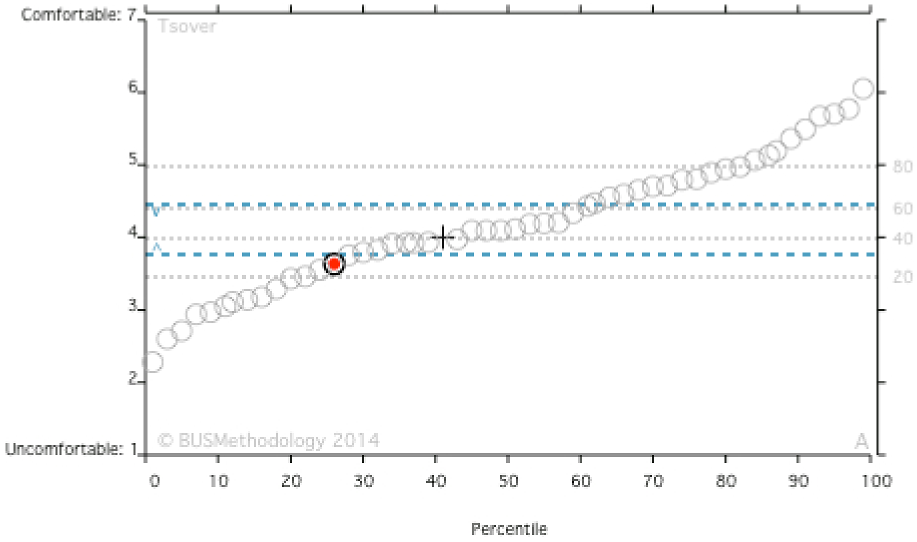


Figure 3-72 Old Post Office temperature in 'summer': overall (BUS Methodology, 2014b).

A review of whether the occupants found temperature in summer either too hot or too cold indicated that 55% of respondents found the temperature in summer neither too hot nor too cold, 22% found it slightly hot, 11% found it moderately hot whereas 11% found it too hot (Figure 3-73). This indicated that that although some of the respondents had voted 'slightly uncomfortable' for the overall temperature in summer variable, it was an indication that they felt a slight inclination towards discomfort. Neutral responses revealed that those occupants felt that conditions were just acceptable, *i.e.* neither too hot not too cold.

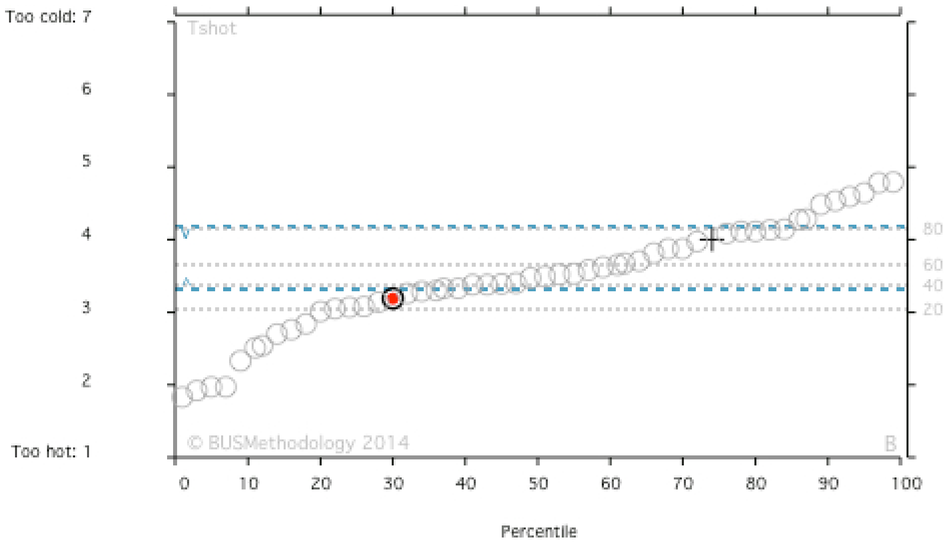


Figure 3-73 Old Post Office temperature in summer: too hot or too cold (BUS Methodology, 2014b).

On the other hand, occupants found temperatures in winter significantly more comfortable with up to 100% of the occupants noting that they found the conditions acceptable. This worked out to a study mean 5.66 on the 7 point scale which was revealed to be significantly more comfortable than the benchmark value of 4.78 (Figure 3-74).

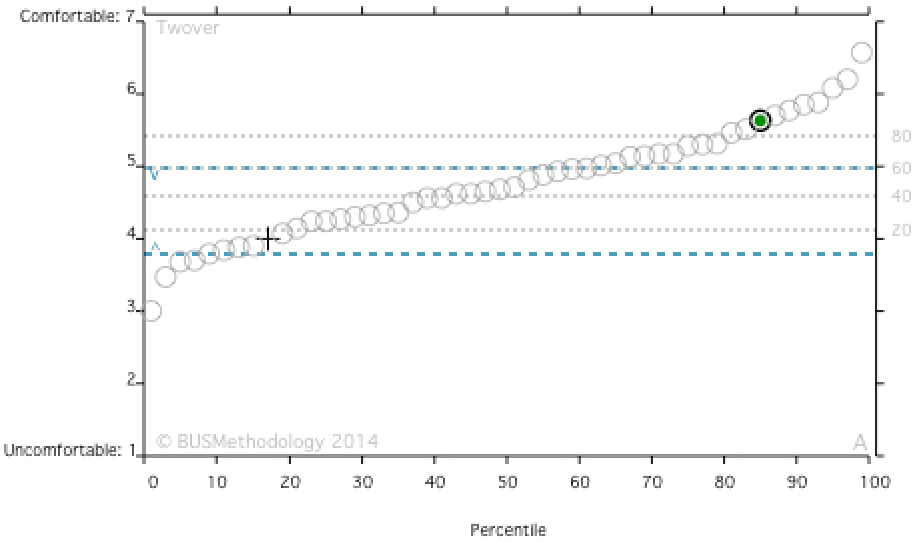


Figure 3-74 Old Post Office temperature in 'winter': overall (BUS Methodology, 2014b).

Further analysis indicated that 60% of the study respondents were usually located on the ground floor location of T1a (antiques shop) and 40% were usually located on the first floor (Residence 01) which was represented by location T2a. For location T1a, 83% of occupants voted that they found the indoor temperature in the summer acceptable. This reflects a 17% deficit in acceptability when compared to the previously predicted adaptive comfort range hours of 100% (refer section 3.3.1). On the other hand, for T2a, 75% of occupants voted that they found the indoor temperature in the summer acceptable. When compared to the predicted comfort range hours of 83%, T2a registered a smaller drop in acceptability of 8%. It was suggested that a higher rate of acceptability from occupants on the ground floor indicated that occupants were more comfortable within that location – a location which has been noted to have relatively lower temperatures as a result of aforementioned passive design strategies and availability of adaptable controls. On the other hand, POE results from occupants of the second floor also indicated a reasonably high level of acceptability.

Of the two sets of results, the POE results for occupant comfort on the first floor location appeared more similar to what was predicted by the adaptive comfort analysis and especially if one considered the 90% acceptability factor given for the adaptive comfort limits. This could be attributed to a variety of reasons. It was proposed that the nature of activities conducted on either floor, made it such that comfort adaptations were much wider in the first floor residential environment. For example, occupants of the first floor level noted that they had ready access to cool water, lighter clothing, could open windows for cooling at night, *etc.* in response to warm conditions. Understandably, these opportunities were fewer in the ground floor commercial environment. It is also worth noting that T2a had greater chances for cross ventilation as determined by occupants; this is in comparison to T1a where this was hindered by blockage of one window on the adjacent side. On the other hand, given that the distribution of respondents on either floor, it is quite possible that the 'margin of error' with respect to predicted versus actual might actually have been more or less similar for both floors.

b) Air (Quality)

A review of the overall air quality in the summer in the Old Post Office found that the respondents rated the building at 3.77 on the 7 point scale in comparison to the benchmark figure of 4.33 (Figure 3-75). From this, it was derived that 55% of respondents felt that the overall air quality was slightly unsatisfactory, with the remaining respondents finding conditions neither satisfactory nor unsatisfactory (11%) and slightly satisfactory (33%), respectively. Further analysis revealed that this result was mainly attributed to the fact that 87% occupants found the air slightly humid in the summer. This would have compromised the occupants' ability of to dissipate heat, factor which would have aided by the provision of air movement. When considering air movement, up to 55% of occupants thought that this was adequate (indicating the air was neither still nor draughty). This indicated that the channelling of breezes indoors did not negatively affect majority of occupants, instead it was a welcome input. However, up to 33% of respondents felt that it was slightly draughty whereas 11% thought that it was moderately still. The building performed well in terms of air freshness and air odour variables with 77% and 87% finding conditions adequate, respectively.

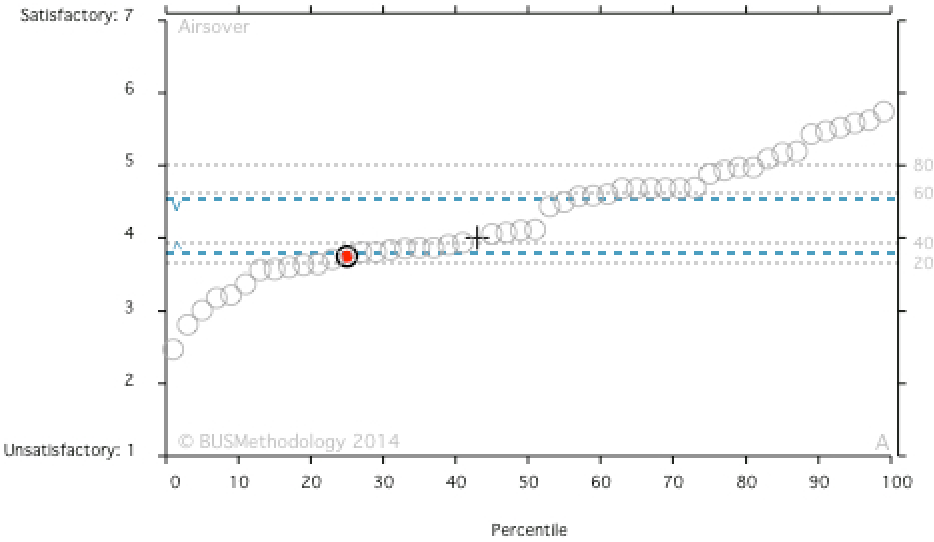


Figure 3-75 Old Post Office air in summer (BUS Methodology, 2014b).

When considering the overall air quality in winter, 88% of the occupants noted that the conditions were moderately satisfactory whereas 11% indicated that conditions were neither satisfactory not unsatisfactory. This worked out to a study mean 5.77, and was seen to perform fairly well (within the 91st percentile) compared to the benchmark score of 4.72 (Figure 3-76). Unlike the results for the air quality in summer, responses regarding level of dryness or humidity of the air during the winter showed a highly level of acceptability with more varied with responses covering slightly dry (22%), neither dry nor humid (33%), slightly humid (33%) and considerably dry (11%). When considering air movement, majority of respondents found the air slightly draughty (77%) with others finding it neither draughty nor still (11%) or slightly still (11%). This indicated that high air movement.

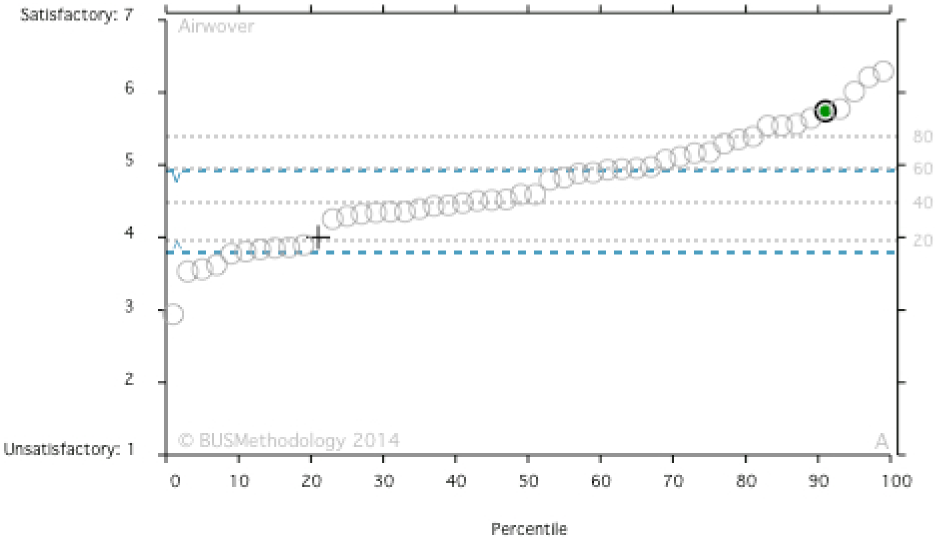


Figure 3-76 Old Post Office air in winter (BUS Methodology, 2014b).

c) Lighting

The lighting variable combined responses to natural and artificial lighting and glare. 55% of occupants found the lighting adequate, 11% found it slightly satisfactory whereas 33% found it slightly unsatisfactory. This worked out to a study mean 4.77 compared to the benchmark score of 5.1 (Figure 3-77). Further review indicated that up to 77% of the occupants found natural lighting adequate, with the rest indicating that they would like it to be slightly brighter indoors. This confirmed study findings that suggested that lighting levels might low albeit tolerable. Further, 100% respondents indicated that artificial lighting was adequate.

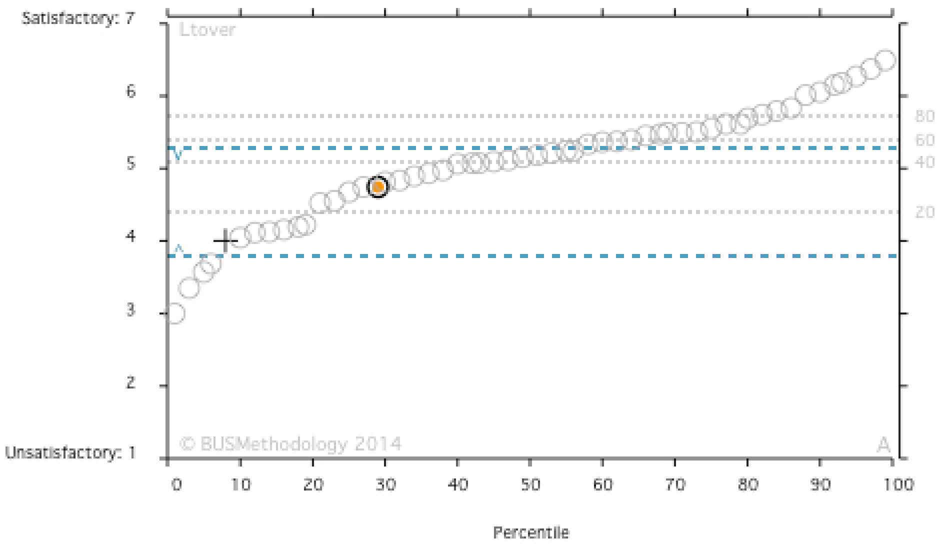


Figure 3-77 Old Post Office overall lighting (BUS Methodology, 2014b).

In section 3.3.2, sun penetration analysis indicated that solar ingress had the potential to cause sun patches indoors. Following up on this, up to 88% of respondents indicated that glare from the sun and sky was not an issue. However, 11% found the glare from the sun and sky as being slight. Similarly, 88% of the respondents indicated that they found instances of glare from artificial lighting was not an issue; however, 11% of respondents indicated that glare from artificial lighting was too much.

d) Control

The main climate controls in the Old Post Office were passive in nature. In this section, user perceptions with respect to accessing personal control measures that are used to restore comfort in the Old Post Office building were examined. Up to 87% of respondents indicated that they found that personal control over cooling was adequate whereas up to 12% found it slightly less than adequate. This good performance was suggested to be indicative of the high level of control offered to occupants of the Old Post Office. Further, a study mean of 3.87 indicated that the Old Post Office performed substantially better than the benchmark value which had a mean of 2.93 (Figure 3-78).

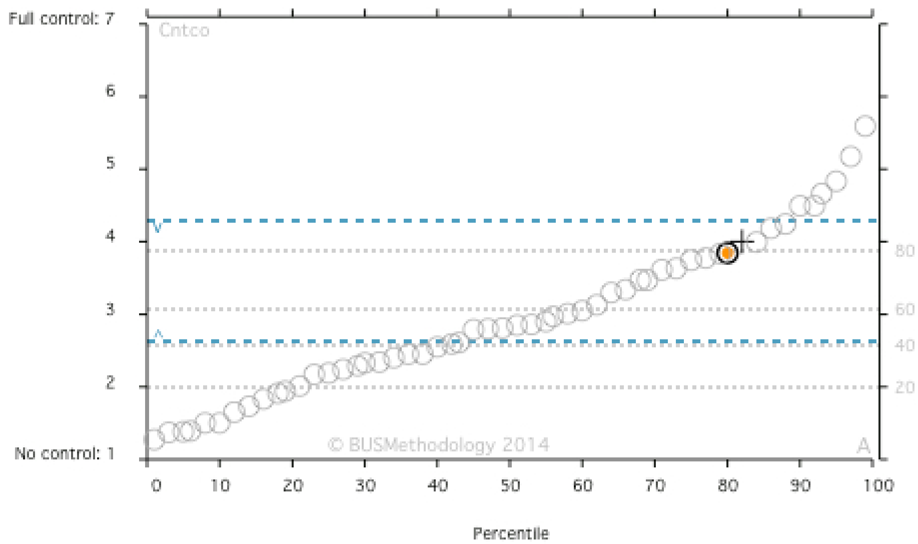


Figure 3-78 Old Post Office control of cooling (BUS Methodology, 2014b).

Further, 62% of respondents indicated that that they had full personal control over ventilation whereas 37% indication that they had adequate personal control. This high level of control may be related to the fact that up to 99% of occupants indicated that they had direct access to an openable window with which they could use to control their immediate environment. The study mean was rated highly at 5.87 on the 7 point scale compared to 3.19 for the benchmark value (Figure 3-79).

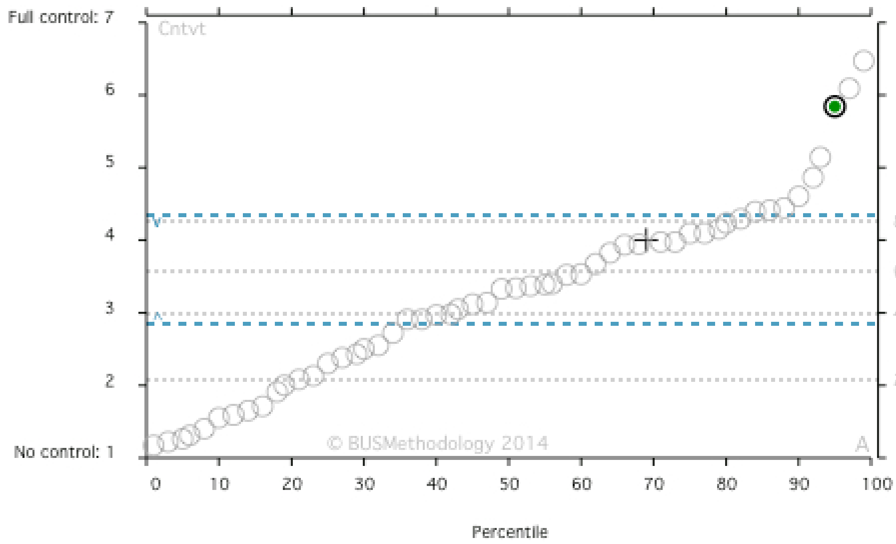


Figure 3-79 Old Post Office control of ventilation (BUS Methodology, 2014b).

In addition, 37% of occupants indicated that they had adequate personal control of lighting whereas 62% indicated that they had just slightly less than full control. A high study mean of 5.25 showed significantly better performance than the benchmark of 3.75 (Figure 3-80).

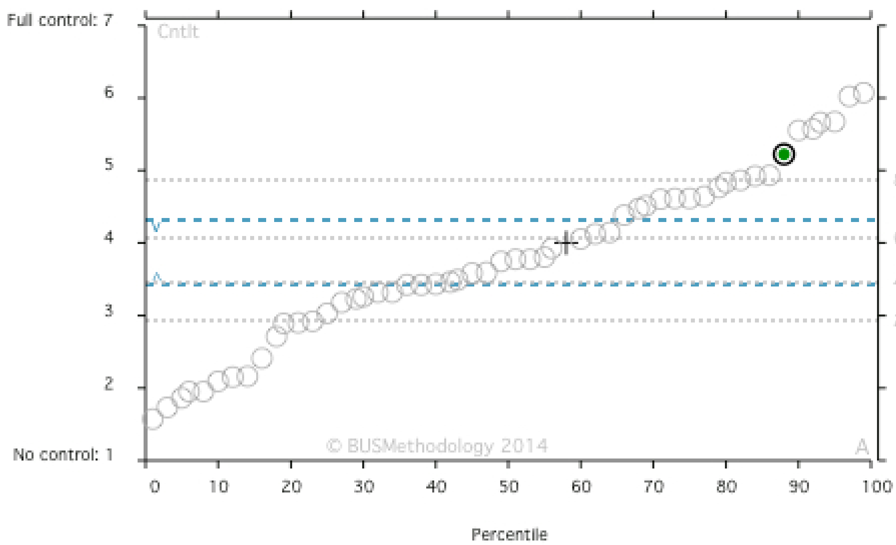


Figure 3-80 Old Post Office control of lighting (BUS Methodology, 2014b).

e) Design and Needs

A review of the Old Post Office building design in relation to occupant needs was also conducted. A review of the findings indicated that occupants felt that the building design was neither satisfactory nor unsatisfactory (11%), slightly satisfactory (11%), moderately satisfactory (66%) and satisfactory (11%). With a study mean of 5.77, the building was found to perform better than the benchmark figure of 4.99 (Figure 3-81). Reasons given by respondents for this high satisfaction score included the fact that they liked the aesthetic of vernacular Swahili architecture exhibited by the Old Post Office building and that they felt that the building served its current purpose well, amongst others.

Similarly, all respondents voted that they found that the building met their needs with up to 44% finding it neither satisfactory nor unsatisfactory, 44% finding it moderately satisfactory and 11% finding it satisfactory. A study mean of 5.33 also indicated that while response to occupants' needs appeared to be met adequately, it was not significantly different from the benchmark value of 5.06 (Figure 3-82). This score was attributed to the fact that the building offered all the necessary requirements for their daily activities.

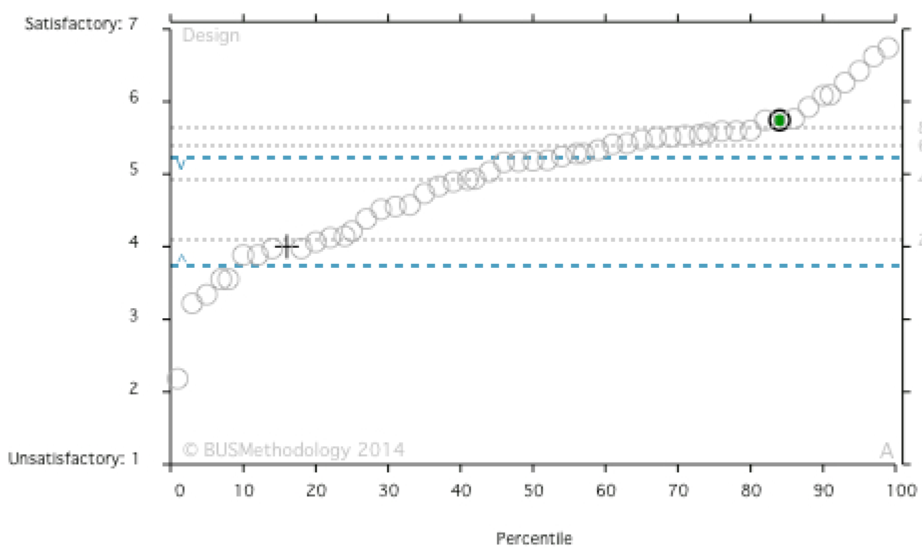


Figure 3-81 Old Post Office building design (BUS Methodology, 2014b).

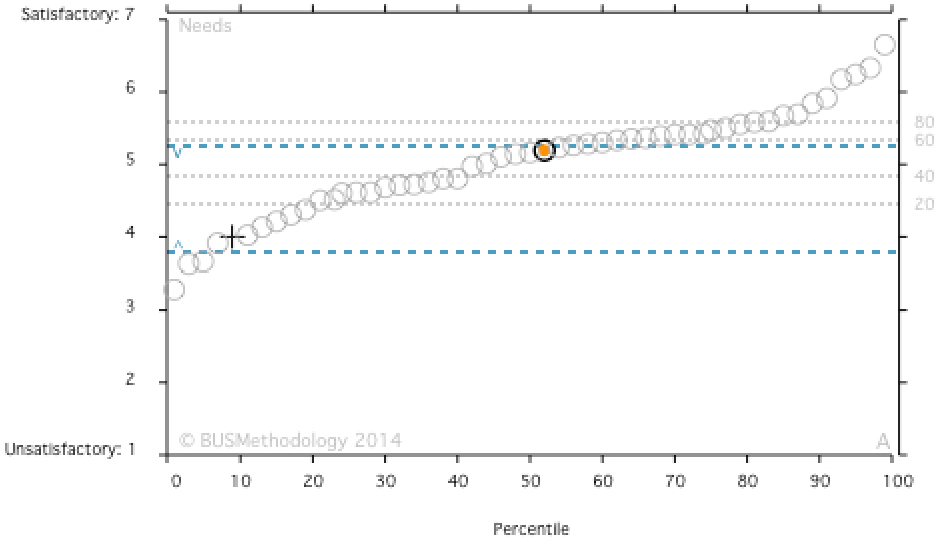


Figure 3-82 Old Post Office needs (BUS Methodology, 2014b).

f) Health (perceived) and Productivity (perceived)

Majority of respondents (77%) indicated that they did not feel more or less healthy when occupying the Old Post Office building. Nonetheless, about 11% did indicate that they felt more healthy as a result of being in the building whereas 11% indicated that the felt slightly less healthy from occupying the building. A study mean of 4.11 indicated that this was similar to the benchmark value of 4.21 (Figure 3-83). A review of the reduction in perceived health was attributed to outdoor noise, lengthy journey distance to work (including traffic jams), amongst others.

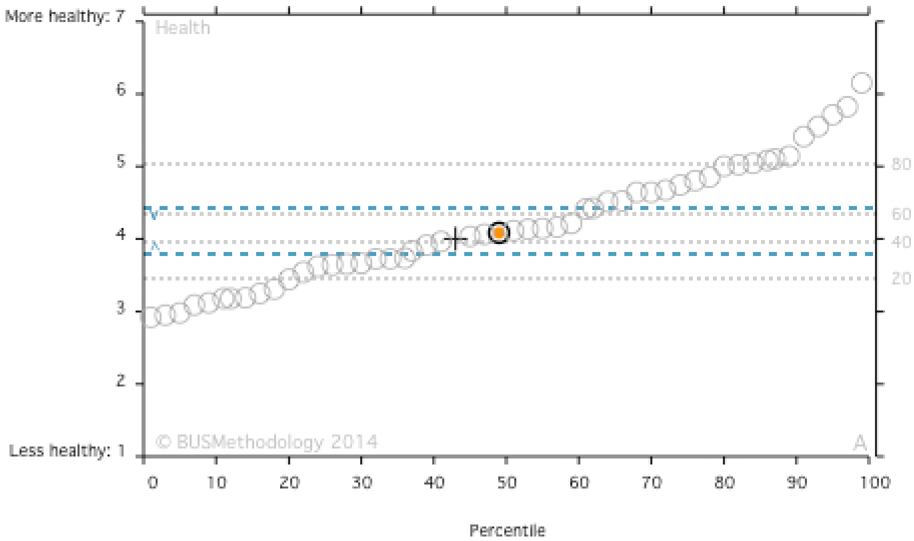


Figure 3-83 Perceived health in the Old Post Office (BUS Methodology, 2014b).

Up to 77% of respondents indicated that they did not feel any more or less productive as a result of carrying out various activities in the Old Post Office building. 11% found that they were 30% less productive whereas another 11% found that they were 20% more productive as a result of performing various activities in the building. A study percentage mean of -1.11 indicated that the building was within the critical benchmark region (Figure 3-84). Interestingly, some respondents indicated that this reduction in productivity was attributed to not wanting to leave the building for offsite work as it was much hotter outside! This indicated a preference of indoor conditions.

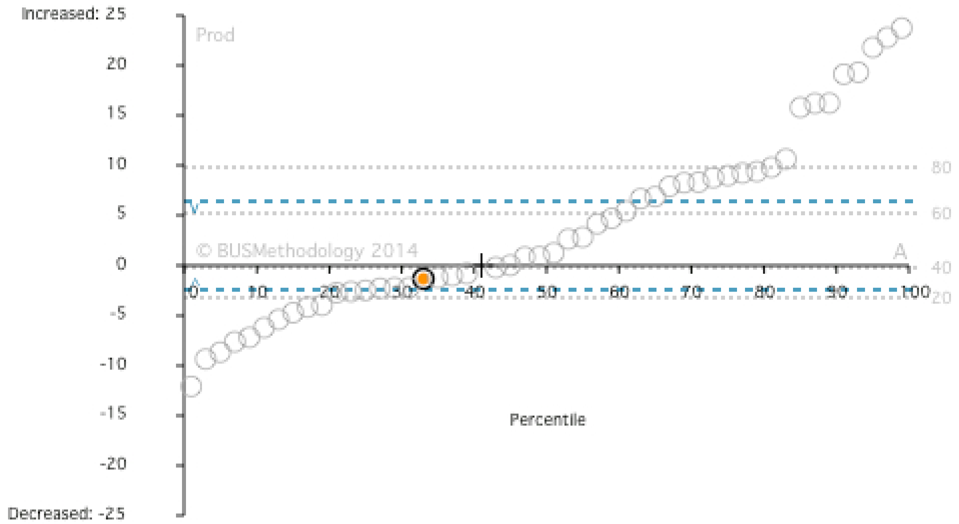


Figure 3-84 Productivity (perceived) in the Old Post Office (BUS Methodology, 2014b).

Overall, the survey findings indicate that the Old Post Office building falls in the top 40% of the BUS 2012 international benchmark database – a reasonably good outcome (Figure 3-85).

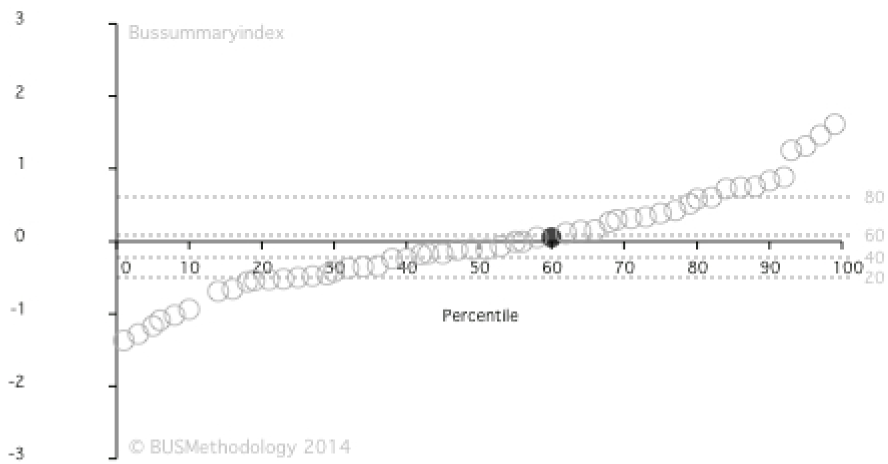


Figure 3-85 Old Post Office BUS summary index (BUS Methodology, 2014b).

The BUS summary index is the average of the comfort index and the satisfaction index, both of which the Old Post Office scored highly, falling within the top 50% and top 40% of the BUS 2012 international benchmark database, respectively. Of the twelve study variables used to give a simple overview of the buildings comfort performance, nine were either better (5) or no different (4) from the benchmark. The forgiveness score was also high (a score of 1.2 out of 1.5, top 10% of the BUS 2012 international benchmark database), indicating that occupants will accept some level of dissatisfaction when taking into account the overall performance of the building.

Good levels of control for cooling, lighting and ventilation were reported by occupants. This indicated that the occupants had good access to adjusting the indoor conditions to suite their requirements. Similarly, respondents also noted that they tended to change their behaviour because of conditions in the building thereby allowing them to extend their comfort further. Majority of occupants reported that they appreciated the cooling sea breeze as it helped enhance their indoor thermal comfort. It was also noted that they felt that indoor temperatures felt significantly cooler indoors and particularly warm afternoon. Additionally, majority of respondents reported that levels of both natural and artificial lighting were adequate with few citing problems of glare.

The main weakness identified in the performance of the Old Post Office building was the temperature in the summer where conditions were perceived as too humid and having varying degrees of warmth. However, provision of air movement and personal control of the same was suggested to have helped make thermal comfort conditions in summer more tolerable. Similarly, problems of noise outdoors (issue is place-dependent rather than design-related) were found to adversely affect overall occupant comfort, it was suggested that substantial external changes would be required to rectify the situation.

3.5 Conclusions

As with a significant number of vernacular Swahili buildings found in the warm humid city of Mombasa, the Old Post Office building consists of a mixed-use building with commercial and residential activities consigned to the ground floor and the first floor, respectively. In general, the field study findings indicated that the building exhibited potentially suitable passive design responses to the local context and climate. Key to the environmental design strategies of the Old Post Office was the provision of adaptive opportunities through which occupants could restore thermal comfort. Indeed, the POE findings indicated that up to 87% of respondents changed their behaviour due to conditions in the building as a means of restoring comfort.

Following the case study analysis of the Old Post Office building, a series of Swahili-inspired environmental design strategies were derived. They included building orientation and mutual shading, outdoor 'living rooms', balconies, doors and screened windows, thick walls with significant thermal mass and use of a ventilated roof attic. A review of these design elements and strategies indicated that they tended to work towards either providing heat gain control (sun shading and thermal mass) or provision for cooling (air movement). This was in keeping with the recommended design strategies in hot and warm humid climates as identified in Chapter 2.

For solar control purposes, it is recommended that buildings along the equator are laid out with their long axis along the east west orientation. In slight contrast to this, the Old Post Office building was found to be orientated with its long axis running along the north-west and south-east axis, seemingly overriding the requirements for solar control. Instead, analysis indicated that both the building and its openings were primarily laid out to encourage the channelling of breezes for cooling indoors from the predominant wind directions of the north-east and the south-east. It was suggested that this necessitated the use of sun shading which was also seen to be a key design intervention used in the Old Post Office building.

In the Old Town area, it is common to have commercial and some domestic activities spill out into the street. Certainly, in the Old Post Office, occupants of the antiques shop tended to have a high level of interaction with their immediate external spaces with majority citing that they enjoyed sitting under the shade, and especially when air movement was sensible. A review of the external spaces around the Old Post Office indicated significant levels of shading, with the streets appearing to be aligned in such a way as to channel predominant prevailing winds. Further, the findings indicated that mutual shading played a significant role in tempering immediate outdoor conditions by reducing average daily solar insolation by over a third of the initial value when no mutual shading was considered. Similarly, a review of wind direction and velocities revealed that the surrounding streets were laid out to channel winds from the Indian Ocean with air velocities recorded between 0900hrs and 1500hrs being greater than 0.25m/s with an average of approximately 3.7m/s.

Consisting of screened or open types, the 1.2m deep balconies at the Old Post Office played the important role of shading the building fabric without compromising the channelling of breezes indoors as well as providing a shaded semi-private zone for occupants. The study findings revealed that in cases of high angle sun, the balconies work well to cut off solar radiation to the fabric below whereas in case of low angle sun, the screens would work well to cut off direct solar radiation infiltration. Generally, the high level of permeability of the balconies meant that both ventilation and solar heat gain control strategies could be integrated to enhance building thermal performance and improve thermal comfort.

The doors and screened windows in the Old Post Office building formed the main means by which natural ventilation was channelled for the supply of fresh air and cooling. A review of the effectivity of these both cross and single-sided ventilation strategies determined that they were both feasible at the Old Post Office building given the room depths of 2.5m to 8m. Further, a review of the fenestration/glazing percentages indicated that the western orientation had significantly less opening area (11.03% in the north-west and 0.59% in the south-west). This was in contrast to the eastern facades which were found to have significantly more opening area (36.32% in the north-east and 13.24% in the south-east). As with the building orientation, the distribution of window openings was attributed to the need to drive localised winds indoors. The main means of ventilation control available to occupants included the opening and closing of doors and windows and the adjustment of the shutters and louvres. Through this, occupants were able to moderate the indoor environment as they saw fit, and for as much as outdoor conditions would allow. Up to 99% of the BUS survey respondents noted that they had adequate or full personal control of ventilation of the indoor spaces.

Generally, recorded air velocities at the Old Post Office ranged between 0.3m/s to 4.5m/s and averaged between 0.9m/s and 1.9m/s. From these measurements the control potential zone (range of outdoor conditions for which air movement has the potential to ensure indoor comfort) was calculated. These findings indicated that the adaptive comfort limits could be increased by up to 5.6°C for air velocities of up to 2m/s. Given that higher velocities were recorded during the afternoon period, this perceived reduction in indoor temperatures explained to some extent how it was that occupants felt comfortable in the fairly warm indoor temperatures.

The Old Post Office building was mainly made of coral stone; this stone was primarily used to construct the notably thick walls measuring up to 730mm for external walls and up to 530mm for internal walls. The wall finishes were made of lime plaster and lime wash; this gave the walls an albedo of approximately 0.93 and enhanced their reflective capabilities thereby reducing solar heat gain via conduction. A review of the overall building fabric indicated that the Old Post Office building appeared heavyweight in nature. This was further confirmed by a review of construction material properties which indicated that external walls had high admittance values of up to 4.01W/m^{2}K; it was noted that the high admittance value typified heavyweight or dense construction.

Further, a review of field data indicated that indoor temperatures in the Old Post Office could be quite steady and up to 7°C cooler than those outdoors. Typically, the indoor DBT fluctuations translated into a delay of indoor peak times by about 3 to 9 hours; with a significantly longer peak delay recorded on the ground floor. It was suggested that this performance was partly attributed to the suitably heavyweight properties of the building fabric. As it was not possible to carry out more definitive tests to confirm this, parametric studies were carried out to test out the effect of increased thermal mass and the results presented in Chapter 5.

Originally, the roof of the Old Post Office had two open gable ends which were later sealed up to prevent birds from accessing the attic. The roof construction consisted mainly of corrugated iron roof sheets on a timber frame and a soft board ceiling, resulting in a high u-value of 3.18 W/m^{2}K (in comparison to a low u-value of 0.74 W/m^{2}K for the first floor ceiling). It was suggested that the combined effect of restricting ventilation of the attic space and the poor insulation properties of the roof led to heat build-up from solar gain being re-radiated downwards. The findings indicated that temperatures in the attic were significantly higher than those on the first floor (by up to 4°C) and even more on the ground floor spaces (up to 6.8°). Also, the attic temperature was almost always as high as or higher (up to 3.1°C) than the corresponding outdoor temperature. Given that solar radiation on the zenith presents the largest risk of heat gain in warm humid climates, it is suggested that well ventilated and better insulated roof would significantly improve indoor performance. Parametric studies covered in Chapter 5 investigate this further.

Monitoring studies suggested that the combination of these design elements and strategies resulted in the significantly lower and steady temperature in the Old Post Office building. An overview of air temperature and relative humidity data indicated that the site conditions were quite similar to what had been predicted in the climate analysis covered in section 1.3. Outdoor temperatures were found to range between 26.8°C and 34.3°C with diurnal temperature range of up to 8.4°C. It was proposed that this temperature diurnal range indicated suitability for night ventilation cooling strategy. On the other hand, indoor temperatures were found to range between 28.3°C and 34.1°C with temperature swings of between 1°C and 4°C.

A review of adaptive comfort limits using data collected during the field study revealed comfort limits of 27.5°C to 31.5°C for the month of March. Using these comfort limits, it was predicted that location on the ground floor would be comfortable for 100% of the time whereas the locations on the first floor would be comfortable for 70% to 83% of the time. Correlation of this data with POE survey comfort results indicated a deficit of 8% (first floor) to 17% (ground floor). Even so, the ground floor still registered higher levels of comfort, a fact that was attributed to the significantly lower and steadier temperatures recorded on the ground floor.

The POE evaluation study gave valuable insights into the building thermal performance in relation to occupant satisfaction. Generally, the majority of the occupants agreed that the Old Post Office performed fairly well rating it within the top 40% of the BUS 2012 international benchmark database. The role of adaptive opportunities was found to be quite significant, with up to 87% of occupants admitting to behavioural changes as a means of restoring comfort. Further, 87% of occupants indicated that they had personal control over cooling. Up to 44% of occupants admitted that the temperatures in the summer were warmer than preferred, however they still considered them tolerable; a factor that was largely attributed to the provision of cooling. On the other hand 100% of occupants found temperatures adequate during the rest of the year.

The extensive investigative work associated with the case study analysis of Old Post Office enabled a detailed understanding of the building performance and the resultant occupant thermal comfort. Importantly, a review of the qualitative and quantitative data collected during the study period led to the derivation of Swahili-inspired design strategies which may be considered suitable and workable architectural and environmental responses to the local context and climate. Based on the findings of this case study review, focus was placed on accurately quantifying the impact of the main identified heat gain control and cooling strategies of shading, thermal mass, and ventilation with respect to office buildings in Mombasa, and the findings were presented in Chapter 5.

4 MODERN CASE STUDY: MOMBASA UNI PLAZA

Mombasa Uni Plaza is a typical modern office building located in the warm humid city of Mombasa, Kenya. The building is characteristic of the 'newer' and mainly lightweight office buildings in the city that tend to be prone to overheating. In this chapter, the findings of an intensive case study analysis of Mombasa Uni Plaza are presented with focus on the environmental performance of the building.

4 MODERN CASE STUDY: MOMBASA UNI PLAZA

Mombasa Uni Plaza is located on Khan Road, off Moi Avenue in Mombasa, Kenya (Figure 4-1 and Figure 4-2). An examination of the general street fabric revealed that there was a significantly less dense layout in comparison to the Old Town area with the buildings laid out as per existing road and plot boundaries. Formerly referred to as Re-insurance Plaza, the building was originally designed to serve as a branch office for an insurance company and to provide supplementary office space for letting purposes. More recently, the property was acquired by the University of Nairobi who maintained the core activity of commercial office space. In addition to this, they also integrated satellite Law and Business Studies campuses (inclusive of offices for staff members) on the lower four floor levels (ground floor to third floor) retaining majority of the space for office purposes.

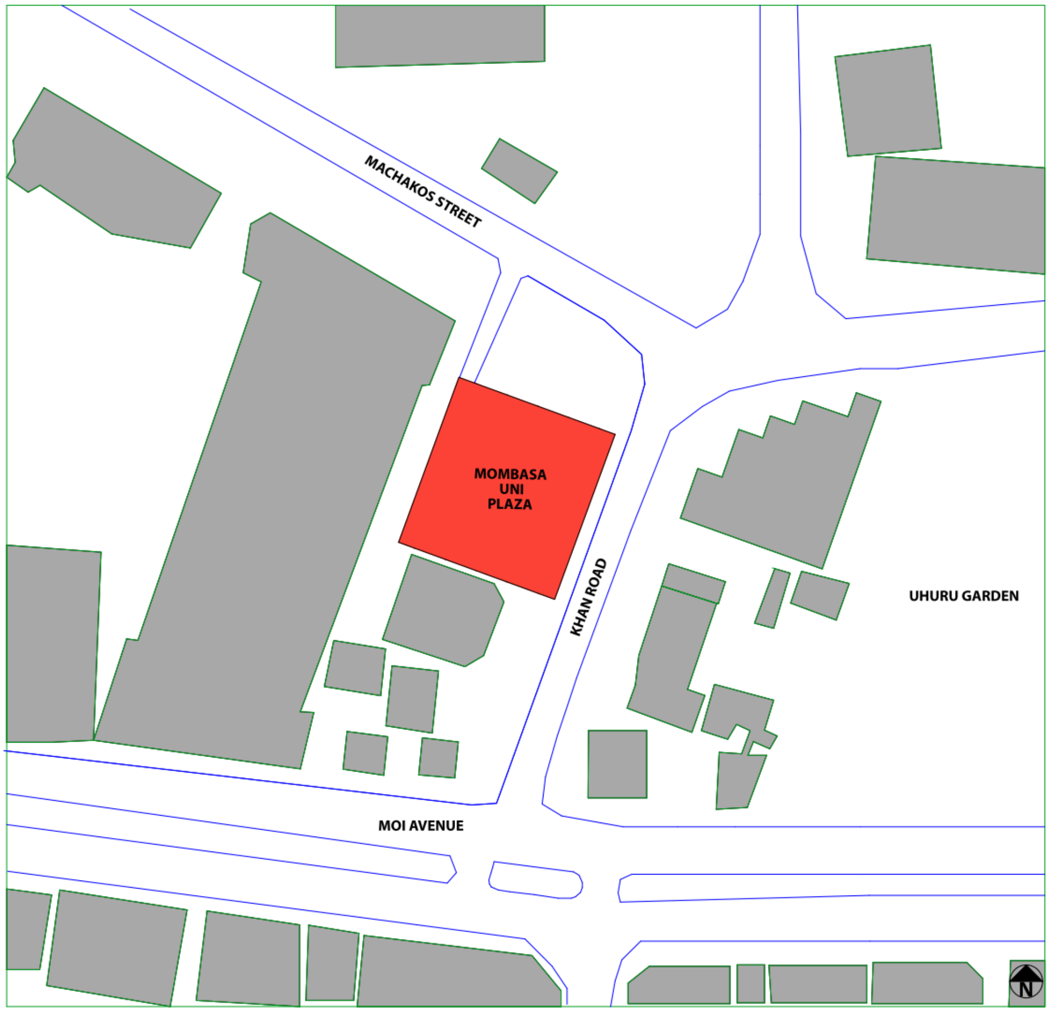


Figure 4-1 Mombasa Uni Plaza (highlighted) site location plan (author-modified from Google Maps).

Figure 4-2 Mombasa Uni Plaza side elevation view.

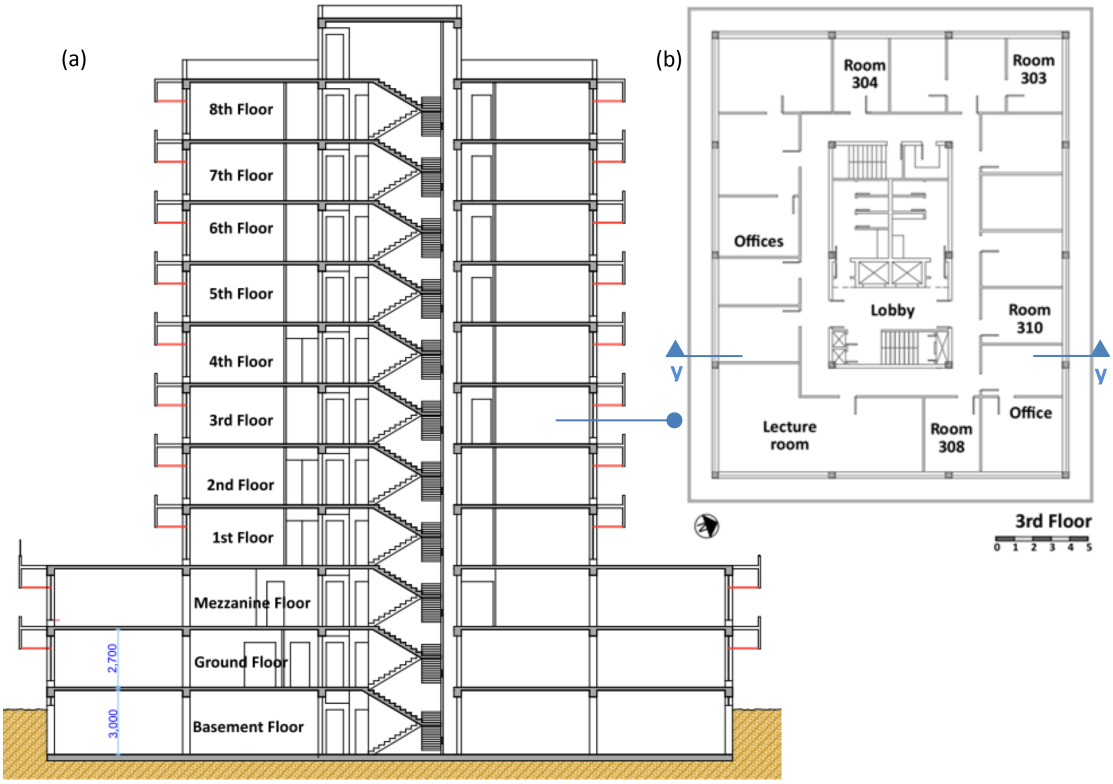


Figure 4-3 (a) Section y-y of Mombasa Uni Plaza (b) Insert of the 3rd floor plan.

Occupants who took part in the POE survey (section 4.3) indicated they had been mainly attracted to the central location of the premises - within the central business district (CBD) of Mombasa. A significant number of buildings within the neighbourhood had recently (or were currently) being renovated to create more commercial spaces. This was an indication of the growing demand for commercial space within the city.

The selection of Mombasa Uni Plaza as a case study building was largely informed by the need to examine a typical naturally ventilated office building in Mombasa. During the case study selection process, it was noted that all the other office buildings accessible to the researcher for purposes of this study were air conditioned to a significant extent. Conversely, Mombasa Uni Plaza was the only building that had selected office spaces using natural ventilation as the main means of ventilation all year round. Therefore, although Mombasa Uni Plaza was only partially naturally ventilated, a review of the building provided the opportunity for the collection of useful site monitoring data.

In addition, although the building appeared heavily shaded, in contrast to the highly glazed and exposed facades of majority of office buildings in Mombasa, it also exhibited high amounts of glazing on all its facades (more critically on the west and east facing facades). As such, it was suggested that this would provide the researcher with a chance to investigate the implication of shading on highly glazed critical facades which are typical to majority of buildings found in Mombasa.

4.1 The Building Design

4.1.1 Building Use, Form and Layouts

Mombasa Uni Plaza comprises of a podium (three floor levels) and a tower (eight floor levels) (Figure 4-4). All the main circulation and building services are centrally placed to form a core that is flanked by a ribbon of mainly office space (Figure 4-5, Figure 4-6 and Figure 4-7). It is noted that all the layouts, detail drawings, sketches and other illustrations of Mombasa Uni Plaza presented as part of this study were prepared by the researcher based on site measurements and observations. This was necessitated by the lack of availability of suitable building information.

Externally, all the floors are enclosed by a uniform strip of glazing that wraps around all the four main facades. This strip of glazing is partially shaded by a series of projections that were originally designed to hold air conditioning units which formed part of the building ventilation system. This ventilation equipment has since been removed, leaving the projections to serve the sole objective of providing partial shading to the extensively glazed facades. Given the presence of these shading elements, it was suggested that although Mombasa Uni Plaza had a significant amount of glazing on all its facades, the building would be more suitably classed as a mid-range typical office building.

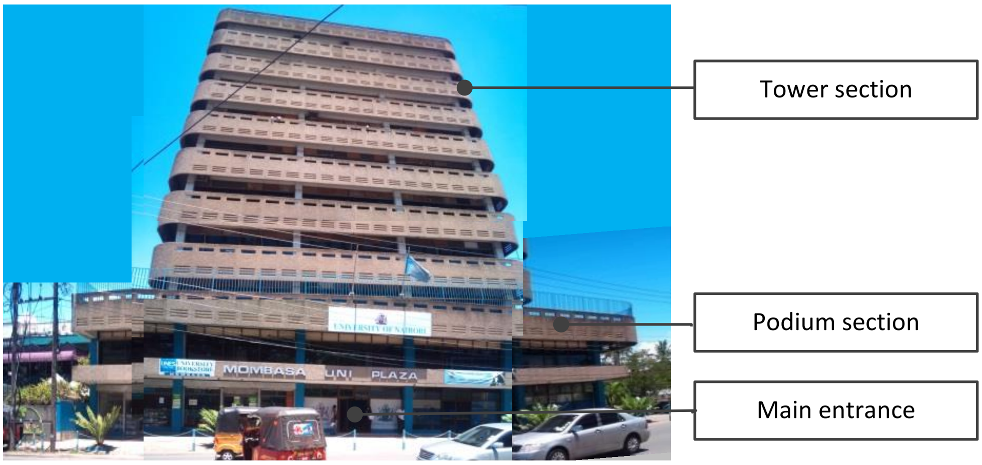


Figure 4-4 Mombasa Uni Plaza front facade and perspective view from Khan Road, Mombasa.

Although the centralised AC ventilation system was later removed for being too costly, individual AC units have now being installed in some offices. Consequently, both natural and artificial means of ventilation are used throughout the building leaving a mixed-mode system in place.

Architectural features typical to office buildings in Mombasa, as highlighted in Chapter 1, were evident in the Mombasa Uni Plaza and its immediate surroundings. For instance, the use of concrete was quite apparent as was the abundance of glazing on the facades.

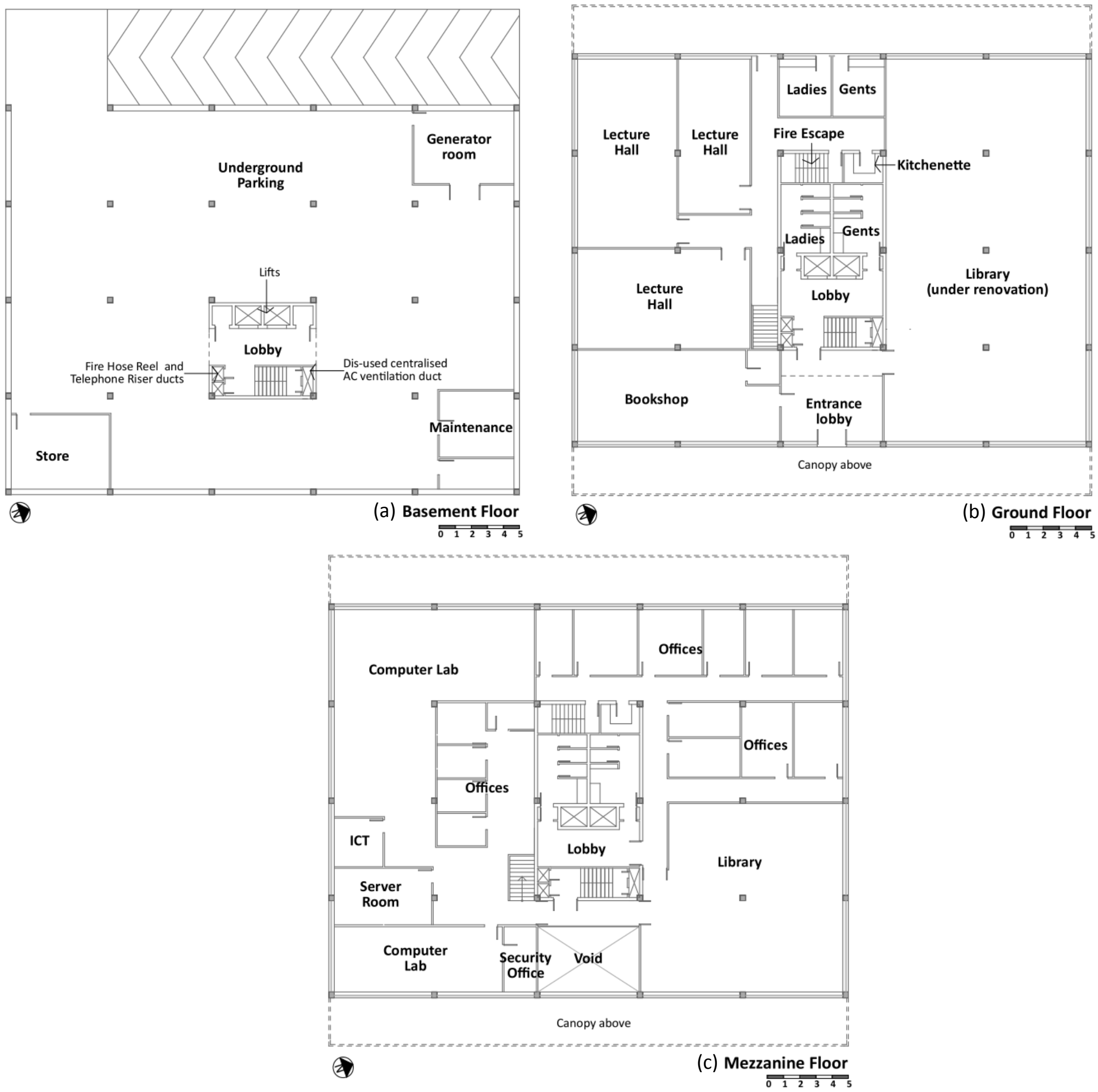


Figure 4-5 (a) to (c) Mombasa Uni Plaza podium layouts (basement, ground and mezzanine floors).

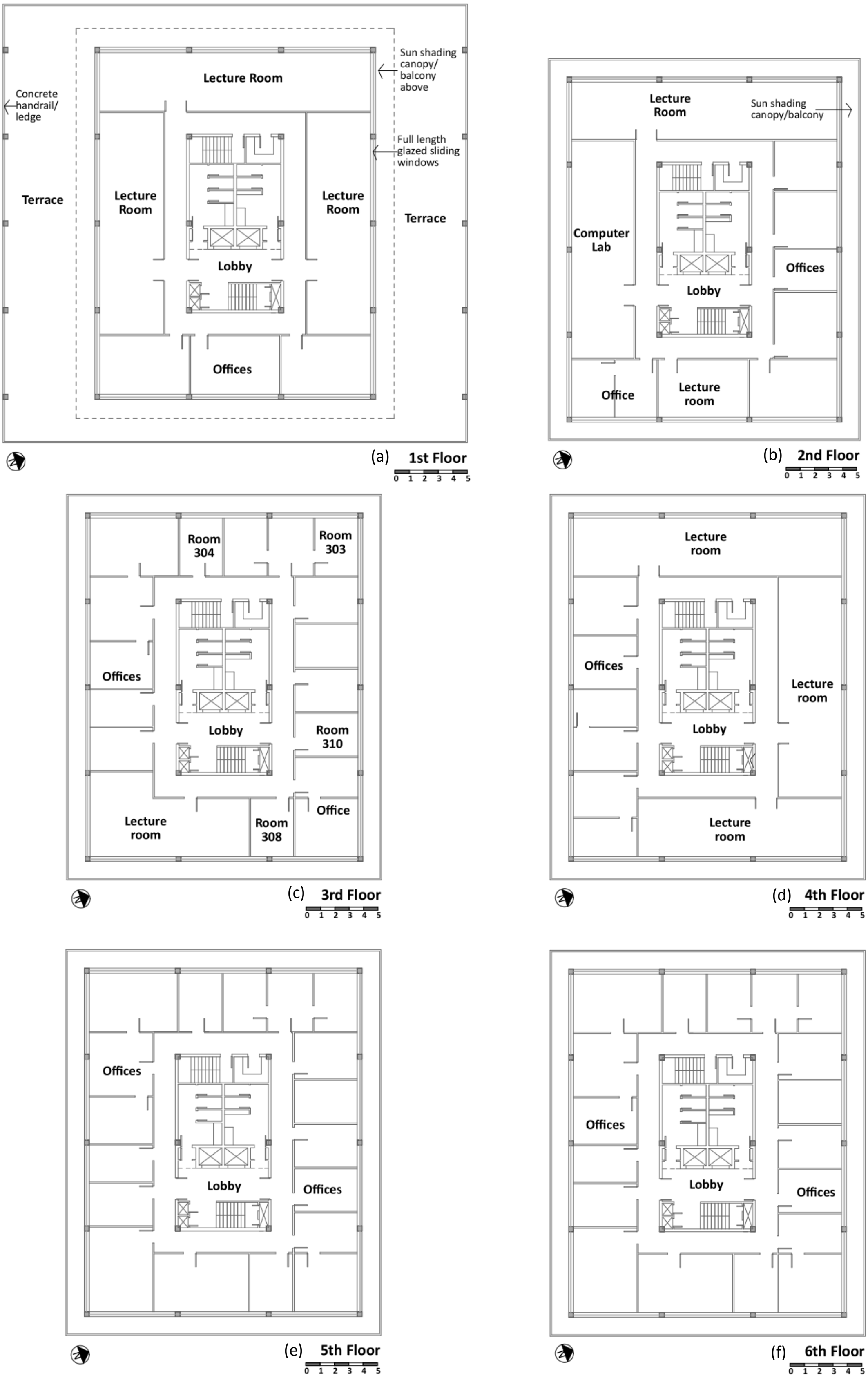


Figure 4-6 (a) to (f) Mombasa Uni Plaza tower layouts (first to sixth floor).

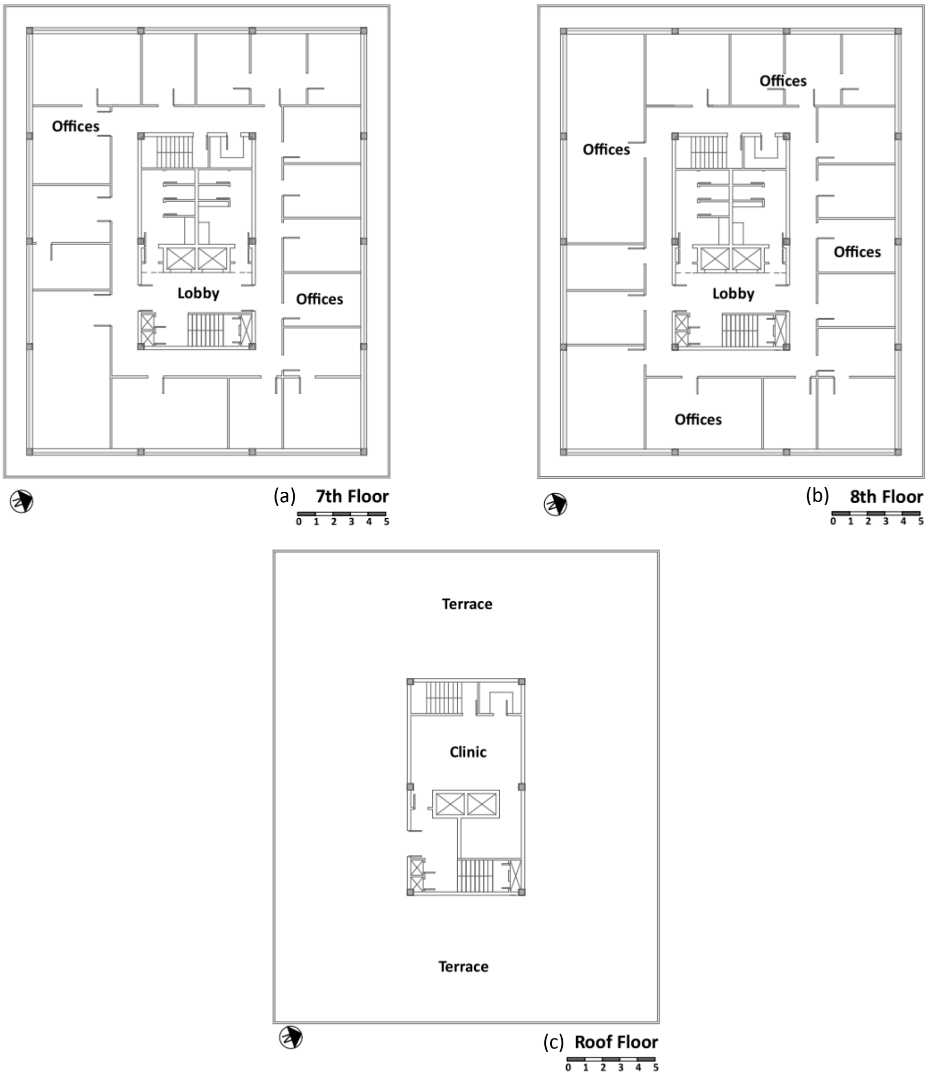


Figure 4-7 (a) to (c) Mombasa Uni Plaza tower layouts (seventh floor to roof floor level).

A pattern of the main building usage and information on occupancy and operation times, was identified and illustrated in Table 4-1.

Table 4-1 Space Use in the Mombasa Uni Plaza

Floor	Space allocation
Ground floor	Bookshop, library, lecture hall
Mezzanine	Offices, library and computer lab
First floor	Offices and lecture rooms (3 no.)
Second floor	Offices, computer lab and lecture rooms (2 no.)
Third floor	Offices and a lecture room (1 no.)
Fourth floor	Offices and lecture rooms (3 no.)
Fifth floor to eight floor	Offices
Roof	Clinic

Typically, the building was operational between 0800hrs and 1800hrs for five days a week. Outside of this time, the building remained largely unoccupied. In keeping with the study aims, the review was focused on the spaces that are used for offices. Generally, the office spaces consisted of single occupancy or multiple occupancy rooms (2 to 15 occupants).

4.1.2 Materials and Construction Methods

As with a significant number of office buildings found in Mombasa, Mombasa Uni Plaza comprises of a concrete and steel frame structure with a large amount of glazing infill. The floor slabs consists of reinforced lightweight concrete with a variety of floor finishes including linoleum (original floor finish, found in most spaces), ceramic floor tiles and carpet (selected offices) and terrazzo (common areas including lobbies, corridors and wet areas). Ceilings were mainly left exposed with a roughcast concrete finish and paint finish in some cases. In the central core, building services were enclosed using 200mm thick concrete hollow blocks with plaster and paint or decorative tiles finish. Office partitions ranged from combinations of aluminium frames with glass or chipboard infill to timber frames with timber board and glass infill. The roof consists of a flat terrace made of a reinforced lightweight concrete slab and finished with rendered concrete tiles. Table 4-2 presents an illustrated overview of the construction properties of Mombasa Uni Plaza.

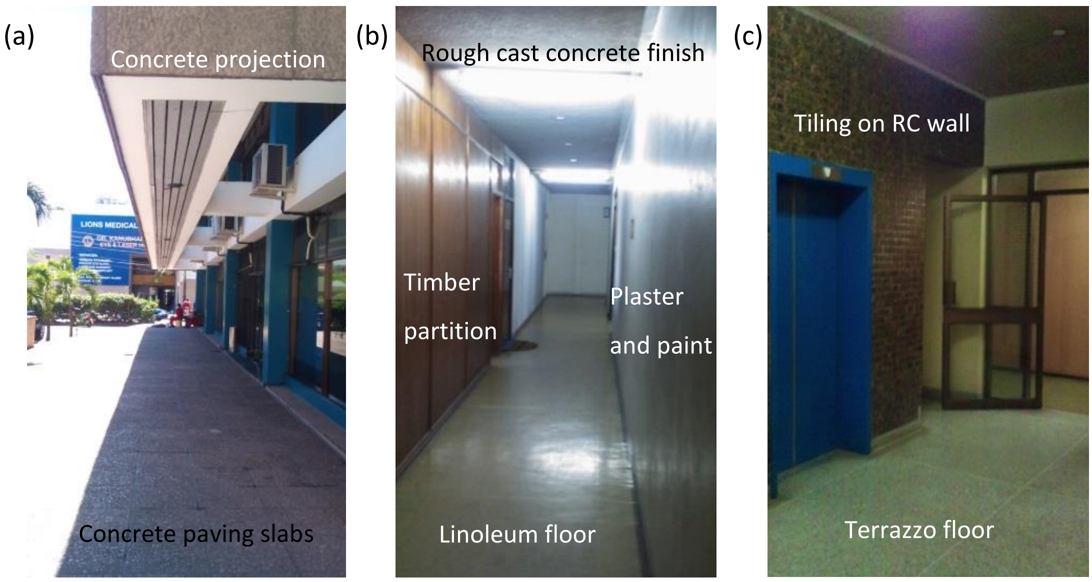
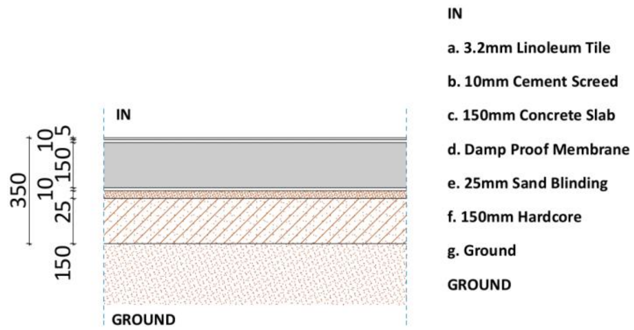
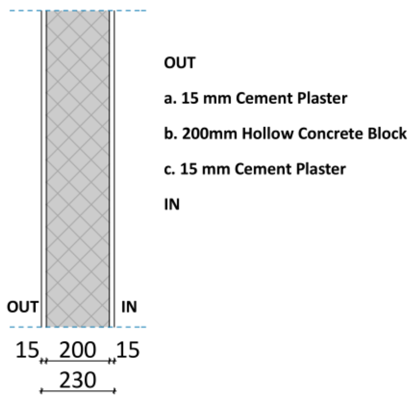
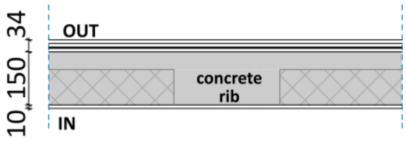


Figure 4-8 (a), (b) and (c) show various external and internal finishes at Mombasa Uni Plaza.

Table 4-2 Mombasa Uni Plaza construction element table (author-generated during field study).

Floor Slabs		
Concrete ground floor slab 	Thickness (mm)	188.2
	U-value (W/m^2K)	1.62
	Admittance (W/m^2K)	3.45
	Time lag (Decrement delay)	6.35
	Decrement Factor	0.58
Concrete suspended floor slab 	Thickness (mm)	173.5
	U-value (W/m^2K)	1.86
	Admittance (W/m^2K)	4.33
	Time lag (Decrement delay)	5.75
	Decrement Factor	0.56
Walls		
Hollow concrete block wall 	Thickness (mm)	230
	U-value (W/m^2K)	1.95
	Admittance (W/m^2K)	3.54
	Time lag (Decrement delay)	5.79
	Thickness (mm)	230

<table>
<tr><th colspan="3">Roof</th></tr>
<tr><td rowspan="5">Flat roof


OUT
a. 10mm Concrete Tile
b. 10mm Cement Screed
c. 4mm Butiminous felt
d. 50mm Lightweight Concrete
e. 100mm Hollow Blocks
f. 10mm Plaster finish
IN</td><td>Thickness (mm)</td><td>184</td></tr>
<tr><td>U-value (W/m^{2}K)</td><td>1.76*</td></tr>
<tr><td>Admittance (W/m^{2}K)</td><td>3.95</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>3.83</td></tr>
<tr><td>Decrement Factor</td><td>0.69</td></tr>
<tr><td colspan="3">* As heat gain is anticipated from the zenith, the U-value is calculated downwards.</td></tr>
</table>

In comparison to the Old Post Office building, majority of the constructions in Mombasa Uni Plaza had relatively high u-values and lower admittance values; this was an indication of lightweight materials. Given that the building was also found to have an extensive glazing area (U-value of 5.56W/m^{2}K), it was suggested that conduction heat transfer through the building envelope might result in substantial solar heat gain that could result in overheating.

4.2 The Building Environmental Performance

Mombasa Uni Plaza is centrally located in the Mombasa CBD, an area that has recently seen the influx of newer office buildings. Similar to Mombasa Uni Plaza (save for the presence of shading), these newer office buildings tend to be lightweight in nature and are characterised by highly glazed facades. Due to the warm climate conditions, a significant number of these often poorly designed office buildings tend to require the integration of active climate control systems to prevent overheating. In this section, the environmental performance of Mombasa Uni Plaza is analysed to evaluate a typical modern office building in Mombasa, Kenya.

As with the Old Post Office building, an intensive field study was conducted at the Mombasa Uni Plaza during the warmest month of the year (March, 2014). During this period, on-site recordings of selected environmental variables were undertaken. The main bulk of this data consisted of indoor and outdoor temperature and relative humidity values which were recorded every fifteen minutes for a period of up to four weeks. Principally, this data was recorded to analyse the indoor conditions in response to building envelope characteristics and impact on occupant comfort. Similarly, spot measurements of temperature, relative humidity and air speed were recorded at selected indoor and outdoor locations. The spot data was mainly used to analyse the impact of air movement on building thermal performance and indoor thermal comfort.

Five Tinytag data loggers were placed in strategic locations on the third floor and the eighth floor as is illustrated in Figure 4-9. T1, T2, T3, T4 and T5 represented indoor temperature data recording locations whereas RH1 and RH2 indicated the relative humidity data recording locations. Refer to section 3.3 for information regarding Tinytag data loggers and see APPENDIX A part 'i' and part 'ii' for Tinytag technical data sheets. The loggers were either suspended from the ceiling or placed on surfaces at a height of between 0.9m to 1.5m from the floor surface level. Care was taken to ensure that the loggers were placed in locations with free air movement and away from direct solar radiation and other heat sources.

The selection of each space for monitoring purposes was based on the following criteria:

a) The spaces were representative of typical office spaces found in the building.
b) Each office was naturally ventilated. As this study is focused on identifying suitable passive design strategies, efforts were made to examine spaces which were naturally ventilated.
c) Each office had glazing at different facade orientations (to enable the examination of the impact of solar control and natural ventilation with respect to each building orientation).
d) Occupants were agreeable to having the data loggers in their office spaces.

With the exception of location T1, the selected spaces were regularly occupied at the time of the study. In terms of space use and size, T1 was an intended multiple occupancy office space measuring 12m by 4.5m, whereas T2, T3, T4 and T5 were single occupancy office spaces measuring 4.5m by 3m.

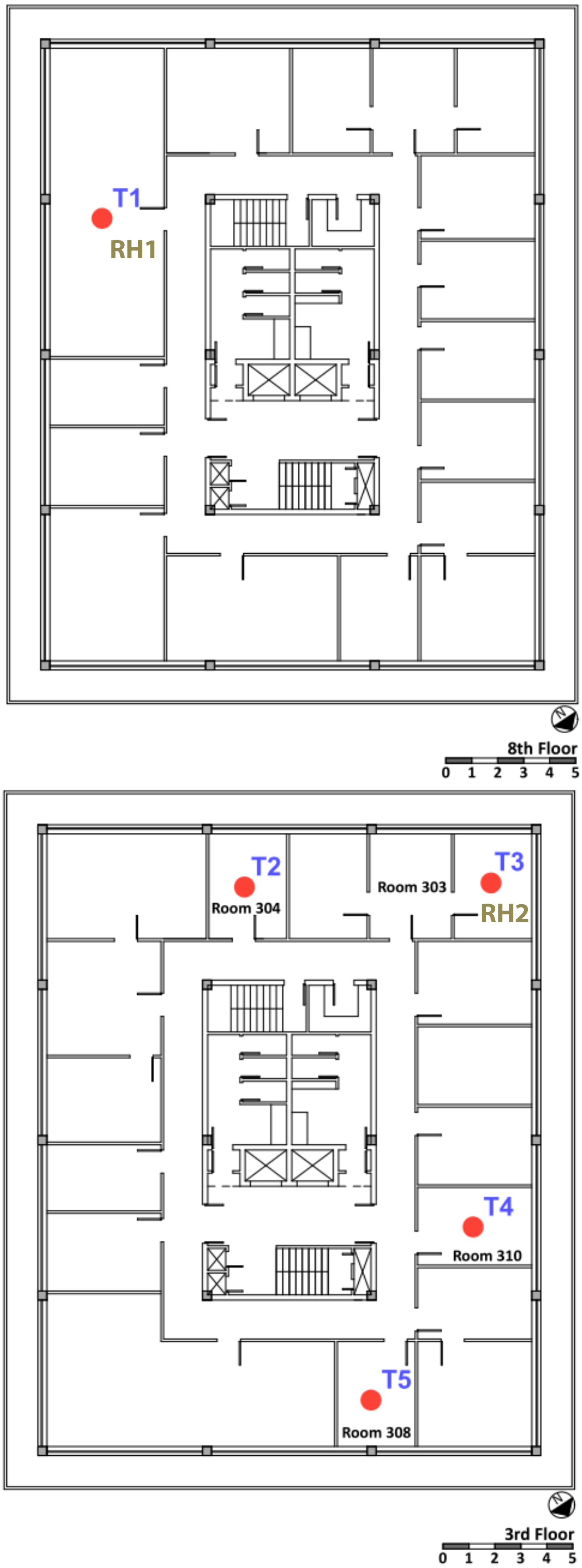


Figure 4-9 Location of temperature and relative humidity data loggers in Mombasa Uni Plaza.

4.2.1 Air Temperature and Relative Humidity

In this section, an analysis of air temperature and relative humidity monitored data is presented with focus on the indoor thermal conditions of the Mombasa Uni Plaza. A summary of the main recorded data is presented in Figure 4-10 (dry bulb temperature – DBT) and Figure 4-12 (relative humidity - RH).

The outdoor temperature data (T_o) was similar to that collected for the Old Post Office building. T_o ranged between 26.8°C and 34.3°C. Typically, T_o peaked in the afternoon (approximately 1200hrs to 1500hrs), with the lower extremes recorded during the early morning period (approximately 0500hrs to 0700hrs). Generally, outdoor DBT remained higher than indoor DBT for a significant period of the time during working hours (0800hrs to 1800hrs). Further, diurnal outdoor DBT ranges were found to be up to 8.4°C. The data analysis revealed that all the indoor spaces had higher average temperatures than the outdoor temperature for most of the day, with majority of the indoor temperature values lying between 29°C and 35°C. Further, indoor temperatures tended to be warmer than those outside by up to 2°C. Similarly, indoor fluctuations were found to be quite similar to those outdoors. This being the case, occupants were more likely to feel the impact of the increasing outdoor temperatures as the day progressed. It was suggested that this performance could be attributed to the lightweight structure and high glazing area that did little to mitigate solar heat gain.

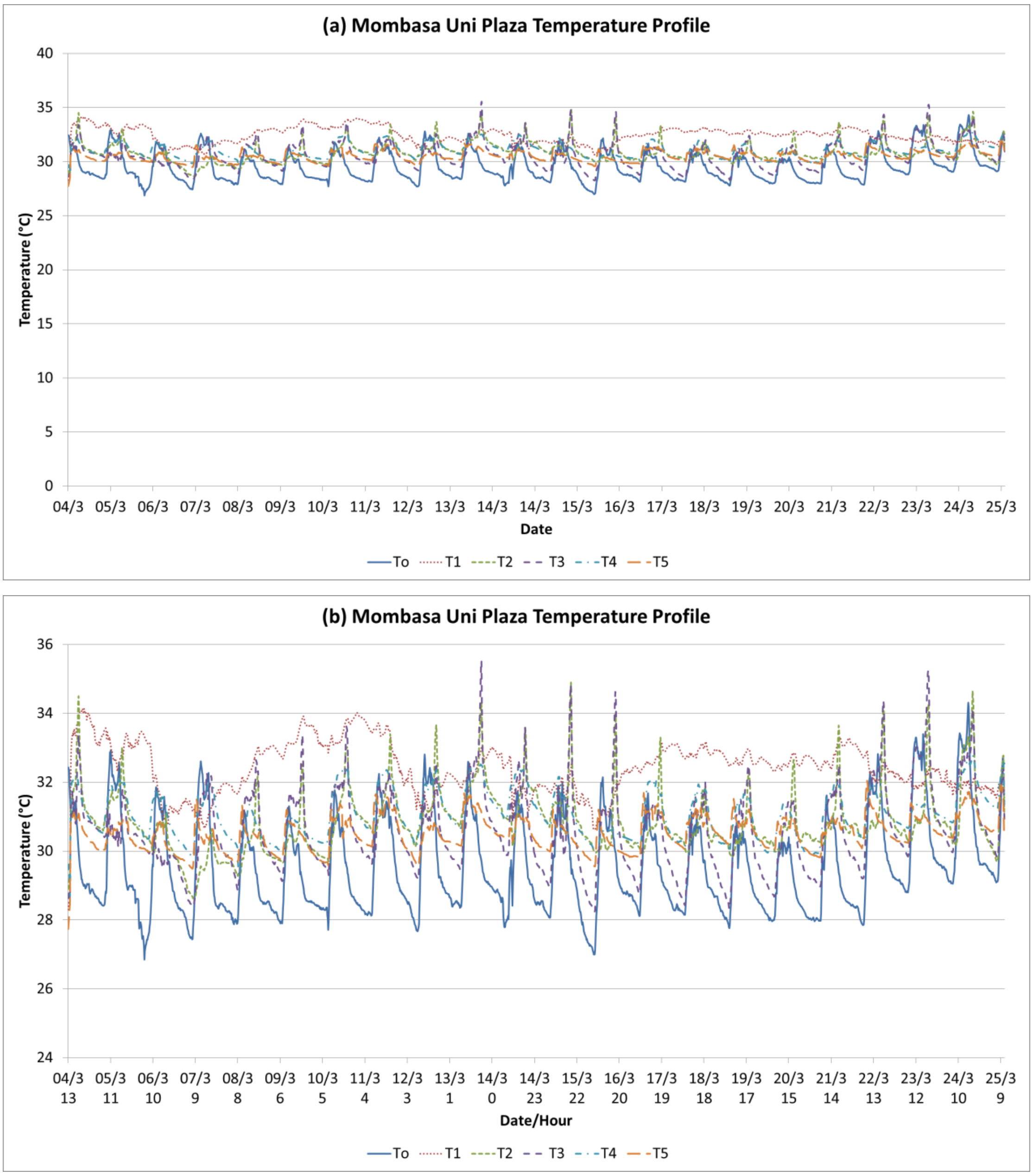


Figure 4-10 (a) Mombasa Uni Plaza outdoor and indoor temperature profiles. (b) A truncated graph below gives a clearer indication of the same.

Of all the monitored spaces, T1 was found to be the warmest, with majority of its temperature values lying above 33°C (Figure 4-11). In addition temperatures in T1 were found to be up to 4°C higher than other indoor spaces. This performance was attributed to the following factors. T1 was a significantly larger office space (four times as large as the individual offices); as such, it had a higher glazing percentage area than the other spaces. Given that this glazing had a majority eastern exposure, it was expected that it would suffer from considerable solar gain (from the morning sun) if not adequately shaded. In addition, given that T1 was located on the topmost floor (with a lightweight concrete flat roof above) it was more likely to be subjected to significant solar gains from the zenith resulting in higher solar heat gain than the other ‘protected’ spaces on the third floor. Further, as T1 was not regularly occupied during the monitoring period, its windows were not opened for ventilation cooling purposes; this would have made it more difficult for the space to lose any heat gained during the day and would also explain why the temperatures in this space showed significantly less fluctuation than other monitored spaces.

On the other hand, T5 was identified to be the best performing space with fewer instances of temperature rising above 33°C. Unlike the other spaces on the third floor, this space had smaller diurnal temperature swings of up to 2°C. It was suggested that this space performed better that other spaces as it had less exposure to solar heat gain owing to its north-east orientation. Further, given that the predominant wind direction is from the north-east and south-east, then it was anticipated ventilation cooling via wind driven air movement was substantial.

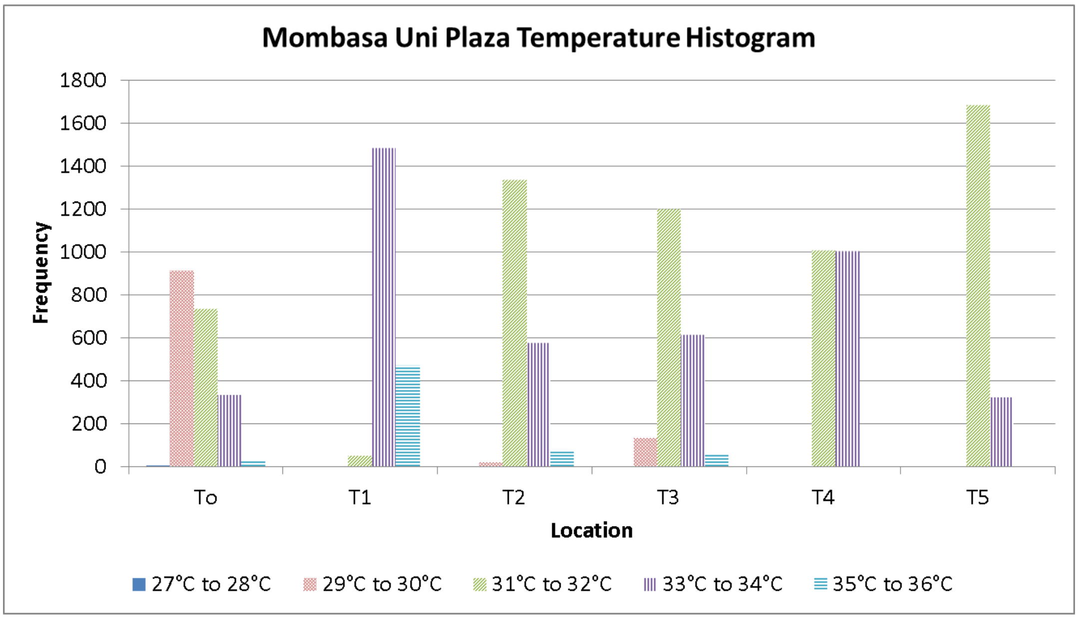


Figure 4-11 Temperature histogram showing frequency of outdoor temperatures in comparison to indoor temperatures in selected monitoring locations in Mombasa Uni Plaza.

As is typical of warm humid regions, relative humidity (RH) recorded during the field study period was characterized by a relatively high levels (Figure 4-12). Outdoor RH (RH_o) ranged between a minimum of 55.5% and a maximum of 90.6% with corresponding T_o values of 30.8°C and 26.8°C, respectively. Indoor RH (RH_i) was recorded on the eighth floor location of RH_i (T1) and the third floor location of RH_i (T2). RH_i (T1) was found to range between 46.0% and 71.5% with corresponding temperatures of 32.5°C and 28.5°C, respectively. RHi (T2) was found to range between 40.5% and 78.1% with corresponding temperatures of 34.5°C and 28.9°C, respectively. Higher RH_i values were recorded during the early morning period at about 0500hrs to 0600hrs whereas lower RH_i levels were recorded during the afternoons, after 1500hrs. RHi (T2) had higher diurnal swings of up to 25% compared to RHi (T1) which had diurnal swings of less than 20%. As with the RH levels recorded at the Old Post Office, this performance was attributed to the changes in air temperature that made it possible for the air to hold more or less water vapour.

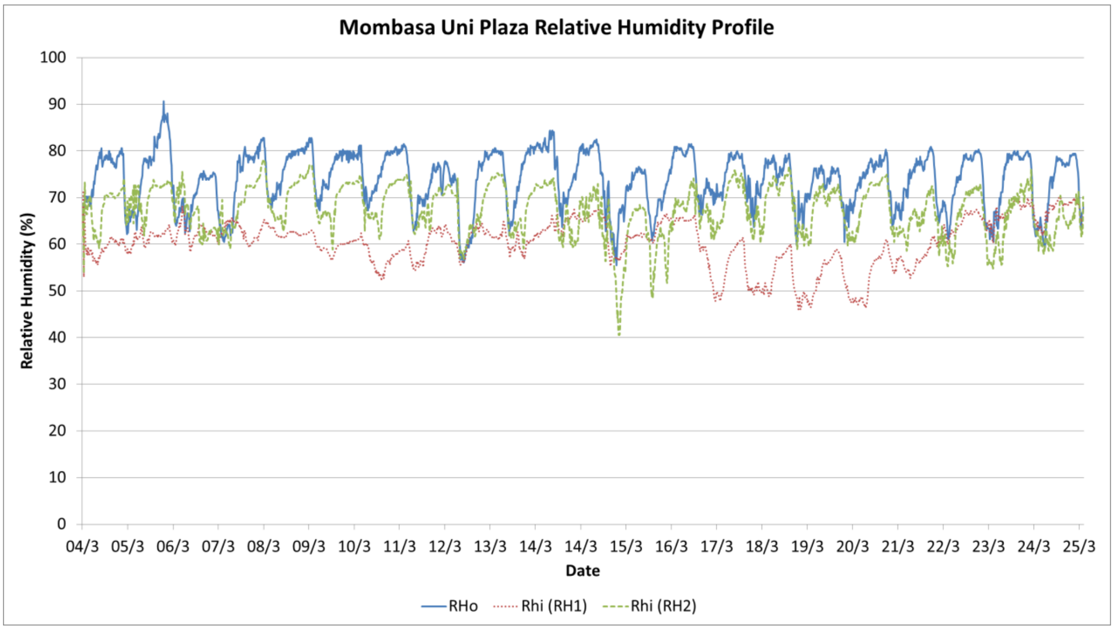


Figure 4-12 Mombasa Uni Plaza outdoor and indoor relative humidity profiles.

Next, the potential for adaptive comfort in Mombasa Uni Plaza was calculated based on data collected during the field study period. Previously in Chapter 3, thermal comfort limits were derived with the outdoor temperature data collected on site and the results presented in Table 3-4. Following a review of these results, the T_c comfort limits of 27.5°C to 31.5°C were adopted for purposes of this study. Using these comfort limits, the frequencies of the recorded field study temperatures were derived and illustrated in Figure 4-13.

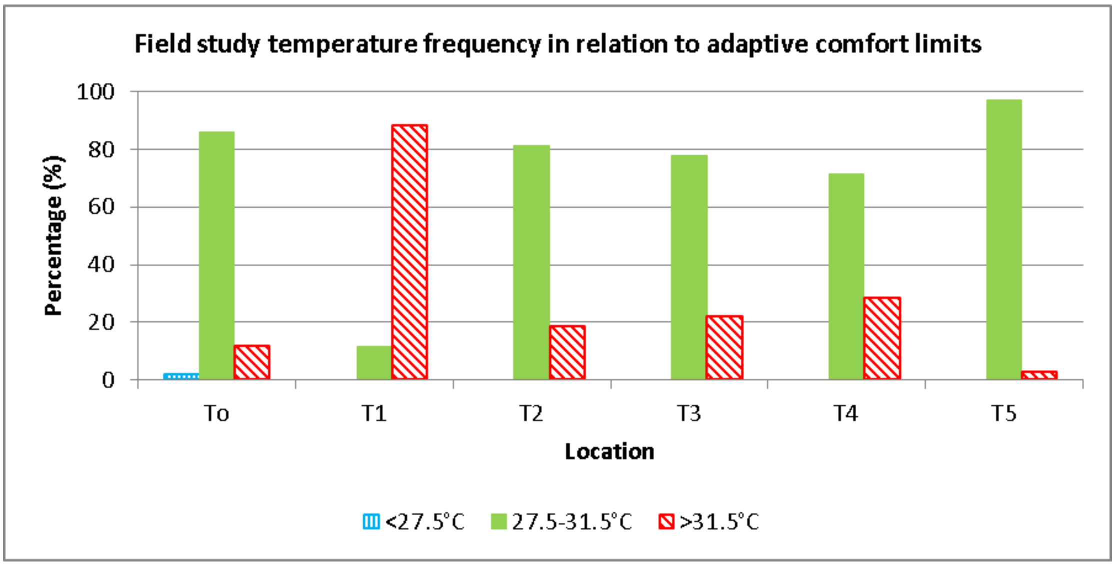


Figure 4-13 Field study temperature data range in relation to predicted adaptive comfort limits.

Generally, Mombasa Uni Plaza performed slightly worse than the Old Post Office building; this was derived from the fact that the building was found to have a larger proportion of its indoor temperatures outside of the predicted adaptive comfort limits (see Figure 3-45 for Old Post Office results). As the temperatures were mainly higher than the upper comfort limits, this was identified as an indication of overheating. T1 was identified as the worst performing office space as its indoor temperatures were within the comfort limit temperatures for only 12% of the time. On the other hand, T5 was found to be the best performing space as its indoor temperatures were within the comfort limits for 97% of the time. In location T2, T3 and T4 indoor temperatures were within the comfort limits for 80%, 77% and 70% of the time, respectively. These results were also considered in the post occupancy evaluation covered in section 4.3 where the thermal comfort of occupants was revisited.

4.2.2 Sun Shading for Solar Control

Previous local climate analysis indicated that the optimum siting of a buildings within the warm humid climate region is along the east west axis, with the longer facades and majority of the openings facing north and south. In Mombasa Uni Plaza the building is offset by approximately 20° off the north-south axis, resulting in the main facades having orientations of 20° (N20°E), 110° (S80°E), 200° (S20°W) and 290°

(N70°W). From this, it was derived that the slightly longer facades were orientated more to the south-east and the north-west. Measuring approximately 24m by 18m (approximate tower length and width dimensions), the sides of the building were fairly equal in size giving a fairly low aspect ratio of 4:3 (75%). In contrast to the Old Post Office (36.32% to 0.59%), Mombasa Uni Plaza had significantly high glazing percentages of approximately 60% on each facade. If not effectively addressed, the implication of the fairly large glazing percentages would be significant solar heat gain in the building.

Initial assumptions attributed the existing building orientation to site constraints (existing plot and road layout). A review of the building was undertaken to establish if the building had been positioned to accentuate or attenuate the impact of localised winds or sun path, respectively. Given the position and siting of the building, it is suggested that the building may be negatively affected by the impact of direct solar radiation, and especially along the longer facades which were exposed to both eastern and western sun (Figure 4-14). Even so, a review of the building indicated that some design elements may have led to a reduction of solar heat gain that would have resulted from this orientation. These elements included: canopies (to cut out high angle sun), tinted windows (to reduce the solar heat gain coefficient and reduce instances of glare) and internal blinds (to control glare) (Figure 4-15).

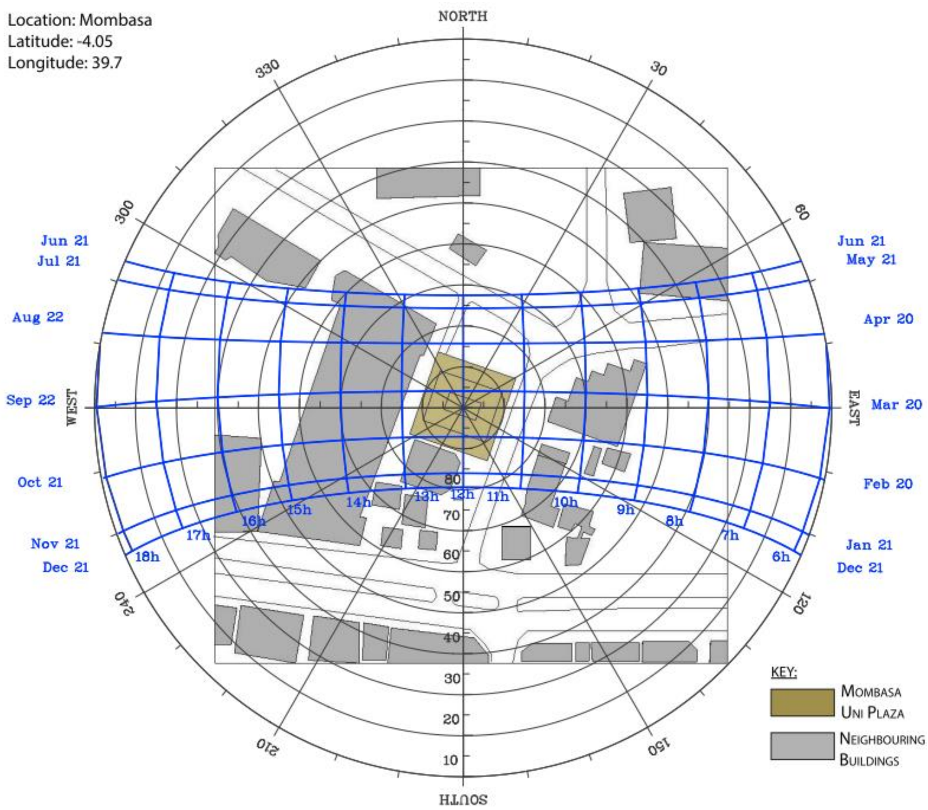


Figure 4-14 Location plan of Mombasa Uni Plaza with a superimposed sun path diagram.

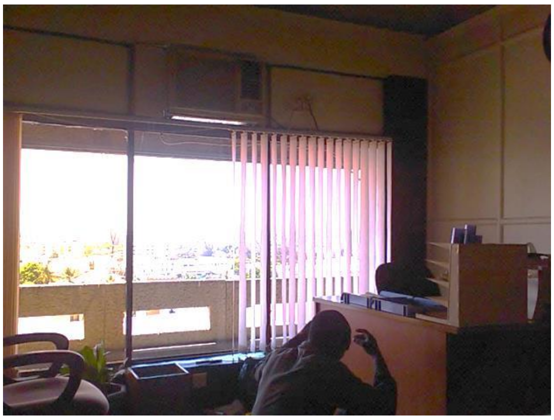
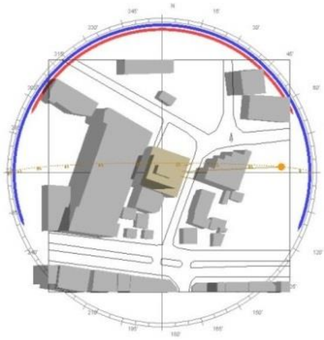
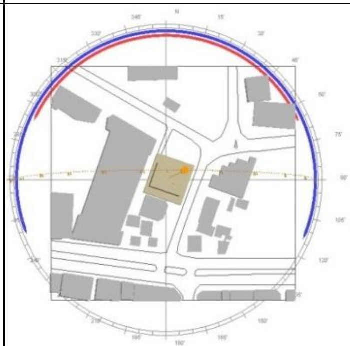
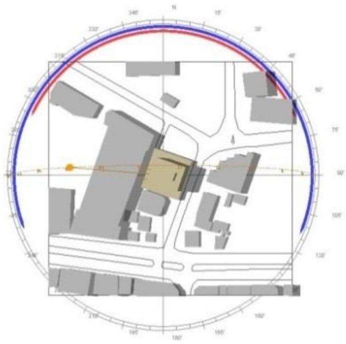
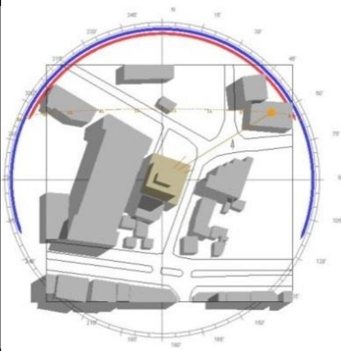
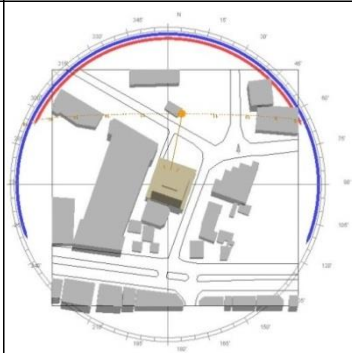
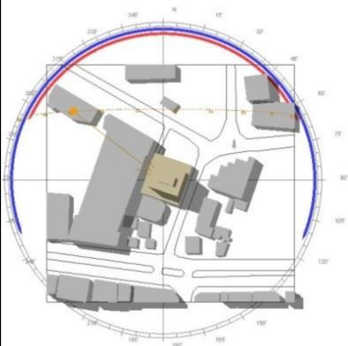
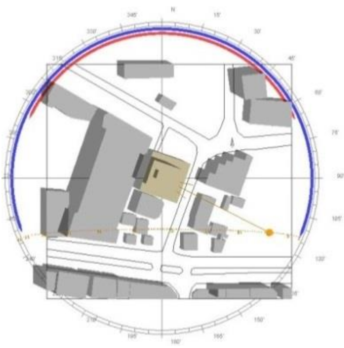
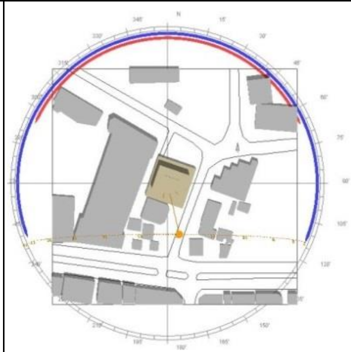
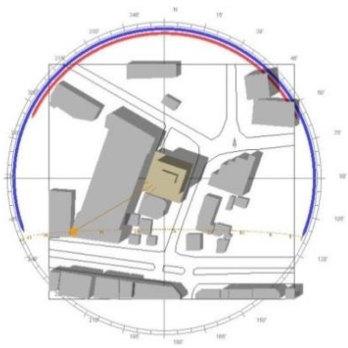


Figure 4-15 A maintenance worker replaces the blinds in one of the offices on the eighth floor.

It was possible to track the apparent sun movement over Mombasa Uni Plaza based on existing building orientation and reveal the anticipated exposure and the impact of solar radiation faced by the building during various times of the year. An illustration of part of this exercise is presented in Table 4-3. The findings suggested that the building would be particularly prone to solar heat gain from the roof plane and the eastern and western facades (which in this case were all the facades in the tower block, especially orientation S20°W and N70°W).

Table 4-3 Mombasa Uni Plaza shadow analysis showing solar altitude angles at key times of the year in relation to the study building (highlighted).

	9am	12pm	3pm
Equinox - March 21st	 45°	 86°	 45°
Summer Solstice - June 21st	 38°	 68°	 38°
Winter Solstice - December 21st	 43°	 70°	 43°

In addition, the existing canopies were evaluated to get an idea of the impact of solar radiation on the interior spaces (Figure 4-16 and Figure 4-17). Earlier in this chapter, it was noted that these projections had been designed to hold and cover the AC units used in the centralised ventilation system. This might explain why the canopies were of similar form, size and depth irrespective of orientation. Given the similarity of the canopies, it was suggested that they might not be working effectively as sun shading elements on all the facades (especially the critical western and eastern facing facades).

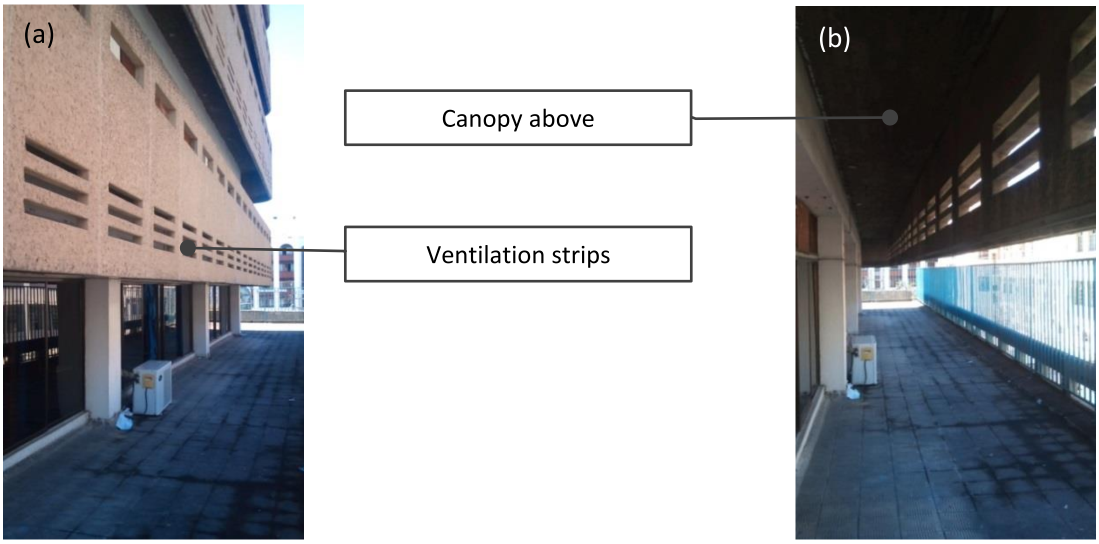


Figure 4-16 (a) Partial external view of the existing canopies from the 1st floor terrace. (b) View of the lower part of the canopy where the lower panels have been removed.

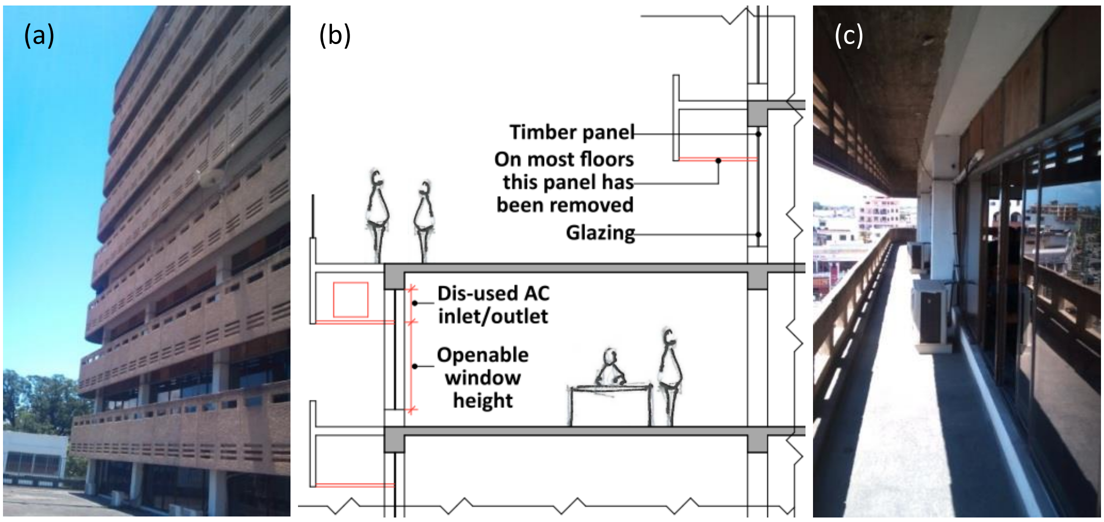


Figure 4-17 (a) External view of the tower facade. (b) Section showing disused AC inlet/outlet zone. (c) View from one of the canopies showing one of the newer AC units used in some of the offices and the tinted glass.

A review of the shading elements indicated that the canopies had a significant impact on solar control at key time of the year as indicated in Figure 4-18. Initial analysis indicated that the 1.2m deep canopies are useful in cutting off high angle sun experienced in the late morning to early afternoon periods (closer to midday). In contrast, the shading elements were not as effective when cutting out low angle sun experienced in the early to mid-morning (eastern facades affected) and afternoons (western facades affected). This was largely due to the presence and location of the ventilation strips shown in Figure 4-16. It was suggested that if the lower panel that held the AC units was still in use this effect would have been curtailed, making the shading elements more effective than they are in their current state.

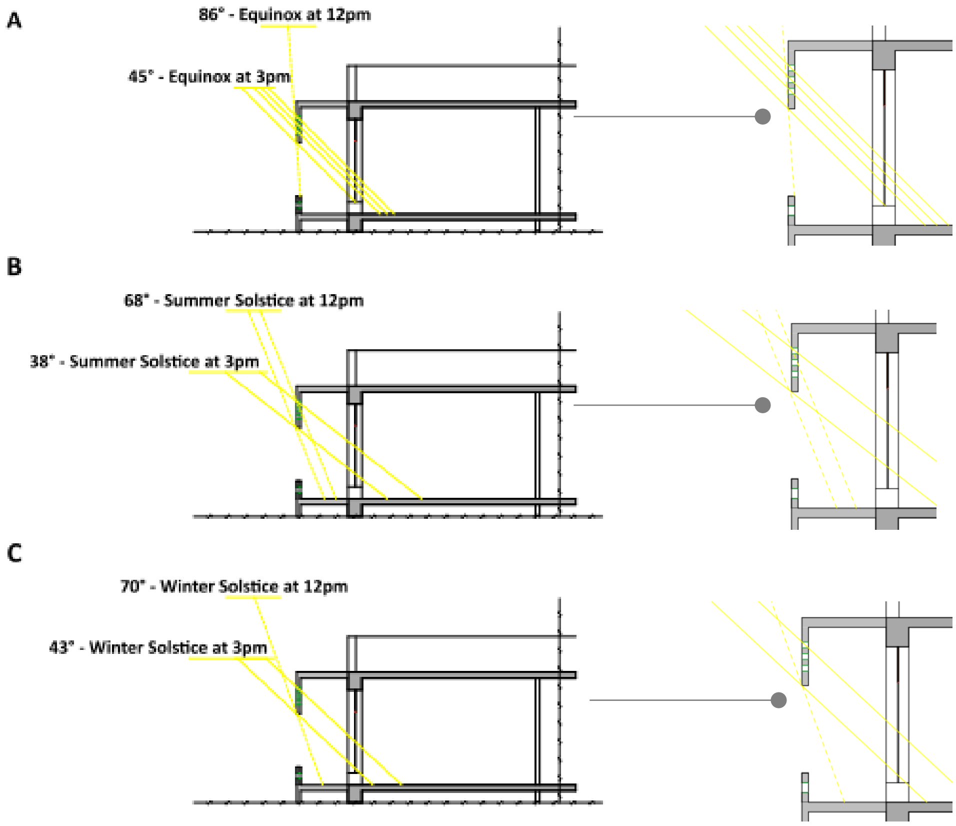


Figure 4-18 (a) to (c) Impact of direct solar radition on a typical office with a critical western facing facade at key times of the year.

Although not examined in greater detail, it was noted that the construction of the shading elements (extended from the floor slabs) had the potential for hot bridging. This could have resulted in increased indoor temperatures. One way of the designers could have tackled this issue would have been to provide a continuous break (possibly with insulation) between the shading element and the main building fabric.

In Mombasa, as the solar altitude angles are high for most of year - ranging from 86° during the equinox, 68° during the summer solstice and 75° during the winter solstice - solar heat gain from high angles can be quite substantial. The sun is consistently at high angles within this latitude; therefore the roof is expected to have higher heat gain potential via solar radiation, as opposed to the walls which are vertically placed. This partially explained why the temperatures recorded on the topmost floor were significantly higher (by up to 4°C) than those on the third floor. In the early mornings or late afternoons, there tended to be instances of insolation on window surfaces, an indicator of increasing risk of solar gain.

Initial analysis suggested that mutual shading did not play as much of a significant role in sun shading as was in the case in Old Town. Whereas neighbouring buildings were close and tall enough to overshadow the podium level of Mombasa Uni Plaza on the north-west and south-west facades, other surrounding buildings appeared either too far away or not tall enough to have any significant effect. To establish the impact of neighbouring buildings on solar heat gain prevention, annual shadow range analysis was conducted using Ecotect for the period between 0800hrs and 1800 hours (Figure 4-19, Figure 4-20 and Figure 4-21). In addition, the annual percentage shading and total sunlight hours were calculated for different heights/levels of the building (Table 4-4).

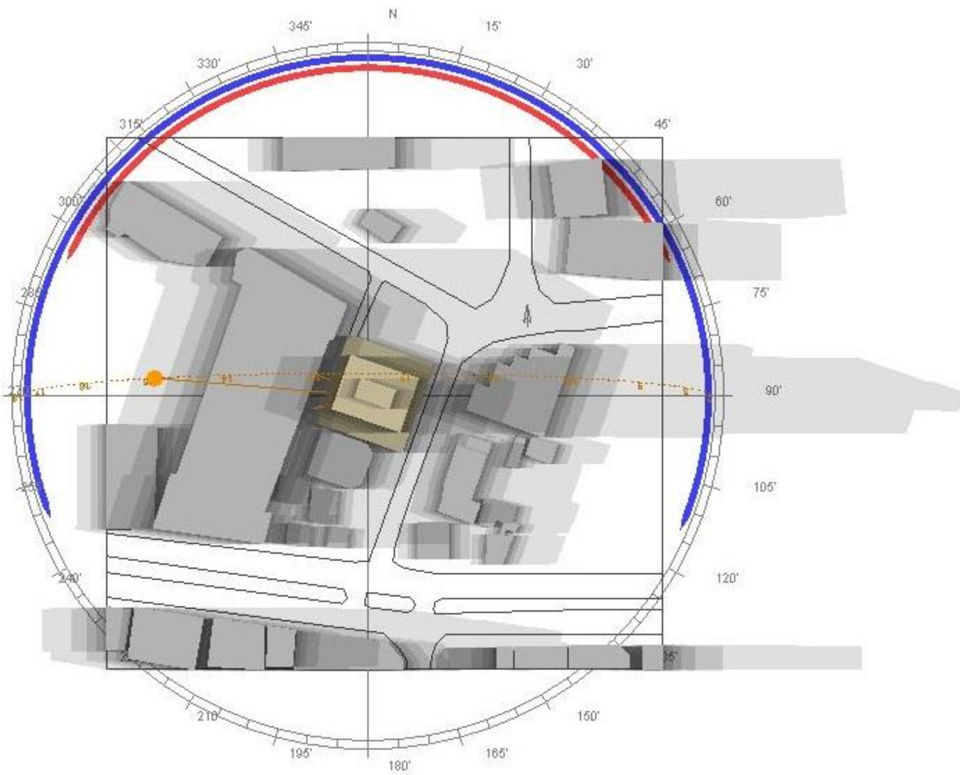


Figure 4-19 Mombasa Uni Plaza equinox shadow range analysis.

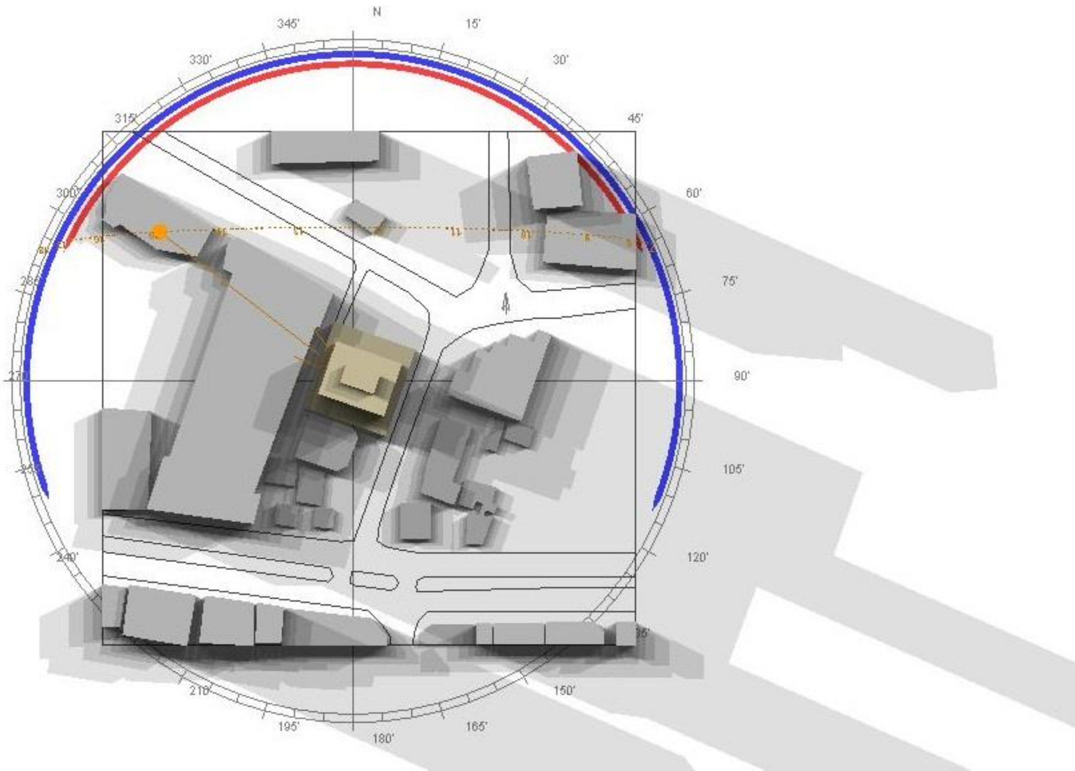


Figure 4-20 Mombasa Uni Plaza summer solstice shadow range analysis.

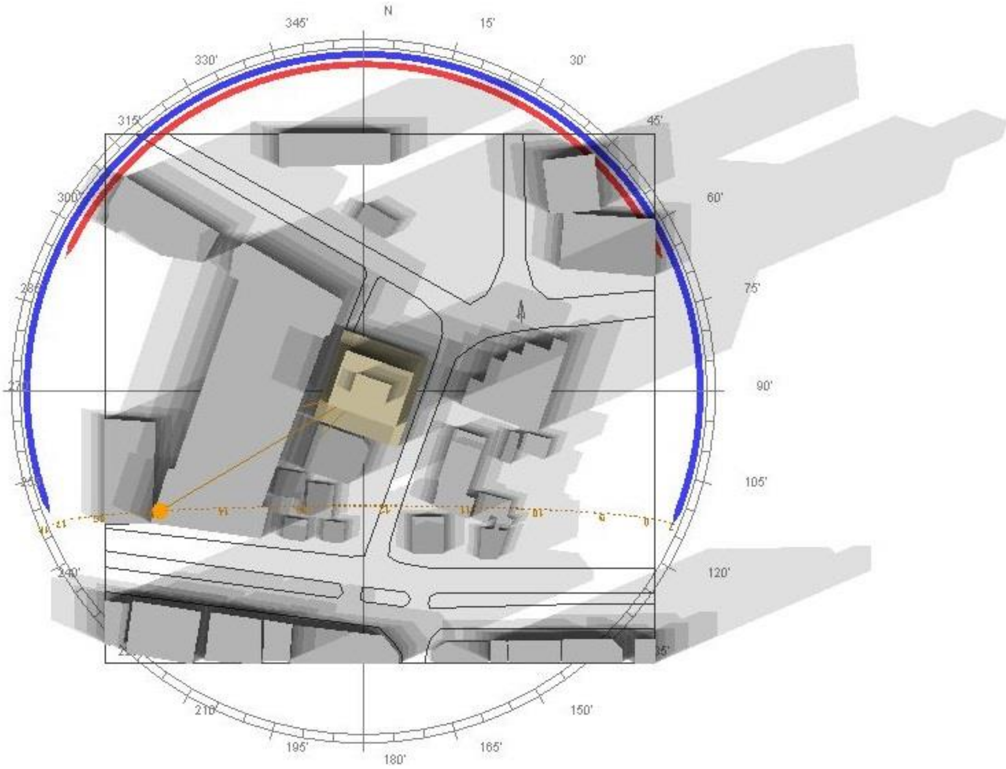
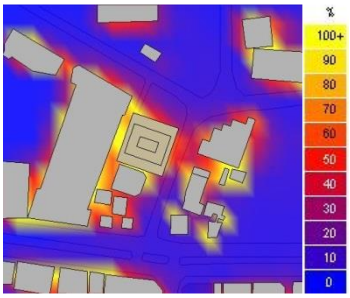
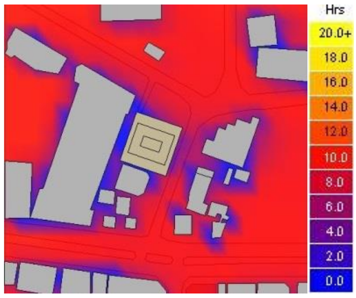
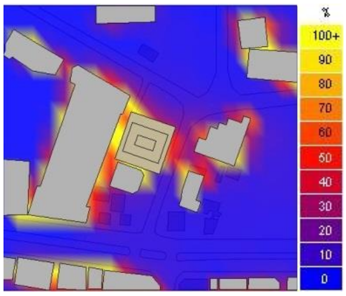
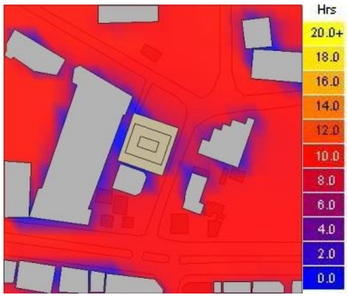
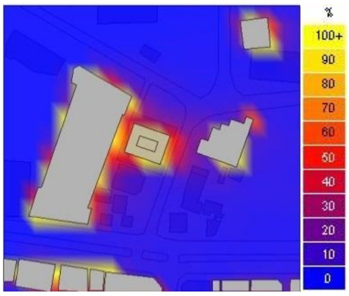
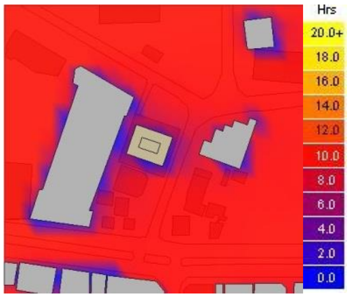
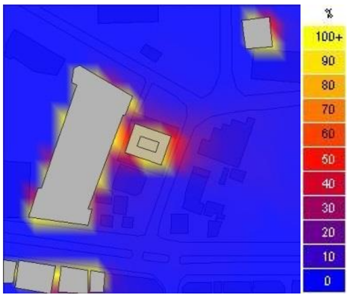
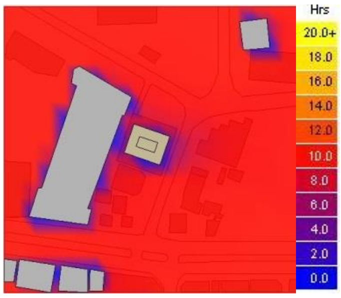
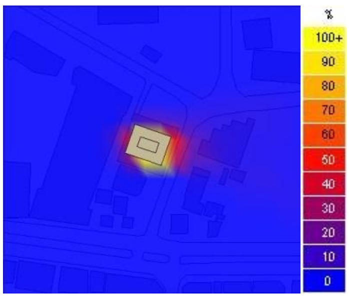
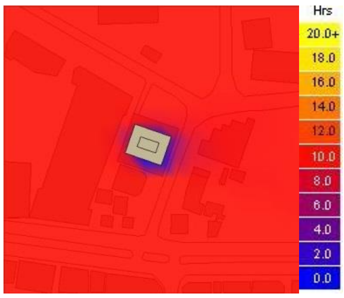
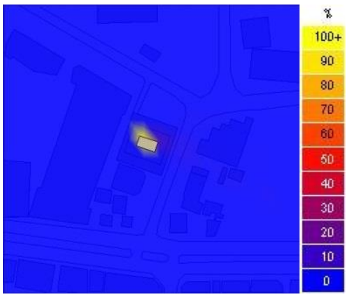
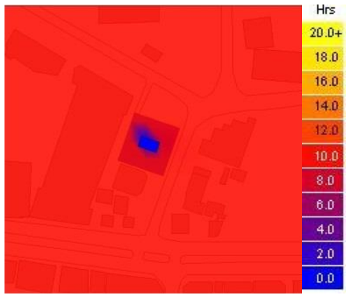


Figure 4-21 Mombasa Uni Plaza winter solstice shadow range analysis.

Table 4-4 Mombasa Uni Plaza percentage shaded and total sunlight hours.

Height (mm)		Percentage Shaded	Total Sunlight Hours
Podium Level	1300		
Podium Level	4200		
Tower Level	7050		
Tower Level	9900		
Tower Level	12750		

Roof Level	24000		

The findings indicated that higher levels in the tower and roof sections were more prone to the effect of solar radiation with the areas closer to the podium have a substantial amount of shading for the neighbouring buildings. Following this, a solar insolation study was conducted to quantify the impact of solar radiation on the respective building facades under existing conditions (Figure 4-22). Simulations run under Ecotect revealed the most and least critical facade (Figure 4-23).

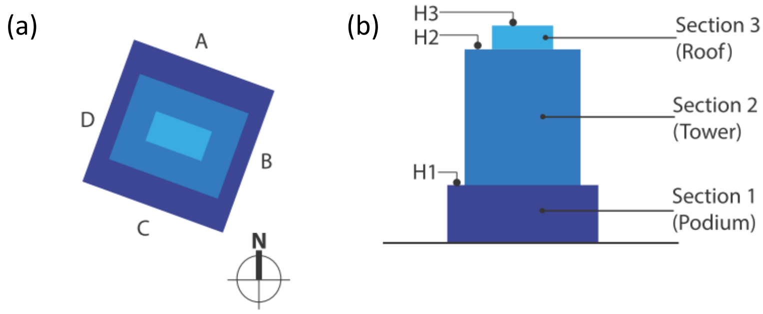


Figure 4-22 (a) Labelling for solar insolation study on existing plan (b) Elevation A and C.

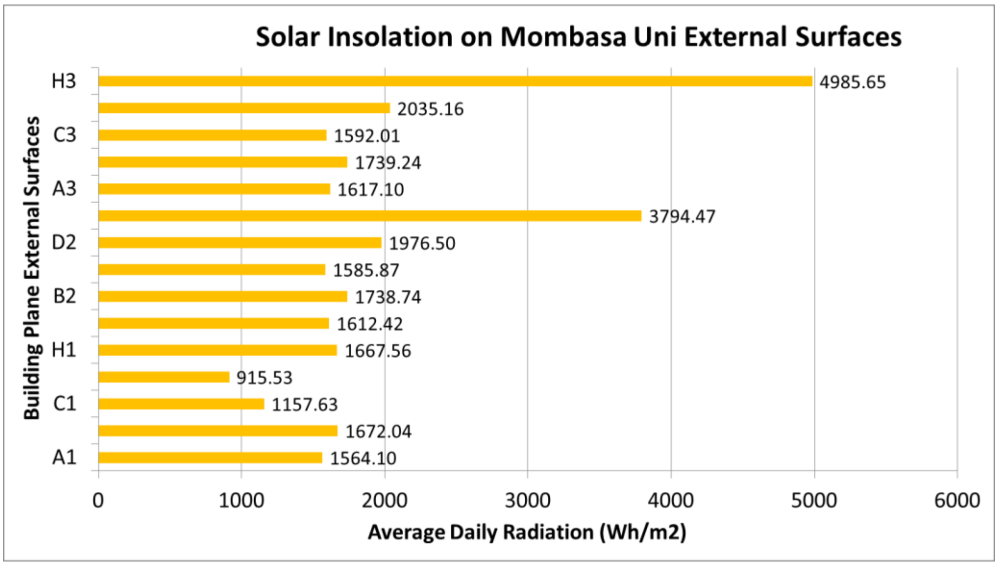


Figure 4-23 Solar insolation values on Mombasa Uni Plaza external surfaces.

The findings confirmed that the horizontal surfaces had the highest solar insolation values of up to 4985.65Wh/m^2 in comparison to a maximum of 2035.16 Wh/m^2 for the worst affected vertical surface (by more than 2.5). Due to its exposure to the western orientation, the most critical vertical plane to be affected by the impact of solar insolation was 'D'. It was noted that as peak solar intensity on the west coincides with the highest outdoor air temperatures, offices in this zone would be prone to higher total peak load. Indeed, location T4 on the third floor (which had this exposure) was found to have the highest indoor temperatures and maximum discomfort hours (30%) compared to other monitored offices on the same floor.

Solar insolation on 'B' was slightly lower than that on 'D' but greater than 'A' and 'C' with majority of the solar insolation attributed to the eastern sun. 'A' and 'C' representing the northern and southern facades, respectively were least affected by solar insolation. Overall, the impact of solar insolation was rated as H, D, B, C and A, from most to least negatively affected, respectively (Figure 4-24 and Figure 4-25). This ranking corresponded to the orientation of the worst to the best performing office space rated as T1, T4, T3, T2 and T5, respectively.

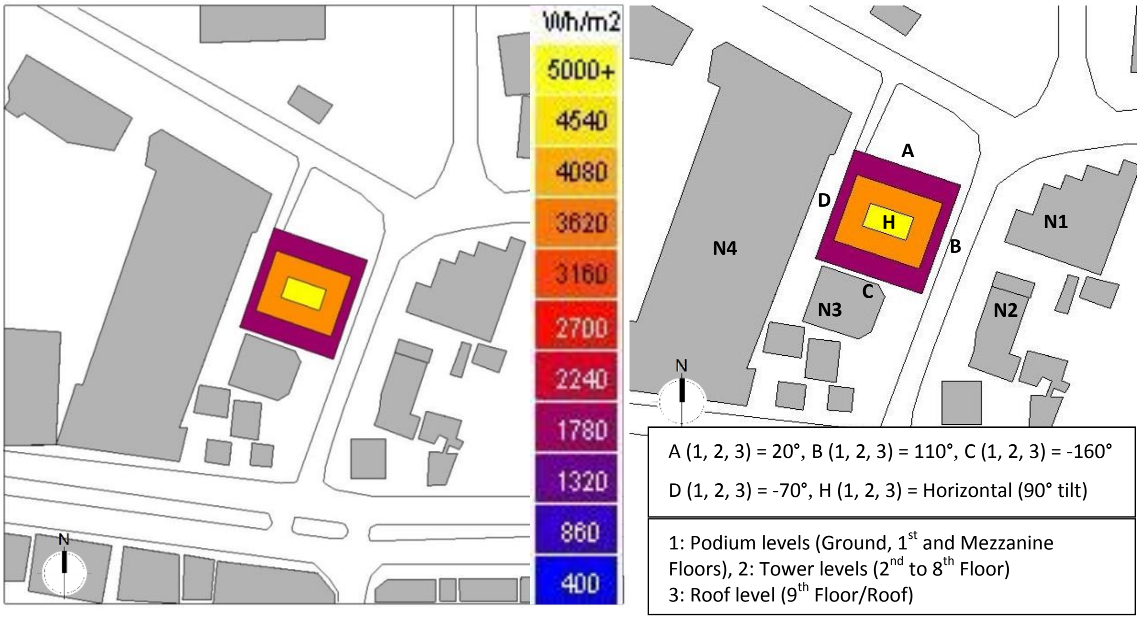


Figure 4-24 Orientation of 'facade sections'.

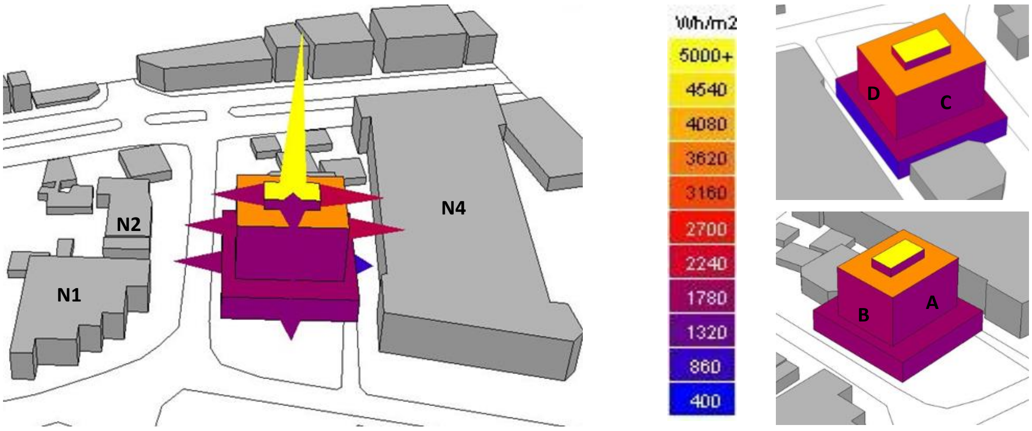


Figure 4-25 Solar insolation on selected building sections.

Further, the impact of average solar radiation on external building surfaces was compared for the conditions of 'with mutual shading' and 'without mutual shading' (Figure 4-26). From this, mutual shading was seen to have the greatest impact the podium level of the building (facade Section 1). This was mainly as a result of close proximity to the neighbouring buildings of N3 and N4. Both N1 and N2 were determined to be too short and too far from the case study building tower section to have any significant impact on solar insolation levels. Of the main building facades within Section 1, D1 was the most affected by a lack of shading and showed an increase of 56% in solar insolation levels. Similarly, C1 showed an increase of 22% in solar insolation levels. A1 and H1 suffered significantly less impact due to lack of mutual shading with minor increases of 2% and 1% respectively. B1 remained unaffected.

On the tower and roof level (facade sections 2 and 3), the impact of mutual shading was very minimal. Of all the facades, only D1 showed an increase in solar insolation levels and only by 1%. All other facade sections were unaffected. This result is attributed to the fact that the neighbouring buildings N3 and N4 were at that point shorter than the case study building. As N4 was taller than N3, it was determined to be responsible for the small increase recorded in D1.

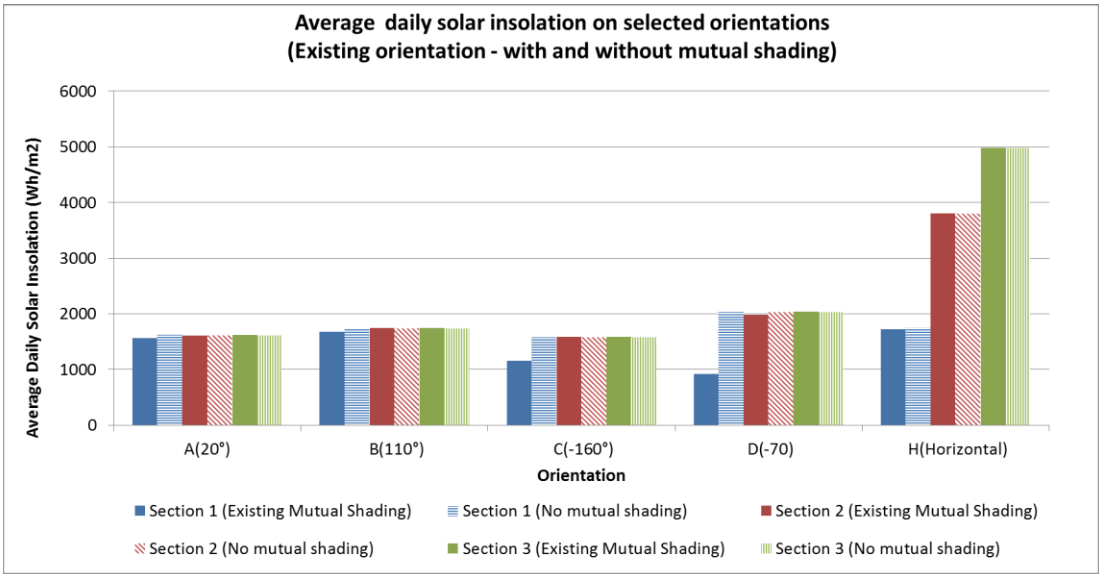


Figure 4-26 Average daily solar insolation on selected orientations (existing orientation - with and without mutual shading).

Earlier, it was noted that the building was not set in a true north-south orientation. Next, an investigation on the effect of building orientation under the 'existing orientation' and 'north-south' orientation (Figure 4-27). The main aim of this study was to gauge the impact of solar radiation on the facades as a result of building orientation. No shading from neighbouring buildings was considered for either option. Although maximum and minimum daily radiation levels remained the same in both conditions, a change to north-south orientation of the building resulted in a minimal total increase of 2% in levels of solar insolation on the building facades. Of all the orientations, 'C' benefitted the most from the true north-south orientation with a reduction of solar insolation of 24%, 25% and 25% for the podium, tower and roof levels, respectively. This is suggested to be as a result of reduced exposure to the western sun. All other surfaces, other than H3 (roof level cover) saw an increase in solar insolation levels as a result of having a 'north-south' orientation. Of these, orientation 'B' showed the greatest increase of 8% on all sections. This is due to increased exposure to the eastern sun in the morning periods. Next was orientation 'A' which showed an increase of 4% (A1) and 5% (A2 and A3). Orientation 'D' showed a small increase of 2% on all sections.

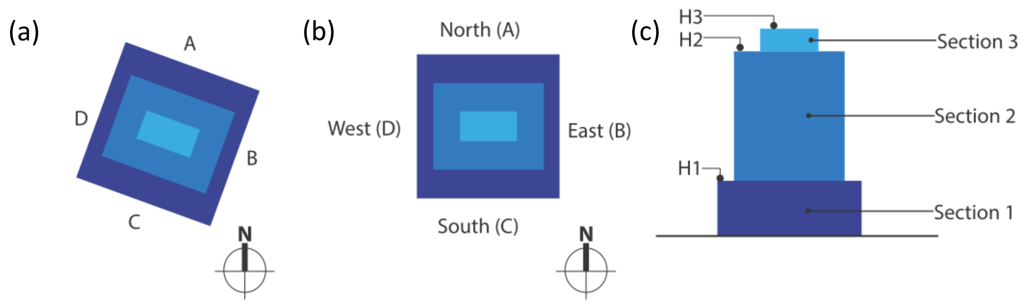


Figure 4-27 (a) Labelling key on existing plan. (b) Rotated north-south plan. (C) Elevation A/C.

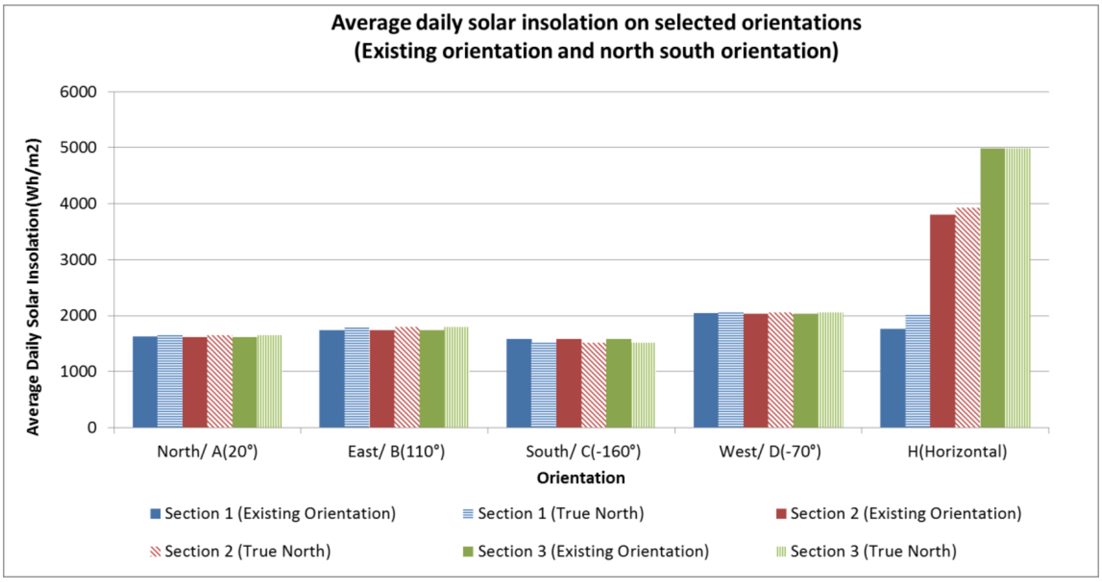


Figure 4-28 Average daily solar insolation on selected orientations (existing orientation and true north orientation).

Further, it was noted that the building's glazing was also possibly partially optimized by the use of tinted glass. It is possible that this might have had an impact in the reduction of glare. Similarly, a reduction in the solar heat gain coefficient could reduce the overall solar heat gain. It was noted that 3mm clear glass has an approximate solar heat gain coefficient value of 0.8; this is compared to value of 0.353 for the 10mm tinted glazing used in Mombasa Uni Plaza (EDSL Tas, 2014b).

To a large extent, daylighting was supplemented by the use of artificial lighting. It was observed that office occupants tended to have the lights turned on for a significant amount of time in the day. Depending on office location in relation to the building orientation, some users choose to use supplementary lighting at certain times of the day. For example, due to the apparent movement of the sun, offices on the north-eastern facade tended to be slightly darker in the afternoon periods, therefore occupants were more likely to have their lights on at that time. In addition, it was noted that occupants were less likely to have their lights on if the windows were open and the sun was high in the sky (to avoid glare). This had the added benefit of allowing for enhanced air movement through single or cross-ventilation. It was also noted that a significant number of offices had interior blinds fitted, these were mainly used to combat glare during low angle sun periods.

Daylight distribution was briefly examined so as to determine if the canopies or tinted glazing had any major negative impact on indoor lighting levels. For this analysis, an office on the eighth floor with south-east orientation (one of the slightly longer facades) was selected. A grid was mapped on the floor plan of the selected office space and the spot lux levels marked out. These lux levels represented averages of data recorded between 0900hrs and 1200hrs on a clear sky day using a lux meter (See APPENDIX A part 'iv' for light metre data sheet) at a height of 800mm (desk height). As would be expected, the analysis revealed that the lux levels fell considerably with progression away from the window location (Figure 4-29). Beyond location 'B' illumination levels were found to fall below the recommended illumination level of 500 lux for normal office work spaces (CIBSE, 2015, p.1-12). This left the indoor area looking rather dark. It was suggested that the use of light shelves might help improve indoor light levels. Although further analysis outside the scope of this study would be required to confirm this, this was suggested to be a potential intervention given that the old AC panel on top of the glazing was no longer in use.

(a)

(b)

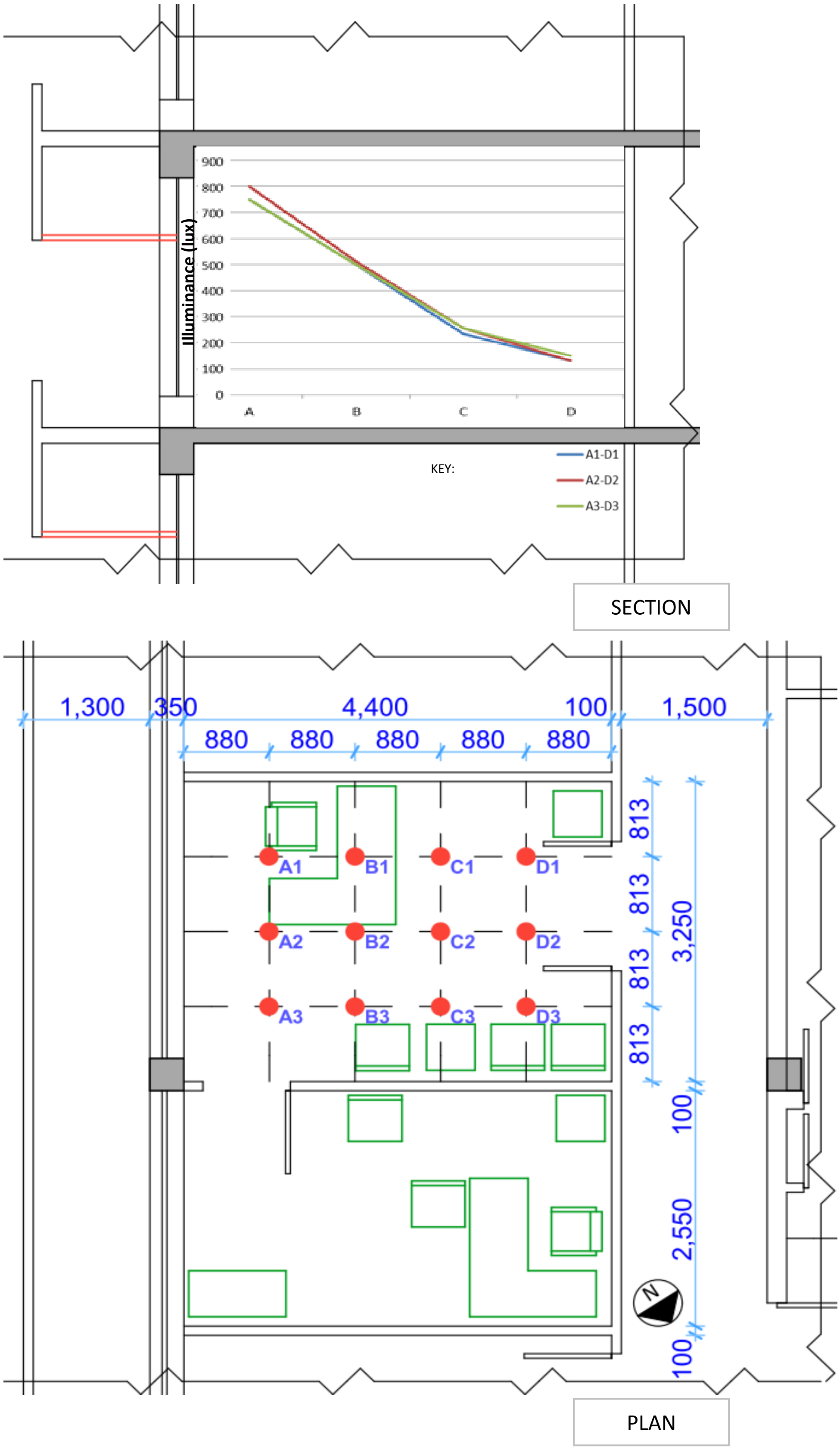


Figure 4-29 (a) Lux distribution graph (at desk height level) and (b) Corresponding grid of an office on the eighth floor - all dimensions are given in millimetres.

On all the floors, supplementary lighting was necessary to allow for adequate illumination in the centralised common spaces which had little access to daylighting. Without supplementary lighting in the central common spaces (lobbies and corridors), it was very dark making it close to impossible to get around safely. Lux levels were considerably lower than the recommended minimum of 100 lux (CIBSE, 2015, p.1-11). Interestingly enough, the use of top lights in the office partitions on the second floor were found to enable desirable daylighting into the common corridor. It was suggested that a similar technique might be desirable on other floors too (Figure 4-30).

(a) (b) (c)

Figure 4-30 (a) Supplementary lighting in a common corridor. (b) A common corridor space with supplementary lighting turned off (the door to one of the offices was left open to enable the photo to be captured without flash lighting). (c) Top lights on one of the office partitions allows for a desirable natural lighting to filter into the corridor.

4.2.3 Air Movement

Previous analysis indicated that the need to provide cooling breezes in naturally ventilated buildings sometimes preceded the building orientation for solar control. Analysis in section 4.2.2 has indicated that Mombasa Uni Plaza did not appear to have been particularly laid out for purposes of solar control. Mombasa Uni Plaza has its longer axis running along the north-east and the south-west (Figure 4-31). Even so, owing to its low building aspect ratio of 4:3 and almost identical glazing percentages of 60%, its facades are quite similar.

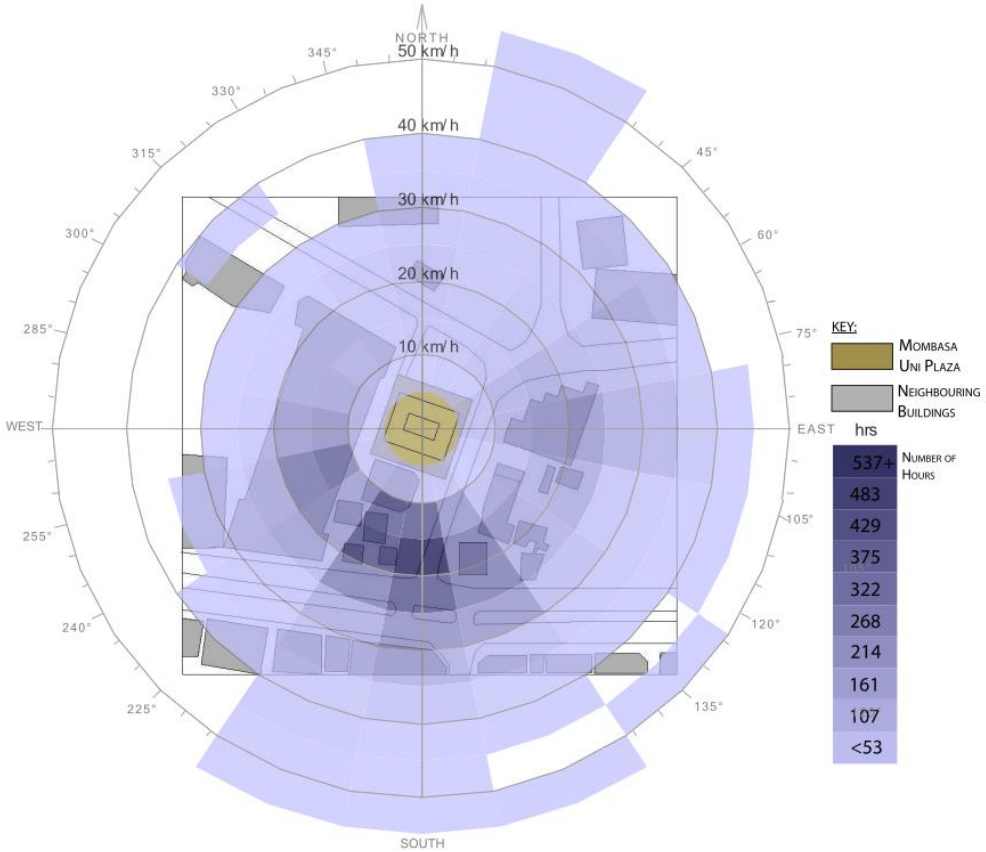


Figure 4-31 Location plan of Mombasa Uni Plaza with a superimposed annual wind rose.

In Mombasa, winds are predominantly from the north-east and the south-east. Given the position of Mombasa Uni Plaza and the significant amount of fenestration on the almost identical facades, it was suggested that the building (especially the tower) was well placed to allow for enhanced air movement for natural ventilation and cooling (Figure 4-32).

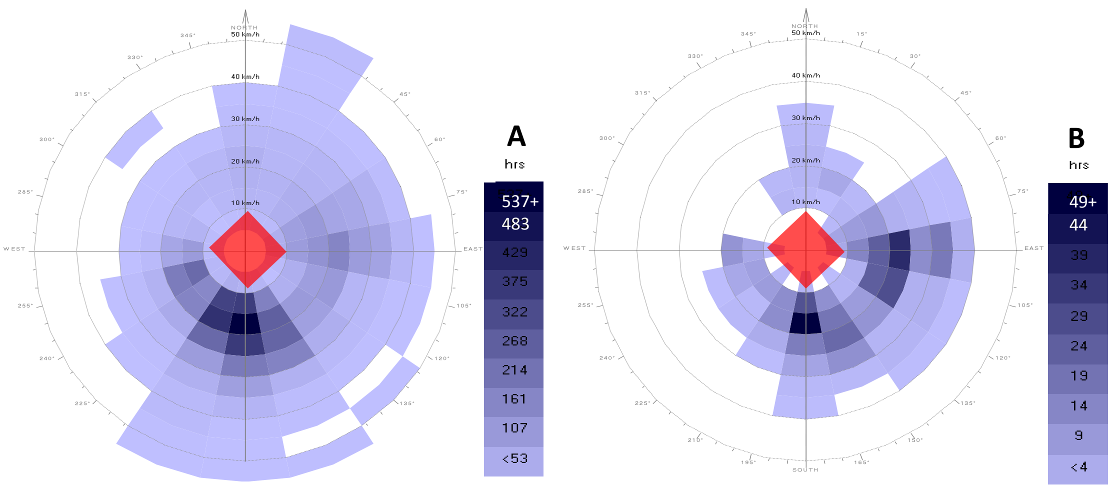


Figure 4-32 (a) Annual wind rose and (b) March wind rose.

Originally, Mombasa Uni Plaza was designed to operate with a centralised integrated air conditioning (AC) ventilation system. Due to high running costs, this system was replaced with a mixed-mode system that differs on zonal basis. These zones consist of spaces which are either naturally ventilated (occasionally with the aid of mechanical ceiling fans) or actively ventilated using standalone AC units which are run during working hours (sometimes this is replaced by natural ventilation in cooler months). Despite the change in the ventilation system, the current building management expressed that running costs remain high due to the constant use of AC units. This situation is worsened by the fact that more tenants in the naturally ventilated office spaces (including those with mechanical fans) have continued to put in requests for the installation of AC units to curb overheating in their offices.

Energy data obtained from energy bills provided by the building management was plotted against the average monthly outdoor temperature for Mombasa. It emerged that consumption tended to follow a similar trend – rising when it was warmest (March) and dropping when it was coolest (June). It is suggested that this is related to the increased need for AC in response to environmental factors. Although energy consumption included other building service requirements, it is suggested that the rise and fall in consumption had a direct relationship to AC usage patterns in response to environmental conditions. This was confirmed by management (refer to section 4.3). Given that the AC units were found to be the most energy intensive components used within the building, this was deemed to be a logical assumption.

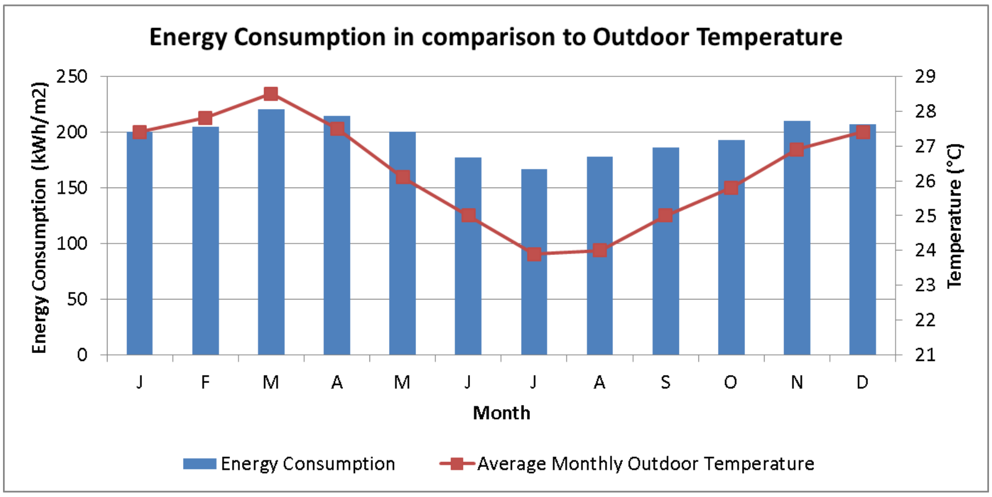


Figure 4-33 Comparison of energy consumption data and outdoor air temperature.

During the study, various ventilation strategies were identified as illustrated in Figure 4-34. They comprised of:

a) Cross ventilation (when the door opposite the window opening is left open or in corner offices with windows on adjacent sides).
b) Single sided ventilation.
c) Stack type ventilation (facilitated by the central staircase core).
d) Air conditioned office spaces.

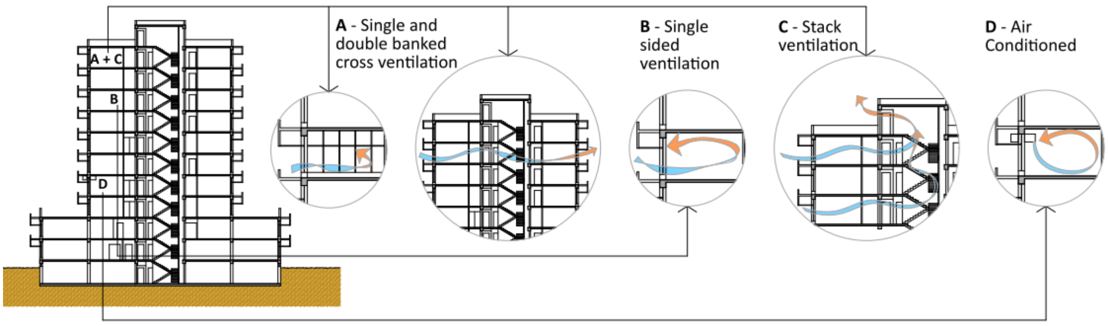


Figure 4-34 Ventilation strategies at Mombasa Uni Plaza.

The predicted effectiveness of the main methods that depended on wind driven ventilation (A and B) was calculated using existing rules of thumb (previously highlighted in section 3.2.4). Given the dimensions of typical office spaces (4.5m floor depth and 2.7m high floor to ceiling height), both single banked cross ventilation (recommended maximum room depth of 13.5m) and single sided ventilation (recommended maximum room depth of 6.75m) were determined to be practical for use in Mombasa Uni Plaza. On the other hand, double banked cross ventilation (recommended maximum room depth of 13.5m) was considered unsuitable as the building cross sectional depths were too large (24m and 18m).

The majority of naturally ventilated offices had mechanical ceiling fans installed. These 240V ceiling fans were of the three-blade variety and approximately 1.2m wide. During the study period, it was found that occupants tended to use the ceiling fans at ‘medium’ to ‘high’ setting. It is suggested that when used in combination with natural ventilation via open windows, this helped to improve indoor thermal conditions by enhancing physiological cooling and driving warmer air outdoors when outdoor temperature was cooler.

Generally, the main windows at Mombasa Uni Plaza were found to be of one type and size. These horizontal sliding windows could be opened in two different configurations as illustrated in Figure 4-35. The number of window openings available for each office was dependent on the office location and floor area. Guided by the existing grid, the maximum office depth is 4.5m with a corresponding room length of 3.0m or multiples of 3.0m (see section 4.1.1). All window openings had an overall height of 1.5m with a sill at 0.3m. Generally, two types of offices were identified (with respect to opening configurations). The first consisted of offices with one-sided openings that span 3.0m wide (for single occupancy offices) or greater (multiple occupancy offices) and the second, offices that have two sided openings on adjacent sides that span 3.0m wide or more.

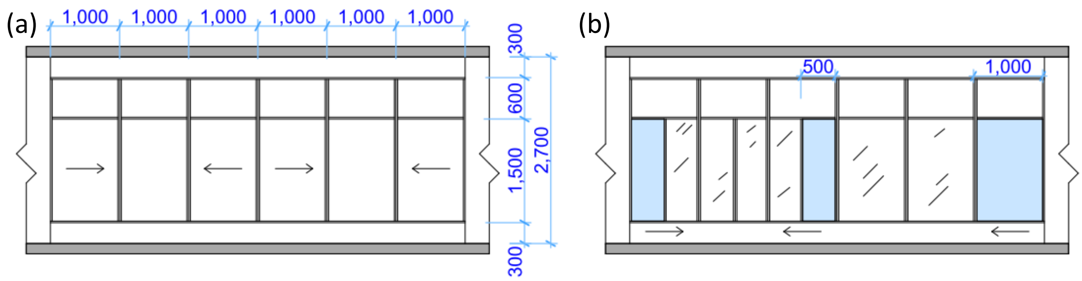


Figure 4-35 (a) Window type for a full 6m span (column to column). (b) Opening configurations (all dimensions are given in millimetres).

The sizes of the windows and their opening areas were significantly large. It was suggested that this had the potential of significantly improving the rate of natural ventilation. Interestingly, the large windows were reminiscent of the 'full body height' windows found in the Old Post Office building which were suggested to have been instrumental in providing adaptive opportunities for occupants. Whereas the windows in the Old Post Office building were highly shaded by timber shutter system that allowed the occupants to control shading, ventilation and lighting, limited opportunities were available in Mombasa Uni Plaza. Instead, the only option that the office occupants had was the opening and the closing of the windows.

During the field study, it was noted that in all the naturally ventilated offices, windows tended to be left open throughout the day. In multiple-occupancy offices, windows were opened at 0800hrs and would remain open until 1800hrs. Similarly in single-occupancy offices, windows remained open from 0800hrs to 1800hrs; if an occupant needed to leave the office (for meetings, classes or other commitments) they would tend to shut the windows and open them on their return. This was revealed to be due to security reasons. Certainly, it was noted that it would be relatively easy for one to access another office on the same floor through the canopies that wrap around the building. It was suggested that one option to resolve this would be the installation of shutters that allowed for free air movement and restricted entry.

During the field study, a number of air movement spot measurements were recorded at various opening locations of Mombasa Uni Plaza at set times of 9am and 3pm and for a series of consecutive days (Figure 4-36). Similarly, corresponding spot temperature and relative humidity readings were recorded for correlation purposes. The main aim of this process was to establish the impact of air movement on the variation of temperature indoors and thermal comfort. Whereas wind speed and direction may vary due to various reasons, certain trends were seen to emerge across the building on analysis of the recorded data.

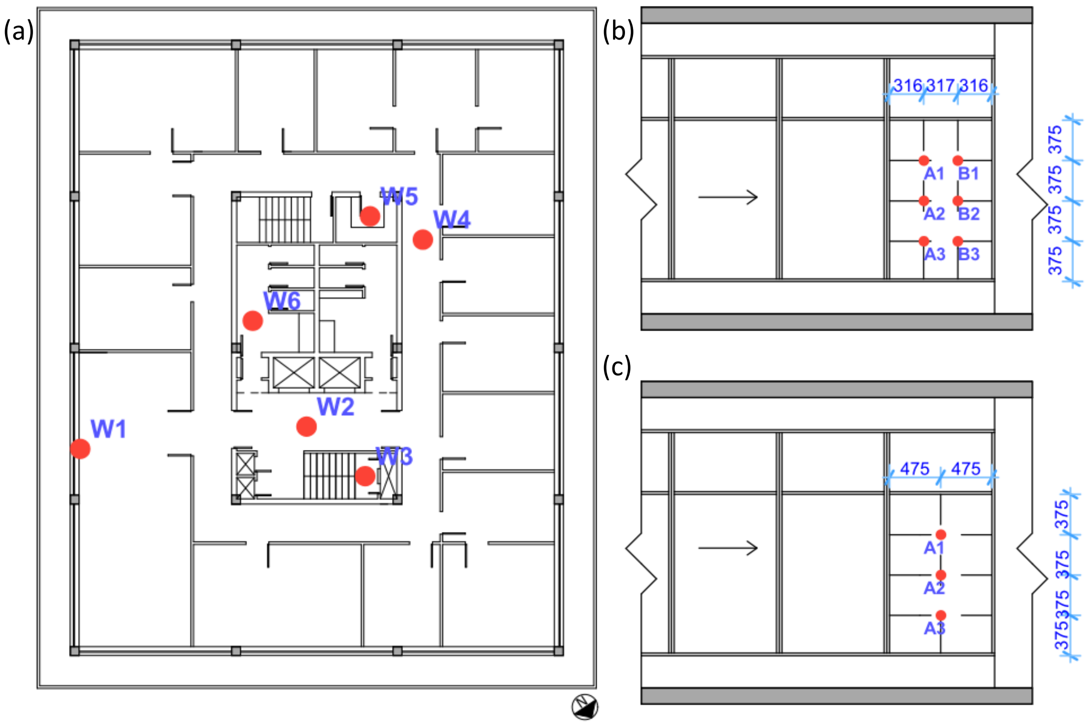


Figure 4-36 (a) Air velocity spot measurement locations on a typical floor plan. (b) and (c) Spot measure points at window openings (all dimensions are given in millimetres).

A review of the data indicated that air velocities tended to increase towards the afternoon period (Figure 4-37). This trend was similar to that established at the Old Post Office. In addition, the higher floors showed consistently higher levels of recorded air velocities. Air velocity measurements revealed that outdoor air speeds on the street level averaged at approximately 2m/s in comparison to those on roof level which doubled to approximately 4m/s (during the afternoon periods). It was suggested that this was possibly as a result of fewer wind obstacles on the higher levels; the tower floors are generally free from the impact of surrounding buildings.

Similarly, indoor air velocities were notably higher on the topmost floors (Figure 4-37). The air velocities on the fourth and fifth floors were found to be particularly higher than the rest, especially during the afternoons. This was attributed to the fact that, in addition to having all windows open, offices on opposite ends of both floors tended to have all doors into the lobby area open thereby augmenting cross ventilation. Whereas this was not ideal (in terms occupant privacy and noise control in an office environment), this worked well to maintain occupant thermal comfort. Repeated measurements carried out over the period of the study within these two floors saw air velocities ranging from 1.6m/s to 2.7m/s with an average of approximately 2m/s to 2.2m/s in office locations (Figure 4-38).

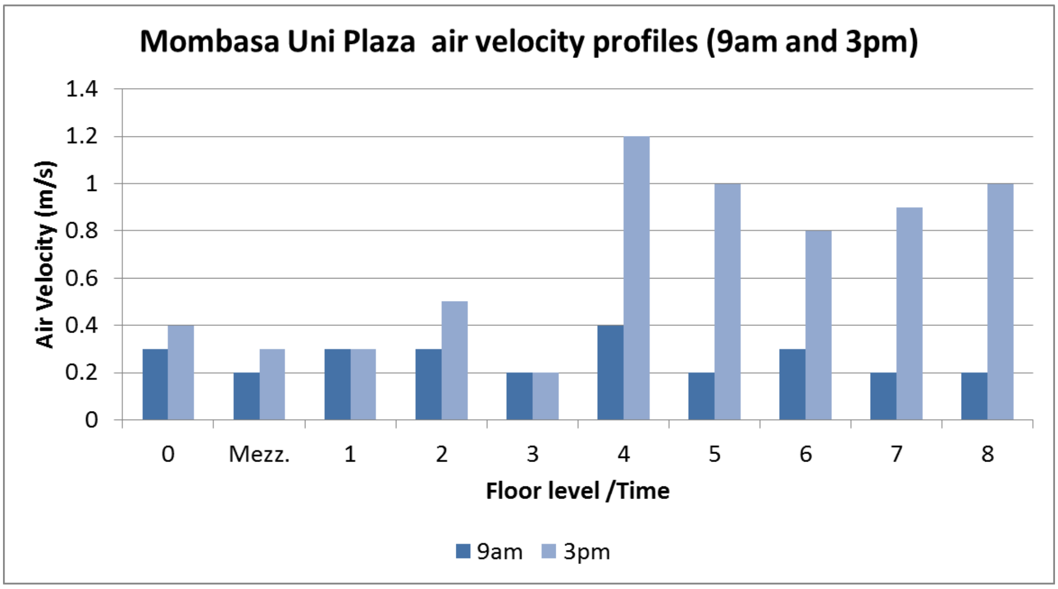


Figure 4-37 Air movement on a representative day in selected office - W1 location - on all floors at 9am and 3pm with corresponding air temperature values.

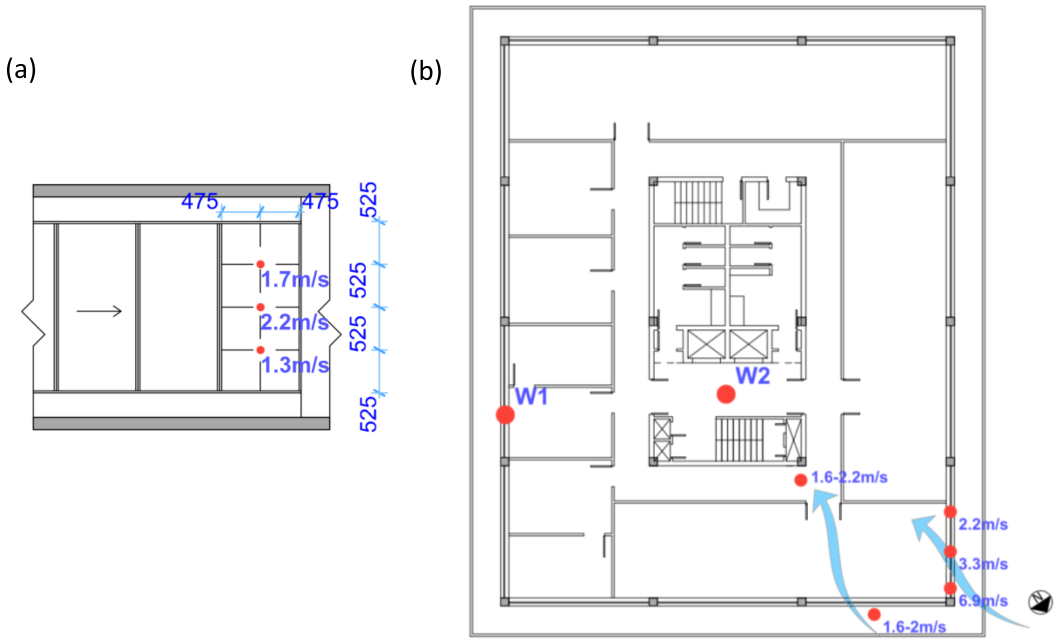


Figure 4-38 (a) Spot measures of air speed at W1. (b) Corresponding inlet values at 3pm.

Corresponding air temperature values showed a slight decline of up to 2°C towards the afternoon period (Figure 4-39). Similarly, temperatures were generally lower in the higher floors. It was suggested that this could have been as a result of ventilation cooling, attributed to the higher air velocities recorded on the higher floors.

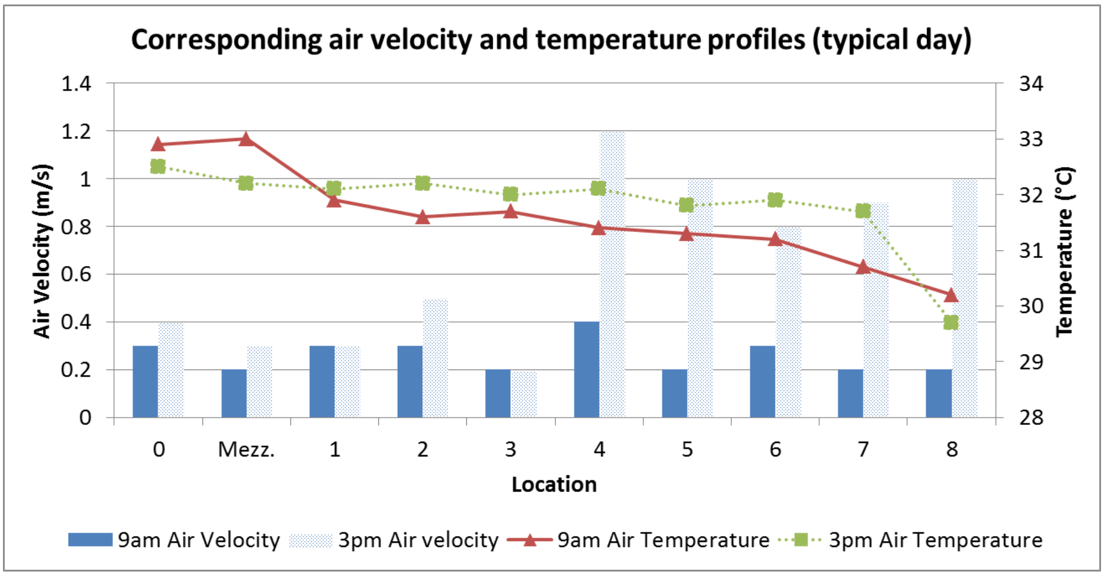


Figure 4-39 Corresponding air velocity and temperature profiles.

With the exception of the fourth and fifth floors, the air in the centralised common areas of the other floors felt quite muggy and still, especially in the afternoon periods. Certainly, the occupants reported that the areas were very stuffy. This is not very clear when examining the corresponding relative humidity data (Figure 4-40). It was suggested that although all the floors had relatively similar RH values (within a 10% range), increased air movement on selected floors (and especially in the afternoons when air temperatures tended to be significantly higher) allowed for physiological cooling that made it feel more comfortable across the highly ventilated floors (Figure 4-42).

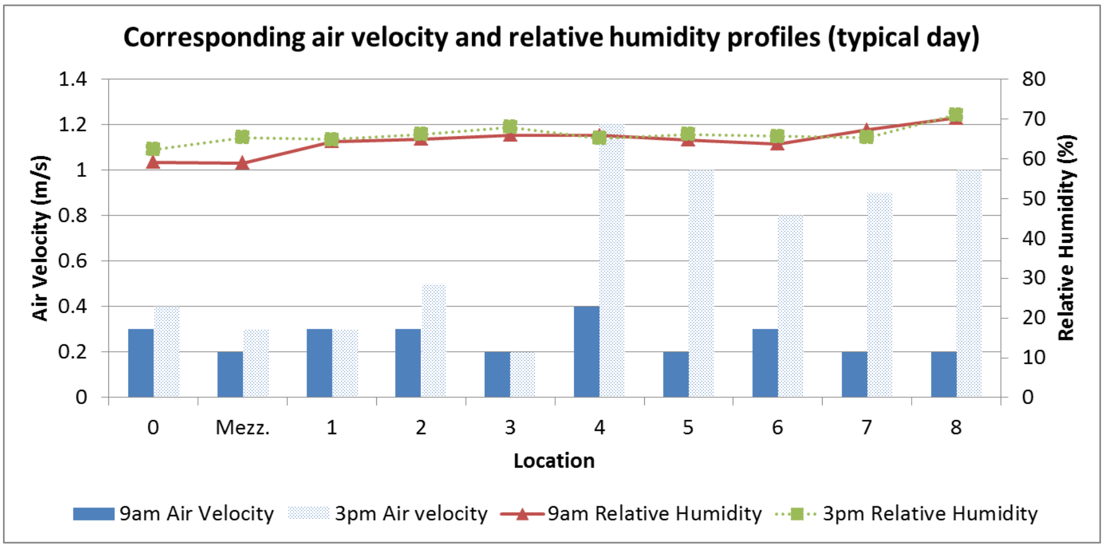


Figure 4-40 Corresponding air velocity and relative humidity profiles.

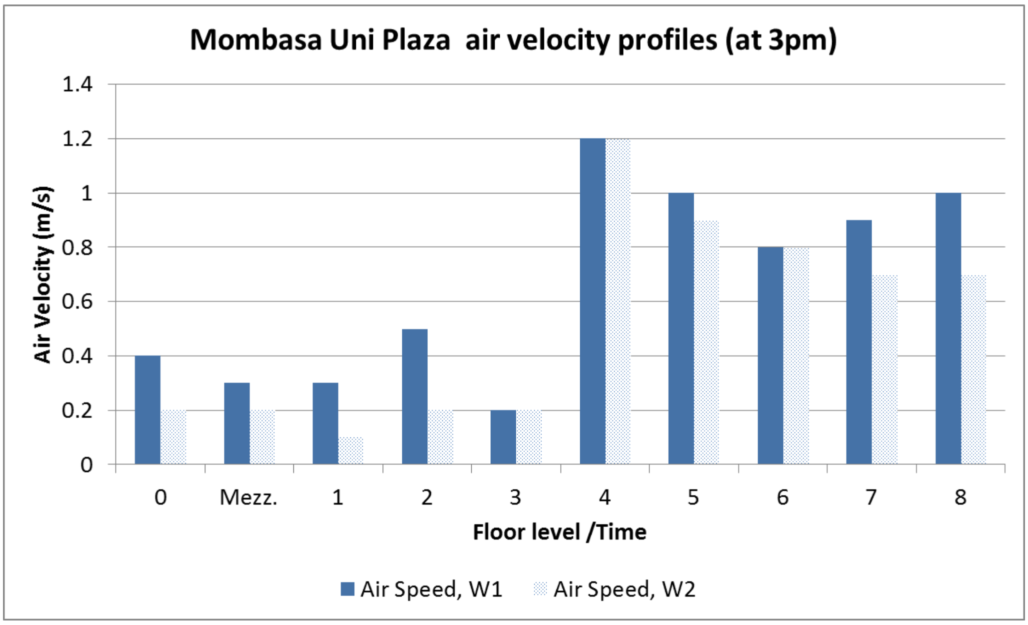


Figure 4-41 Air velocities on a representative day in locations W1 and W2 on various floors at 3pm (representative of afternoon air velocities).

This analysis revealed that the disuse of the original AC ventilation system (vents shown in Figure 4-42) seems to have negatively affected conditions within the centralised common area. Further, it was suggested that the lack of suitable inlets and outlets for the channelling of air to enhance sensible air movement within the centralised common areas served to inhibit ventilation cooling thereby increasing levels of discomfort. However, going by the positive impact of cross ventilation on the fourth and fifth floors, it is suggested that the situation could be improved by the introduction of air vents leading from the office zones and into the common spaces. Spot measurement taken in the lobbies of the various floors and the stairwell indicated that when roof doors were open, air movement was highly sensible relieving much of the stuffiness that was often perceived in the same area. This gave an indication of the potential of a combination of wind-driven and stack ventilation as was explained in section 2.2.1.

(a) (b)

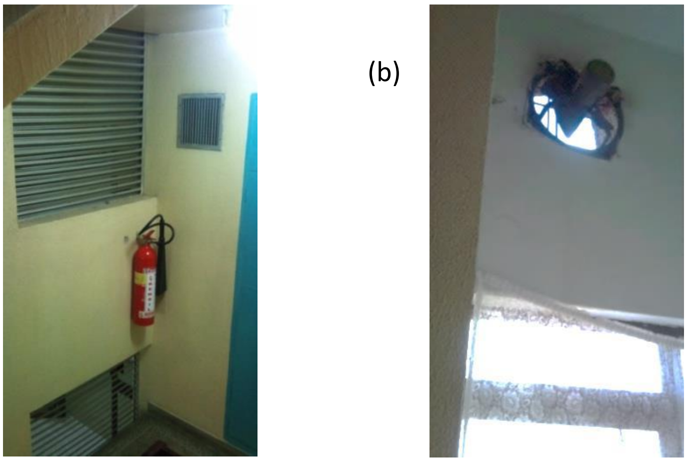


Figure 4-42 (a) Ventilation outlets located in the Lobby/Main Staircase area. (b) Makeshift extract vent at the top floor level.

Additional spot measurements taken at window openings sought to give an indication of air velocity levels along the height of a typical window (Figure 4-43). These readings revealed that air velocities tended to be higher at the top of the window openings (Figure 4-44). In addition, it was also noted that air speed tended to peak towards the afternoon periods – notably when outdoor temperatures peaked - potentially when it was most required for ventilation and physiological cooling purposes.

Previous adaptive comfort analysis revealed that for air speeds of up to 2m/s, it is possible to estimate the apparent cooling effect of air movement as indicated in Equation 2-5. The apparent cooling effect of air movement for a typical office in Mombasa Uni Plaza, measuring 6.0m by 4.5m by 2.7m high, was calculated using Equation 2-5 and the perceived reduction in air temperature plotted in comparison to the recorded air velocities and presented in Figure 4-44. It was proposed that these reductions in perceived indoor temperature would be suitable in improving comfort conditions for occupants. Considering the air velocities in naturally ventilated offices on the fourth and fifth floor tended to be significantly higher in the afternoons (ranging between 1.6m/s and 2.7m/s, with averages of 2m/s), it was suggested that they would be perceived as being more thermally comfortable than those on floors with lower air velocities. However, even where air velocities were low, it was suggested that occupants could use mechanically powered ceiling fans to enhance air movement and promote physiological cooling (examined further in section 4.3).

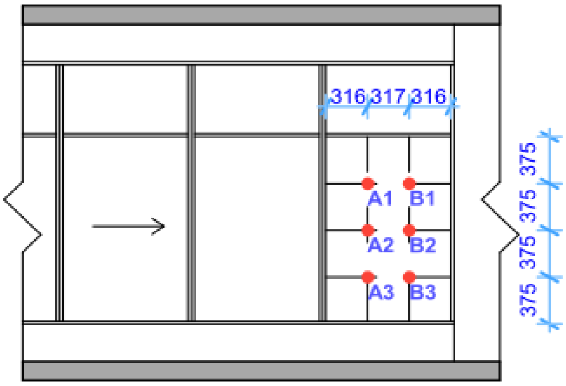


Figure 4-43 Air velocity measurement locations along and across a typical window opening.

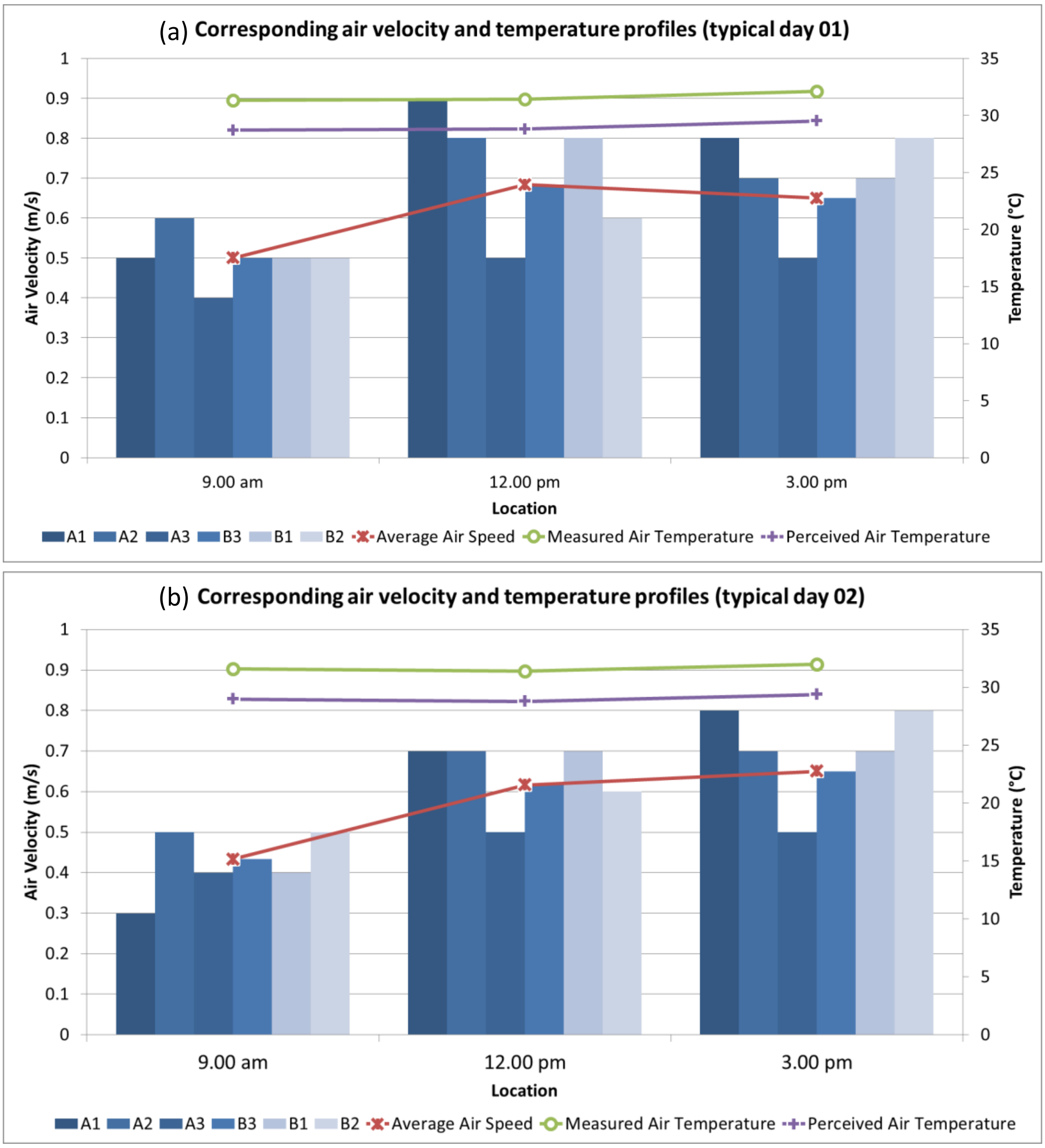


Figure 4-44 Correlation of recorded air velocities and recorded and perceived air temperatures for two typical consecutive days (a) and (b).

4.3 Post Occupancy Evaluation

As part of this field study, a post occupancy evaluation was conducted to provide further insights into the building thermal performance of Mombasa Uni Plaza. As with the previous case study analysis, the collection of this data served to augment the measured findings by relating the observed and measured building thermal performance with user satisfaction. Opinion was sought from occupants regarding the best and worst aspects of the user experience in the building, their level of understanding of aspects related to user comfort as well as any other issues relevant to their interaction with the building. In addition, the building manager was interviewed on matters regarding building operation and usage patterns, maintenance and energy consumption. The following section aims to summarise this process and its outcome.

4.3.1 Semi-structured Interview

Following a walkthrough of Mombasa Uni Plaza with the building manager, a semi-structured interview (APPENDIX B) was conducted to get further insight into factors that directly affect the building's thermal performance and resultant user comfort.

a) Building Operation and Usage Patterns

Mombasa Uni Plaza was found to house mainly commercial and office activities. Generally, the office spaces were of either single-occupancy or multiple-occupancy type. Mainly, Mombasa Uni Plaza was operational between 0800hrs and 1800hrs for five days a week. During these periods occupancy levels in offices tended to be greater than 80%. Overall, it was reported that the building occupants had not raised any issues regarding the building performance and their comfort as relates to building operations and usage patterns.

b) System Operation

System operations in Mombasa Uni Plaza showed a low level of automation. This was a significant shift from when the building had a centralised ventilation system that was controlled during working hours for all the main office spaces. Currently, majority of the building systems and their means of operation were identified to be easily accessible, occupant controlled and with low levels of automation. In naturally ventilated office spaces, the main passive control system consisted of openings which could be adjusted by occupants to encourage air movement for ventilation and cooling. It was also reported that ventilation could be augmented by use of mechanical fans during extreme conditions. These fans were operated using local fan controls placed in each office. In artificially ventilated offices, occupants had local controls or switches with which they were able to turn the AC on or off and set the thermostat to temperature values of their choice. The most common issues reported regarding systems operation included failure of AC units or noise from fans.

c) Maintenance

Maintenance and repairs of Mombasa Uni Plaza were reported to be the sole responsibility of the University of Nairobi Estates Department. Usually, maintenance and repair work was carried out on breakdown or as a result of programmed work. As a representative of the Estates Department, the building manager was responsible for the main running of the building, including the organisation of any maintenance work. Under ordinary circumstances, if the occupants had any maintenance concerns, they would report them to the building manager who would then evaluate the matter before arranging for maintenance or repair work. It was noted that there was an on-site maintenance team who dealt with most day to day issues. Where intensive work is required, a request for approval of works would usually be forwarded to the head office of the Estates Department for review and approval. On receipt of approval, work would be undertaken as required. It was noted that this process was often quite lengthy and had resulted in a significant number of complaints from occupants.

A review of the logged maintenance and repair requests revealed that majority of these requests included: servicing of the lifts, servicing of AC units, installation of AC units, replacement or fixing of noisy fans and replacement of lighting fixtures. In the case of ventilation control elements, these breakdowns would often affect building use and would often result in occupant dissatisfaction.

d) Other Control and Interfaces

Artificial lighting in the office spaces was controlled using simple conventional switches that were easily accessible by occupants. Similarly, in common areas, lighting was controlled by conventional switches. Typically, lighting in common areas would be left on overnight as part of the security measures. Given that these zones also lacked provisions for daylighting, the lights would remain on all day.

Frequent power outages often compromised electricity supply for all building services. Consequently, the management had opted to install high powered generators to cater for such occurrences. However, it was noted that these generators were not very reliable, as they were often in need of repair. This had resulted in numerous complaints from occupants whenever backup power was unavailable.

e) Energy Consumption

Of the issues discussed, high energy consumption was a constant concern. It was noted high energy consumption for AC purposes had resulted in extremely high electricity bills - a factor that was apportioned to use of AC units in a significant number of spaces for most of the year. Part of the building management team that was carried over from the previous ownership noted that the main reason for the removal of the original centralised ventilation system was high running costs. Even so, costs were still deemed to be unnecessarily high. Additionally, it was revealed that it is especially difficult to monitor AC energy use per office as the metres did not capture individual office consumption. As a condition of the typical tenancy agreements, tenants were charged fixed rate irrespective of individual office energy consumption. It was suggested that this may have led occupants to be uneconomical in their usage; reports indicated that some occupants had been known to intentionally leave their ACs running overnight.

Further, it was noted that the management had been inundated with numerous requests from tenants in naturally ventilated offices (and especially those in multiple-occupant offices) to install ACs in their offices. It was established that the Estates Department were particularly hesitant to do so as it was bound to drive energy consumption and costs even higher. In a quest to drive energy consumption down, the building management has requested the Estates Department to facilitate an energy audit that would recommend possible energy saving solutions. In addition, it was noted that because of frequent power outages and inefficient backup generators, it was still difficult to maintain comfort conditions within AC offices resulting in numerous occupant complaints. Lighting did not appear to be as much of an issue in terms of energy consumption.

4.3.2 BUS Occupant Study

As was explained in section 3.4.2, the results of the BUS occupant study can be used to provide insights into the occupant experience and building performance and to propose solutions to improve the same. Background information regarding the BUS methodology was presented in section 3.4.2.

The Mombasa Uni Plaza survey (APPENDIX C) received a good response rate of 80%. Generally, the respondents consisted of 90 occupants, both male and female, of generally good health and who were accustomed to warm humid climatic conditions (Figure 4-45). Typically, the subjects had a metabolic rate ranging from 0.7 to 1.6 met (depending on the task at hand) and a clothing insulating value of less than 0.6 clo at any given period.

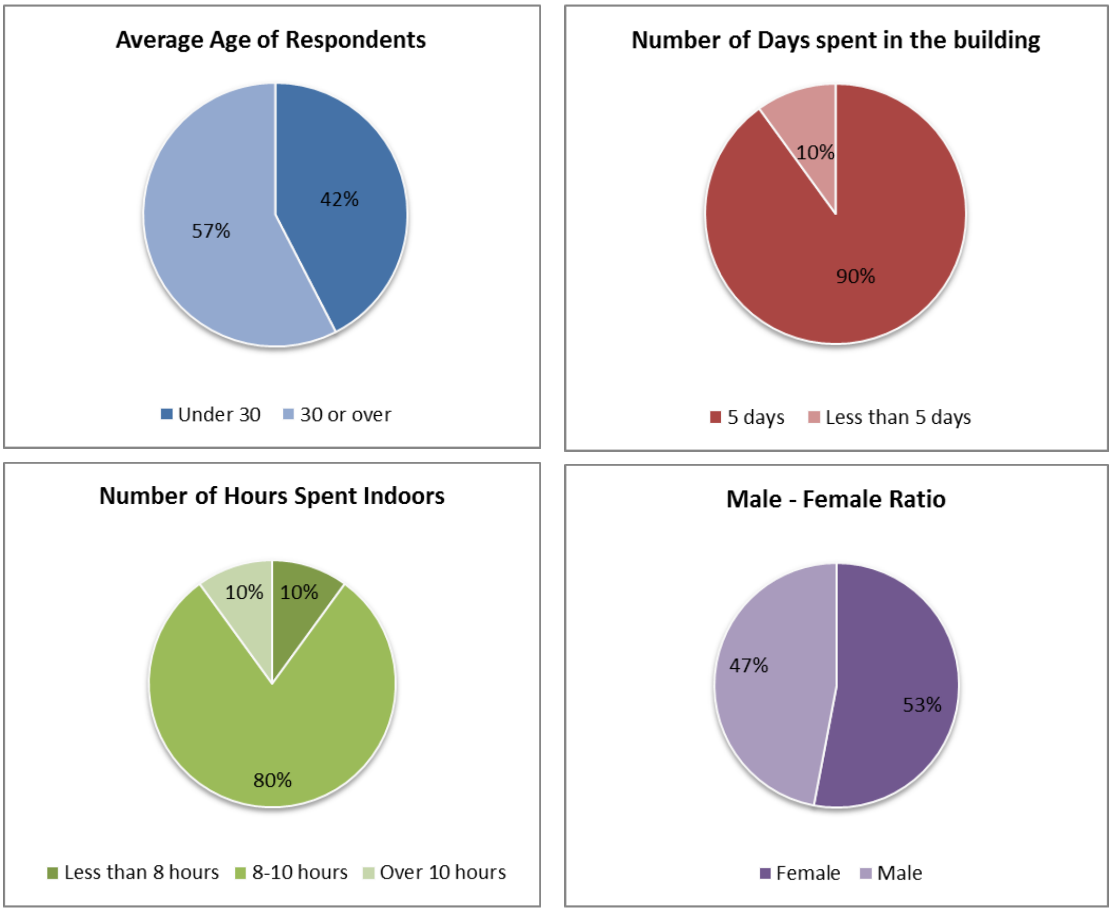


Figure 4-45 General statistics of the Mombasa Uni Plaza BUS study respondents.

The Mombasa Uni Plaza POE was focused on occupant thermal comfort and building thermal performance; efforts were made to elaborate the findings derived from responses related to those variables. A summary of the main overall variables of the Mombasa Uni Plaza BUS analysis results were presented in Figure 4-46 (refer to Figure 3-70 for similar Old Post Office analysis results). It shows the main variables that were investigated and the scale at which the occupants rated them.

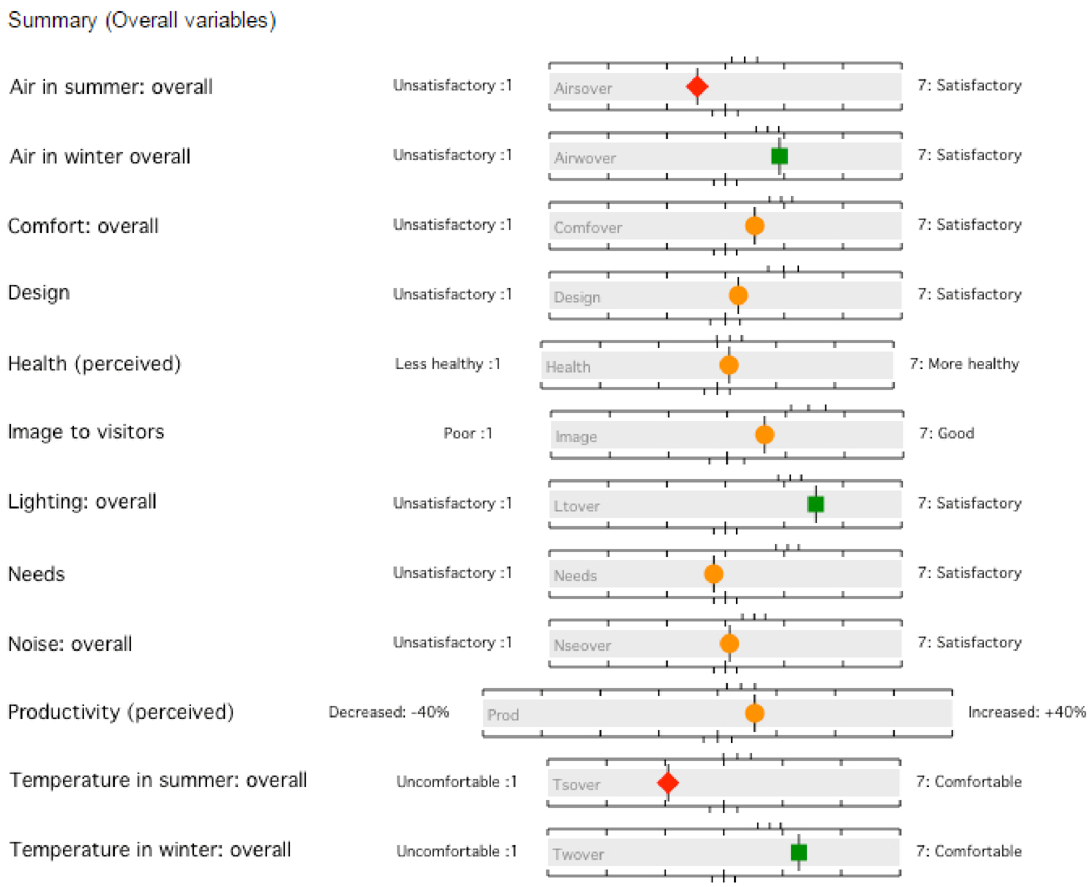


Figure 4-46 Mombasa Uni Plaza BUS results overview (BUS Methodology, 2014a).

When all the variables were considered, the overall comfort performance of Mombasa Uni Plaza was rated by occupants as being average on the satisfaction scale. This was represented by a score of 4.5 on the 7 point scale compared to a benchmark mean value of 4.95. Although this rating did not appear too far from the benchmark, given its overall comfort percentile score of the building of 24, the building was considered to have performed rather poorly when compared to similar type buildings (Figure 4-47). Comments given by occupants cited ventilation problems (stuffiness), the need for more air conditioning (possibly an indication of thermal discomfort) and unreliable lifts and generators as issues that affected their perception of overall comfort.

Further, the survey results indicated that only 40% of study respondents ever changed their behaviour due to conditions in the building; this was in stark comparison to 87% of the respondents in the Old Post Office building. This was suggested to be a possible indication of a lack of a similar range of adaptive opportunities. For those who choose to change their behaviour due to conditions in the building, the main reported adaptive changes included wearing of fewer layers or lighter clothing, eating of less hot foods and opening of windows for longer periods.

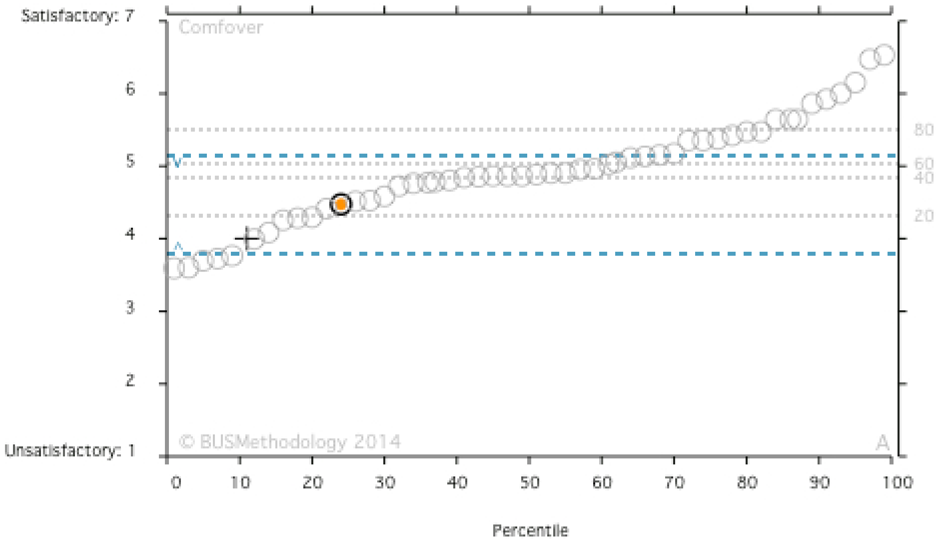


Figure 4-47 Mombasa Uni Plaza overall comfort BUS rating (BUS Methodology, 2014a).

Interestingly, the best performing variable was identified to be 'lighting' which scored high on the satisfaction index with a rating of 5.54 compared to a benchmark value of 5.1, and a percentile score of 73 indicating that the building performed significantly better than the benchmark and scale midpoint. This result was mainly attributed to the provision of artificial lighting rather than from daylighting. On the other hand, the worst scoring variable was identified as 'temperature in summer', where 64% of respondents indicated that they experienced a significant level of dissatisfaction. This was identified to be partly as a result of occupants finding it uncomfortably hot. Both of these variables were examined in greater detail in the next sections of this study.

a) Temperature

To enable a comparison of field study data findings and respondent's responses, the 'temperature in summer' variable was considered first. This is because this variable covered occupant responses to temperatures experienced in the warmer period of the year *i.e.* when the field study was conducted and the period for which the predicted adaptive comfort was determined. The occupant survey results for overall temperature in summer revealed that occupants found the indoor temperature in summer uncomfortable (20%), moderately uncomfortable (22%), slightly uncomfortable (22%). This indicated a 64% dissatisfaction rate and worked out to a score of 3.05 on the 7 point scale, this was revealed to be significantly worse than the benchmark mean of 4.23 (Figure 4-48).

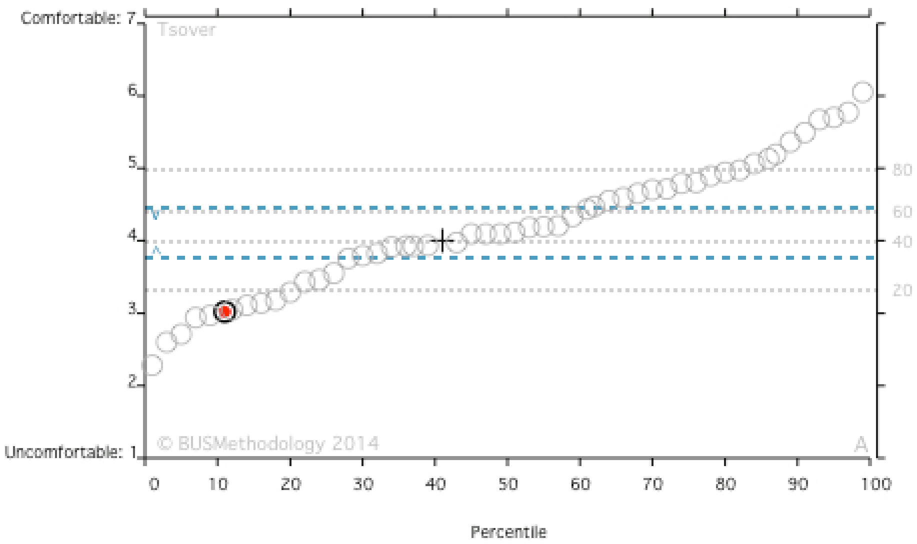


Figure 4-48 Mombasa Uni Plaza temperature in 'summer': overall (BUS Methodology, 2014a).

An examination of whether the occupants found temperature in summer either too hot or too cold indicated that up to 61% of respondents were dissatisfied, from this number 7% found it slightly hot, 31% found it moderately hot whereas 23% found it too hot (Figure 4-49). This discomfort was suggested to be an indication of overheating during the warmer months.

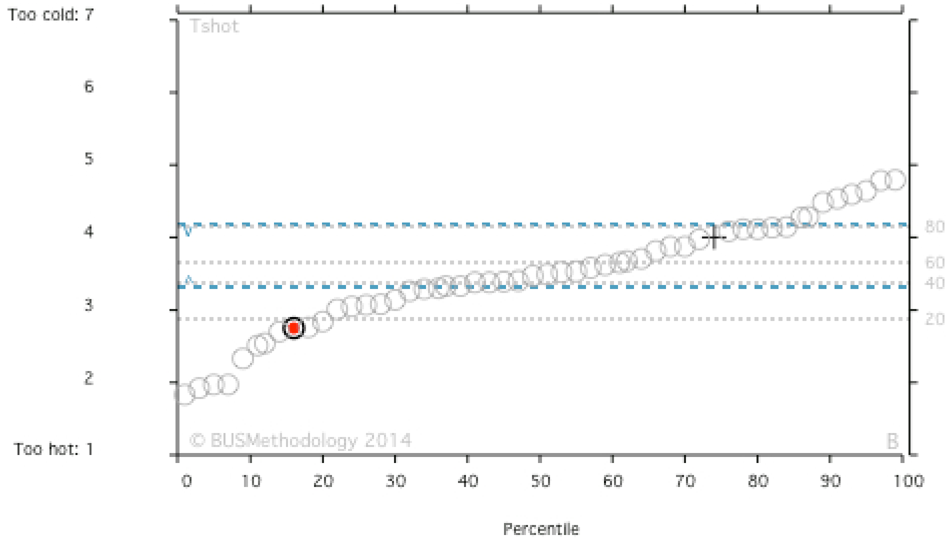


Figure 4-49 Mombasa Uni Plaza temperature in summer: too hot or too cold (BUS Methodology, 2014a).

The 'temperature in summer' results were compared to the predicted adaptive comfort limits calculated in section 4.2.1 where a review of monitoring data indicated that indoor temperatures recorded in the warmest month in Mombasa Uni Plaza offices would be considered comfortable for up to 67.2% of the time (average percentage derived from the five office spaces analysed on third and eighth floor). This revealed that the predicted comfort was overestimated by 28.2%. This may be attributed to a variety of reasons. On one hand, it was suggested that the small range of adaptive opportunities hindered occupants' capability to restore comfort. Further, as majority of the indoor temperatures considered in the derivation of comfort were based on the third floor, a floor which was also found to have significantly low levels of air movement, this indicated that the occupants were less likely to experience physiological cooling necessary for the extension of comfort.

On the other hand, occupants found temperatures in winter significantly more comfortable with up to 87% of the occupants noting that they found the conditions acceptable. This worked out to a study mean 5.28 on the 7 point scale which was revealed to be significantly more comfortable than the benchmark value of 4.78 (Figure 4-50). This improvement in levels of satisfaction was attributed to fact that up to 80% of the respondents did not feel that the temperatures in the winter months were uncomfortably warm.

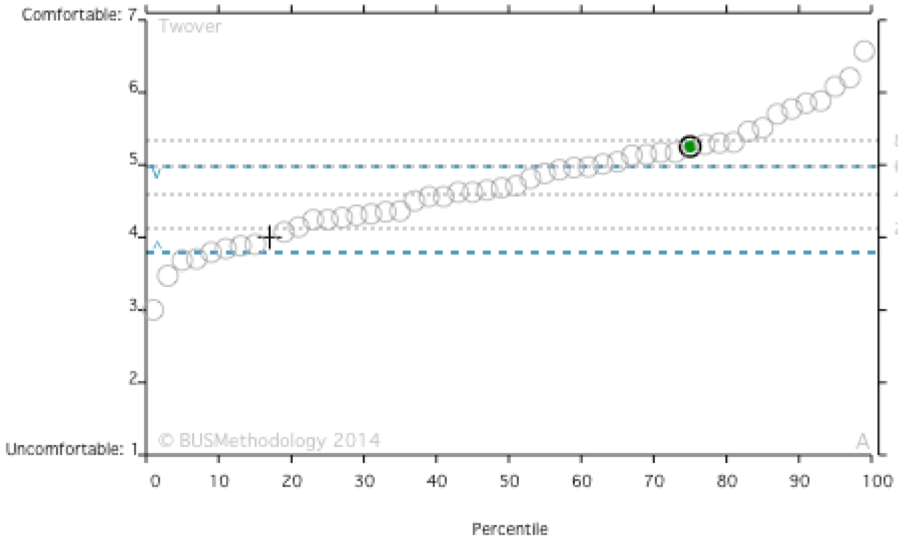


Figure 4-50 Mombasa Uni Plaza temperature in 'winter': overall (BUS Methodology, 2014a).

b) Air (Quality)

A review of the overall air quality in the summer found that 45% of the respondents were dissatisfied with conditions. Respondents rated the building at 3.52 on the 7 point scale in comparison to the benchmark figure of 4.33 (Figure 4-51). Dissatisfied respondents rated the overall air quality as being slightly unsatisfactory (17%), moderately unsatisfactory (17%) and unsatisfactory (13%). This was partially attributed to the fact that up to 41% of respondents found the air humid (an indication that physiological cooling was hindered). Further, 34% of respondents' found the air stuffy. This was possibly due to poor ventilation in the common areas.

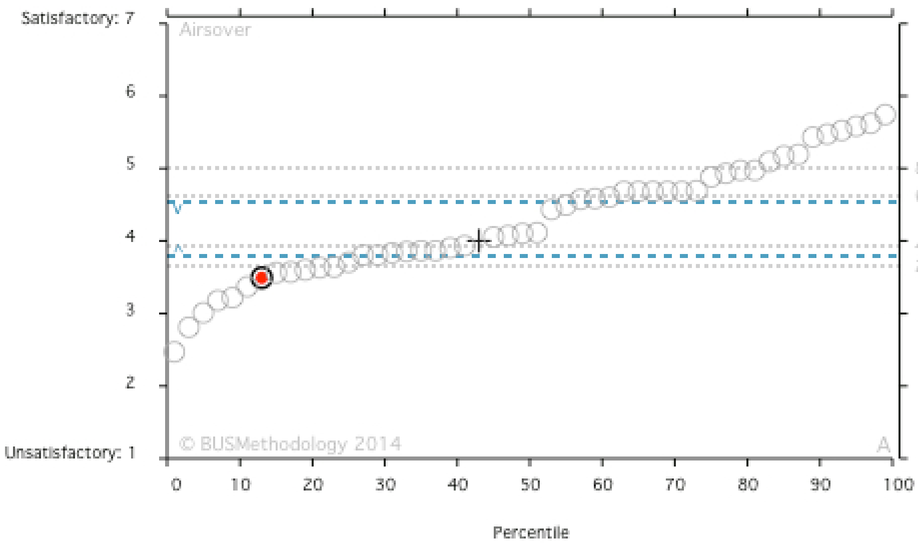


Figure 4-51 Mombasa Uni Plaza air in summer (BUS Methodology, 2014a).

In contrast, only 7% of the occupants were dissatisfied with the overall air quality in winter. This worked out to a study mean 4.92 compared to the benchmark score of 4.72 (Figure 4-52). It was suggested that this positive response was largely triggered by the occupant response to indoor humidity levels. Unlike the results for the air quality in summer, responses regarding level of dryness or humidity of the air during the winter showed a highly level of acceptability with only 7% of the respondents indicating dissatisfaction. However, there was no change to the response to stuffiness with up to 34% indicating that they felt stuffy in the winter too.

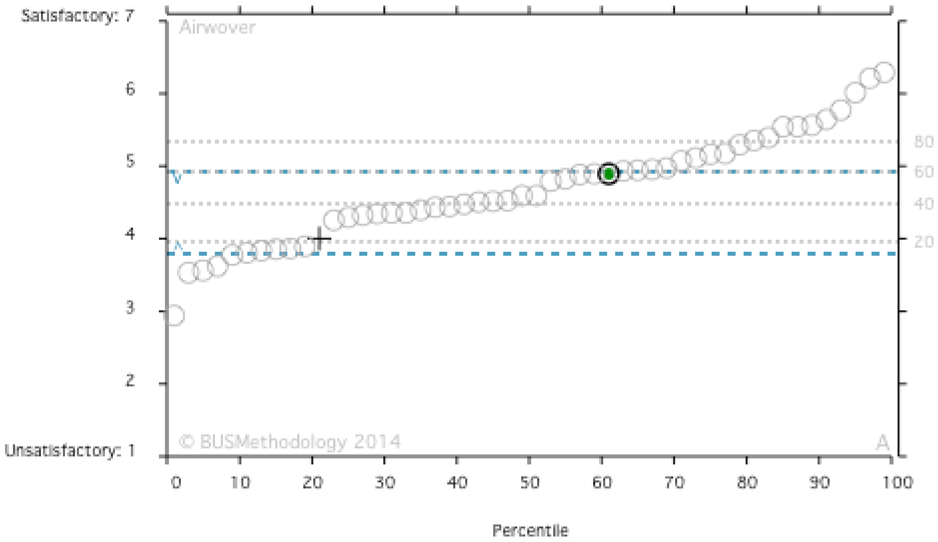


Figure 4-52 Mombasa Uni Plaza air in winter (BUS Methodology, 2014a).

c) *Lighting*

The overall lighting quality variable combined aspects of both natural and artificial lighting and glare. A review of the analysis findings indicated that only 7% of occupants found lighting conditions unsatisfactory. This worked out to a study mean 5.54 compared to the benchmark score of 5.1 (Figure 4-53). This considerably good performance was attributed to the artificial lighting provisions. It was noted that building was heavily reliant on artificial lighting with respondents noting that it could get too dark if the lights were switched off, especially in the common areas. This confirmed earlier study findings that suggested that lighting levels were significantly low. Furthermore, 18% of the respondents indicated that they found the glare from the sun and sun uncomfortable. Although not a significant proportion, it was suggested that this might have been the reason why majority of offices had been fitted with blinds. The blinds were also found to allow occupants to open the windows and allow for partially restricted air movement without causing any glare issues.

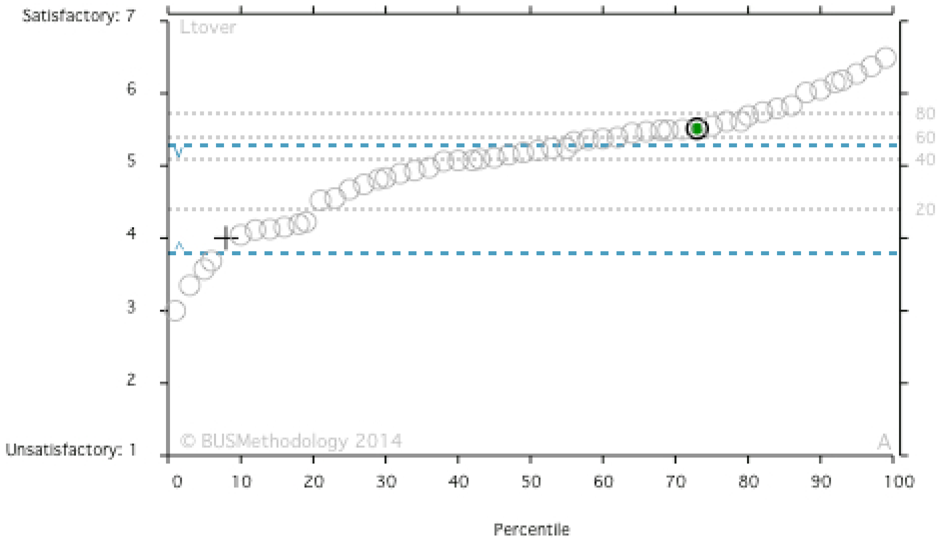


Figure 4-53 Mombasa Uni Plaza overall lighting (BUS Methodology, 2014a).

d) Control

Mombasa Uni Plaza was found to have a mixed-mode ventilation system. In this section, user perceptions with respect to access to personal control measures (as relates to passive controls) that are used to restore comfort in Mombasa Uni Plaza were examined and the findings presented. The only available means of cooling for respondents was through the opening of windows and the turning on of mechanical fans. In terms of cooling control, respondents indicated that they had no control (12%), adequate control (29%), slight control (27%), moderate control (16%) and full control (14%).

This average performance was indicative of the fact that whereas some of the occupants did have adequate control over their cooling, they still did not feel that it allowed them to restore comfort, especially in the warmer months. Indeed, it was noted that up to 48% of respondents had requested for changes to cooling and ventilation. This was a further indication of dissatisfaction with the existing conditions and controls. Majority of these requests were from occupants wanting access to air conditioning units and an overhaul of ventilation in the common spaces. Even so, a study mean of 4.66 indicated that the Mombasa Uni Plaza performed significantly better than the benchmark value which had a mean of 2.93 (Figure 4-54).

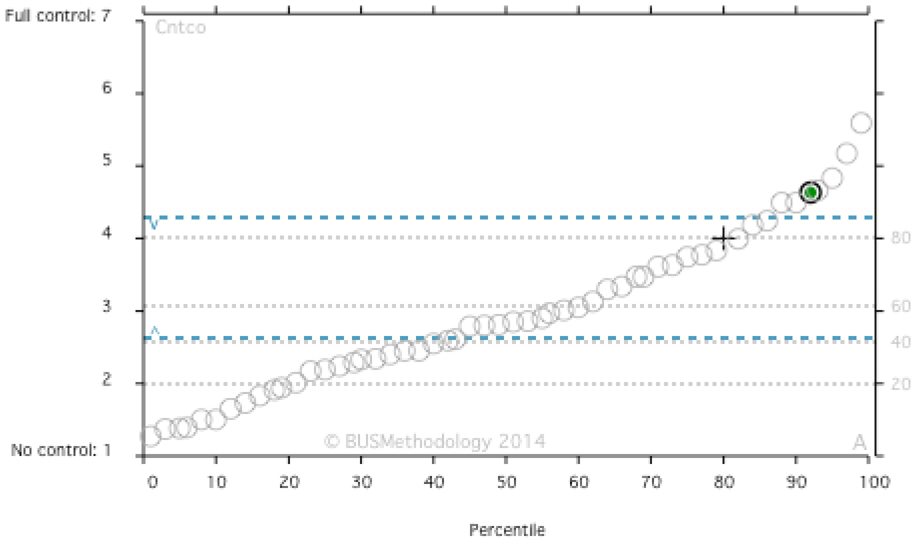


Figure 4-54 Mombasa Uni Plaza control of cooling (BUS Methodology, 2014a).

With regards to control over ventilation, up to 34% respondents indicated that they were dissatisfied with the level of control. Other respondents indicated that they had adequate control (25%), slight control (14%), moderate control (16%) and full personal control (8%). As with cooling control, ventilation control was related to the access to and control of window openings. The fact that majority of respondents found that they had adequate control (63%) was correlated to the fact that up to 66% of respondents indicated that they had direct access to an openable window with which they could use to control their immediate environment. The study mean was considered average with a rating of 3.87 on the 7 point scale compared to 3.19 for the benchmark value (Figure 4-55).

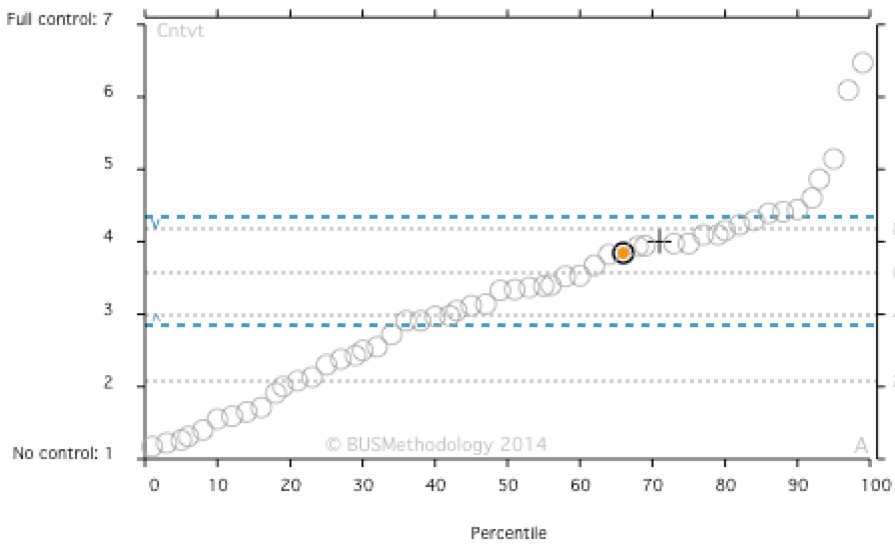


Figure 4-55 Mombasa Uni Plaza control of ventilation (BUS Methodology, 2014a).

Up to 68% of respondents reported that they had significant control over lighting. This also factored into why respondents had rated lighting as one of the best performing variables. This was broken down into adequate control (22%), slight control (18%), moderate control (14%) and full control (14%). A high study mean of 4.29 indicated that the occupants had a good level of lighting control, and was significantly better than the benchmark figure of 3.75 (Figure 4-56).

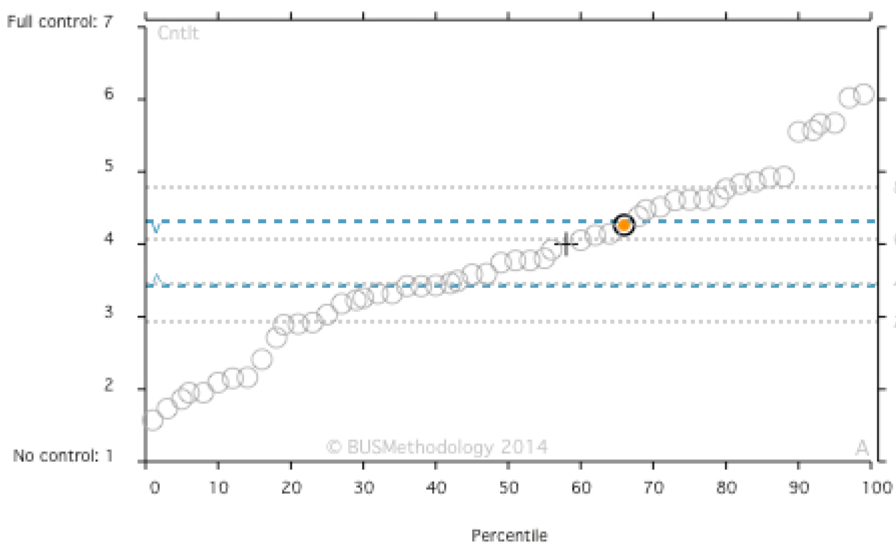


Figure 4-56 Mombasa Uni Plaza control of lighting (BUS Methodology, 2014a).

e) Design and Needs

A review of Mombasa Uni Plaza's design in relation to occupant needs indicated that occupants felt that the building design was neither satisfactory nor unsatisfactory (26%), slightly satisfactory (9%), moderately satisfactory (11%) and satisfactory (15%). On the other hand, up to 35% of respondents indicated dissatisfaction with the overall building design. With a study mean of 4.22, the building was found to perform worse than the benchmark figure of 4.99 (Figure 4-57). In as much as a number of respondents indicated that conditions were satisfactory, they also cited that there was need to improve ventilation systems and other building services (lift and generator). Similarly, a significant number of respondents indicated that they were highly dissatisfied with the maintenance, revealing that they had to wait for considerable amounts of time to get attended to. Positive comments indicated that the building offered a high level of flexibility (in terms of space reorganisation) and good views of the city.

In addition, up to 40% of respondents indicated that the building did not meet their needs. The study mean of 3.8 showed that the building performed significantly worse than the benchmark value of 5.06 (Figure 4-57). Respondents indicated that the issues that contributed to this relatively high level of dissatisfaction included poor air circulation (stuffiness), poor maintenance, and lack of adequate security, amongst others.

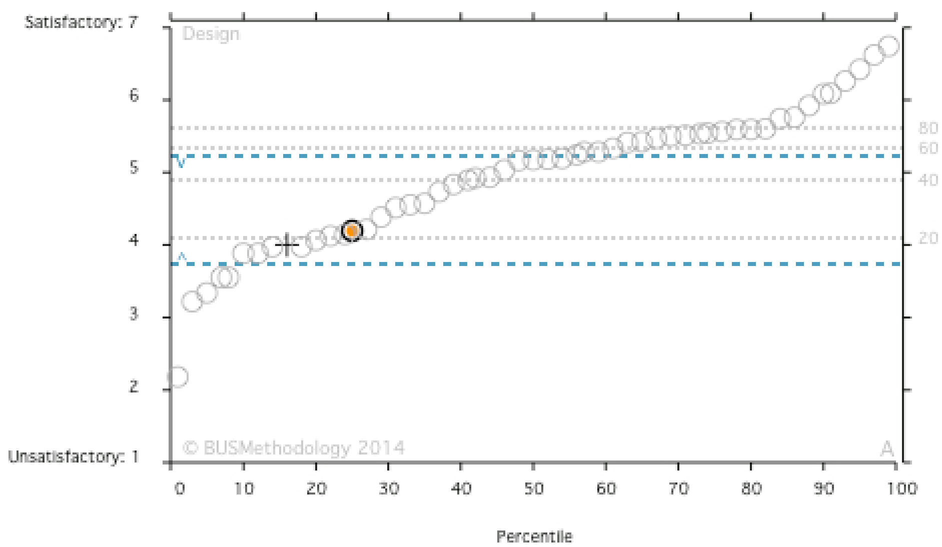


Figure 4-57 Mombasa Uni Plaza building design (BUS Methodology, 2014a).

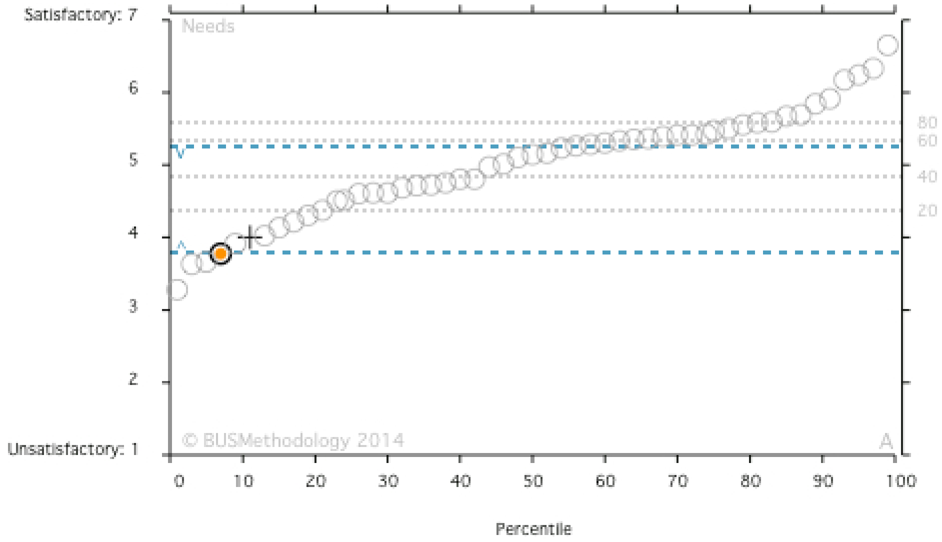


Figure 4-58 Mombasa Uni Plaza needs (BUS Methodology, 2014a).

f) Health (perceived) and Productivity (perceived)

Up to 45% of respondents indicated that they did not feel more or less healthy when occupying the Mombasa Uni Plaza. Nonetheless, about 29% did indicate that they felt more healthy as a result of being in the building whereas 23% indicated that the felt less healthy from occupying the building. A study mean of 4.2 revealed that this was similar to the benchmark value of 4.21 (Figure 4-59). Respondents indicated that the reduction in perceived health was attributed to stuffiness of the building, uncomfortably warm indoor temperatures and a poor level of cleanliness in common facilities.

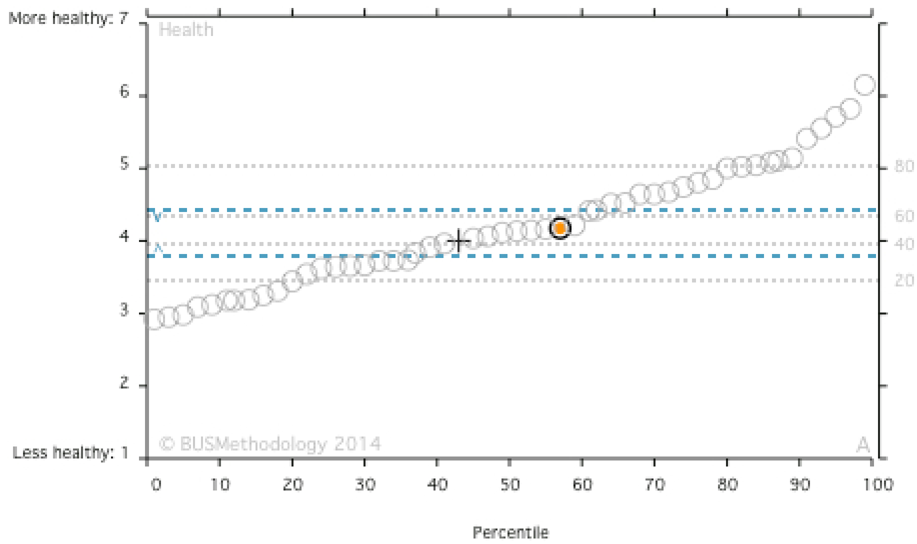


Figure 4-59 Perceived health in the Mombasa Uni Plaza (BUS Methodology, 2014a).

The responses to perceived productivity showed a wide range of answers. Up to 14% of respondents indicated that they did not feel any more or less productive as a result of carrying out various activities in Mombasa Uni Plaza. In terms of increased productivity, respondents reported that they felt 10% more productive (18%), 20% more productive (12%), 30% more productive (14%) and 40% or more productive (8%). In terms of reduced productivity, respondents indicated that they felt 10% less productive (14%), 20% less productive (14%) and 30% less productive (4%). Respondents attributed their perceived increase in productivity to reduced noise and dust levels indoors, and the ability to use the fan during overheating periods. Conversely, respondents attributed poor productivity to increasingly warm temperatures indoors and noise from other building occupants. The study percentage mean of 6.32 indicated that the building was within well within the critical benchmark region (Figure 4-60).

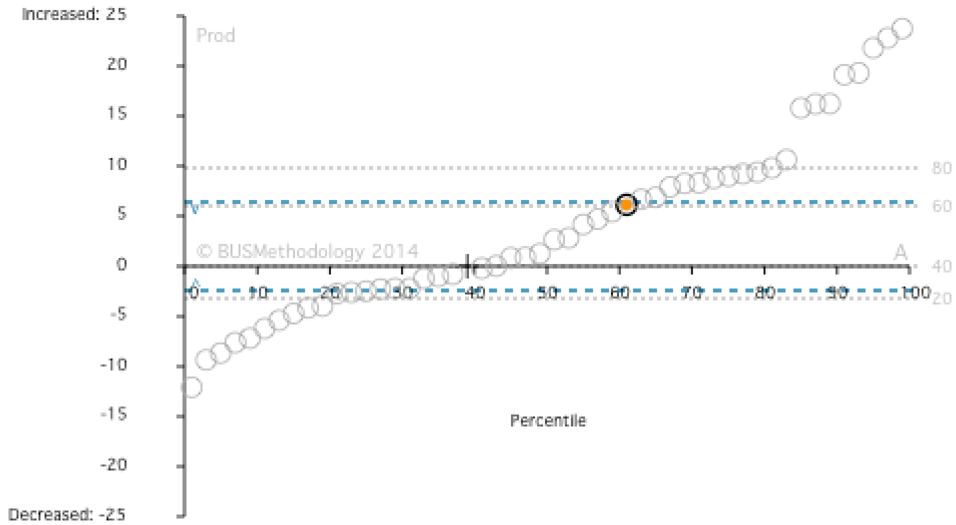


Figure 4-60 Productivity (perceived) in Mombasa Uni Plaza (BUS Methodology, 2014a).

Overall, the survey findings indicate that Mombasa Uni Plaza falls in the low 30% of the BUS 2012 international benchmark database. This index consisted of the average of the comfort index and the satisfaction index, of which Mombasa Uni Plaza scored poorly, falling within the low 40% and low 30% of the BUS 2012 international benchmark database, respectively (Figure 4-61).

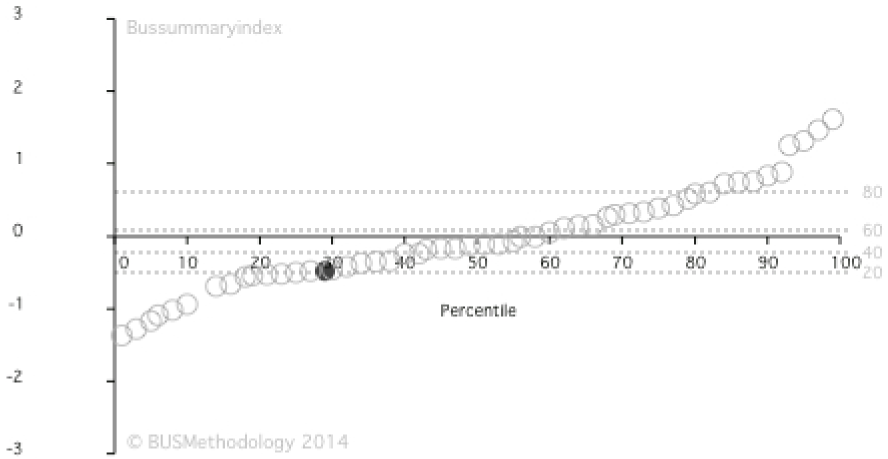


Figure 4-61 Mombasa Uni Plaza BUS summary index (BUS Methodology, 2014a).

Of the twelve study variables used to give a simple overview of the buildings comfort performance, two were rated worse than the benchmark, seven were rated as good as most benchmarks whereas two were better than the benchmark. The forgiveness score was average (a score of 1.02 out of 1.5, low 40% of the BUS 2012 international benchmark database), indicating that occupants did not easily accept dissatisfaction when taking into account the overall performance of the building.

Good levels of occupant satisfaction were reported for the variables of overall lighting, temperature in winter and air in winter. Satisfactory lighting was largely attributed to adequate provision of artificial lighting; however, concerns were raised about the particular low illumination levels when artificial lighting was unavailable. Higher levels of comfort in the cooler months were attributed to slightly lower indoor temperatures and lower humidity levels. The main weaknesses identified in the performance of the Mombasa Uni Plaza were the temperature in the summer and air in winter variables where conditions were perceived as being too warm, and too humid and stuffy, with little chance for relief from adaptive opportunities. Furthermore, poor responses to maintenance and repair requests were cited as reasons why occupants were dissatisfied.

A comparison of the BUS occupancy survey findings derived from the vernacular case study of the Old Post Office building and Mombasa Uni Plaza was conducted to gauge overall occupant responses in both buildings. Generally, the findings indicated that the Old Post Office building performed significantly better than Mombasa Uni

Plaza (Table 4-5). In terms of overall comfort, the Old Post Office was rated within the top 30% of the BUS 2012 international benchmark database; this was in comparison to the low 30% rating for Mombasa Uni Plaza. In terms of thermal comfort, better performance in the Old Post Office building was largely attributed to greater provision of adaptive opportunities. Similarly, it was suggested that structural controls such as building orientation for channelling of breezes and heavy shading served to temper conditions allowed for generally better indoor conditions.

Table 4-5 BUS study percentage people dissatisfied indices for the Old Post Office and Mombasa Uni Plaza.

Variable	Old Post Office	Mombasa Uni Plaza
Temperature in summer: overall	33%	64%
Temperature in summer: too hot	22%	57%
Temperature in winter: overall	0%	10%
Temperature in winter: too hot	0%	22%
Air in summer: overall	55%	47%
Air in summer: too humid	0%	43%
Air in summer: too stuffy	0%	34%
Air in winter: overall	0%	7%
Air in winter: too humid	11%	30%
Air in winter: too stuffy	37%	34%
Controls: overall	0%	20%
Controls: cooling	12%	12%
Controls: ventilation	0%	34%
Controls: lighting	0%	28%

4.4 Conclusions

Mombasa Uni Plaza is typical to the highly glazed office buildings found in the city of Mombasa. Previous research has indicated that these types of building often result in overheating. More often than not, this necessitates the installation of actively powered climate control systems. Indeed, a review of the history of Mombasa Uni Plaza found that the building was originally designed with an active centralised ventilation system in place. Later, this system was replaced by a mixed-mode system that consisted of natural ventilation in some spaces and active ventilation via individual AC units in other spaces. Reasons given for the switch cited the high costs and high maintenance requirements. Even so, it was determined that running cost attributed to current AC use is considerably high.

A review of the building construction materials indicated that the building was significantly lightweight with its main external hollow concrete block walls having a u-value of $1.96W/m^2K$. Similarly, the building was found to have a significant amount of glazing - approximately 60% of each facade. It was suggested that this lack of significant thermal mass contributed to higher indoor temperatures that fluctuated in a similar manner to outdoor temperatures. As such, it was suggested that the occupants were left vulnerable to the changing outdoor conditions, and especially during the afternoons when maximum outdoor temperatures were experienced.

As was highlighted in previous chapters, the roof zone was found to be particularly prone to solar heat gain from the zenith. Solar insolation analysis indicated that roof and terrace surfaces experienced more than double the amount of solar insolation experienced on the wall surfaces. On the topmost floor, this resulted in temperatures being up to 4°C higher than those on lower floors. Further, it was noted that poor building orientation had exposed the building to the western and eastern sun, making it harder to control solar gain and glare through the highly glazed surfaces.

Sun shading for the mitigation of solar heat gain was also examined. A review of the existing wrap-around canopies indicated that they were not necessarily designed for that purpose but rather to hold the pre-existing ventilation system equipment. Nonetheless, initial analysis revealed that the shading would be useful in cutting out high angle sun in the late morning to early afternoon periods. To quantify the performance of this canopy with respect to indoor comfort conditions, parametric analyses were carried out and the results presented in Chapter 5. Further review indicated that Mombasa Uni Plaza partially benefitted for mutual shading from neighbouring buildings. However, owing to the height and proximity of neighbouring buildings, the scale at which this happened was determined to be rather low, unlike the Old Post Office building. Lower facade zones were found to benefit with reductions in solar insolation of up to 56% and others much less.

Predicted comfort analysis revealed that the monitored spaces would be able to provide comfort for an average of 67.2% of the time (during the warmest month of March). Further occupant studies revealed an overestimation of approximately 28.2%; this was attributed to the presence of fewer adaptive opportunities and inadequate ventilation for physiological and ventilation cooling purposes.

In naturally ventilated spaces, air movement was the found to be the main means by which the indoor spaces were ventilated. The main ventilation controls available to occupants included the opening and closing of doors and windows. Through this, occupants were able to moderate the indoor environment for as much as outdoor conditions would allow. Only 63% of the BUS survey respondents noted that they adequate or full personal control of ventilation of the indoor spaces. This was directly related to the fact that just 66% of the respondents indicated that they had direct access to a window. Concerns were raised about the poor environmental conditions in the central common spaces, with many users commenting that they had felt that the air was humid and stuffy. This was attributed to the lack of adequate ventilation.

Generally, recorded air velocities at Mombasa Uni Plaza ranged between 0.2m/s to 2.7m/s and averaged by as high as 2m/s in some locations during the significantly warmer afternoons. From these measurements, the control potential zone (range of outdoor conditions for which air movement has the potential to ensure indoor comfort) was calculated. These findings indicated that the adaptive comfort limits could be increased by up to 5.6°C for air velocities of up to 2m/s. Given that higher velocities were recorded during the afternoon period, this perceived reduction in indoor temperatures explained to some extent how it was that occupants felt comfortable in the fairly warm indoor temperatures in some offices.

It was noted that air velocities generally tended to be more than two times higher in the topmost floors. This was partially attributed to the reduction of obstacles that might hinder free air movement on the higher levels. In addition, it was suggested that the opening of both doors and windows encourages cross ventilation that significantly improved comfort conditions for occupants. In similar type office buildings, this approach could be integrated via the provision of outlet vents to cater for adequate cross ventilation.

The BUS occupancy study gave valuable insights into the building thermal performance in relation to occupant satisfaction. Generally, the majority of the occupants agreed that Mombasa Uni Plaza performed fairly poorly rating it within the low 30% of the BUS 2012 international benchmark database. This was principally attributed to up to 61% of occupants finding temperatures in summer warmer than comfortable, and the air more humid and stuffy than was comfortable. Up to 40% of users said that they changed their behaviour in a bid to restore comfort.

The case study analysis of Mombasa Uni Plaza enabled a detailed understanding of the building performance and the resultant occupant thermal comfort. Evidence of overheating in the building and consequent occupant discomfort was apparent in a review of indoor conditions with respect to occupant responses. Corresponding occupant feedback revealed that users found indoor temperatures too hot during the warmer part of the year - in some cases this led to repeated requests for AC unit installation. The building management and owners have indicated that current energy consumption and resultant energy bills are unsustainable, so it is highly unlikely that they would be willing to respond positively to those requests. Further analysis conducted in Chapter 5 will seek to isolate individual factors and the extent to which they are resulting in poor building thermal performance, with the aim of deriving potential solutions.

5 GENERIC PARAMETRIC STUDY

Based on the field study results discussed in Chapter 3 and 4, selected Swahili-inspired thermal design strategies, suitable for contemporary office buildings situated in the warm humid region of Kenya, are examined and presented in this chapter. With the aid of computer based dynamic simulations, the impact of thermal mass, ventilation and shading on the thermal performance of a typical office building, and the consequent effect on thermal comfort of occupants, was investigated.

5 GENERIC PARAMETRIC STUDY

The parametric study covered in this chapter has been built on the premise that the application of selected Swahili-inspired thermal design strategies to contemporary office buildings in the warm humid region of Kenya could reduce the potential for overheating. Consequently, this would lead to improvements in the thermal performance of the buildings and in the thermal comfort of occupants.

Based on the results presented in Chapter 3, which were also discussed in a paper developed as part of this study entitled "*Climate-responsive Vernacular Swahili Housing*" (Kiamba et al., 2014), it was proposed that the use of thermal mass, passive ventilation strategies and external shading could significantly contribute to improved indoor thermal conditions in buildings in warm humid regions. As is typical of design strategies recommended for warm-humid climates (Chapter 2), these Swahili-inspired strategies were found to work through either the mitigation of heat gain (external shading), or the management of heat gain and losses (thermal mass) or the 'flushing' out of warmer air from indoor spaces (natural ventilation).

In this parametric study, dynamic simulation techniques were used to develop an understanding of the critical parameters using EDSL Tas thermal analysis simulation software. By using simplified building models, the application of this modelling tool facilitated the appreciation of the effect of varying thermal mass, natural ventilation strategies and external shading to the thermal performance of a typical office building. Further, using simplified building models proved advantageous as it allowed for fewer inputs and clearer correlation of direct inputs to the results.

Overall, the main aim of this parametric study was to quantify the impact of implementing the selected passive Swahili-inspired strategies to a typical contemporary office building in Mombasa, Kenya; and in so doing demonstrate their potential to reduce instances of overheating that lead to the use of active cooling outside of extreme (warmest) periods of the year.

Additionally, the parametric study covered in this chapter formed the basis of further simulation studies presented in Chapter 6 and Chapter 7.

5.1 Simulation Basis

A review of contemporary non-domestic buildings in Mombasa, Kenya has revealed the predominance of highly glazed lightweight buildings which rely on costly and unsustainable active climate control systems (Chapter 1 and 4, Figure 5-1). Due to the region being inundated by unstable economic security and dwindling energy resources (Chapter 1), it was proposed that there is an urgent need to explore viable climate-responsive design alternatives suitable to local conditions.

In Chapter 3, it was revealed that the local precedent of Swahili vernacular architecture showed a suitability of plan, form and fabric characteristics to the local climate. It was suggested that these passive design strategies showed potential for application in contemporary office buildings in the local warm humid region. To validate the suitability of these Swahili-inspired strategies further, the next step involved the evaluation of the effect of these strategies on the thermal performance of a typical office building and the resultant effect on the thermal comfort of occupants.

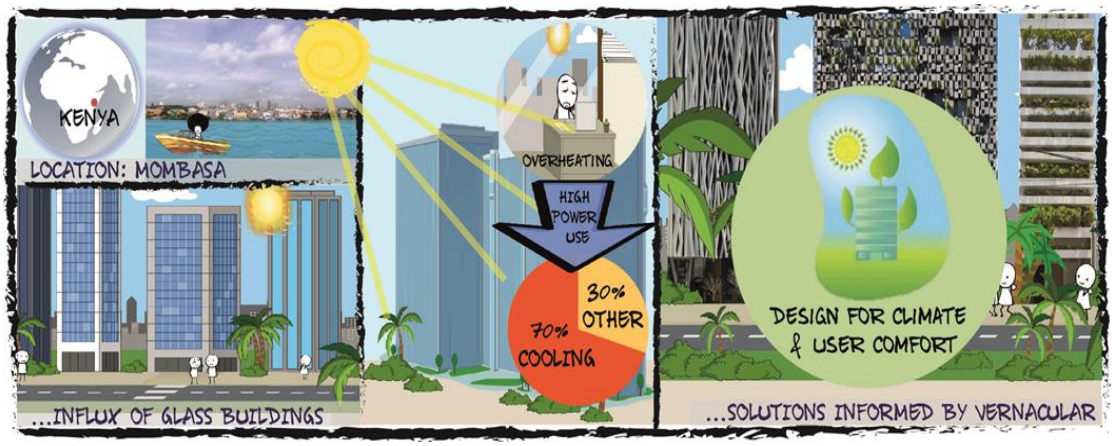


Figure 5-1 The local Kenyan context and a proposal for the way forward.

Following on-site monitoring and occupancy studies carried out and presented in Chapter 3 and Chapter 4, dynamic thermal computer simulations were undertaken to assist in drawing meaningful conclusions on the efficacy of the selected design strategies. In addition to validating what was revealed during the field study investigation, this process helped in quantifying what could not be accurately measured during the on-site monitoring.

5.1.1 The Simulation Software

Tas version 9.3.2, developed by EDSL (Environmental Design Solutions Limited), is a building thermal analysis software programme that is used to simulate the thermal performance of buildings. The main applications of the software include the assessment of environmental performance, natural ventilation analysis, energy consumption, plant sizing, among others (EDSL Tas, 2014b). To simulate the thermal performance of buildings, Tas adopts a fundamental approach of dynamic simulation. With this method, the thermal state of the building is traced through a series of hourly snapshots, providing the user with a detailed picture of how the building will perform across a typical year. Further, this approach allows for greater clarity in the modelling process as the user is able to account for the numerous thermal processes that occur in the building model (EDSL Tas, 2014a).

Tas software is split into three different modules: 3D modeller, building simulator and the results viewer. The 3D modeller is used for creating the building models for simulation in the building simulator module. In the building simulator module, the model is simulated by assessing conduction, convection, advection, long-wave radiation, solar radiation , casual gains and plants with radiative and convection portions (EDSL Tas, 2014a, Rodrigues, 2009). A series of equations combine all the aforementioned variables to solve for the sensible heat balance for each zone specified in the model. The Tas theory manual provides more details of the calculation procedures and validation (EDSL Tas, 2014a).

Tas assumes a steady state condition corresponding to an inside air temperature of 18°C in all zones and an outside air temperature obtained from the first hour of the weather data file used. Nonetheless, for every simulation, preconditioning is carried out to ensure that the effect of the initial steady state condition is negligible at the start of the period at which the user is interested in. Results from the simulation process are examined using the results viewer where a user-selected combination of parameters from any zone or surface can be displayed and compared. The results can also be exported from Tas to a third party programme such as Microsoft Excel for further user-defined analysis.

In addition to the three modules, Tas holds a regularly updated comprehensive database from which a variety of conditions can be stipulated for simulation purposes. For instance, common construction materials and glazing types can be allocated from the materials database before running the building simulator module. Further, occupancy types are represented by a calendar with the possibility of having different day types with varying schedules of use.

Although Tas was selected for its accuracy in thermal calculations, it is understood by the author that no mathematical estimate can truthfully predict or replicate real conditions that are influenced by changing climate conditions and varying occupant activities. In addition, as results are largely dependent on the data input, care was taken to select any assumptions. Before running the building simulator module, climate data for a selected location across the globe is input to reflect the local conditions thereby giving a more accurate representation of building performance on site. Tas holds a database for over 2500 locations worldwide. Each climate data file consists of a group of parameters relating to the weather site and hourly values of seven climate variables including global radiation, diffuse radiation, cloud cover, dry bulb temperature, relative humidity, wind speed and wind direction. For locations unavailable on the database, users may import data files in various formats from other credible sources.

5.1.2 Climate Data

All the simulation studies presented in this chapter, and later in Chapter 6 and Chapter 7, were confined to the use of climate data for the warm humid city of Mombasa located on latitude -4.03 and longitude +39.62 and at an altitude of 55m. The climate file used in Tas was sourced from the Energy Plus database (U.S Department of Energy, 2013) in .epw format for the weather data location of Mombasa (Moi International Airport 638200 – SWERA) .

Prior to the simulation process, a comparison was made between the real data measured on site (monitored during the field study period presented in Chapters 3 and 4), real data measured at the nearest weather station (for the period similar to the aforementioned field study period) and the climatic data sourced from the

Energy Plus database. Specifically, outdoor temperature data collected during the field study period (F) was compared to that sourced from the main local weather station – Moi International Airport (A) and also to the Energy Plus typical year hourly data set (E).

As this study is based on the adaptive comfort model discussed in Chapter 1, which is grounded on the idea that outdoor temperature is the main comfort parameter that determines the indoor thermal comfort of occupants, emphasis was placed on the outdoor temperature data set. Data sets for both 'F' and 'A' were compiled for the same period (1st to 31st March 2014) whereas, for 'E', a data set for the days numbered 60 to 90 (which correspond to the month of March) was used.

Results indicated that both 'A' and 'E' data sets tended to fluctuate in a similar manner and displayed a similar trend (see Figure 5-2). It was suggested that this similarity was due to the fact that, although 'A' was real data recorded on site whereas 'E' represented conditions of a typical year, both data sets were representative of data recorded at the same weather station – Moi International Airport. This being the case, it was considered valid for both data sets to show significant correlations due to similarities in location.

On the other hand, field data set 'F' varied from both 'A' and 'E' as it exhibited slightly higher minimum temperatures by up to 3°C difference (Table 5-1). It was suggested that this temperature difference could be attributed to the urban heat island effect. 'Urban heat island' is a term that refers to an urban area that is significantly warmer than the surrounding rural areas, and especially at night, due to human activities. This is attributed to several factors including: high building and user densities, use of heat retaining building and surface materials and also the removal of 'waste heat' from various human activities (Szokolay, 2008). A comparison of both climate data collection sites reveals that whereas the Moi International Airport weather station is located in an open and low building density site the field study site is located in the city centre, which has significantly higher building densities and even higher levels of human activity.

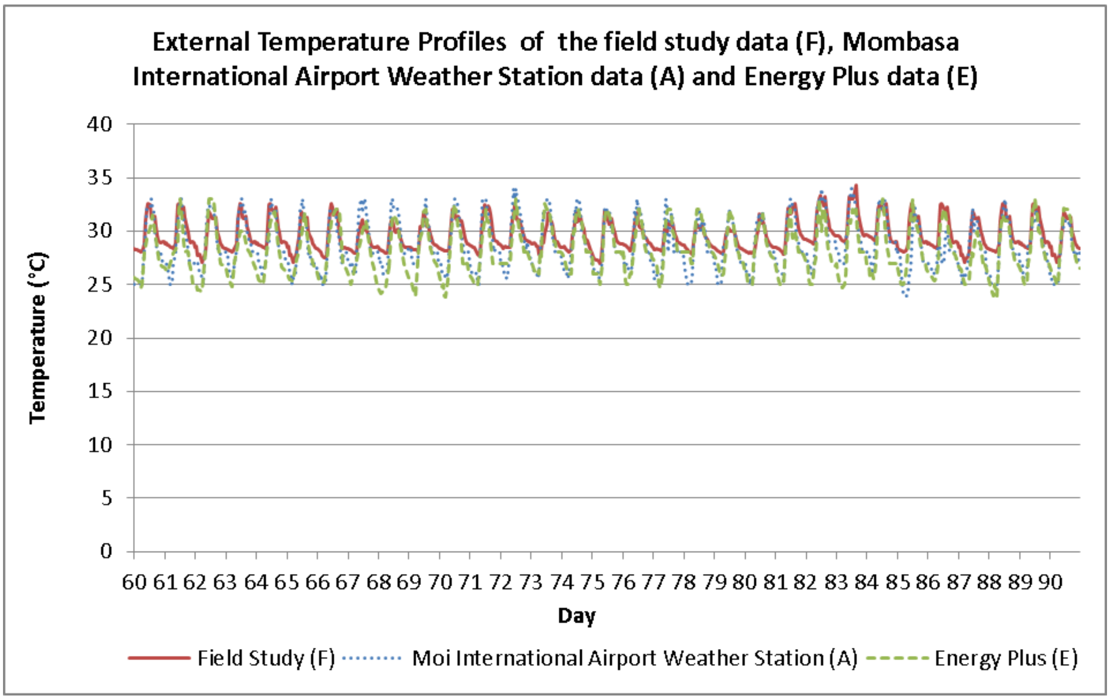


Figure 5-2 Comparison of field study data (F), main local weather station (A), and the Energy Plus climate data (E) for the month of March (Referred to as days 60 to 90 in Tas).

Table 5-1 Maximum, average and minimum temperature values in March for the various climate data sets

Temperature (°C)	Field study period data (F)	Closest weather station (A)	Energy Plus data (E)
Maximum	34.3	34.0	33.0
Average	29.6	28.7	28.1
Minimum	27.0	24.0	23.8

A review of the climatic data revealed that although the ‘E’ climate file was representative of a typical year, it might not be suitable for designing buildings systems that could meet worst-case scenarios occurring in a location. Previous climate analysis presented in Chapter 1 revealed that, in Mombasa, the worst-case scenario involves overheating during the warmer months of January to March. March was identified as the warmest month of the year in Mombasa and the period when buildings were most likely to overheat. Consequently, to allow simulation results to be as close as possible to reality, a new climate data set – ‘C’ was produced. In this file, the dry bulb temperatures of the calendar period (March - day 60 to day 90), of the Energy Plus climate data set (the main simulation weather data file used in Tas) were substituted with the real site data collected on site in March 2014.

In addition to this review, a brief analysis of future climate scenarios with respect to thermal performance and overheating was conducted for Mombasa using Meteonorm. The objective of this process was to review the potential implication of climate change on the performance of the previously studied vernacular and modern case study buildings and the proposed Swahili-inspired design strategies in the years 2030, 2050 and 2100. The projected high emissions scenario (A1B) outdoor temperatures of the aforementioned years were compared to those of the main energy plus climate data file (E). The climate change predictions indicated that outdoor temperature values would increase by a maximum of 1°C in the year 2030, 1.7°C in the year 2050 and 3°C in the year 2100 (Figure 5-3).

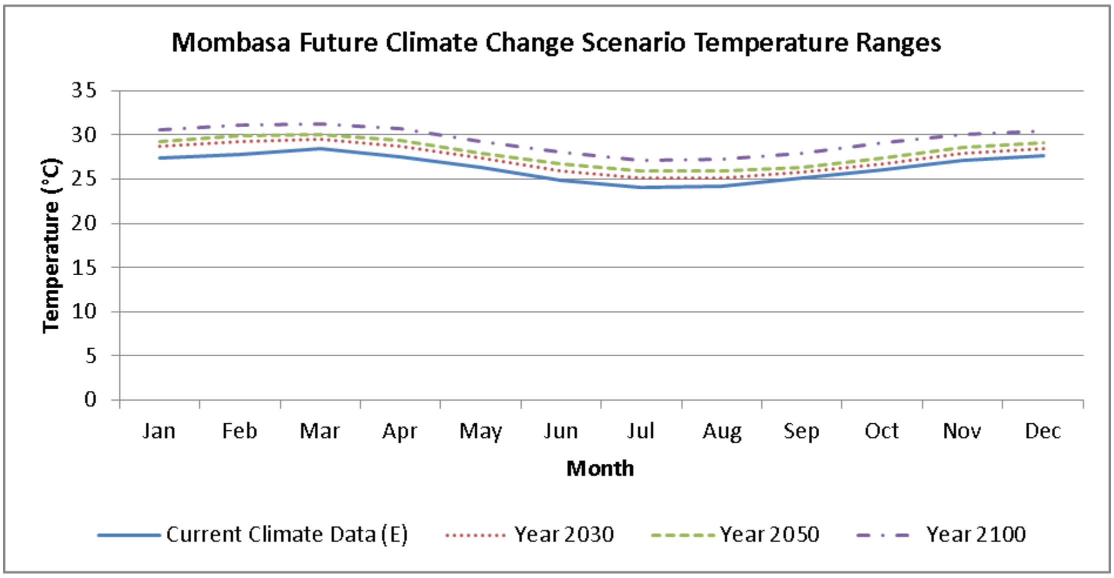


Figure 5-3 Mombasa future climate change scenario temperature ranges.

Further review of the outdoor temperature data indicated that even though the temperature was expected to rise by up to 3°C in the year 2100, the average outdoor temperatures would still remain below 31.5°C (the calculated adaptive comfort upper limit for Mombasa – refer to section 3.3.1). Given that this upper comfort limit was used in the analysis of thermal comfort performance of the Old Post Office building and Mombasa Uni Plaza in Chapters 3 and 4, respectively, then both buildings would be expected to perform in a similar manner (albeit with higher temperature minimums) under the examined future climate scenarios. This being the case, it was suggested that if the Swahili-inspired design strategies were applied to contemporary office buildings, they would provide appropriate climate change adaptation measures need to tackle increased overheating in naturally ventilated buildings and reduce the need for cooling energy in air conditioned buildings in Mombasa.

These findings also gave credence to the suitability of the new climate data file 'C' which integrated real site data. It was anticipated that by selecting a climate data file with significantly higher temperature minimums (incidentally up to 3°C higher than the typical year 'E' file, similar to the predicted future climate change scenario) then the building designing strategies derived from the proposed simulations would be deemed suitable in tackling overheating.

5.1.3 Construction Types

Previous analysis in Chapter 1 and Chapter 3 revealed that Swahili architecture appears to be predominantly heavyweight in nature. This is stark contrast to the typically lightweight local contemporary office buildings. Field studies covered in Chapter 3 and 4 revealed that the former tended to exhibit steadier indoor temperatures with lower peaks compared to the latter. This revelation augmented the need to examine the potential of the selected design strategies in improving building thermal performance.

As a starting point, the build-up of the construction types used in the simulation process was determined by a review of the construction types found to have been used in both the vernacular Swahili case study building (Old Post Office in Chapter 3) and in the modern case study building (Mombasa Uni Plaza in Chapter 4). By using similar construction types, it was anticipated that it would be more likely to match the thermal performance displayed by the selected buildings. More importantly, this would make it possible to illustrate the desirable effect of the potentially suitable design strategies highlighted in the vernacular study.

Next, a review of building materials in Kenya was undertaken to identify the most common materials used locally. Ready availability and cost of materials was found to play a significant role in what was more common place (K'Akumu, 2007). It was revealed that the construction types used in the Old Post Office building were common to vernacular Swahili buildings found in Mombasa (Mombasa Municipal Council and National Museums of Kenya, 1990). Similarly, the construction types used in Mombasa Uni Plaza were found to be common to those currently used in a significant number of office buildings in the local region (Institute of Quantity Surveyors of Kenya, 2014). The selection of the construction materials used in this study was largely based on materials that are locally appropriate *i.e.* materials which are readily available and widely accepted as suitable for local needs. Consequently, materials such as insulation which would understandably be useful in curbing heat gain (see section 2.1.2) but is not commonly used or widely accepted in Kenya - other than for ducting or sound proofing purposes (National Planning and Building Authority - Kenya, 2009) - were not covered in depth.

Further, in order to comply with local building standards, an in depth examination of the Kenyan National Building Regulations was undertaken to ensure that all construction type requirements for office type buildings were met. It is important to remember that whereas the overall research study is geared towards providing insights into solutions for local building practitioners, they would still be expected to comply with local building regulations.

Currently, no specific recommendations are outlined for the thermal properties of the specific building elements – instead, regulations are focused on structural properties. However, there is a requirement for designers to include 'an appropriate choice of construction materials and sun shading elements to mitigate heat gain' (National Planning and Building Authority - Kenya, 2009, NN31 Energy Efficiency and Thermal Comfort, Section NN31.2, part 'C'). The degree of heat gain control and what is an appropriate choice of construction materials are not stipulated.

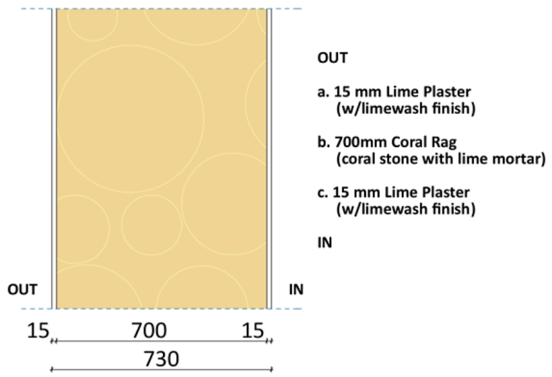
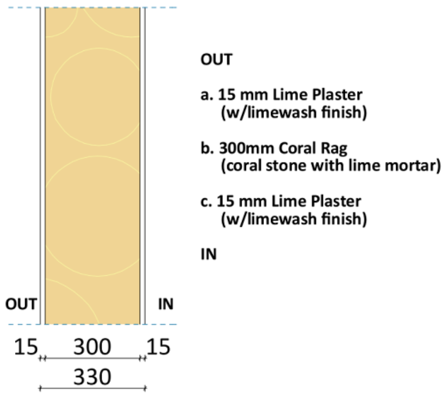
Based on the aforementioned reviews, the following is a breakdown of the main construction types adopted for the simulation processes covered in this study:

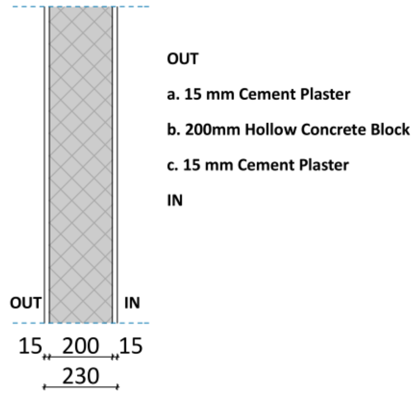
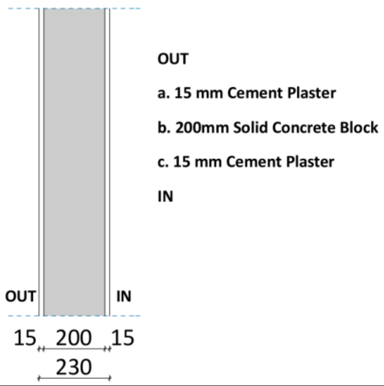
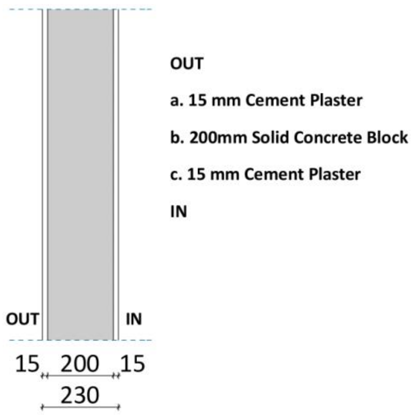
a) External and Internal Walls Construction Types (illustrated in Table 5-2):

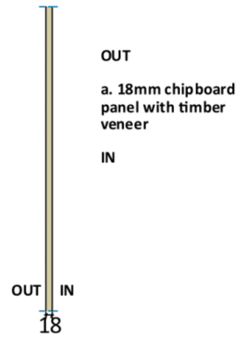
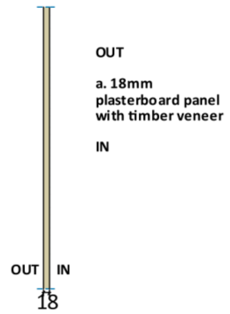
i) For simulations examining the performance of the vernacular typology, natural quarry stone (coral rag) was considered for internal walls of up to 530mm thick and for external walls of up to 730mm thick. The range of these wall thicknesses is similar to those found in the Old Post Office building (Chapter 3 and Kiamba et al. (2014)) and also those found in typical Swahili building types (Ghaidan, 1975, Mombasa Municipal Council and National Museums of Kenya, 1990). Typically, the coral rag is bonded with lime mortar that is then finished off externally and internally with lime plaster and lime wash – detail regarding the construction method is provided in Chapter 3.

ii) The main building frame of the typical contemporary office building consists of reinforced concrete columns and beams. Other than glazing, the main infill material consists of precast lightweight hollow concrete blocks or solid concrete blocks. This is quite similar to what is used in a significant number of buildings in Mombasa, where blocks are readily available in thicknesses of 100, 150 and 200mm (Institute of Quantity Surveyors of Kenya, 2014). Current statistics indicate that many developers are more likely to use similar sized buildings blocks for walling purposes (Institute of Quantity Surveyors of Kenya, 2014, Kenya National Bureau of Statistics, 2013). Indoors, office partitions range from combinations of aluminium frames with glass or chipboard infill to timber frames with timber board and glass infill. In this study, only internal walls made of chipboard and plasterboard, similar to what was mainly found on site, were considered.

Table 5-2 Properties of simulation wall types (author-generated).

<table>
<tr><th>Swahili Vernacular</th><th colspan="2">Properties</th></tr>
<tr><td rowspan="5">Coral rag wall (CRW730 - Heavyweight)
</td><td>Thickness (mm)</td><td>730</td></tr>
<tr><td>U-value (W/m^{2}K)</td><td>0.45</td></tr>
<tr><td>Admittance (W/m^{2}K)</td><td>4.01</td></tr>
<tr><td>Time lag (Decrement delay) [hours]</td><td>9.37</td></tr>
<tr><td>Decrement Factor</td><td>0.00</td></tr>
<tr><td rowspan="5">Coral rag wall (CRW330 - Medium weight)
</td><td>Thickness (mm)</td><td>330</td></tr>
<tr><td>U-value (W/m^{2}K)</td><td>0.93</td></tr>
<tr><td>Admittance (W/m^{2}K)</td><td>3.89</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>14.22</td></tr>
<tr><td>Decrement Factor</td><td>0.13</td></tr>
</table>

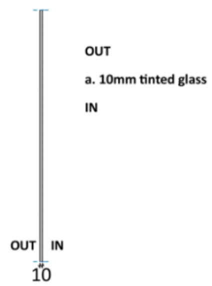
<table>
<tr><th>Contemporary</th><th colspan="2">Properties</th></tr>
<tr><td rowspan="5">Hollow concrete block wall (HCB230 – Lightweight)

</td><td>Thickness (mm)</td><td>230</td></tr>
<tr><td>U-value (W/m^{2}K)</td><td>1.95</td></tr>
<tr><td>Admittance (W/m^{2}K)</td><td>3.54</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>5.79</td></tr>
<tr><td>Decrement Factor</td><td>0.49</td></tr>
<tr><td rowspan="5">Solid concrete block wall (SCB230-01 – Lightweight concrete)

</td><td>Thickness (mm)</td><td>230</td></tr>
<tr><td>U-value (W/m^{2}K)</td><td>1.3</td></tr>
<tr><td>Admittance (W/m^{2}K)</td><td>3.55</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>8.06</td></tr>
<tr><td>Decrement Factor</td><td>0.41</td></tr>
<tr><td rowspan="5">Solid concrete block wall (SCB230-02 - Heavyweight concrete)

</td><td>Thickness (mm)</td><td>230</td></tr>
<tr><td>U-value (W/m^{2}K)</td><td>2.78</td></tr>
<tr><td>Admittance (W/m^{2}K)</td><td>4.98</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>6.59</td></tr>
<tr><td>Decrement Factor</td><td>0.42</td></tr>
</table>

Chipboard internal partition (IPCB18) 	Thickness (mm)	18
	U-value (W/m^{2}K)	2.62
	Admittance (W/m^{2}K)	2.67
	Time lag (Decrement delay)	0.57
	Decrement Factor	0.99
Plasterboard internal partition (IPPB18) 	Thickness (mm)	18
	U-value (W/m^{2}K)	3.29
	Admittance (W/m^{2}K)	3.30
	Time lag (Decrement delay)	0.33
	Decrement Factor	1

b) Glazing (illustrated in Table 5-3):

In Kenya, where extensive glazing or curtain walling is required, all glazing must conform to BS 13830 (Curtain walling - Product Standard) and BS EN 13119 (Curtain walling - Terminologies) and have a minimal glass thickness of 6mm (National Planning and Building Authority - Kenya, 2009, Section LL5 Architectural Glazing or Cladding). In this case, the modern case study building was found to have 10mm Suncool Classic 25/34 Bronze glazing, in an aluminium frame was adopted for all the simulations.

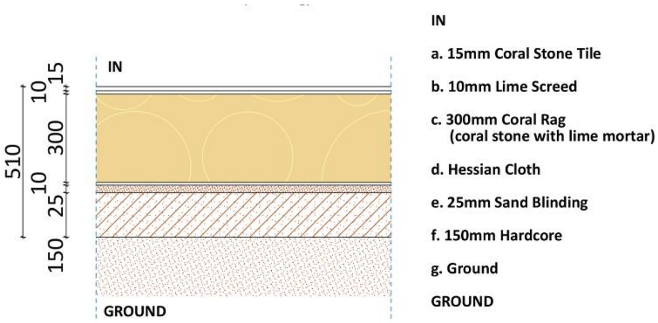
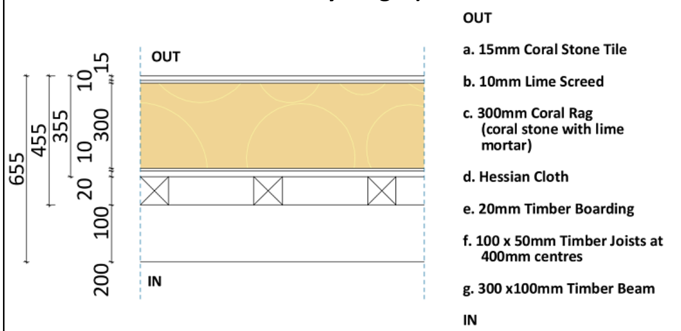
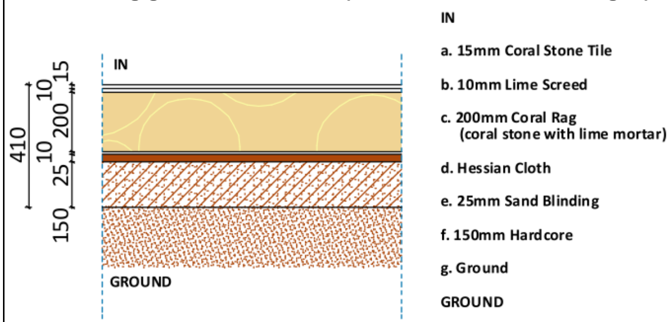
Table 5-3 Glazing construction properties (author-generated).

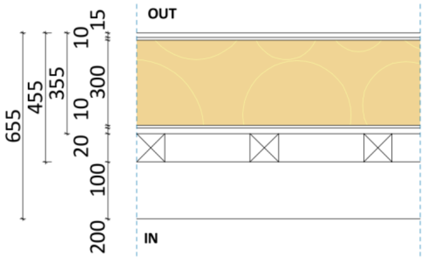
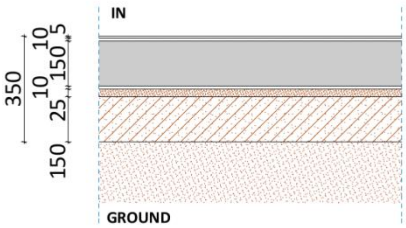
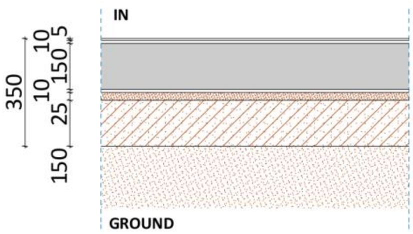
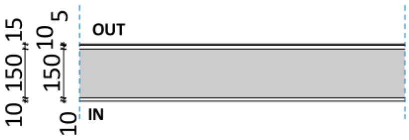
All simulations	**Properties**	
Glazing on aluminium/timber frame 	Thickness (mm)	10
	U-value (W/m^{2}K)	5.56
	Admittance (W/m^{2}K)	-
	Time lag (Decrement delay)	-
	Decrement Factor	-

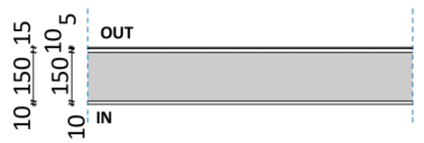
c) Floor slabs/ceilings:

Slab construction types were selected based on reviews of vernacular and modern case studies (Table 5-4). Additionally, for the contemporary simulation solutions, inference was made from local planning and building regulations as was deemed appropriate. Specifically, first floor/suspended floor slabs cannot be more that 175mm in thickness, if of solid construction (National Planning and Building Authority - Kenya, 2009, JJ5.2).

Table 5-4 Floor slab/ceiling construction properties (author-generated).

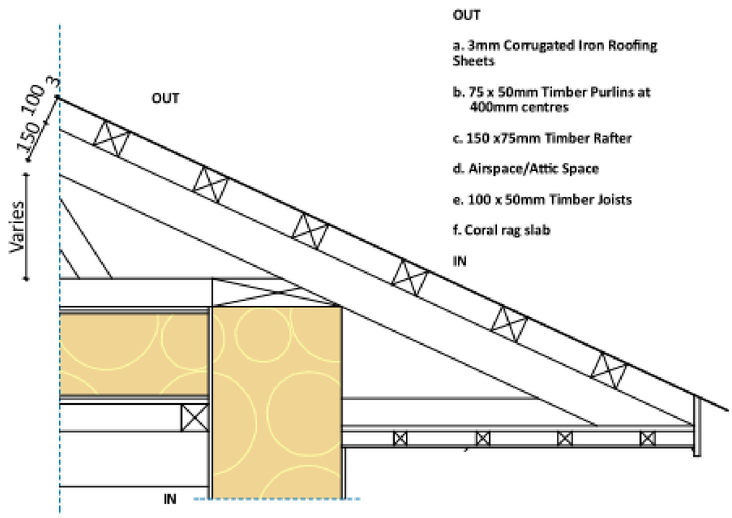
<table>
<tr><th>Swahili vernacular</th><th colspan="2">Properties</th></tr>
<tr><td rowspan="5">Coral rag ground floor slab (CRS350 – Heavyweight)

</td><td>Thickness (mm)</td><td>350(minus hard core)</td></tr>
<tr><td>U-value (W/m²K)</td><td>0.91</td></tr>
<tr><td>Admittance (W/m²K)</td><td>3.93</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>15.31</td></tr>
<tr><td>Decrement Factor</td><td>0.11</td></tr>
<tr><td rowspan="5">Coral rag suspended floor slab/ceiling (CRS345 – Heavyweight)

</td><td>Thickness (mm)</td><td>345(minus joists and beam)</td></tr>
<tr><td>U-value (W/m²K)</td><td>0.80</td></tr>
<tr><td>Admittance (W/m²K)</td><td>2.79</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>15.87</td></tr>
<tr><td>Decrement Factor</td><td>0.08</td></tr>
<tr><td rowspan="5">Coral rag ground floor slab (CRS5250 - Medium weight)

</td><td>Thickness (mm)</td><td>250(minus hard core)</td></tr>
<tr><td>U-value (W/m²K)</td><td>1.05</td></tr>
<tr><td>Admittance (W/m²K)</td><td>2.80</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>10.76</td></tr>
<tr><td>Decrement Factor</td><td>0.22</td></tr>
</table>

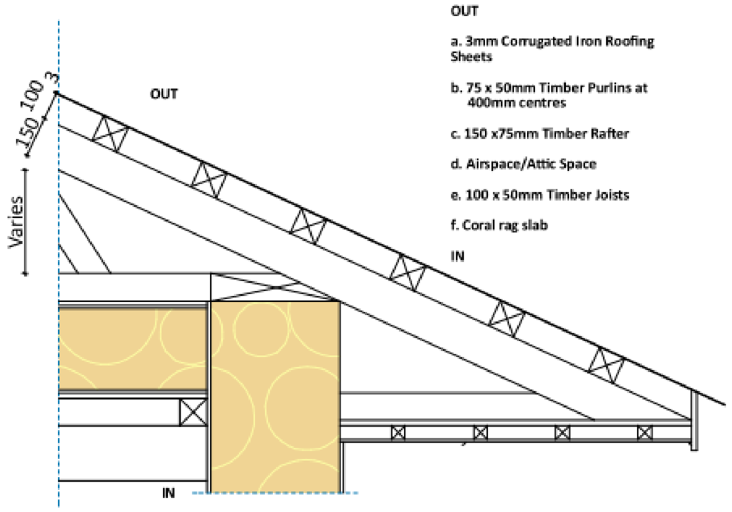
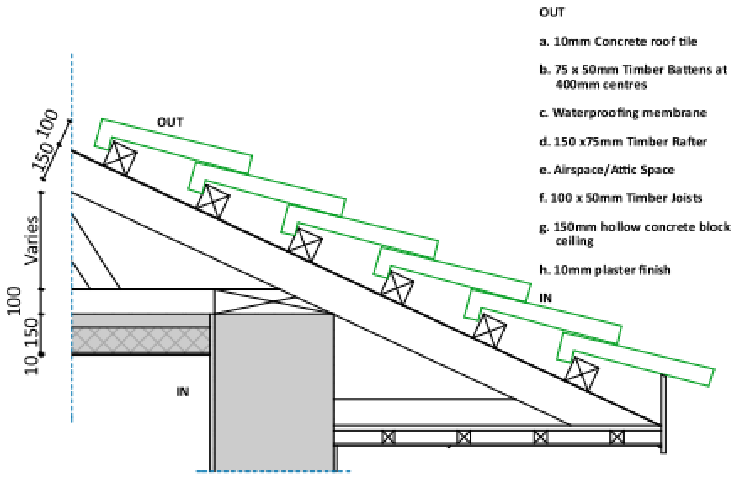
Coral rag suspended floor slab (CRS245 – Medium weight)  OUT a. 15mm Coral Stone Tile b. 10mm Lime Screed c. 300mm Coral Rag (coral stone with lime mortar) d. Hessian Cloth e. 20mm Timber Boarding f. 100 x 50mm Timber Joists at 400mm centres g. 300 x100mm Timber Beam IN	Thickness (mm)	245(minus joists and beam)
	U-value (W/m^{2}K)	1.04
	Admittance (W/m^{2}K)	2.80
	Time lag (Decrement delay)	11.08
	Decrement Factor	0.21
Contemporary	**Properties**	
Concrete ground floor slab (01GFS150– Lightweight)  IN a. 3.2mm Linoleum Tile b. 10mm Cement Screed c. 150mm Concrete Slab d. Damp Proof Membrane e. 25mm Sand Blinding f. 150mm Hardcore g. Ground GROUND	Thickness (mm)	188.2
	U-value (W/m^{2}K)	1.62
	Admittance (W/m^{2}K)	3.45
	Time lag (Decrement delay)	6.35
	Decrement Factor	0.58
Concrete ground floor slab (02GFS150 – Heavyweight)  IN a. 3.2mm Linoleum Tile b. 10mm Cement Screed c. 150mm Concrete Slab d. Damp Proof Membrane e. 25mm Sand Blinding f. 150mm Hardcore g. Ground GROUND	Thickness (mm)	188.2
	U-value (W/m^{2}K)	3.08
	Admittance (W/m^{2}K)	4.55
	Time lag (Decrement delay)	5.36
	Decrement Factor	0.57
Concrete suspended floor slab (01FS150 - Lightweight)  OUT a. 3.2mm Linoleum Tile b. 10mm Cement Screed c. 150mm Concrete d. 10mm Plaster finish IN	Thickness (mm)	173.5
	U-value (W/m^{2}K)	1.86
	Admittance (W/m^{2}K)	4.33
	Time lag (Decrement delay)	5.75
	Decrement Factor	0.56

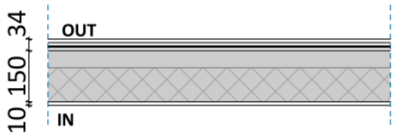
Concrete suspended floor slab (02FS150 – Heavyweight)	Thickness (mm)	173.5
	U-value (W/m^{2}K)	3.01
	Admittance (W/m^{2}K)	4.40
	Time lag (Decrement delay)	4.96
	Decrement Factor	0.58

d) As with both wall and slab construction, a review of the roof construction was informed by types of constructions appraised in both case studies and also with reference to local planning and building regulations. General design u-values given in Table 5-5 were listed as informed by research done by Koenigsberger et al. (1973).

Table 5-5 Roofing construction properties (author-generated).

Contemporary Office Building Materials	Properties	Roof Cover	Roof + Attic + Ceiling
Corrugated iron sheet roofing with coral rag ceiling (heavyweight) 	Thickness (mm)	Varies	
	U-value (W/m^{2}K)	3.18	0.69
	Admittance (W/m^{2}K)	-	1.91
	Time lag (Decrement delay)	-	16.75
	Decrement Factor	-	0.05

<table>
<tr><td rowspan="5">Corrugated iron sheet roofing with coral rag ceiling (medium weight)

</td><td>Thickness (mm)</td><td colspan="2">Varies</td></tr>
<tr><td>U-value (W/m^2K)</td><td>3.18</td><td>0.72</td></tr>
<tr><td>Admittance (W/m^2K)</td><td>-</td><td>1.29</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>-</td><td>12.08</td></tr>
<tr><td>Decrement Factor</td><td>-</td><td>0.13</td></tr>
<tr><td rowspan="5">Concrete tiling roofing with hollow block ceiling (lightweight w/attic)

</td><td>Thickness (mm)</td><td colspan="2">Varies</td></tr>
<tr><td>U-value (W/m^2K)</td><td>1.70</td><td>1.31</td></tr>
<tr><td>Admittance (W/m^2K)</td><td>-</td><td>1.50</td></tr>
<tr><td>Time lag (Decrement delay)</td><td>-</td><td>4.03</td></tr>
<tr><td>Decrement Factor</td><td>-</td><td>0.69</td></tr>
</table>

Flat roof (Lightweight – Hollow Pot Slab)  **OUT** **a. 10mm Concrete Tile** **b. 10mm Cement Screed** **c. 4mm Butiminous felt** **d. 50mm Lightweight Concrete** **e. 100mm Hollow Blocks** **f. 10mm Plaster finish** **IN**	Thickness (mm)	184
	U-value (W/m^2K)	1.76
	Admittance (W/m^2K)	3.95
	Time lag (Decrement delay)	3.83
	Decrement Factor	0.69
Flat roof (Heavyweight)  **OUT** **a. 10mm Concrete Tile** **b. 10mm Cement Screed** **c. 4mm Butiminous felt** **d. 50mm Concrete** **e. 10mm Plaster finish** **IN**	Thickness (mm)	184
	U-value (W/m^2K)	2.77
	Admittance (W/m^2K)	4.10
	Time lag (Decrement delay)	5.31
	Decrement Factor	0.55

5.1.4 Simulation Scope, Method and Assumptions

The simulation study covered in this chapter is divided into two phases (Phase 1 and Phase 2).

Phase 1 examines the effect of thermal mass and natural ventilation strategies on the indoor temperatures and the subsequent impact on indoor thermal comfort of occupants. Using the Tas 3D modeler, a “shoe box” model was built for the initial analyses (Figure 5-4). The use of a simplified generic model facilitated the changing of individual parameters in each simulation so that the correlation between the input and the output would be as conclusive as possible. Dimensions of the model were set at 6m by 6m by 6m, with a pitched roof height of 7.5m (Figure 5-4). Three thermal zones were outlined: the ground floor covering the volume up to 3m height, the first floor covering the volume up to 6m height and the attic enclosed under the remaining 1.5m height.

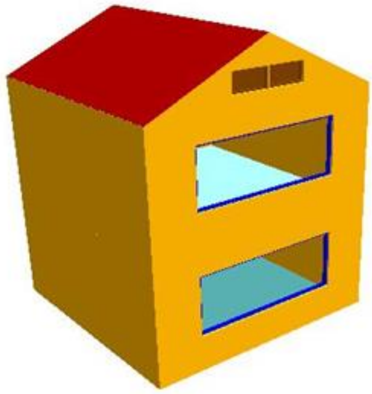


Figure 5-4 Simplified generic model/Base Case model Tas 3D image.

The geometry and spatial dimensions of the model were defined based on a review of typical office buildings and their plot sizes and the recommended room and grid sizes outlined by the local building regulatory authority (City Council of Nairobi, 2004, p.3, National Planning and Building Authority - Kenya, 2009, BB 99.2).

As a rule of thumb, floor areas for typical low to mid rise office buildings in Kenya tend to range between 650-800m². On one part, this is due to the need to enhance financial viability - developers tend to buy and build on plot areas of 0.1Ha (1000m²) or more. Mainly, these typical areas may be attributed to local regulation requirements. The minimum allowable plot area for office buildings in the city centre - set at 0.05Ha (500m²) with ground coverage (GC) of up to 80% and a corresponding plot ratio (PR) of up to 600%. Outside of the city centre, GC can fall to 60% with a PR of 350% or less if located closer to a residential neighbourhood (City Council of Nairobi, 2004, p.3).

Guided by the minimum spatial requirement of 7m² for any habitable room and the minimum width requirement of 2.1m (National Planning and Building Authority - Kenya, 2009, BB 99.2), grids of 6m by 6m or 6m by 5m are found to be commonplace to not only maximize GC for financial gain but also to allow for suitable subdivision indoors. This was the case in the contemporary office case study building which was found to have a typical grid of 6m by 6m. Based on this review, a grid of 6 by 6 was adopted for all the simulation models.

A ceiling height of 3m was adopted for all the simulation models. Under local regulations, a minimum ceiling height for habitable spaces, including offices is set to 2.4m over a minimum of 70% of the total floor area of the selected space, with not less than 2.1m over the remaining floor area (National Planning and Building Authority - Kenya, 2009, BB 101 Room Height). That considered it was established that most office spaces tend to be up to 3m high to accommodate service fittings.

The glazing area of the model was restricted to the North and South facades with $6m^2$ allocated to each facade. This was informed by climate analysis recommendations, ventilation and daylighting requirements and ventilation rates based on national building regulation minimums (National Planning and Building Authority - Kenya, 2009). Local regulation requirements stipulate that every room used for habitation should be provided with natural lighting and ventilation by means of one or more windows such that the aggregate superficial area of glass in the window/s is not less than one tenth of the area of the floor of the room. Additionally, the aforementioned window/s should be to the extent of a minimum of one sixteenth of the area of the floor of the room be opened (National Planning and Building Authority - Kenya, 2009, BB94.1 and BB94.2).

The roof pitch was set at a minimum of 22.5°, conforming to the local planning and building regulations (National Planning and Building Authority - Kenya, 2009, Section KK4 Waterproofing) for the most common local roofing materials including corrugated iron sheets (CIS) and concrete or clay tiles.

Outside of the building geometrical characteristics, many input parameters in dynamic simulations represent quantities that are difficult or impossible to measure accurately so estimates and assumptions should be used. As these have a large influence on the results, these initial simulations were kept as simple as possible.

General assumptions for the Phase 1 Base Case model (Case 1) are shown in Table 5-6. Variations to the construction type properties of the Base Case model were made to generate Case 2 and 3 as is outlined below and in Table 5-7.

a) Case 1: Base Case ‘heavyweight’ Swahili inspired levels of thermal mass

b) Case 2: ‘medium weight’ Swahili inspired levels of thermal mass

c) Case 3: Typical ‘lightweight’ contemporary office building levels of thermal mass

All other conditions remained the same.

Table 5-6 General assumptions for Base Case model (Case 1) – PHASE 1

Fixed Parameters	
Weather data	Calibrated EnergyPlus for Mombasa, Mombasa-Moi 638200 (SWERA), was used. Location: Latitude -4.03, Longitude: +39.62, Altitude: 55m
Calendar	Simulations were run for a typical year (8760 hour annual simulation).
Occupancy times	No occupancy was considered in Phase 1.
Comfort temperature range	Adaptive comfort limits were derived as a function of outdoor temperature (Nicol and Humphreys, 2002) giving a comfort range of 27.5 to 31.5°C for free-running buildings (Chapter 1).
Ventilation	5 air changes per hour [ach] - based on the regulatory requirements of the National Planning and Building Authority - Kenya (2009, NN10.9)
Infiltration	1 air change per hour (ach); this is an empirical value and is used to simplify the analysis.
Internal Gains	No internal gains were considered in Phase 1.
Glazing and frame types	10mm Suncool Classic 25/34 Bronze glazing, (U-value: 5.56W/m^2°C) in timber frame (A glazing area of 60% of each facade was maintained for all simulations).
Shading	None. No shading is considered in Phase 1.
Varied Parameters	
Base case construction	**Typical heavyweight Swahili building thermal mass** (these parameters were varied for Case 2 and 3 as indicated in Table 5-7).
Ground floor slab	350mm coral rag (Admittance, all based on 24 hour cycles: 3.93W/m^2K)
Suspended floor slab	345mm coral rag (Admittance: 2.79 W/m^2K)
External walls	730mm coral rag (Admittance: 4.01 W/m^2K)
Roof with attic/ceiling	Corrugated iron sheet roofing with coral rag ceiling (Admittance: 1.91 W/m^2K)

Table 5-7 Variations to Base Case model – PHASE 1

Typology	Case 2	Case 3
	'Medium weight' Swahili thermal mass	**Typical 'lightweight' building thermal mass**
Ground Floor Slab	250 mm coral rag (Admittance: 2.80 W/m^2K)	188.2mm lightweight reinforced concrete slab (Admittance: 3.45 W/m^2K)
Suspended Floor Slab	245mm (Admittance: 2.80 W/m^2K)	173.5mm (Admittance: 4.33 W/m^2K)
External Walls	330mm coral rag (Admittance: 3.89 W/m^2K)	230mm lightweight concrete hollow block wall (Admittance: 3.55 W/m^2K)
Roof with ceiling	Corrugated iron sheet roofing with coral rag ceiling (Admittance: 1.29 W/m^2K)	Corrugated iron sheet roofing with lightweight concrete hollow block ceiling (Admittance: 3.95 W/m^2K)

Building on the results of the Phase 1 simulations, the second stage of the study - Phase 2 - examined the impact of thermal mass, natural ventilation and shading on the thermal performance of a typical office building and the subsequent effect on the thermal comfort of occupants. Using a simplified model of the selected building (Mombasa Uni Plaza - Chapter 4) shown in Figure 5-5, dynamic simulations were conducted using Tas and the results analysed and presented.

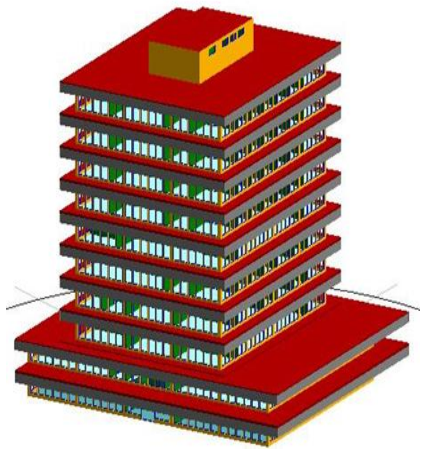


Figure 5-5 Base case Tas 3D model based on Mombasa Uni Plaza.

As real data was collected from Mombasa Uni Plaza (Chapter 4), the approach taken in these simulations was to first and foremost get as close as possible to what happened in reality and then to simulate the building for the selected design strategies. Accordingly, the Tas model was built as close as possible to reality (inclusive of shading) and the model calibrated for further simulations (Section 5.3).

The general assumptions for the Phase 2 Base Case model (existing lightweight building) and a variant – Case 'A' (heavyweight thermal mass) are presented in Table 5-8.

Table 5-8 General assumptions for Base Case model – PHASE 2

Fixed Parameters		
Weather data	Calibrated EnergyPlus for Mombasa, Mombasa-Moi 638200 (SWERA), was used. Location: Latitude -4.03, Longitude: +39.62, Altitude: 55m	
Calendar	Simulations were run for a typical year.	
Occupancy times	In Phase 2, occupancy periods are restricted to 0800 to 1800hrs on weekdays only (working hours). Occupation densities of $16m^2$ per person were considered (based on a single occupancy office size and CIBSE (2015, p.6-2)).	
Comfort temperature range	Adaptive comfort limits were derived as a function of outdoor temperature (Nicol and Humphreys, 2002) giving a comfort range of 27.5 to 31.5°C for free-running buildings (Chapter 1).	
Ventilation	5 air changes per hour [ach] - based on the regulatory requirements of the National Planning and Building Authority - Kenya (2009, NN10.9)	
Infiltration	1 air change per hour (ach); this is an empirical value and is used to simplify the analysis.	
Internal Gains	$29W/m^2$ – Occupancy, lighting and equipment gains (based on benchmark values for internal heat gains for offices with occupation densities of $16m^2$ per person derived from CIBSE (2015, p.6-2)).	
Model	Base Case - ('Lightweight' office building thermal mass – Mombasa Uni Plaza)	Case 'A ' - ('Heavyweight' thermal mass – using modern construction types)
Floor/ Ceiling	150mm Lightweight reinforced concrete (RC) slab (Admittance: $4.33W/m^2K$)	150mm Dense RC slab (Admittance: $4.40W/m^2K$)
Roof	Concrete Tiles with lightweight concrete slab (with attic ventilation) (Admittance: $3.95W/m^2K$)	Concrete Tiles with dense RC slab (with attic ventilation) (Admittance: $4.10W/m^2K$)
Walls	External: 200mm Lightweight concrete (Admittance: $3.54W/m^2K$) Internal: Chipboard on studs (Admittance: $2.67W/m^2K$)	External: 200mm Heavyweight RC (Admittance: $4.98W/m^2K$) Internal: Plasterboard on studs (Admittance: $3.30W/m^2K$)
Glazing and frame types	10mm Suncool Classic 25/34 Bronze glazing, in aluminium frame. Glazing area restricted to 60% of facade area.	10mm Suncool Classic 25/34 Bronze glazing, in aluminium frame. Glazing area restricted to 60% of facade area.
Shading	1200mm canopy (as per existing)	1200mm canopy

As the study is focused on naturally ventilated buildings, no mechanical cooling or heating was modelled at this stage. For both Phase 1 and 2, only natural ventilation strategies were considered to achieve the aforementioned ventilation rate of 5ach. For day time ventilation (DTV), the window schedule was set up so that the apertures would open during occupancy hours, from 0800 to 1800hrs. Where night ventilation (NTV) was introduced, the windows would also open from 1800 to 0800hrs. In both cases, windows would close if the outdoor temperature exceeded indoor temperature.

Roof vents were left permanently open to facilitate adequate ventilation as is recommended by the National Planning and Building Authority - Kenya (2009, NN 29 Ventilation in Roof Spaces). It has been explained that for regions close to the equator, high levels of solar heat gain at the zenith can significantly raise indoor temperature and also that the provision and ventilation of attic spaces can significantly improve indoor conditions (Chapter 1, 2 and 3).

5.2 Phase 1 Results: Simplified Model

The results indicated that the thermal performance of the model worsened upon a reduction in building thermal mass. This poor performance was distinguished by significantly higher indoor temperatures and an increase in the number of discomfort hours (periods when the indoor temperature exceeded the adaptive thermal comfort maximum of 31.5°C during occupancy hours - 0800 to 1800hrs).

To illustrate the effect of thermal mass, the indoor dry bulb temperature profiles were plotted for the warmest week in March (Figure 5-6 and Figure 5-7). Additionally, the effect of the selected ventilation strategy (DTV only or DTV and NTV) on the thermal performance was also revealed. It is noted that, although the local climate is fairly constant all year round, March was selected for illustrative purposes as it is the warmest month of the year and the most prone to overheating.

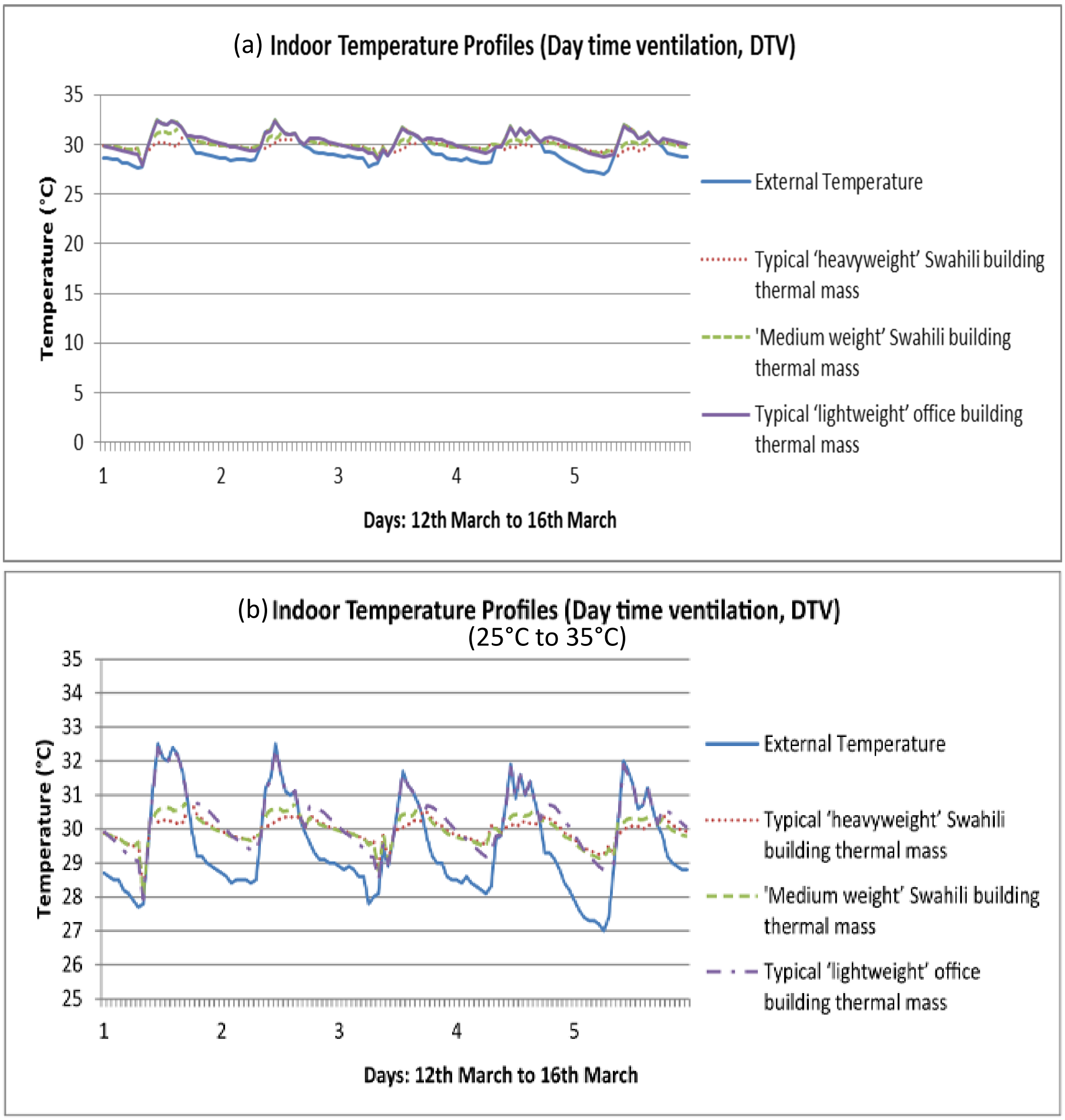


Figure 5-6 (a) Representation of indoor temperature profiles (ground floor zone) for the warmest week, with day time ventilation (DTV). (b) A truncated graph gave a clearer indication of the same.

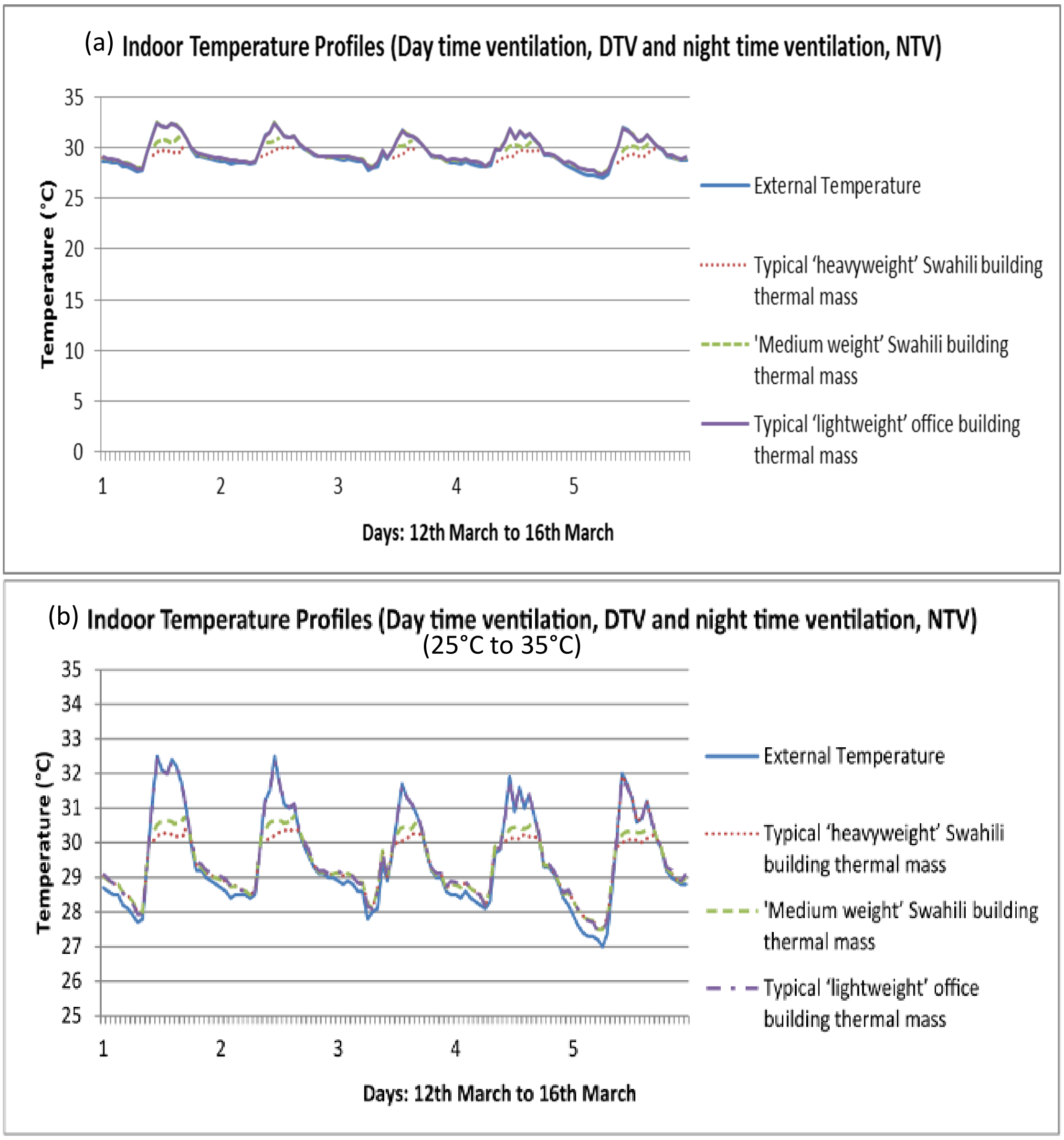


Figure 5-7 (a) Representation of indoor temperature profiles (ground floor zone) for the warmest week, with daytime (DTV) and night time ventilation (NTV). (b) A truncated graph gave a clearer indication of the same.

It was revealed that, the main benefit of thermal mass in the typical heavyweight Swahili building (Case 1) was that the variation in indoor temperatures was smaller and also nearer to the average external temperature. Additionally, in comparison to options with less thermal mass, indoor temperatures would be up to 2°C lower in the heavyweight option during peak outdoor temperature periods. Further, when day time ventilation (DTV) was run, indoor temperatures would generally remain lower than those outdoors during occupancy hours. In this instance we see that the thermal storage capabilities of the heavyweight option facilitate the steady absorbance of heat at the surface, conducting it inwardly and storing it until exposed to the cooler air of the evening/night.

Similarly, although it performed poorer than the heavyweight option, the medium weight thermal mass option (Case 2) also exhibited significantly little variation in indoor temperatures. Correspondingly, during out door peaks, indoor temperatures were up to 1.5°C lower. In addition, when DTV was run, indoor temperatures remained lower than those outdoors during occupancy hours.

In comparison, results for the typical lightweight model (Case 3) indicated that the internal temperature fluctuations and peaks tended to be similar to those outdoors. Unlike the two previous cases, when DTV was run for Case 3, indoor temperatures did not fall significantly lower than those outdoors. However, it was noted that during unoccupied hours, indoor temperatures did tend to respond faster to a reduction in outdoor temperatures leading to a reduction of up to 0.5°C during this period. This performance is explained by the properties of the lightweight option. Due to a lack of adequate thermal storage mass, the resulting heat gain led to overheating during the day. At night, the quick response enabled larger heat loss than other options.

For all the cases, it was noted that the introduction of night time ventilation (NTV) resulted in a reduction of indoor temperatures of up to 2°C (Figure 5-7). Additionally, following the introduction of NTV, indoor temperatures for all cases were very similar and tended to fluctuate in a similar manner to those outdoors outside of occupancy periods. Here we see that night ventilation can be used to modify the mass effect, where the day's average is higher than the comfort limit, to assist the heat dissipation process.

Further, a comparison of the thermal performance (maximum, minimum and average) of the various zones in each individual case (Case 1, 2 and 3) revealed that the ground floor zone performed better than the first floor and roof zone (Figure 5-8 and Figure 5-9). The study location – Mombasa – is located near the equator (4°S) where the sun's path is near to the zenith, so the roof receives very strong solar irradiation. In this case, it is suggested that the two upper zones insulate the lower zones from the effect of this solar gain thereby allowing for lower indoor temperatures in that zone.

The roof zone indoor temperatures were found to remain relatively similar to the outdoor temperatures. This may be attributed to a number of factors including the relatively high exposure to solar heat gain and the relatively low insulation property of the corrugated iron sheet (CIS) roofing used in all cases. Nonetheless, it was determined that this performance could have been worse had it not been for the permanent all-day ventilation (ADV) in the attic space. The ventilation strategy facilitated the 'flushing out' of the accumulated heat gain thereby reducing the zone temperatures. Indeed, separate simulations run without any ventilation to the roof zone indicated a significant temperature increase of up to 42%.

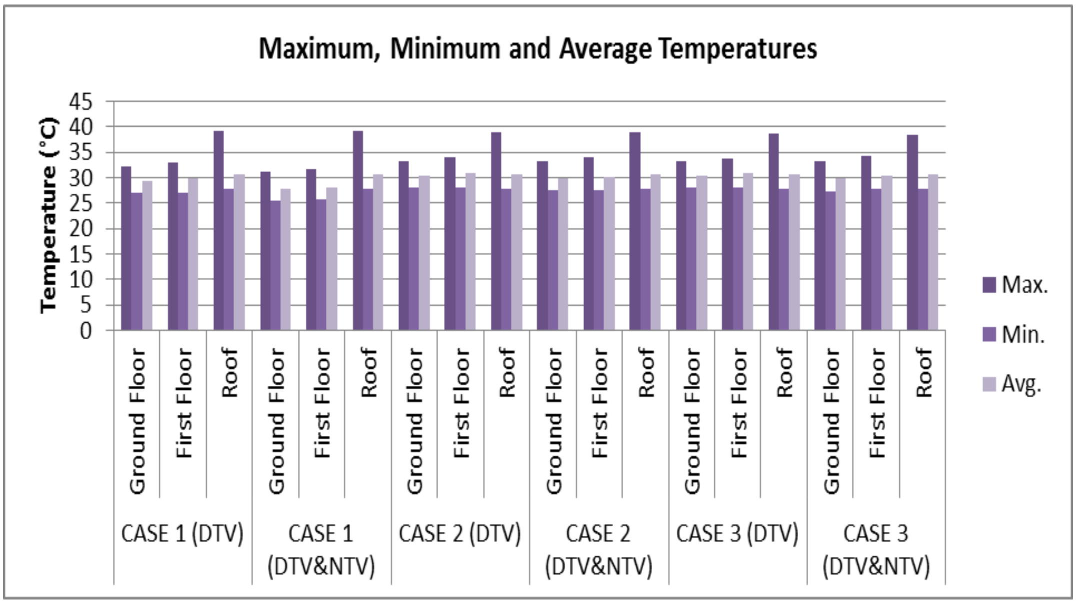


Figure 5-8 Comparison of maximum, minimum and average temperatures for all zones in each case.

An evaluation of the percentage time outside comfort during the occupancy period of all the three cases indicated that the heavyweight option performed better than both the medium weight and lightweight options. Of all the three types, the lightweight option performed most poorly (Figure 5-9). A review of comfort conditions in each case during the warmest month of March found that the percentage of hours outside comfort in the ground floor zone ranged from 15% to 19%. This percentage increased to 18% to 22% for the first floor zone and expectedly rose to 45% to 48% in the roof zone. In comparison, it was found that lightweight (Case 3) performed worse than heavyweight (Case 1) by up to approximately 3% and slightly less than that for medium weight (Case 2). This percentage fell to approximately 2% when annual comfort values were analysed.

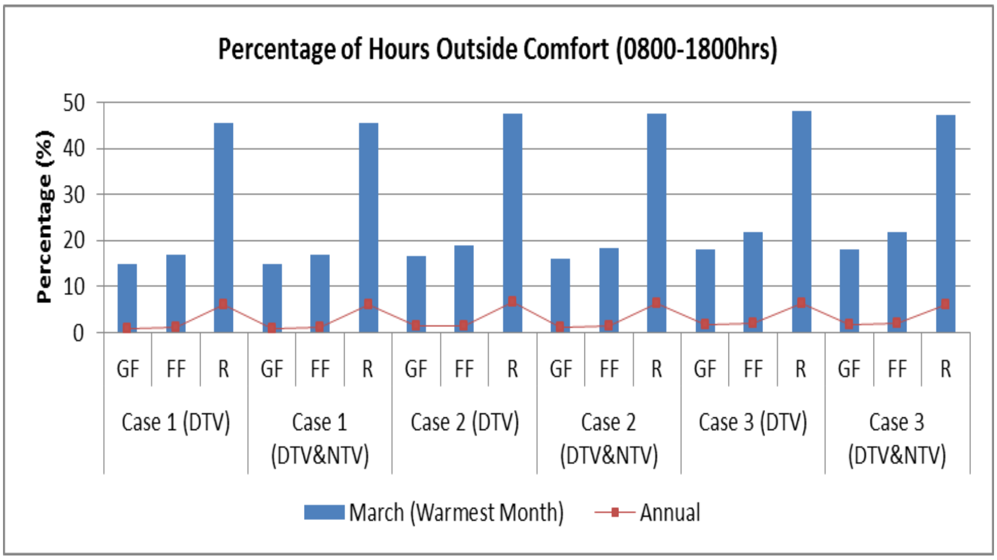


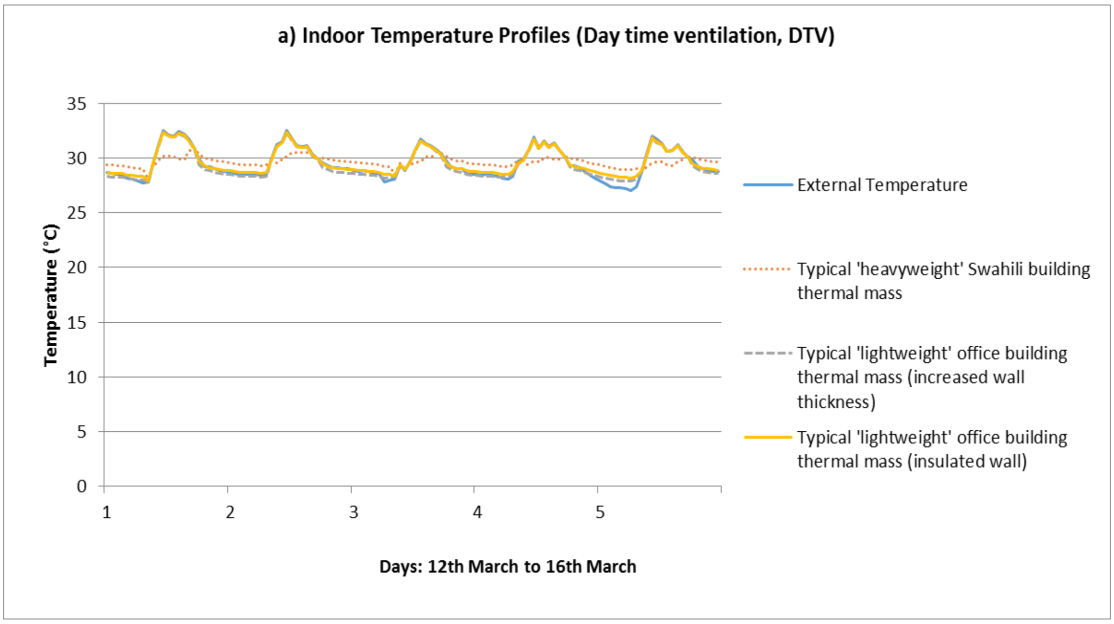
Figure 5-9 Percentage of hours outside comfort (above 31.5°C) for the ground floor (GF), first floor (FF) and roof (R) for all the cases.

Following a review of these results, further simulation analysis was conducted to establish whether the good performance of the heavyweight option could be largely attributed to the thermal mass properties of the selected construction rather than solely those of its low u-values (refer to section 5.1.3 and 5.1.4 for material properties and modelling assumptions). It is noted that whereas the heavyweight fabric option did have higher admittance values than the lightweight option (up to 4.01W/m^{2}K for heavyweight walls compared to 3.5 W/m^{2}K for lightweight walls), it also had a significantly lower u-values (up to 0.45 W/m^{2}K for heavyweight walls compared to 1.95W/m^{2}K for lightweight walls).

To obtain similar theoretical u-values to the heavyweight option, the properties of the lightweight option were adjusted in two ways - by increasing the thickness of the building fabric (Case 3 – thick walls) and by applying insulation on the external surfaces (Case 3 – insulated walls). In addition to this, the properties of the floor/ceiling slabs were similarly adjusted to ensure that both heavyweight and lightweight options had a similar u-value (0.8 W/m^{2}K) and y-value (2 to 3 W/m^{2}K).

The properties of the roof remained similar to previous simulations in all cases (u-value of 3.18 W/m^{2}K).

As with the previous simulations, the results indicated that the heavyweight option performed significantly better that the two lightweight options (Figure 5-10 and Figure 5-11).



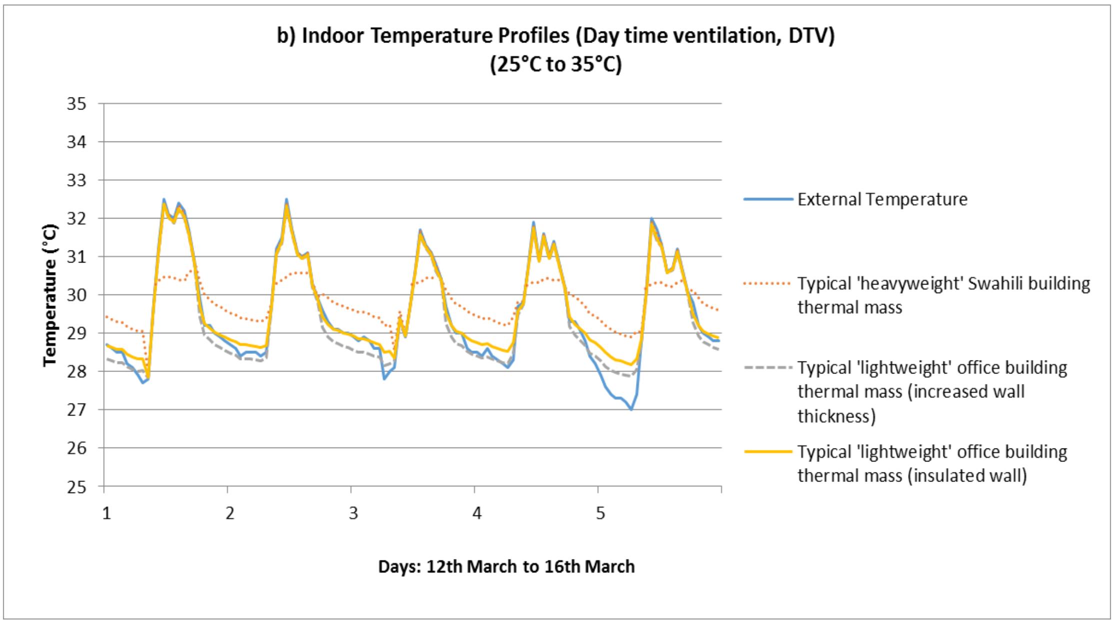


Figure 5-10 (a) Representation of indoor temperature profiles (ground floor zone) for the warmest week, with day time ventilation (DTV). (b) A truncated graph gave a clearer indication of the same.

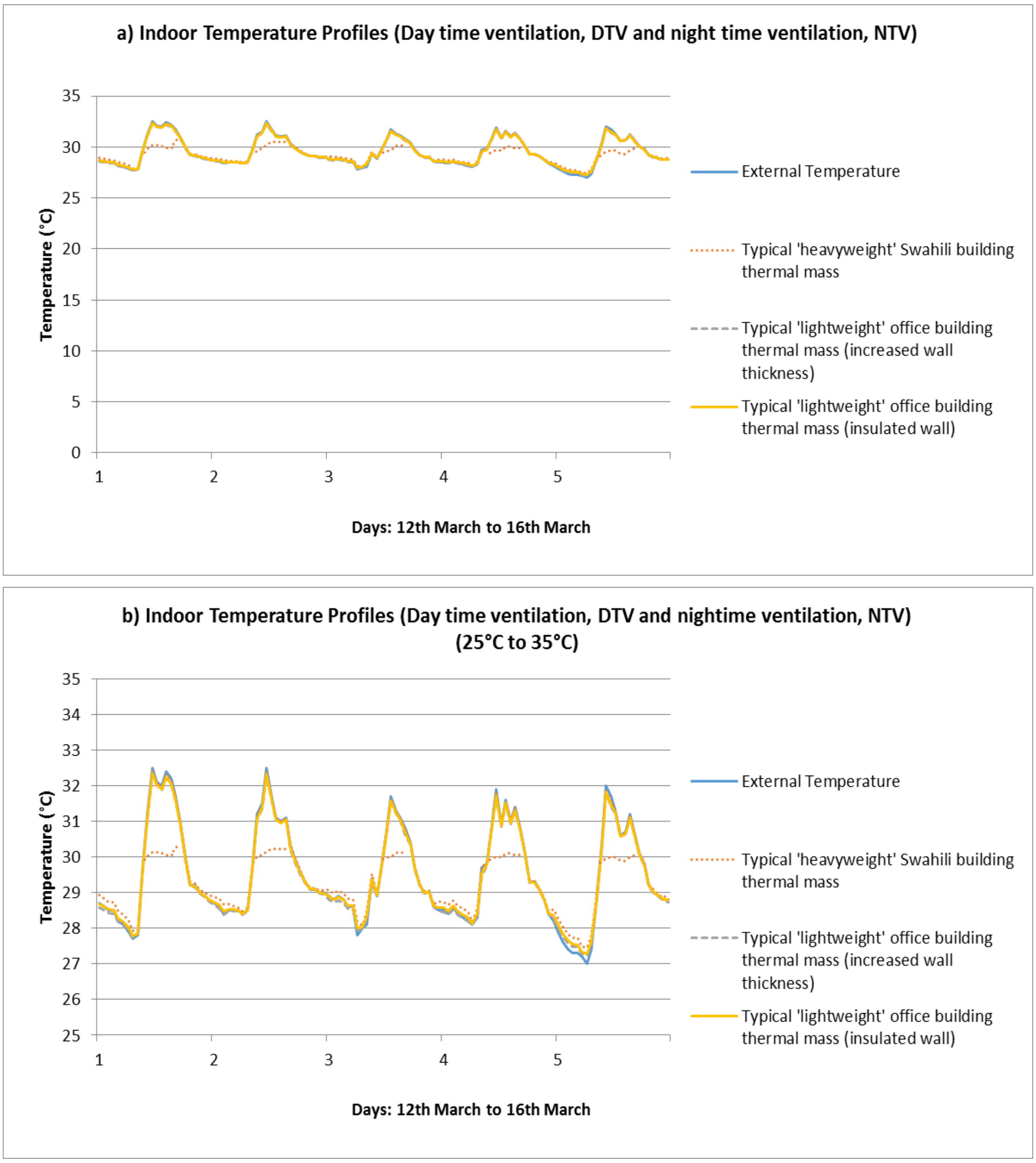


Figure 5-11 (a) Representation of indoor temperature profiles (ground floor zone) for the warmest week, with daytime (DTV) and night time ventilation (NTV). (b) A truncated graph gave a clearer indication of the same.

For the heavyweight option (Case 1), indoor temperatures were up to 1.5°C lower than peak outdoor temperatures when only day time ventilation was considered. This temperature difference increased to 2°C when night time ventilation was introduced. This confirms the previous finding that indicated that night ventilation can be used to modify the mass effect to assist the heat dissipation process. In comparison, internal temperature fluctuations and peaks in the lightweight model

(Case 3 – thick walls and insulated walls) indicated that the indoor conditions tended to be fairly similar to those outdoors.

Similarly, as with the previous comparison of the thermal performance (maximum, minimum and average temperatures) of the various zones in each individual case (refer to Figure 5-8), the ground floor zone was found to perform better than the first floor and roof zone in all the cases (Figure 5-12). From this, it was also derived that the heavyweight option showcased slightly lower maximum and average temperature values than the lightweight options. Interestingly, the lightweight insulated option was seen to have slightly higher maximum temperatures than the lightweight option with a thicker fabric (by up to 0.5°C higher in the ground and first floors and up to 1.5°C in the roof attic). This performance was attributed to the insulation reducing the ability of the building fabric to loose accumulated heat during cooler periods other than via flushing out of accumulated heat in the space.

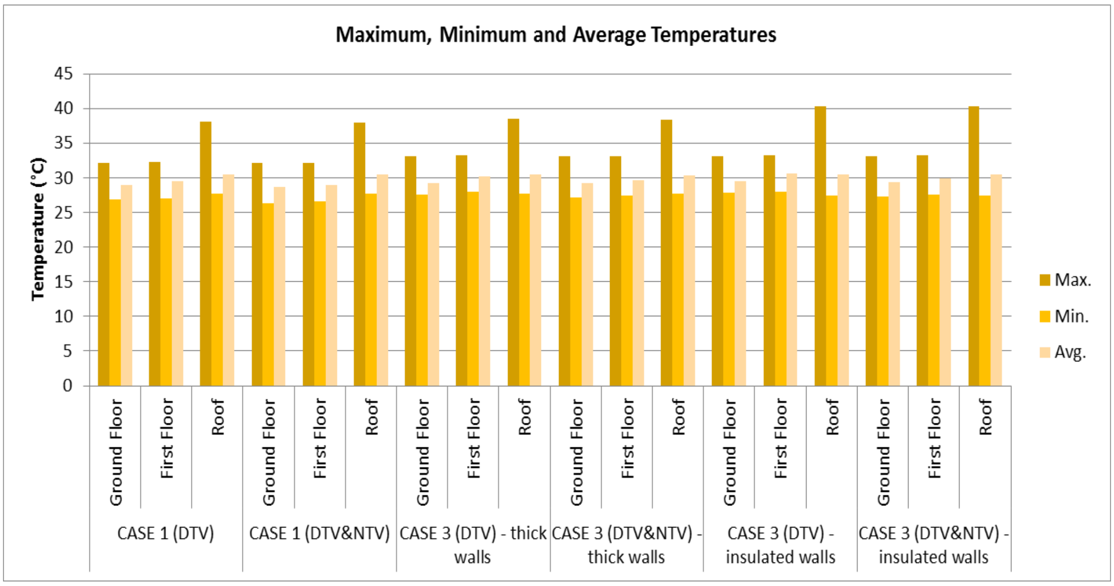


Figure 5-12 Comparison of maximum, minimum and average temperatures for all zones in case 1 and 3 (increased thickness and insulated walls).

An evaluation of the percentage time outside comfort during the occupancy period of all the three cases indicated that the heavyweight option performed better than both lightweight options (Figure 5-13). A review of comfort conditions in each case during the warmest month of March found that the percentage of hours outside comfort in the ground floor zone ranged from 11.8% (heavyweight) to 18%

(lightweight – thicker walls) and 18.9% (lightweight – insulated walls). This percentage increased to 13.2% (heavyweight) to 19.4% (lightweight – thicker walls) and 21.6% (lightweight – insulated walls) on the first floor zone and expectedly rose to 45% to 50% in the roof zone. Generally, Case 3 (lightweight - insulated walls) performed worse than heavyweight (Case 1) by up to 7.1% (ground floor), 8.4% (first floor) and 5% (roof attic). Case 3 (lightweight - insulated walls) also performed slightly worse than Case 3 (lightweight – thick walls) by up to 1% (ground floor), 2.2% (first floor) and 2% (roof attic). On the other hand, annual comfort hours were up to 2% fewer in the lightweight options compared to the heavyweight one.

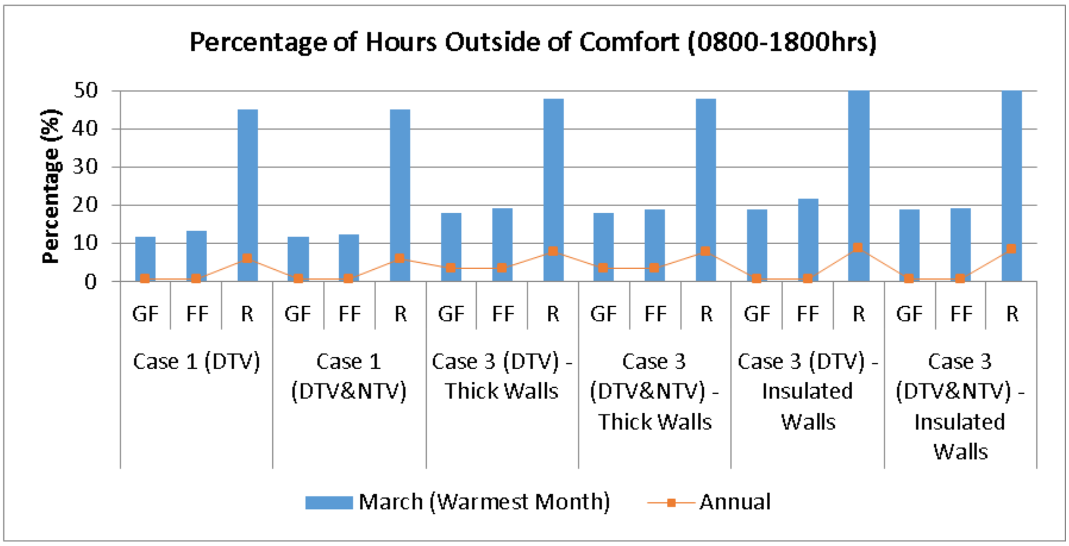


Figure 5-13 Percentage of hours outside comfort (above 31.5°C) for the ground floor (GF), first floor (FF) and roof (R) for all the cases.

Overall, it was determined that the thermal mass properties of the heavyweight option helped it perform better in the provision of lower indoor temperatures and more comfort hours than the lightweight options. Further, it was noted that whereas the provision of insulation might work to control conduction heat gain, there was the risk of causing slightly higher indoor temperatures/more discomfort hours, possibly due to the inability of the fabric to get rid of accumulated heat during the night time. Although the use of insulation was not examined in great detail for purposes of this study (a review of commonly used materials indicated that its use has not been established locally – section 5.1.3), it was suggested that further work that examined its role especially with respect to ventilation design strategies would be useful.

5.3 Phase 2: Typical Full Building Model Calibration and Results

Following the review of the thermal performance and thermal comfort implications of thermal mass and natural ventilation strategies on a generic building model, the next step involved the examination of the impact of similar strategies and shading to the thermal performance of a typical office building. A simplified model of the Mombasa Uni Plaza case study building was generated using Tas to carry out the next set of simulations (Figure 5-14). To reduce the modelling complexity and to closely exemplify the building, two floors – the third and eighth floor, both of which were examined in detail in Chapter 4 - formed the focus of the study (Figure 5-15).

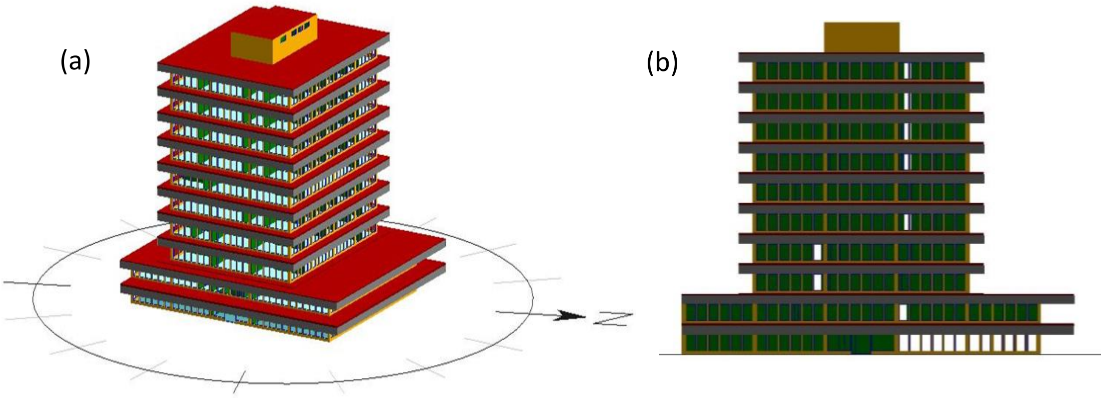


Figure 5-14 (a) Perspective and (b) front elevation view of the Base Case model as generated in Tas.

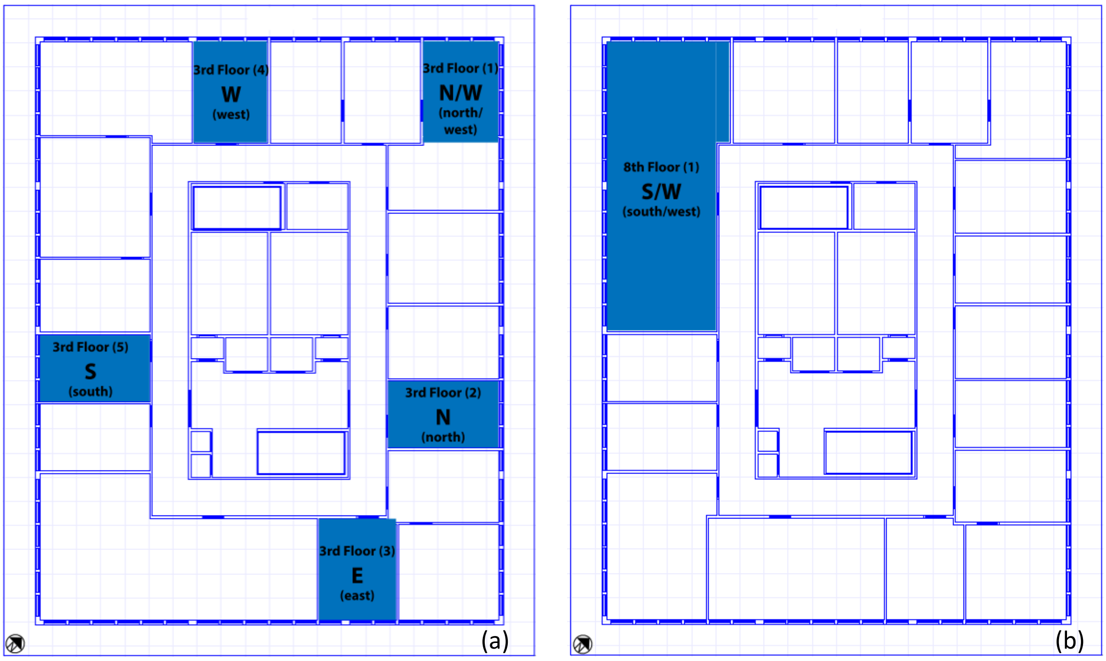


Figure 5-15 (a) Third Floor and (b) Eighth Floor plans showing the zones to be investigated.

5.3.1 Calibration of the Mombasa Uni Plaza model

Prior to carrying out simulations for phase two, a comparison of monitored data and predicted data was carried out to gauge the accuracy of the simplified model of Mombasa Uni Plaza. The aim of this process was to get as close as possible to what happened in reality and in so doing calibrate the model for further simulations covered in this chapter and the next. The methodology of this calibration involved the following steps (Clarke et al.):

i. use the simulation process to obtain model prediction and parameter sensitivities (initial simulation runs)
ii. capture a high quality data set on site (conducted during the field study process – Chapter 4)
iii. quantify any residuals and determine their cause
iv. implement modifications to model inputs to reduce any residuals to produce the calibrated model

To begin with, the Base Case model was built and a series of simulations run to generate results for comparison purposes. The general assumptions of the calibration model and the simulation matrix are presented in Table 5-9 and Table 5-10, respectively. Consequently, results from the simulations output were compared to results from fieldwork measurements for the indoor temperature profile (of selected zones) for the entire duration of the monitored period (March - days 63 to 84).

Table 5-9 General assumptions for Base Case model (Mombasa Uni Plaza) – Calibration

Weather data	Calibrated EnergyPlus for Mombasa, Mombasa-Moi 638200 (SWERA), was used. Location: Latitude -4.03, Longitude: +39.62 Altitude: 55m
Calendar	Days 63-84 (March) – Field study period/warmest period of the year
Occupancy times	Occupancy periods are restricted to 0800 to 1800hrs on weekdays only (working hours). Occupation densities of 16m^2 per person were considered (based on a single occupancy office size and CIBSE (2015, p.6-2)).
Comfort temperature range	Adaptive comfort limits were derived as a function of outdoor temperature (Nicol and Humphreys, 2002) giving a comfort range of 27.5 to 31.5°C for free-running buildings as seen in Chapter 1.
Ventilation	Third Floor: Varies from 5 to 10 air changes per hour (ach), under Day Time Ventilation (DTV) as per site conditions observed during the field study – also conforming to National Planning and Building Authority - Kenya (2009, NN10.9) requirements , Eighth Floor: Zero Ventilation (ZV), infiltration only - (as per site conditions; the zone was unoccupied during the field study period)
Infiltration	1 air change per hour (ach)
Internal Gains	Varies from zero to 29W/m^2 – Occupancy, lighting and equipment gains (based on benchmark values for internal heat gains for offices with occupation densities of 16m^2 per person derived from CIBSE (2015, p.6-2)).
Glazing and frame types	10mm Suncool Classic 25/34 Bronze glazing, (U-value: 5.56W/m^2°C) in aluminium frame
Shading	1200mm horizontal overhang/canopy (as per existing)
Floor/ Ceiling	150mm Lightweight reinforced concrete slab (Admittance: 4.33W/m^{2}K)
Walls	External: 200mm Lightweight concrete (Admittance: 3.54W/m^{2}K) Internal: Chipboard on studs (Admittance: 2.67W/m^{2}K)
Roof	Concrete tiles with lightweight concrete slab (with attic ventilation) (Admittance: 3.95W/m^{2}K)

Table 5-10 Simulation Matrix

Model	**Base Case (Mombasa Uni Plaza)**
Dataset	Indoor dry bulb temperature (°C) - DBT
Simulation A	Comparison between Field data (FD) and Calibrated data (CD1), no internal gains
Simulation B	Comparison between Field data (FD) and Calibrated data (CD2), no internal gains. As 'Simulation A' but with increased ventilation rate
Simulation C	Comparison between Field data (FD) and Calibrated data (CD3), As 'Simulation B' but with internal gains added

a) Simulation A Results

The results presented in Table 5-11 and Figure 5-16 were compiled for the warmest month of March (data collection period) and the corresponding simulation days ranging between day 63 to day 84. At this stage, no internal gains were considered; instead, these simulations were focused on the building fabric, ventilation and infiltration model inputs.

As is highlighted in Table 5-11, the results indicated that the field data (FD) and the simulated data derived from the initial calibrated file (CD1) showed little variation in their average indoor temperatures (DBT) values (differences ranged between -0.2°C and 0.9°C). As the zone 3rd Floor Room (5) was not monitored during the field study, therefore its results cannot be compared and are only indicated for information purposes.

Additionally, CD1 predicted indoor temperatures were are found to be slightly warmer than FD indoor temperatures in all the selected zones apart from the zone in the north facing room (2), which was slightly cooler (Figure 5-16). Further comparison indicated that both FD and CD1 tended to fluctuate in a similar manner with peak and low temperatures tending to occur at similar times (Figure 5-16).

Table 5-11 Comparison between field data (FD) and simulated calibrated data (CD1) in March.

Location	**3rd Floor (1)**		**3rd Floor (2)**		**3rd Floor (3)**		**3rd Floor (4)**		**3rd Floor (5)**		**8th Floor (1)**		**External**	
General orientation (Exposed Surfaces)	N (20°) & W (290°)		N (20°)		E (110°)		W (290°)		S (200°)		S (200°), W(290°) & Roof		-	
Data	FD	CD1	FD	CD1	FD	CD1	FD	CD1	FD	CD1	FD	CD1	FD	CD1
Ventilation	DTV	DTV	DTV	DTV	DTV	DTV	DTV	DTV	DTV	DTV	ZV	ZV	-	-
Average DBT (°C)	30.6	31.1	31.1	30.9	30.5	30.9	31.1	31.5	-	31.0	32.4	33.3	29.6	29.6
Difference (°C)	0.5		-0.2		0.4		0.4		-		0.9		0	

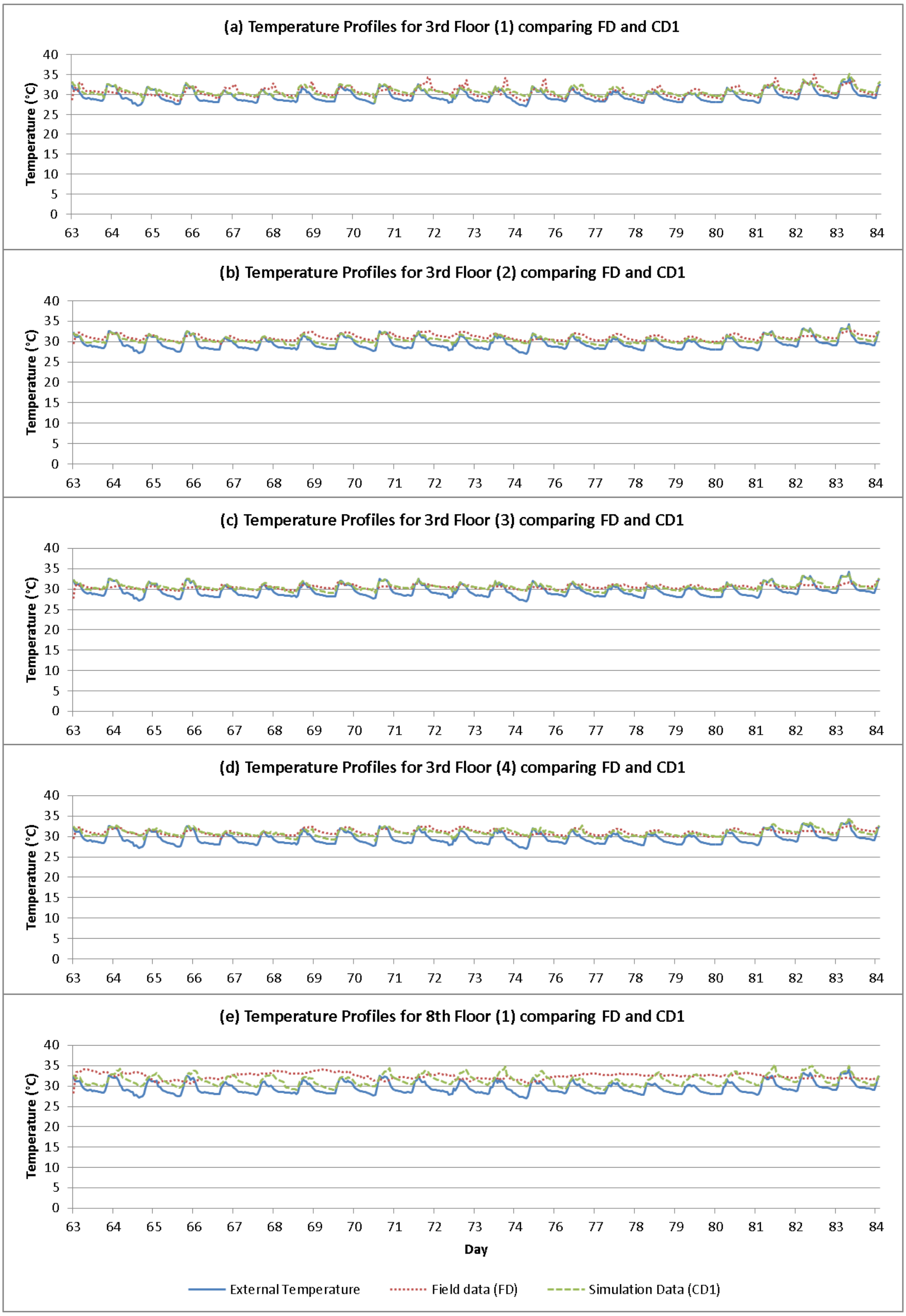


Figure 5-16 Temperature Profiles, (a) to (d) third floor (zone 1 to 4) and (e) eighth floor (zone 1) - Field Study (FD) and Simulated (CD1) cases.

After a review of the selected model assumptions and inputs and the running of a number of simulation runs, it was determined that the difference between the predicted and monitored indoor temperatures might be explained by the fact that ventilation rates frequently tended to be significantly higher on site. Regularly, occupants would also leave room doors open to enhance air movement. In Chapter 4, it was established that occupants would tend to leave their windows open during occupancy periods (0800 to 1800hrs). Additionally, occupants would also run ceiling fans on 'high' at the same time. A combination of all these factors contributed to the enhancement of cross ventilation across office spaces and buoyancy effects through the central service/ staircase core.

In comparison to this high ventilation scenario, the CD1 simulations are based on daytime ventilation (DTV) where windows are opened during the occupancy period (0800 to 1800hrs) and closed only if the outdoor temperature exceeded indoor temperatures. In the next set of simulations (CD2), adjustments were made to accommodate the effect of a higher ventilation rate during occupancy. A review of building fabric inputs was also conducted to ensure they were a close as possible as what was recorded on site.

b) Simulation B Results

In this section, a comparison of the results of field data (FD) and those derived from the second set of simulations (CD2) are presented. The aim of these simulations was to examine further the impact of the building fabric and the existing ventilation strategies inputs on the building thermal performance and to achieve prediction results closer to what was monitored. All other previous assumptions highlighted in Simulation 'A' for CD1 remained the same.

From this, it was found that no significant adjustments could be made to the Tas model building fabric input. This was because the material types and element sizes employed in the Tas model were found to be as close as possible to site conditions. This being the case, the ventilation strategy was investigated further. Based on the field study review (Chapter 4), it was noted that day time ventilation (DTV) was employed in all the selected rooms on the third floor level. Occupants also tended to open both windows and doors to improve cross ventilation across their office spaces. Similarly, ceiling fans were frequently turned on to create breezes that created a cooling effect for occupants. This is with the exception of the eighth floor zone, which remained unoccupied/ closed up during the monitoring period and the simulation process.

In the selected office spaces, occupants tended to use ceiling fans and open their windows/doors to increase the effect of air movement for cooling. Considering that most users tended to use the mid to high power setting on the fans, it was determined that this and the combination of open windows and doors (acting as inlets and outlets) would have resulted in improved circulation of air in and out of the office spaces. Besides working to providing a cooling breeze for occupants, warmer air would also be expelled at a significantly faster rate from the office spaces either through cross ventilation of buoyancy forces.

It is understood that whereas ceiling fans do not work by cooling indoor air but rather by creating a wind chill effect, the effect of increasing air movement propagated by the fans could result in enhancing the extraction of warmer air through fenestration openings and subsequent distribution of cooler outdoor air. This being the case, the ventilation flow rate for rooms was increased to 10ach from 5ach. This is also in keeping with local regulations that stipulate 4-10 ach for mid to high rise office buildings (National Planning and Building Authority - Kenya, 2009, p. N8). Results outlined in Table 5-12 and Figure 5-17 reveal that the predicted indoor temperatures derived from CD2 were slightly lower than those in CD1. Nonetheless, attributed to the change in the ventilation rate, the CD2 predictions were found to be of a more similar trend as those monitored (FD).

Table 5-12 Comparison between field data (FD) and simulated calibrated data (CD2).

Location	**3rd Floor (1)**		**3rd Floor (2)**		**3rd Floor (3)**		**3rd Floor (4)**		**3rd Floor (5)**		**8th Floor (1)**		**External**	
General orientation (Exposed Surfaces)	N (20°) & W (290°)		N (20°)		E (110°)		W (290°)		S (200°)		S (200°), W(290°) & Roof		-	
Data	FD	CD2	FD	CD2	FD	CD2	FD	CD2	FD	CD2	FD	CD2	FD	CD2
Ventilation	DTV	DTV	DTV	DTV	DTV	DTV	DTV	DTV	DTV	DTV	ZV	ZV	-	-
Average DBT (°C)	30.6	30.7	31.1	30.5	30.5	30.6	31.1	30.9	-	30.5	32.4	31.7	29.6	29.6
Difference (°C)	0.1		-0.6		0.1		-0.2		-		0.7		0	

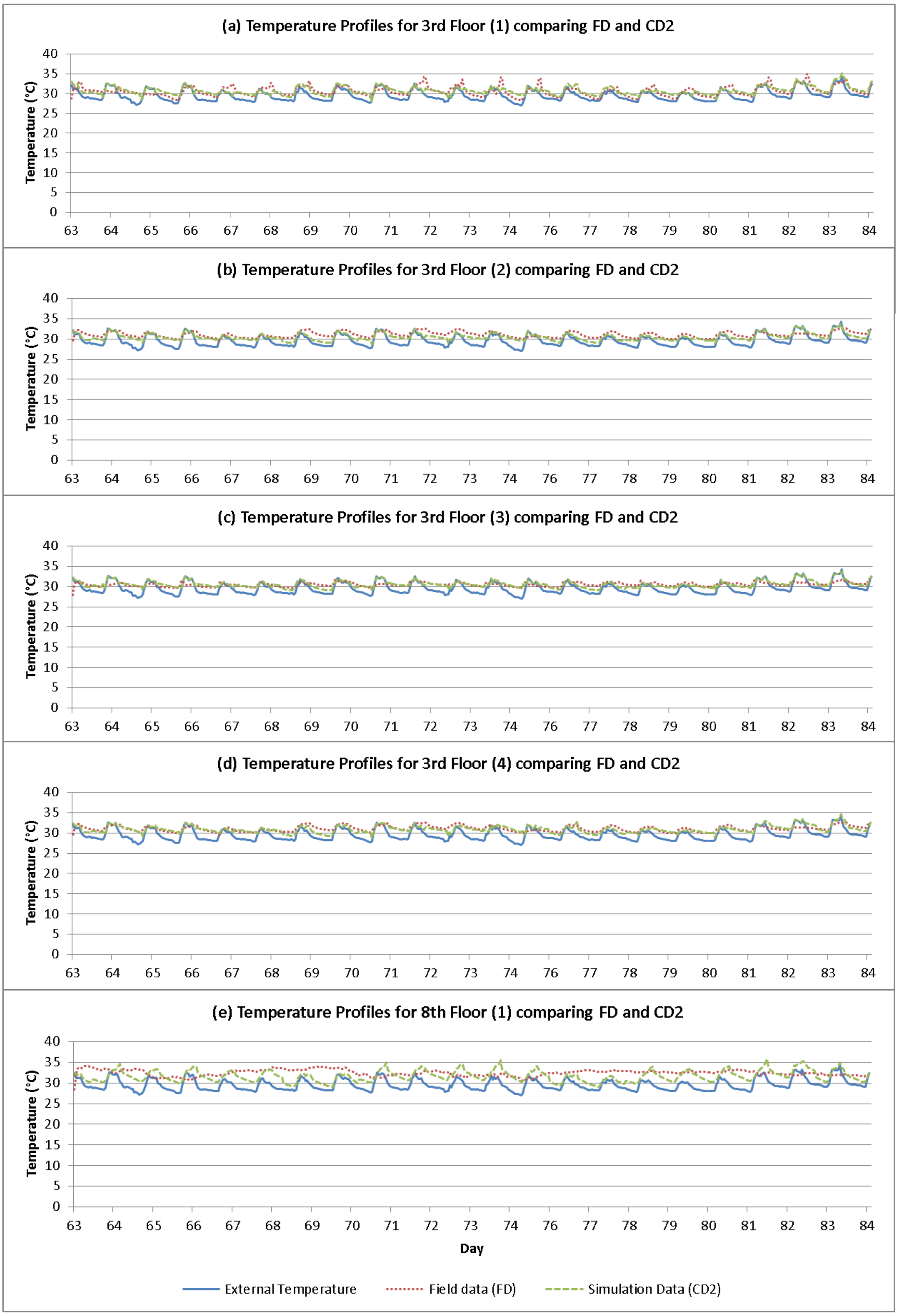


Figure 5-17 Temperature Profiles, (a) to (d) third floor (zone 1 to 4) and (e) eighth floor (1) - Field Study (FD) and Simulated (CD2) cases.

c) Simulation C Results

Following a review of the building fabric and ventilation inputs, further calibration simulations were run to incorporate the effect of light. For each zone/room identified, an internal gain of 29.0W/m^2 was applied – this was based on site observations and CIBSE guidelines for a typical office space (CIBSE, 2015, p.6-3).

As would be expected, the simulation results showed a slight increase in the predicted indoor average temperature (see Table 5-13 and Figure 5-18). Overall, the predicted simulation indoor temperature results (CD3) were found to be slightly warmer than the monitored data (FD). Nonetheless, the predicted average indoor temperature remained quite similar to the monitored data with deviations between -0.2 to 0.7°C. The maximum deviation of 0.7 was predicted for the uninhabited zone on the eighth floor. It was suggested that other site variables that were not taken into account because of simplifying the study model, (including the impact of neighbouring buildings and vegetation, particularly on the north and west facades) may have contributed to this deviation in temperature.

Table 5-13 Comparison between field recorded data (FD) and simulated data (CD3) in March.

Location	3rd Floor (1)		3rd Floor (2)		3rd Floor (3)		3rd Floor (4)		3rd Floor (5)		8th Floor (1)		External	
General orientation (Exposed Surfaces)	N (20°) & W (290°)		N (20°)		E (110°)		W (290°)		S (200°)		S (200°), W(290°) & Roof		-	
Data	FD	CD3	FD	CD3	FD	CD3	FD	CD3	FD	CD3	FD	CD3	FD	CD3
Ventilation	DTV	DTV	DTV	DTV	DTV	DTV	DTV	DTV	DTV	DTV	ZV	ZV	-	-
Average DBT (°C)	30.6	30.8	31.1	30.9	30.5	31.0	31.1	31.3	-	31.0	32.4	31.4	29.6	29.6
Difference (°C)	0.2		-0.2		0.5		0.2		-		0.7		0	

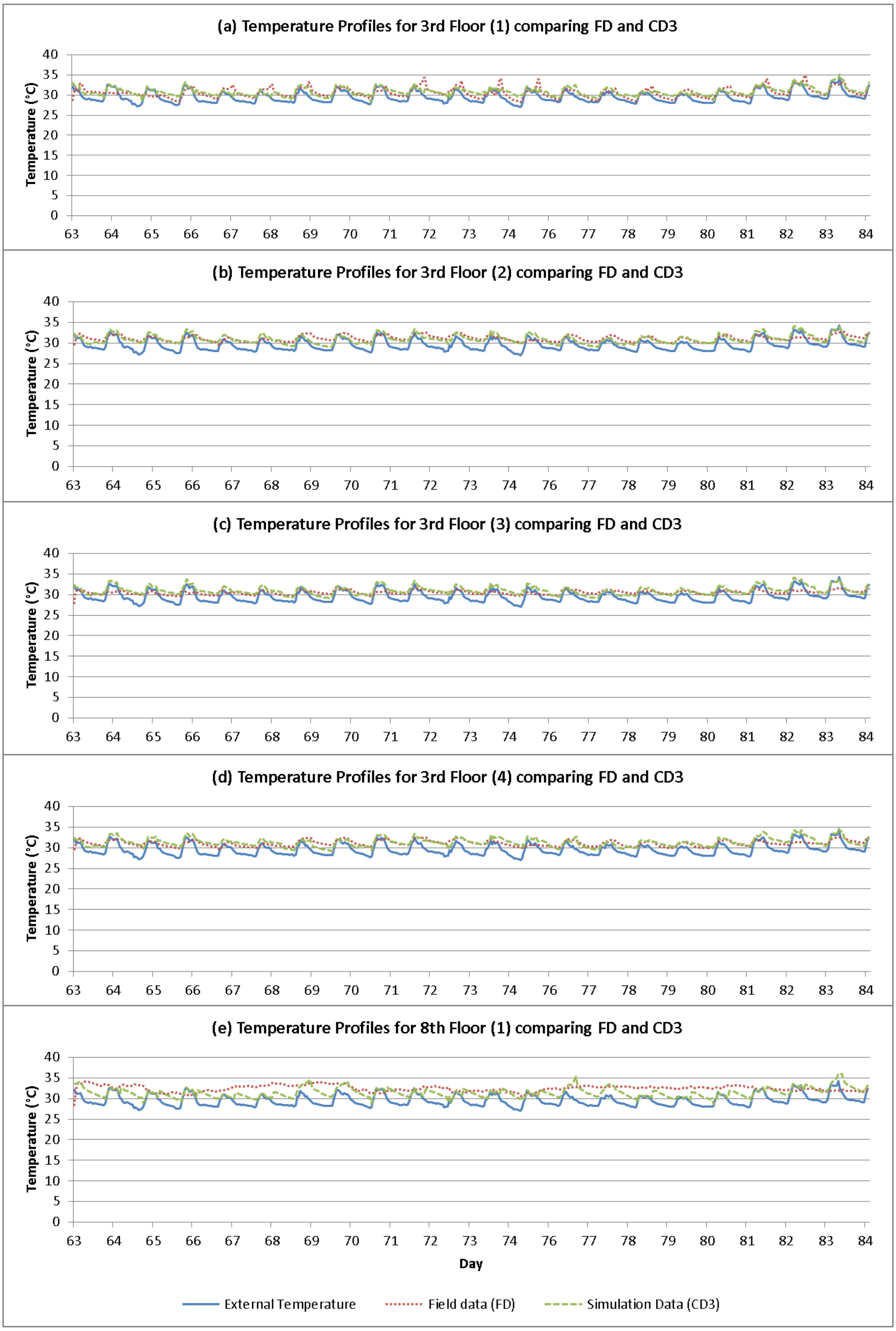


Figure 5-18 Temperature Profiles, (a) to (d) third floor (zone 1 to 4) and (e) eighth floor (1) - Field Study (FD) and Simulated (CD3) cases.

It was determined that the predicted results obtained from the final simulated model (CD3) were quite similar to those monitored and recorded during the field study process. To highlight this further, a typical day was selected as a reference day to compare the predicted and monitored temperature profiles for a 24-hour period (Figure 5-19). Although the CD3 temperatures were slightly warmer in selected zones, both data sets were seen to fluctuate in a similar manner with peaks being achieved at similar times.

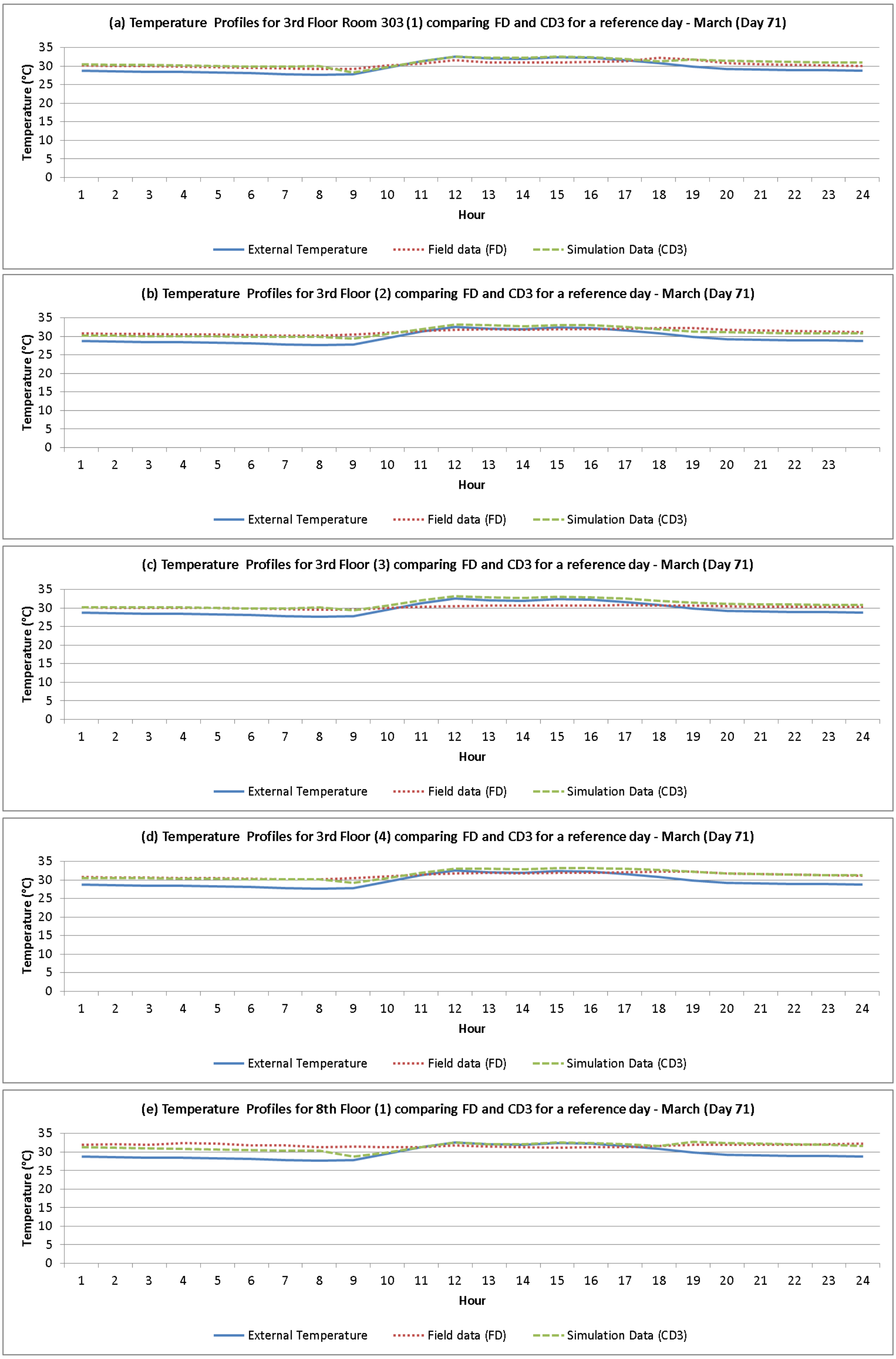


Figure 5-19 Temperature Profiles comparing indoor temperature profiles of simulated (CD3) versus field study (FD) results (a) to (e) on a reference day (Day 71).

A review of the percentage time above comfort limits (above indoor temperature of 31.5°C – based of the adaptive comfort limits) revealed that the variations between site and predicted results were not significant (Figure 5-20).

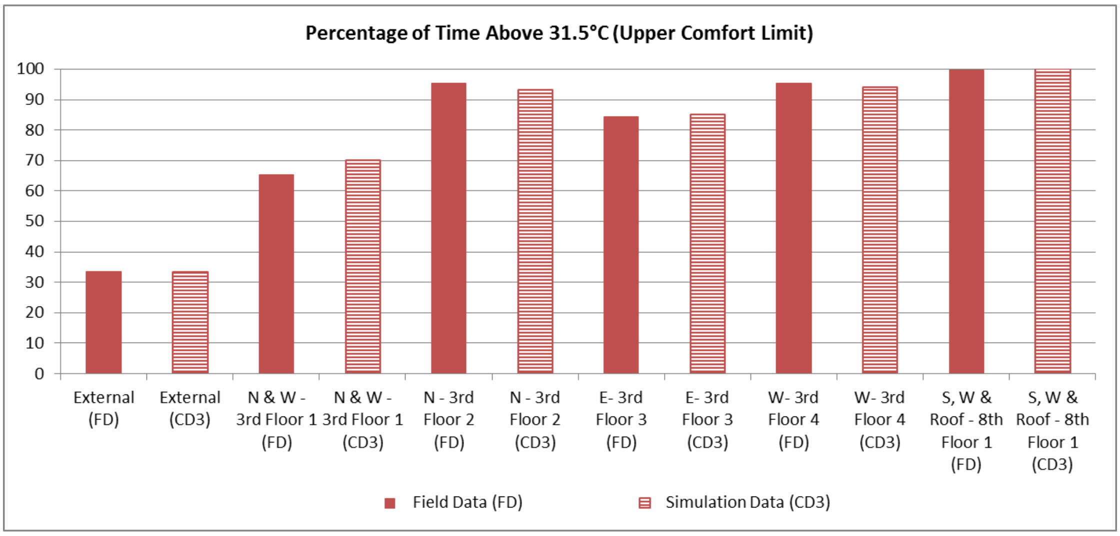


Figure 5-20 Percentage of temperatures in relation to adaptive comfort limits.

Similarly, peak temperatures differences between FD and CD3 were found to be relatively low for both cases (Figure 5-21) with a maximum difference of 1.5°C in the East and West locate zones. Indoor peak temperature analysis shows that the simulation results are higher by approximately.

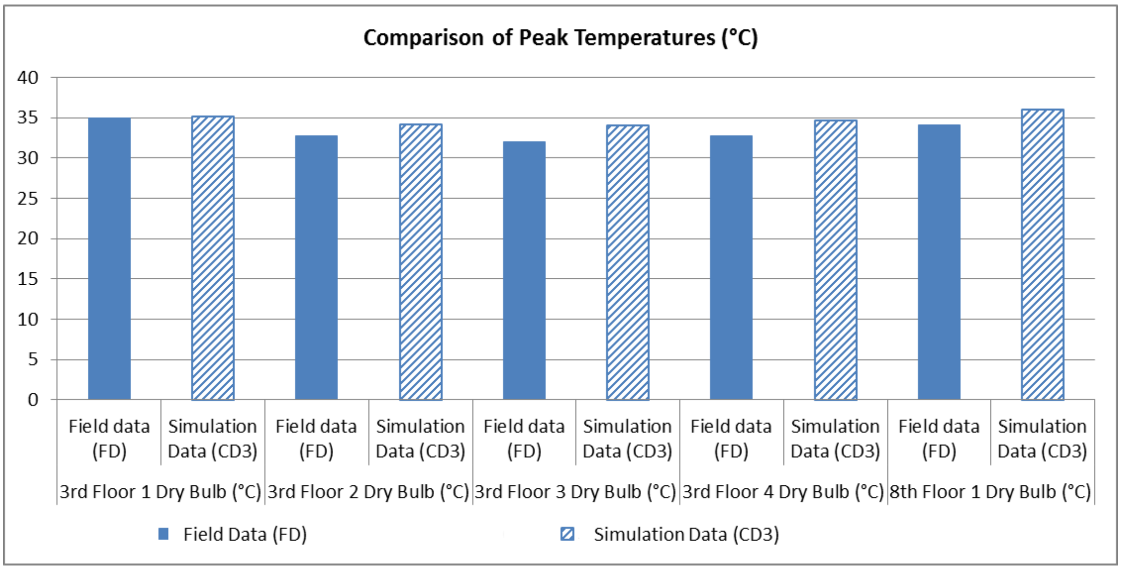


Figure 5-21 Peak temperatures for field study and simulated case.

To conclude the calibration process, the Pearson's correlation test was conducted for both the field data (FD) and the simulated data (CD3) to establish if the two data sets showed any correlation. The Pearson product-moment correlation coefficient is a statistical measurement of the correlation (linear association) between two sets of values. The Pearson product-moment correlation coefficient for two sets of values, *x* and *y* is given by the formula:

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}}$$

Equation 5-1 Pearson correlation coefficient (Rodgers and Nicewander, 1988, p.61)

where *x* and *y* are the sample means of the two arrays of values. If the value of *r* is close to +1, this indicates a strong positive correlation, and if *r* is close to -1, then this indicates a strong negative correlation (Rodgers and Nicewander, 1988).

The results comparing FD and CD3 are presented in Table 5-14. The results revealed a highly positive link, which indicates a strong positive correlation between the two sets of values. These results prove the validity and reliability of the Tas model for use for further simulations.

Table 5-14 Pearson correlation test results for field data (FD) and simulated (CD3) data.

General orientation/ Location	N & W – 3rd Floor (1)	N – 3rd Floor (2)	E – 3rd Floor (3)	W – 3rd Floor (4)	S, W & Roof - 8th Floor (1)
Test result, r	0.8	0.9	0.9	0.9	0.9

Full building simulation predictions cannot replicate real life monitored conditions for many reasons including: inaccuracy of software, inputs assumed over one hour periods (unlike what happens on site) location of temperature measurements (computer simulations will give one average reading per zone per hour), inaccuracy in monitoring equipment, differences in weather data, among others. In this case, many factors were influential in the finding of the Tas model prediction results; finding a specific cause is not feasible as it may have been due to any or all of the stipulated inputs indicated for each of the various simulations. Despite the large number of combinations and simulations undertaken, it was not possible to achieve predicted trends closer to the monitored data. Consequently, the focus of this section took on a more holistic approach where the full performance was the objective. Following this review, the model used in CD3 with all its assumptions was subsequently simulated for phase two of this study. The results are described in the next section.

5.3.2 Typical Full Building Model Results

Following the calibration of a simplified model of Mombasa Uni Plaza (CD3 model), the next set of simulations (phase 2) were undertaken to investigate the effect of thermal mass, natural ventilation strategies and shading on a typical office building in Mombasa.

As is illustrated in Figure 5-22 and Figure 5-23, the results of this second phase of the study indicated that the use of the heavyweight option (Case ‘A’) gave rise to a higher frequency of lower indoor temperatures in comparison to when using lightweight option (Base Case). Further to this, the indoor temperatures in the Case ‘A’ were found to be more stabilized than those in the Base Case. This trend is similar to the results derived in the initial study (phase one).

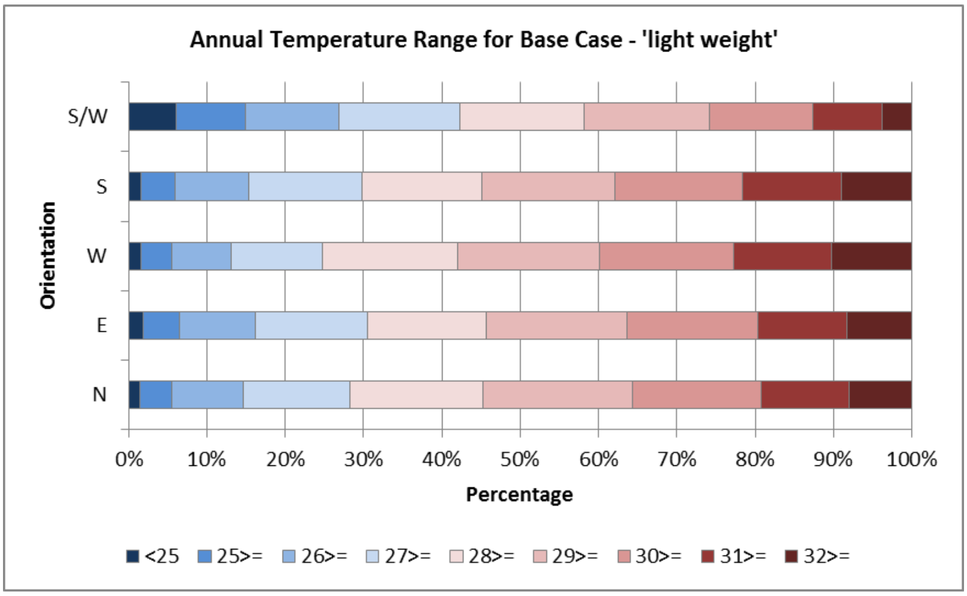


Figure 5-22 Annual temperature range for Base Case – lightweight.

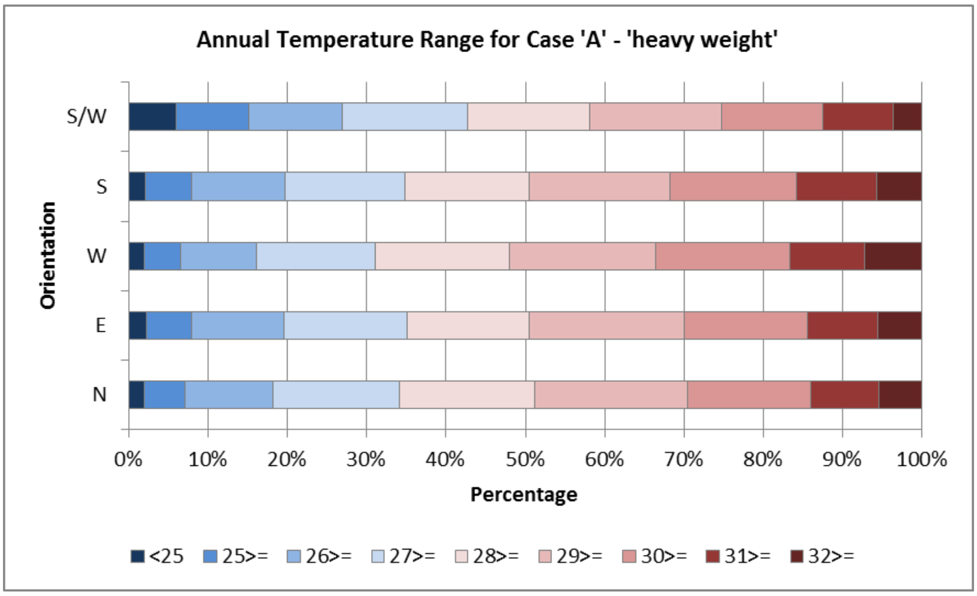


Figure 5-23 Annual temperature range for Case 'A' – heavyweight.

As a rule of thumb, diurnal ranges of below 5°C are considered ineffective (Section 2.2.3). The use of thermal mass is more common in hot and dry climates where the diurnal range often varies between 10 and 20°C (refer to Chapter 2). Although the diurnal temperature range monitored on site was not as high as this, these results demonstrated that the comparatively lower diurnal range was still useful in bringing about a reduction in indoor temperature. During the monitoring period (March - warmest month), it was observed that the site diurnal range lay between 6°C and 8.4°C – a temperature range which would be suitable for the effective performance of thermal mass. These results confirmed that the diurnal temperature range was indeed suitable for the effective performance of thermal mass.

In this study, focus was placed on the results predicted for occupancy periods. Due to the nature of the activities conducted in a typical office building, they tend to be occupied between the 0800 and 1800hrs. This being the case, when using thermal mass, it was determined that it was unlikely that occupants would experience discomfort as a result of any re-radiated heat released into the space during the evening period.

The effect of increased thermal mass on thermal comfort of occupants was evident when examining the percentage of time (annual) when temperatures were considered to be outside of comfort during the occupancy period (Figure 5-24). In the selected zones (corresponding to the four main orientations), an increase in thermal mass was found to improve indoor comfort conditions during occupancy hours by up to 5%. This had the greatest impact on the rooms with West orientation. Next to the zenith, the western faced is the most pone to solar heat gain from low angle sun in the afternoon period. This study has also revealed that the use of shaded thermal mass can lead to significant performance improvements as is indicated in Figure 5-24.

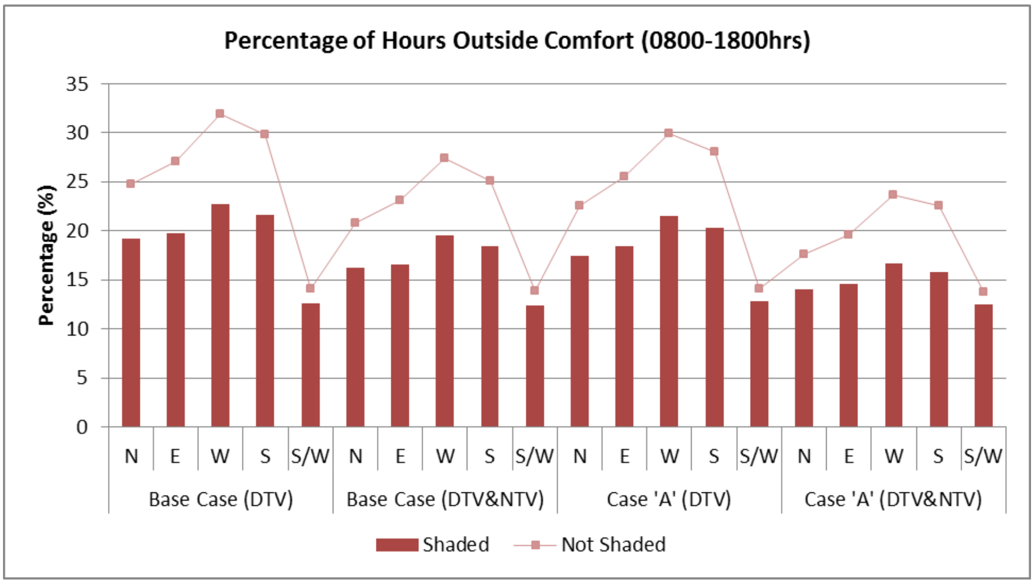


Figure 5-24 Percentage of hours outside comfort (above 31.5°C). N (north), E (east), S (south) and W (west) represent the four rooms based on orientation. S/W represents a room exposed to the south and west on the topmost floor (8th Floor).

In addition to a review of the thermal performance of zones on the third floor, a review of a zone on the eighth floor was undertaken to examine the thermal impact of thermal mass on the top floor/roof (due to the impact of solar radiation on the zenith). Unlike the third floor zones, the results indicated that the thermal benefit on the topmost floor was minimal upon an increase of thermal mass (Figure 5-24). It was inferred that this might have been due to excessive solar gain received on the roof surface. Interestingly, a change from a flat roof to a pitched roof (concrete tiled roof with a ventilated attic space and a heavyweight ceiling below – refer to Table 5-5) during the simulation process resulted in a thermal comfort improvement of up to 3%.

The introduction of night time ventilation improved the indoor thermal conditions in both the heavyweight (Case 'A') and the lightweight options (Base Case). However, this performance improvement was more significant in Case 'A'. It was suggested that this difference may be explained by the fact that the heavyweight thermal mass retains coolth obtained during the night cooling period that is then released indoors during the daytime. In as much as the lightweight option was able to loose heat faster during the evening periods, it was disadvantaged by the fact that it also absorbs heat rapidly during the day – thereby causing overheating.

Further, during the night time ventilation period (1800 to 0800hrs), the indoor temperatures of both cases are quite similar to the outdoors temperatures. In comparison to a daytime ventilation only strategy (DTV), the combination of DTV and night time ventilation (NTV) improved comfort hours by up to 7% and 5% for the heavyweight and lightweight typologies, respectively.

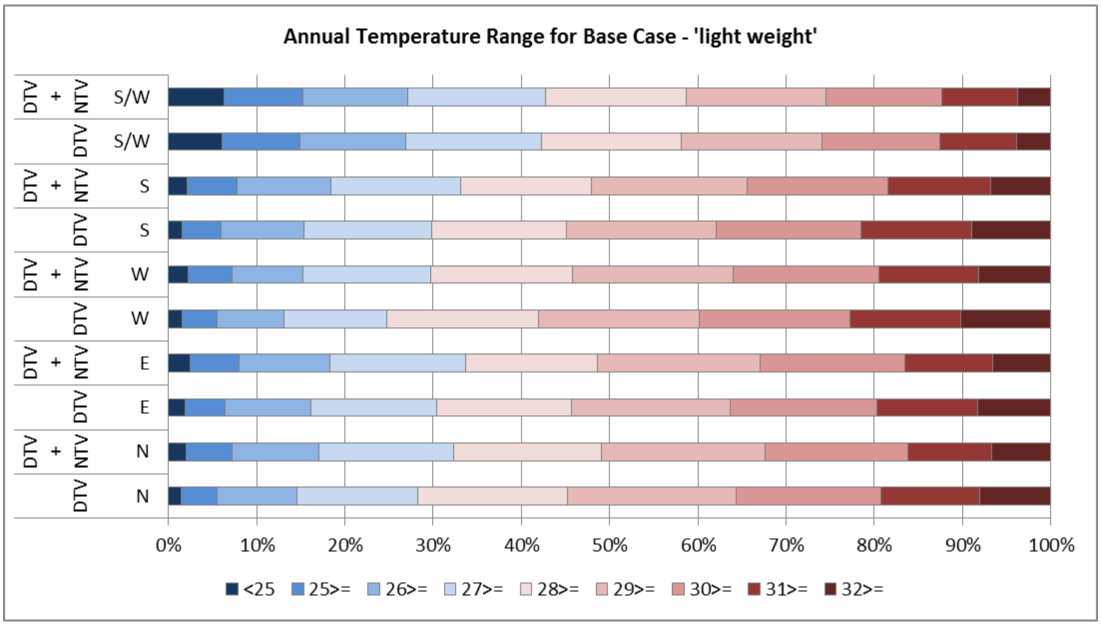


Figure 5-25 Annual temperature range for Base Case comparing results of DTV only and a combination of DTV and NTV.

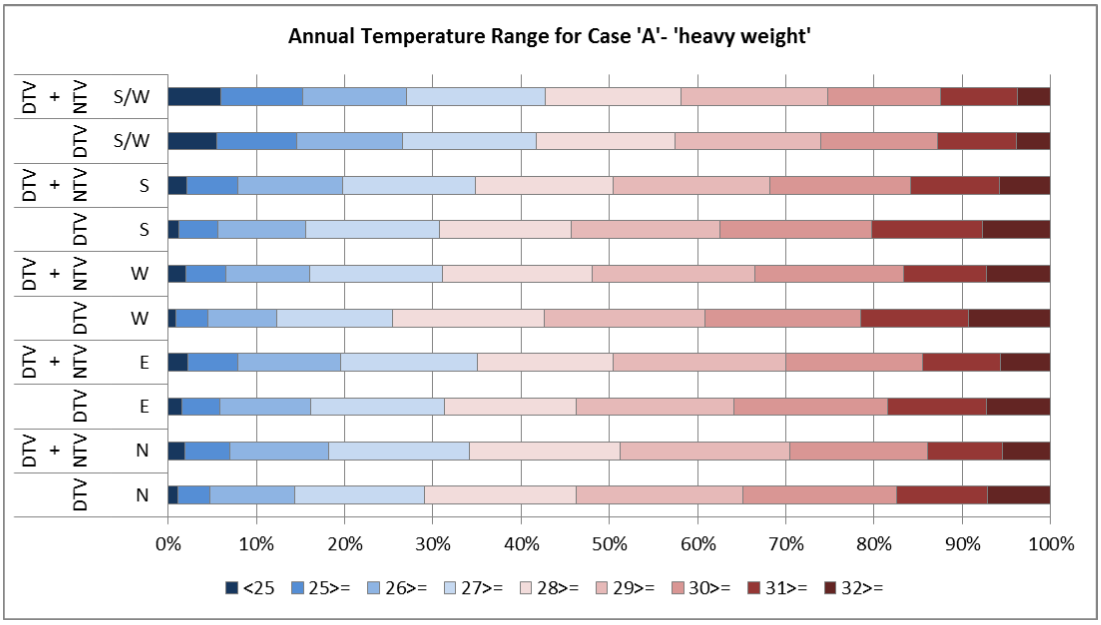


Figure 5-26 Annual temperature range for Case 'A' comparing results of DTV only and a combination of DTV and NTV.

Following a review of the impact of sun shading on building thermal performance it was revealed that the protection of the building envelope from undue solar gain is crucial to safeguarding the thermal performance of both the heavyweight and lightweight options. This was determined to be especially critical to Case 'A' - heavyweight building. Unlike the lightweight mass that could cool down rapidly after sunset, the exposure of the heavyweight mass to solar radiation could lead to increased heat storage in the fabric that would later dissipate indoors.

For both the Base Case and Case 'A', comparisons were made for thermal comfort performance with the existing shading (1.2 m deep horizontal canopy on each level) and without any shading (Figure 5-27). Results revealed that exposure of the glazing and the thermal mass to solar gains resulted in a substantial increase of discomfort hours during occupancy periods of up to 10%.

Of all the zones examined on the third floor, the room with western orientation was found to be most negatively affected by the absence of shading. Reference to the climate analysis in Chapter 1 revealed that this is due to the fact western orientation is prone to higher solar gain during the afternoon periods when solar levels are at their highest.

Although the shading element on the 8th floor room/zone was fixed in a similar manner to that on the 3rd floor rooms/zones, it did little to alter indoor comfort conditions by more than 1.5%. This was identified to be due to the fact that the existing shading was designed to protect the facade surfaces and not the exposed roof. As mentioned earlier in the review of thermal mass performance, the introduction of a pitched roof cover (acting as a shading element) and a ventilated attic space resulted in a 3% reduction in discomfort hours.

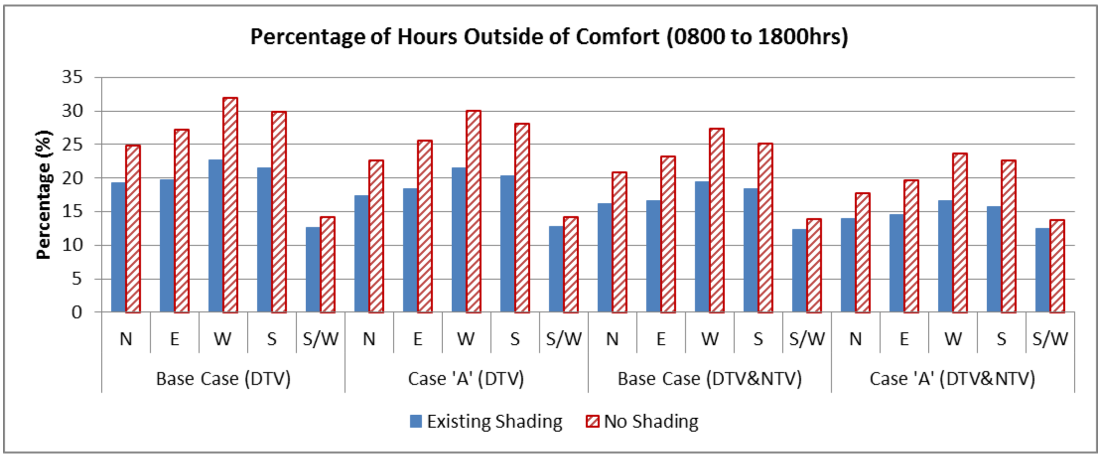


Figure 5-27 A comparison of the percentage of hours outside of comfort (above 31.5°C) during occupancy hours, with and without the existing shading elements (1200mm canopy on all levels).

These results illustrated that shading was significant in improving indoor thermal performance and extending thermal comfort for occupants. It was concluded that the lack of sun shading encouraged higher instances of overheating and could consequently lead to poor indoor thermal comfort conditions.

5.4 Conclusions

This chapter has been focused on the thermal performance impact of implementing selected Swahili-inspired design strategies to a typical contemporary office building. This was based on a previous review of local architectural solutions in Chapters 3 where it was inferred that Swahili vernacular architecture showed a suitability of plan, form and fabric characteristics. Following this, identified Swahili-inspired passive design strategies applicable to contemporary office buildings in the warm humid region were selected and examined to gauge their impact on building thermal performance and the resultant thermal comfort of occupants.

Subsequently, a parametric study using dynamic thermal modelling was conducted. Initially, the impact of varying thermal mass properties and natural ventilation strategies was examined using a simplified model. Next, the dynamic simulation examining the aforementioned strategies and shading of a selected typical office building in the warm-humid city of Mombasa was undertaken. Although this chapter was contextually bound to a simplified generic building and a typical building in a specific site context, conclusions applicable to similar building types in warm humid climates can be drawn from it.

One of the key field study findings was the significant impact of thermal mass on the building thermal performance, especially during occupancy hours. An increase of thermal mass resulted in a reduction in indoor temperatures of up to 2°C (during peak outdoor temperature times) and an improvement of 5% in comfort hours (during occupancy periods). In addition, when the heavyweight building fabric was used, indoor temperatures tended to be fairly constant for a significant period of time when compared to outdoor conditions. Conversely, indoor temperatures in the lightweight building tended to fluctuate in a manner similar those outdoors thereby exposing this building construction typology to higher instances of overheating during occupancy periods. The lightweight typology was found to have up to 3% fewer comfort hours than typologies with increased thermal mass. Similarly reductions in indoor temperatures were fairly small and averaged at about 0.5°C (outside of occupancy periods). In addition, it was noted that the introduction of a ventilated roof attic and a ceiling/slab with significant thermal mass resulted in a significant reduction in discomfort hours of up to 3%.

Further to this, it was established that natural ventilation played a prime role in moderating indoor conditions. Whereas thermal mass was used to avert or reduce the influx of solar heat gain indoors, natural ventilation was used to remove any heat build-up and to generate cooling breezes. This allowed for the cooling of both the building and occupants. It was determined that the combination of day time ventilation (DTV) and night time ventilation (NTV) resulted an improvement in comfort conditions by up to 7% and 5% in the heavyweight and lightweight typologies, respectively. It was suggested that the ability of the heavyweight option to store coolth for use during the occupancy hours could explain its better performance.

The analyses also indicated that shading is a main design strategy for the local climate. As is the case with thermal mass, shading works primarily by preventing the build-up of heat gain indoors. The study revealed that the performance of the building significantly improved with the presence of the existing shading and resulted in lower temperatures indoors. Consequently, this improved thermal comfort by up to 10% during occupancy periods. From this, it was derived that shading devices installed on the exterior of the building had helped to reduce the overheating potential.

In addition to the testing of these main design strategies, the analysis of future climate scenarios with respect to potential overheating in office buildings was conducted for the years 2030, 2050 and 2100. The results indicated that the average outdoor temperatures would remain below 31.5°C (the calculated adaptive comfort upper limit for Mombasa). Given that this upper comfort limit was used in the analysis of thermal comfort performance of the Old Post Office building and Mombasa Uni Plaza in Chapters 3 and 4, both of which set the basis for the simulation studies presented in this chapter, it was suggested that the results presented in this chapter would still hold firm. Consequently, the proposed design strategies would still provide appropriate climate change adaptation measures needed to tackle increased overheating in naturally ventilated buildings and reduce the need for cooling energy in air conditioned buildings in Mombasa.

In general, the results indicate that despite the relatively low diurnal temperature range common in warm humid regions, thermal mass, if used effectively can lead to significant improvement of building thermal performance and resultant indoor thermal comfort conditions. In addition, the combined effect of responsive sun shading (to mitigate solar heat gain) and a combination of daytime and night time ventilation (to flush out stored heat) results in extended comfort hours and a subsequent reduction in the need for energy intensive mechanical cooling in the typical local office building.

6 SPECIFIC PARAMETRIC STUDY: EXTERNAL SHADING DEVICES

Following a review of design strategies that significantly impact the thermal performance of office buildings and enhance comfort in warm humid climates, this chapter is focused on examining shading as an effective design strategy in the warm humid city of Mombasa. A systematic procedure was developed to establish a correlation for evaluating the shading performance of horizontal, vertical and egg crate shading devices based on the projection factor ratio and solar heat gain coefficients through dynamic simulation of shading variables for latitude 4°S, which represents Mombasa in Kenya.

6 SPECIFIC PARAMETRIC STUDY: EXTERNAL SHADING DEVICES

In warm humid climates, solar heat gain through glazing can represent a substantial input of heat into a building. Frequently, this can lead to increased electricity consumption for active air conditioning that is often expensive and unsustainable. Following the identification of Swahili-inspired thermal design strategies, namely thermal mass, natural ventilation and shading in Chapter 3, and a performance review of the same in Chapter 5, it was determined that external shading devices can significantly reduce the amount of solar heat gain transmitted into buildings. Consequently, this can lead to lower internal temperatures and consequent improvement of the thermal comfort of occupants.

The use of shading systems for climate control in warm climates is well documented. Previous research has indicated that if shading devices are properly installed on the exterior of the building, they can block solar radiation effectively before it passes through glazing and in so doing reduce the overheating potential in warm humid climates (Koenigsberger et al., 1973, Szokolay, 2008, Givoni, 1998). Whilst there are obvious merits of employing external shading devices to local office buildings, there appears to be a lack of understanding or guidance regarding their application and with respect to their thermal performance benefits. Although existing literature advises on the suitability of shading devices (Chapter 2), guidelines tend to be mainly generic in nature. Most importantly, most of the available guidance can be difficult to navigate and time consuming for designers, resulting in a much lower uptake than expected or desirable.

Given the wide variety of buildings and the range of climates in which they can be found, it is difficult to make sweeping generalisations about the design of shading devices. Shading strategies that work well at one latitude, may be completely inappropriate for other sites at different latitudes. Even within the warm humid region (spanning between 15° north and south of the equator) subtle differences in shading control may arise.

These latitude (and hemisphere) specific solar path differences are critical to provide essential data for effective external shading device design. To design effective external shades, designers must know the precise solar path angles for each location they design for, and in this case, how they compare to place-based cooling requirements.

6.1 Simulation Basis

To the best of the researcher's knowledge, little has been done to categorise the performance of external shading elements for solar heat gain control and thermal comfort optimization applicable to the local latitude of 4°S. A review of relevant building regulations for countries that lie along this latitude including Brazil, Peru and Indonesia revealed that they either were in the process of undertaking research to address this concern or recommended the use of the Overall Thermal Transfer Value (OTTV). Originally developed by ASHRAE, the use of OTTV has since been discontinued by many countries after being found unsuitable due to underestimating the impact of solar gain through fenestrations (Chapter 2). Currently, Kenyan national building regulations recommend the use of external shading devices to promote energy efficiency in office buildings. However, this only covers the 'what can be done' part of the equation leaving out equally important guidelines that show 'how this can be effectively implemented' and how to quantify or demonstrate the potential benefits.

To bridge this gap in existing literature, simple indices were developed to help designers determine the thermal efficacy of different types of external shading in office buildings. To begin with, the performance analysis of various shading types (horizontal, vertical and egg crate) was undertaken to determine the influence of each configuration in the reduction of solar heat gain and consequently the reduction in indoor temperature.

A series of dynamic simulations were run for a typical office building in Mombasa to derive the average monthly solar heat gain coefficient (SHGC) values of external shades (horizontal, vertical and egg crate) for a typical year. These SHGC values (expressed as a percentage, in decimals between 0 and 1) account for the amount of solar gain due to direct and diffuse shading on a window surface, and indicate the effectiveness of the external shading devices. In warm climates, the main climate related problem lies with overheating and the need to mitigate heat gain (Chapter 1), therefore the lower the SHGC value the better.

To be useful in determining the impact of solar heat gain in typical office buildings sited along latitude 4°S, SHGC values were derived for sixteen cardinal orientations and correlated to projection factor (PF) ratios (a simple ratio used to define the relationship between the shading element depth and window size). By quantifying the effect of external shading on reducing indoor temperatures and consequently extending indoor thermal comfort for occupants, it was found that direct correlations could be made between the application of external shades and the resultant thermal performance of a typical office building.

Further to this, based on building information on the glazing area, window orientation and PF ratio estimates of the potential annual energy savings in a typical office building were made. It was suggested that these guidelines could serve as a reference for other designers who sought to estimate the impact of the proposed external shading (as defined by the SHGC values) on the thermal performance of office buildings, the resultant thermal comfort of occupants and overall cooling energy reduction (mechanically ventilated buildings).

6.1.1 Simulation Scope, Method and Assumptions

In this chapter, to help develop an understanding of the critical parameters involved in the derivation of SHGC values and later the prediction of energy savings, a series of parametric studies were conducted using dynamic simulation developed using Tas. This approach proved advantageous as it enabled the review of the thermal performance impact of a wide variety of shading configurations and PF ratios as applied to varied orientations of a typical office building.

A simplified model of a typical office building in Mombasa (Mombasa Uni Plaza) was used as a vehicle (Figure 6-1). This assumption was based on the fact that the model was based on spatial, glazing and material properties common to office buildings found in Mombasa. This Base Case model was similar to that which was built and calibrated for the Phase 2 studies in Chapter 5, Section 5.1.4 where it was used to carry out the initial shading studies. Here, changes made to the Base Case model only affected the type and sizing of the external shading elements. This means that the building's thermal performance was reviewed with and without (as would be the case with unprotected highly glazed buildings) shading elements. All other elements and assumptions remained as was illustrated in Table 6-1.

(a)

(b)

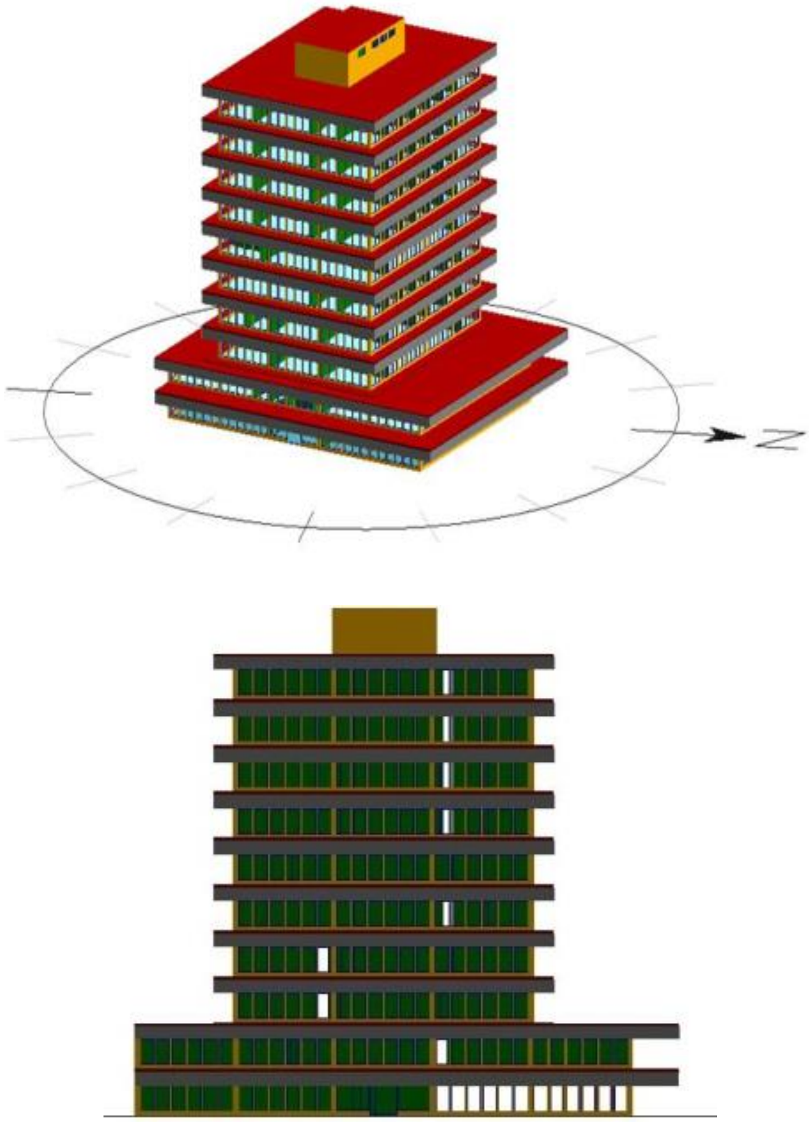


Figure 6-1: Perspective (a) and front elevation (b) of the Base Case model based on a typical office building.

Table 6-1 General assumptions for Base Case model.

Fixed Parameters	
Weather data	Calibrated EnergyPlus for Mombasa, Mombasa-Moi 638200 (SWERA), was used. Location: Latitude -4.03, Longitude: +39.62, Altitude: 55m
Calendar	Simulations were run for a typical year.
Occupancy times	Occupancy periods are restricted to 0800 to 1800hrs on weekdays only (working hours). Occupation densities of $16m^2$ per person were considered (based on a single occupancy office size and CIBSE (2015, p.6-2)).
Comfort temperature range	Adaptive comfort limits were derived as a function of outdoor temperature (Nicol and Humphreys, 2002) giving a comfort range of 27.5 to 31.5°C for naturally ventilated buildings (Chapter 1). A comfort temperature range of 20.3 to 26.7°C derived using the PMV comfort method for 90% percentage people satisfied was considered for simulations run to estimate energy savings in a mechanically run buildings (Chapter 1).
Ventilation	5 air changes per hour [ach] - based on the regulatory requirements of the National Planning and Building Authority - Kenya (2009, NN10.9)
Infiltration	1 air change per hour (ach); this is an empirical value used to simplify the analysis.
Internal Gains	$29W/m^2$ – Occupancy, lighting and equipment gains (based on benchmark values for internal heat gains for offices with occupation densities of $16m^2$ per person derived from CIBSE (2015, p.6-2)).
Model	Base Case - ('Lightweight' office building thermal mass – Mombasa Uni Plaza)
Floor/ Ceiling	150mm Lightweight reinforced concrete slab (Admittance: $4.33W/m^2K$)
Roof	Concrete tiles on lightweight concrete slab (Admittance: $3.95W/m^2K$)
Walls	External: 200mm Lightweight concrete (Admittance: $3.54W/m^2K$) Internal: Chipboard on studs (Admittance: $2.67W/m^2K$)
Varied Parameters	
Glazing and frame types	10mm Suncool Classic 25/34 Bronze glazing with a SHGC of 0.353, in aluminium frame (simulation set A) 3mm clear glass glazing with a SHGC of 0.8, in aluminium frame (simulation set B and C) Glazing area was restricted to 60% of the facade area.
Shading	Varies in terms of shading configuration and depth (refer to Table 6-2).

Following the calibration of the typical office building model (presented in Section 5.3.1), dynamic simulations were run for a variety of shading types (horizontal, vertical and egg crate) and depths to test their efficacy in various orientations (simulation set A). To give a clear indication of the thermal performance of each shading type, the percentage number of hours (per annum) indicating when the indoor air temperature was predicted to be above the upper comfort limit in Mombasa (during occupancy hours only) was reviewed. For these initial simulations, the shading types were organised into various configurations (Figure 6-2) and depths (Table 6-2). The colour coding applied to Figure 6-2 corresponds to Table 6-2 and Table 6-3.

The shading configurations examined in this study were based on the three main types commonly applied to buildings (Section 2.1.1). The shading depth minimum of 0.3m (and multiples of the same) for horizontal and vertical shading applied in this study was informed by a series of studies conducted in the tropics, taking into account day lighting and aesthetic considerations, as well as the view angle requirements from the internal space (Wong and Li, 2007, p.1403, Liping and Hien, 2007, p. 4013). Owing to their slightly more complex shading masks (Section 2.1.1); smaller depths were considered for egg crate shades.

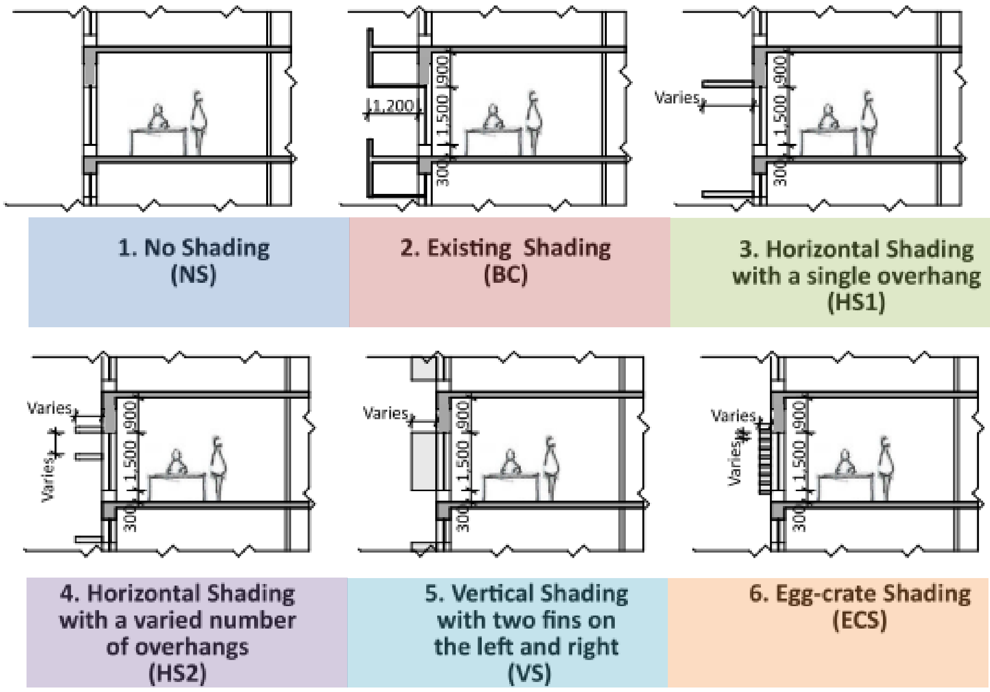


Figure 6-2 Simulation set A shading configurations (1 to 6).

Table 6-2 Simulation set A simulations matrix.

Shading configuration	Shading device depths investigated (m)	
	Horizontal (m)	Vertical (m)
No Shading (NS)	-	-
Existing Shading (BC)	1.2	-
Horizontal shading with one overhang (HS1)	0.3, 0.6, 0.9, 1.2, 1.5, 1.8	-
Horizontal shading with multiple overhangs (HS2)	0.3 x 3 no., 0.6 x 2 no., 0.6 x 3 no.	-
Vertical shading with two fins, left and right (VS)	-	0.3, 0.6, 0.9, 1.2
Egg crate shading (ECS)	0.1, 0.15, 0.3, 0.45, 0.6, 0.9	0.1, 0.15, 0.3, 0.45, 0.6, 0.9

The subsequent stage of the simulation study involved the derivation of the solar heat gain coefficient (SHGC) values for external shading. First, simulations were run for the selected typical office building under its existing orientation (simulation set B). As the existing building is offset by approximately 20° off the north-south axis, the four selected zones were found to represent building facade orientations of 20° (N20°E), 110° (S80°E), 200° (S20°W) and 290° (N70°W) (Figure 6-3).

Next, to allow for the interpretation and application of the simulation results to similar office buildings of different orientations (simulation set C), adjustments to the building orientation were made to derive SHGC values applicable sixteen facade orientations. These orientations included N – 0/360°, NNE – 22.5°, NE - 45°, ENE – 67.5°, E - 90°, ESE – 112.5°, SE - 135°, SSE -157.5°, S - 180°, SSW – 202.5°, SW- 225°, WSW – 247.5°, W - 270°, WNW – 292.5°, NW - 315° and NNW – 337.5°. Further to this, estimates of energy savings due to a reduction of the SHGC values were calculated for each of the selected orientations.

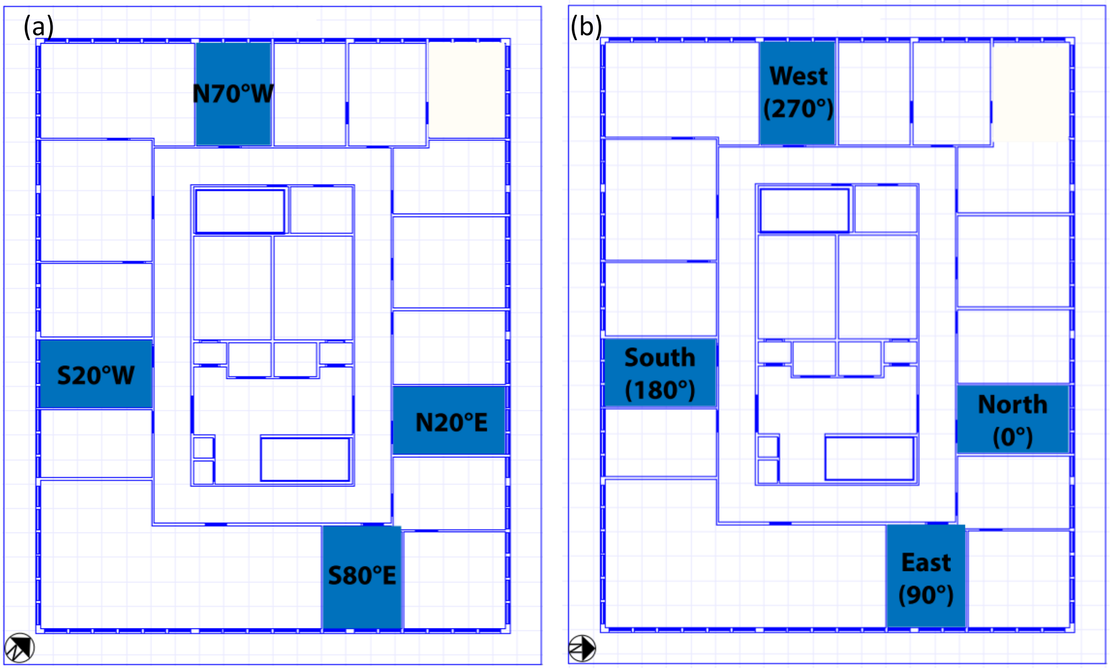


Figure 6-3 (a) Floor plan showing the existing zone/orientation layouts for simulations plan A and B. (b) For simulation plan C, the positioning of the building in Tas was adjusted to evaluate results for various orientations.

To enable clearer interpretation of results, the selected shading configurations were categorised into 'projection factor' ratios and derived using Equation 6-1:

$$PF = {}^{A}/_{B}$$

Equation 6-1 Projection factor ratio of external shading (ASHRAE, 2013a)

where PF is the projection factor, A is horizontal depth of the external shading projection, which is the distance between outside edge of shading to the outside surface of the glass (m), and B is the sum of the height of the fenestration plus the distance from the top of the fenestration to the bottom of the farthest point of the external shading projection (m). Figure 6-4 illustrates the PF ratio for horizontal and vertical shading; for egg crate shading a combination of both horizontal and vertical projection factors are considered. For both horizontal and vertical shading, it is common for the shading elements to be offset from the fenestration by some distance or tilted at an angle. Further, it is possible to have different sized fins on the left and right sides of the fenestration. Methods have been developed for deriving PF ratios for these and more specialised cases (Hong Kong Buildings Department, 2014, ASHRAE, 2013a, Eley Associates, 2004). Figure 6-5 presents the more common cases.

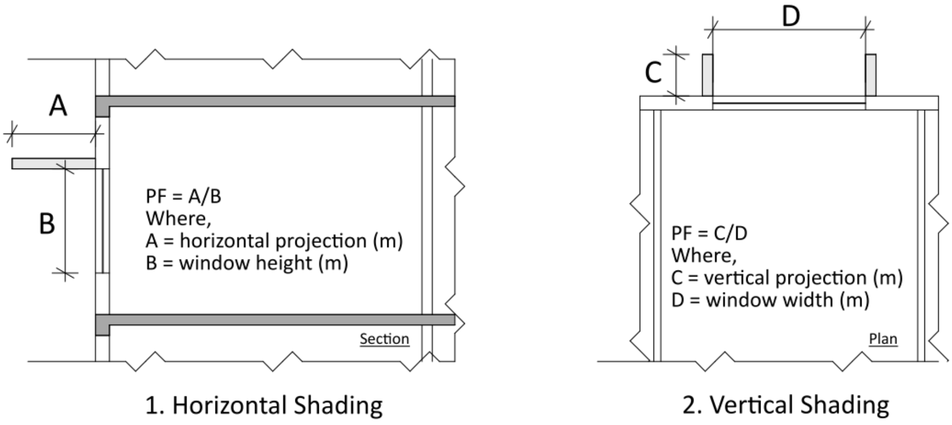


Figure 6-4 Projection factor ratio for horizontal (1) and vertical (2) shading elements.

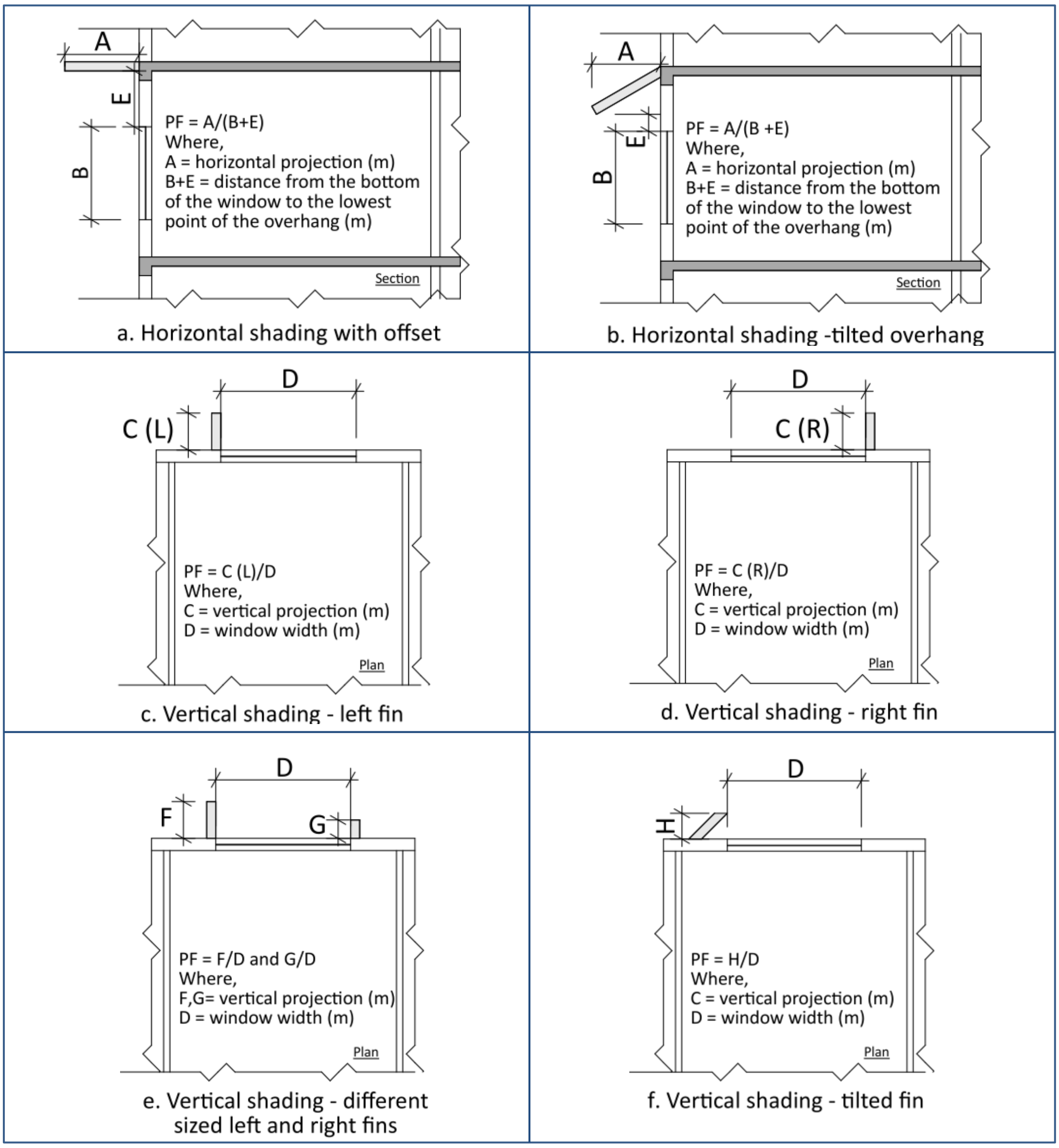


Figure 6-5 (a) to (f) Projection factor ratio for common shading element placements.

For modelling purposes, a window glazing area of $4.5m^2$ was used for each zone/orientation. This was based on window dimensions of 1.5m (window height - B) by 3m (window width - D). These dimensions were based on site measurements obtained from the selected typical office building (Mombasa Uni Plaza – Chapter 4). PF ratios derived for shading considered for this fenestration opening are shown in the simulation matrix presented in Table 6-3.

Table 6-3 Simulation set B and C simulations matrix

Shading configuration	Shading device depths (m)		Corresponding projection factor ratio	
	Horizontal (m)	Vertical (m)	PF ratio (Horizontal)	PF ratio (Vertical)
Horizontal shading with one overhang (HS1)	0, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8	-	0, 0.2, 0.4, 0.6, 0.8, 1, 1.2	-
Vertical shading with two fins, left and right (VS)	-	0, 0.3, 0.6, 0.9, 1.2	-	0, 0.1, 0.2, 0.3, 0.4
Egg crate shading (ECS)	0, 0.3, 0.6, 0.9	0, 0.3, 0.6, 0.9	0, 0.2, 0.4, 0.6	0, 0.1, 0.2, 0.3

For simulation set A, only natural ventilation strategies were considered. Similarly to Chapter 5, ventilation and infiltration rates were set at 5ach and 1ach, respectively based on local building requirements (National Planning and Building Authority - Kenya, 2009, NN10.9). For each ventilation strategy, an aperture schedule was set up so that the windows would be open during the specified periods only, as indicated below:

a) Zero ventilation (ZV): Windows were not opened (infiltration only).
b) Daytime ventilation (DTV): Windows were opened from 0800 to 1800hrs.
c) All day ventilation (ADV): Windows were opened for 24 hours.

For all strategies, except ZV, it was assumed that the windows were shut if outdoor temperature exceeded indoor temperature. During weekends, only infiltration at the rate of 1ach was factored in. The window-opening schedules were informed by previous parametric studies conducted in Chapter 5 and were meant to simulate conditions when the windows were shut; open and shut as occupants generally would and open for night cooling.

6.1.2 Estimating solar heat gain coefficient (SHGC) values

For transparent elements such as windows, solar heat gain (Qs) can be calculated as is shown in Equation 6-2:

$$Qs = A \times G \times SHGC$$

Equation 6-2 Total solar heat gain for transparent surfaces (Szokolay, 2008, p.40)

where Qs is the solar heat gain (W), A is the glazing surface area (m^2), G is the global irradiance incident on the glazing surface (W/m^2) and SHGC is the solar heat gain coefficient.

For any given fenestration system, the SHGC indicates the total amount of solar heat that passes through glazing (Szokolay, 2008). SHGC is presented in the form of a decimal fraction indicating what part of the incident radiation reaches the interior. This non-dimensional term is derived as shown in Equation 6-3.

$$Solar\ heat\ gain\ coefficient = \frac{Solar\ heat\ transmitted}{Solar\ irradiance\ of\ the\ window\ surface}$$

Equation 6-3 Solar heat gain coefficient (Szokolay, 2008, p.40)

The use of SHGC is relatively new and was developed to replace the use of the shading coefficient (SC) (Building Sector Energy Efficiency Project - BSEEP, 2013, Szokolay, 2008). SC is defined as the ratio of the solar heat gain through the glazing considered compared to that of 3mm double strength glass (Szokolay, 2008, p.40). Previously, the product of the SC, area of glazing and solar heat gain factors (calculated values of solar irradiance) was used to derive the total solar heat gain. However, since different manufacturers were found to specify different properties of double strength glass, the SC varied depending on the manufacturer. This drove the shift to the more accurate SHGC.

Due to relatively high solar exposure in warm humid regions (Chapter 1), it was deemed practical to design for a low SHGC to reduce the risk of overheating.

Generally, the total SHGC of a fenestration system ($SHGC_{total}$) is influenced by three variables as is illustrated in Equation 6-4:

$$SHGC_{total} = SHGC_{external} \times SHGC_{glazing} \times SHGC_{internal}$$

Equation 6-4: Total solar heat gain coefficient (Building Sector Energy Efficiency Project - BSEEP, 2013, p.114)

where $SHGC_{total}$ is the total solar heat gain coefficient of the fenestration system; $SHGC_{external}$ is the solar heat gain coefficient of external shading devices (1, if no external shading device is used); $SHGC_{glazing}$ is the solar heat gain coefficient of the glazing and $SHGC_{internal}$ is the solar heat gain coefficient of internal shading devices (1, if no internal shading device is used).

Equation 6-4 indicates that the SHGC values of external shading, glazing type and internal shades have equal weightage in their ability to reduce solar heat gain in buildings. This means that a significant reduction in the value of either one can lead to a significant reduction in the total solar heat gain admitted through fenestration.

External shades are more effective than internal shades because they block solar radiation before it gets into the building whilst internal shades try to reflect the radiation outwards. Their effectiveness was found to be largely dependent on their colour and reflectivity, a factor that varies with manufacturer products and design team selections. Even so, a significant proportion of the short wave radiation that is transmitted through the glazing ends up being absorbed by the shade itself and heating the adjacent space (Chapter 2). In addition, it was found that the SHGC value of the same internal shading device differed depending on the type of glazing it was combined with (McCluney and Mills, 1993). For purposes of this analysis, the $SHGC_{internal}$ was left constant and had a value of 1 for all the simulations conducted. This decision was based on the low efficacy of $SHGC_{internal}$ and the need to consider too many performance variables that tend to be very specific to individual buildings.

For the simulations run in simulation set A, no SHGC values were derived. At that stage, simulations were run primarily to undertake a performance analysis of various shading configurations. Glazing properties for the Base Case model remained as is indicated in Table 6-1 (as per existing selected typical office building – Mombasa Uni

Plaza). For simulation set B and C the SHGC $_{glazing}$ of the Base Case model was set at 0.86 as per the properties of clear single glazing (ASHRAE, 2013b, p. 17.5). As with the SHGC $_{internal}$, the SHGC $_{glazing}$ remained constant as only one type of glazing was used for all the simulations run to derive SHGC values. All this considered the reduction in the SHGC $_{total}$ was estimated taking into account the effect of the application of external shading devices of varying configuration and depth *i.e.* a reduction in SHGC $_{external}$.

As this study only considered fixed shading elements, it was expected that the shading coefficient for each orientation would vary due to relative movement of the sun throughout the day and year (the extent to which this happened was found to depend on the PF ratio – higher PF ratios would result in less variation as more solar radiation was blocked). To condense these results, the average SHGC values for all the daylight hours (found to fall between 0600 and 1900 hrs) were calculated for the 21st day of each month of the year (Table 6-4) and for various PF ratios for each of the sixteen orientations. According to ASHRAE (2013a), the 21st of the month is usually a convenient day for solar calculations because of its significance on four particular days: June 21st and December 21st represent the summer and winter solstices (and longest and shortest days) and March 21st and September 21st which are the closest to the equinox (same length days).

Table 6-4 Selected days of a typical year used for the solar calculations conducted in simulations B and C.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Day of the year	21	52	80	111	141	173	202	233	265	294	325	355

Following the estimation of SHGC values, energy simulation studies based on the climate data of a full year (8670 hours) were conducted. This study found that the reduction in the SHGC values offered reasonably good estimates of the energy saved. Subsequently, potential annual energy reduction estimates for the external shading devices per glazing area (kWh/m^2) for each SHGC reduction were calculated and presented for the sixteen selected orientations.

6.2 Simulation A results

The results indicated that the thermal performance of the typical office building was significantly improved by the application of external shading devices. Performance of the shading type applied was found to vary depending on the shading configuration, depth and facade orientation. This performance was gauged by examining the increase or decrease of the percentage number of discomfort hours during working hours only (0800 to 1800hrs). For comparison purposes, similar sized zones on an intermediate floor (3rd floor) with similar sized window openings of various facade orientations (N20°E, S80°E, S20°W, N70°W, N, E, S and W) were analysed with and without shading and the results presented in Section 6.2.1 and 6.2.2.

6.2.1 Horizontal, vertical and egg crate shading performance - N20°E, S80°E, S20°W, N70°W.

At first, the results of the simulation model without external shading elements (NS) were generated and compared to the results of simulation model with the existing shading (BC), which consisted of a 1.2m deep overhang. The analysis revealed that the existing shading significantly decreased annual discomfort hours indoors during working hours (Figure 6-6). BC performed better than NS by up to 27.3%, 6.6% and 5.6% under the ZV, DTV, and ADV ventilation strategies, respectively.

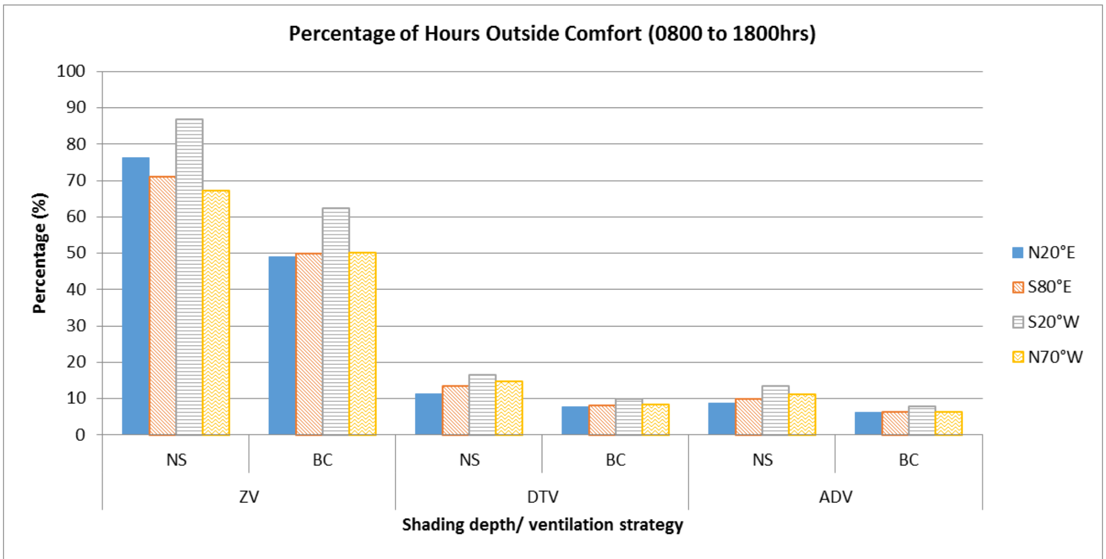


Figure 6-6 Comparison of percentage of hours outside comfort (above 31.5°) without shading (NS) and with shading (BC); under zero ventilation (ZV), day time ventilation (DTV) and all day ventilation (ADV) strategies.

The shading performance analysis run under ZV revealed that shading was useful in reducing the impact of solar gain and subsequently improved the thermal comfort even in the absence of natural ventilation. This was suggested to be potentially beneficial in air conditioned buildings where uncontrolled solar gain often increases cooling loads, plant size and overall running costs. The introduction of natural ventilation led to further reduction of discomfort hours. It was suggested that combining both design strategies would be advantageous in similar office buildings; where shading could be used to mitigate solar heat gain and natural ventilation used to flush out the unwanted heat gain, leaving air conditioning for warmest periods.

Next, the horizontal depth of the overhang was varied at incremental intervals of 0.3m and the impact on the percentage number of discomfort hours reviewed. A maximum depth of 1.8m was considered as informed by a review of optimum shading depth values derived for the selected building. The findings revealed that increasing the horizontal shading depth from NS to 1.8m significantly decreased discomfort hours indoors by up to 32.8%, 7.6% and 6.3% for simulations that were run under ZV, DTV and ADV, respectively (Figure 6-7). The rate of the reduction in discomfort hours subsided after the horizontal depth exceeded 1.2m. As the projection factor was higher than 0.8 (for a shading depths greater than 1.2m and window height of 1.5m), little else other than tilting the shade could work to reduce solar heat gain from a lower angle sun.

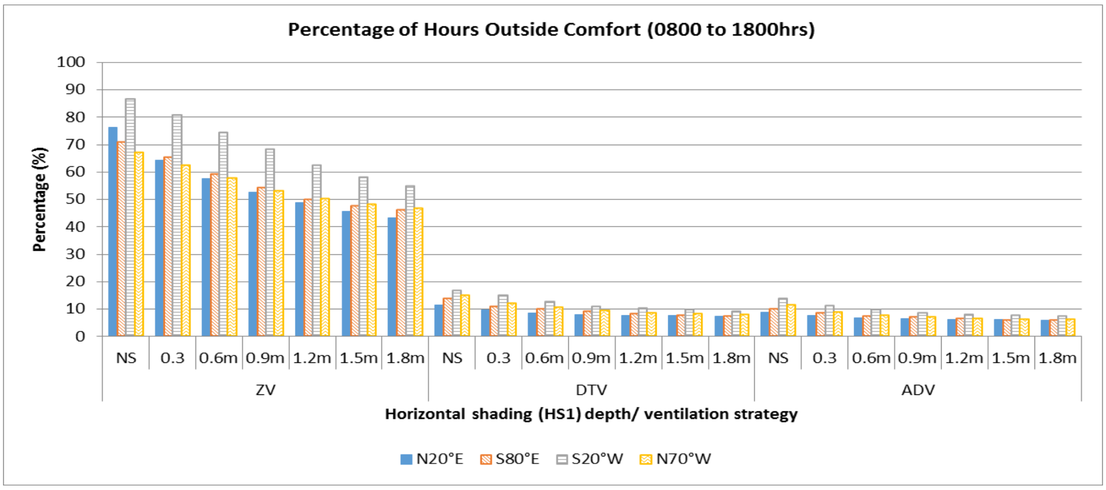


Figure 6-7 Reduction in discomfort hours due to application of various horizontal shade (HS1) depths; under zero ventilation, day time ventilation and all day ventilation strategies.

For the next set of simulations, the horizontal shade depth was broken down into a multiple number of shorter shading elements. This was done for practical purposes as large shading elements are often considered unsightly and/ or structural burdens. These results were compared to those of single overhang of similar overall horizontal depth. The results revealed that the shading elements totalling up to 1.8m significantly decreased discomfort hours indoors during working hours by up to 32.8%, 7.6% and 6.4% for simulations run under ZV, DTV and ADV, respectively (Figure 6-8). These results indicated that it was possible to reduce the overall depth of individual horizontal shading elements and get the same reduction in discomfort hours (found to lie within ±1%) by using more practical multiple shading elements of shorter depth.

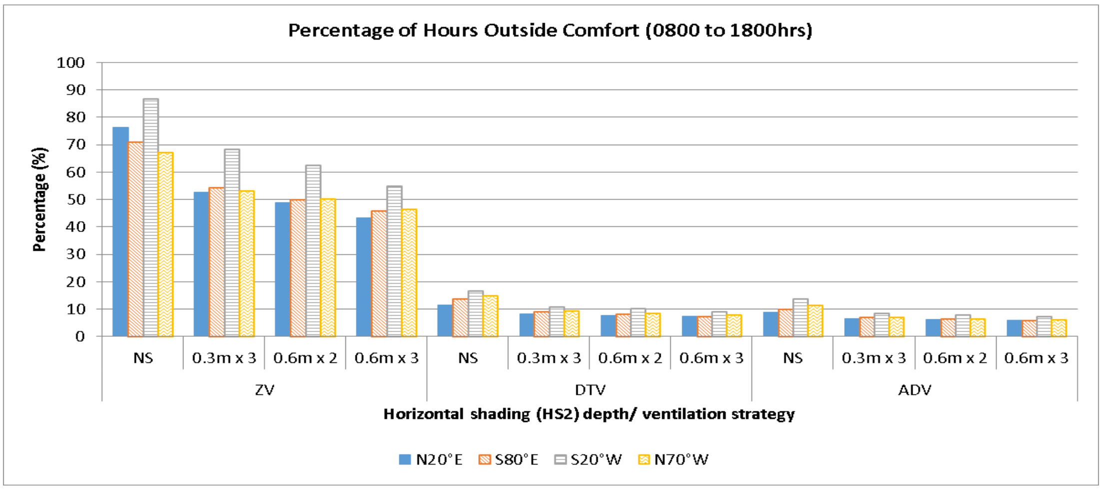


Figure 6-8 Reduction in discomfort hours due to application of various horizontal shade (HS2) depths; under zero ventilation, day time ventilation and all day ventilation strategies.

The impact of vertical shading in reducing discomfort hours indoors during working hours was reviewed independently of any other shading type. Two shading fins, positioned on the left and right of the window openings, of various depths were considered and the results presented in Figure 6-9. The results revealed that the shading type significantly decreased discomfort hours indoors during working hours by up to 39.8%, 8.3% and 6.2% for simulations run under ZV, DTV and ADV, respectively. These significant reductions were attributed to the shading blocking out of solar heat gain from low angle sun in the mornings and afternoon periods. In comparison to horizontal shading elements, it was also noted that the vertical shading had less impact in the reduction of discomfort hours (Section 6.2.2).

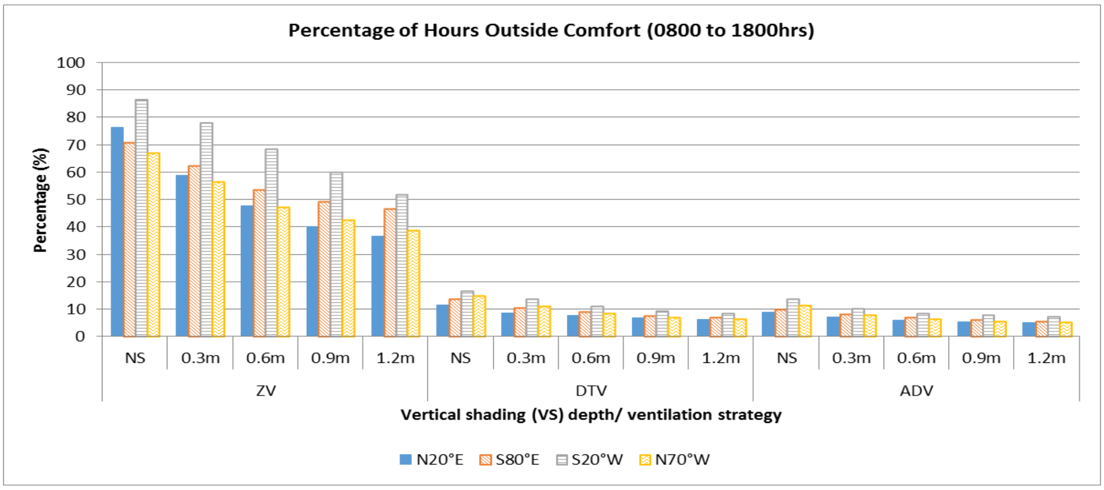


Figure 6-9 Reduction in discomfort hours due to application of various vertical shade (VS) depths; under zero ventilation, day time ventilation and all day ventilation strategies.

Following the review of the horizontal and vertical shading, the performance of a combination of egg crate shading was analysed for all the selected zones of varying orientations. The results indicated that egg crate shading led to a significant reduction of discomfort hours indoors during working hours. It was found that the number of discomfort hours was almost halved in comparison to horizontal or vertical elements and for much smaller shade depths. This performance was attributed to the complex shading masks created by egg crate shading.

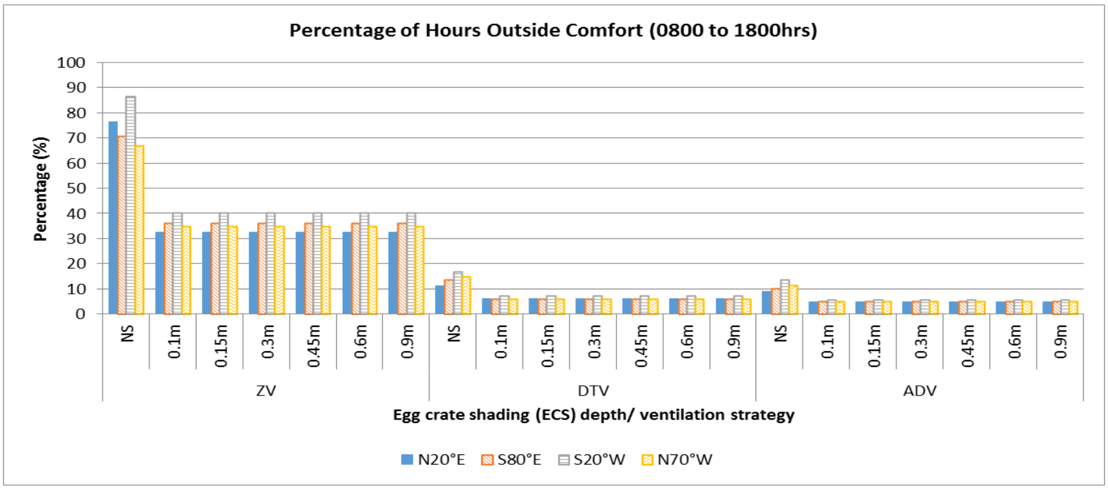


Figure 6-10 Reduction in discomfort hours due to application of various egg crate shading (ECS) depths; under zero ventilation, day time ventilation and all day ventilation strategies.

6.2.2 Horizontal, vertical and egg crate shading performance – North (N), East (E), South (S) and West(W).

Following the review of the simulation results, the next set of simulations examined the performance of the three shading types with respect to four cardinal orientations (N, E, S and W). The main aim of this process was to determine the most suitable shading type for each orientation. Due to the relative movement of the sun, various orientations in varied latitude locations experience varied levels of solar radiation (Chapter 1). A review of the average solar radiation in latitude 4°S revealed that the west and the east orientations were more prone to solar heat gain specifically due to the low angle of the sun in the afternoon and morning periods, respectively. Figure 6-11 shows the average solar radiation experienced during the equinox. This makes it harder to shade windows located on these facade orientations. On the other hand, due to the sun being almost always overhead, the north and south orientations are less susceptible to solar heat gain.

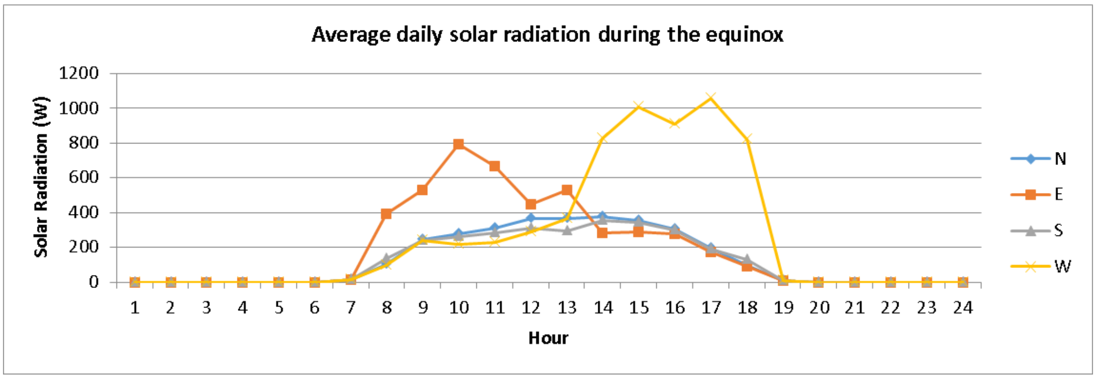


Figure 6-11 Average daily solar radiation during the equinox for selected orientations.

For horizontal shading, the west orientated zone showed the greatest reduction in discomfort hours with each increase in shading depth. Although this zone showed the highest reduction, it still experienced the highest proportion of discomfort hours in comparison to the east, north and south orientated zones. This was also the case in the east orientated zone although to a smaller extent. Following a review of the results illustrated in Figure 6-12, it was surmised that the horizontal shades were more effective in reducing the percentage number of discomfort hours in the zones orientated to the north and south and were less effective in the east and west.

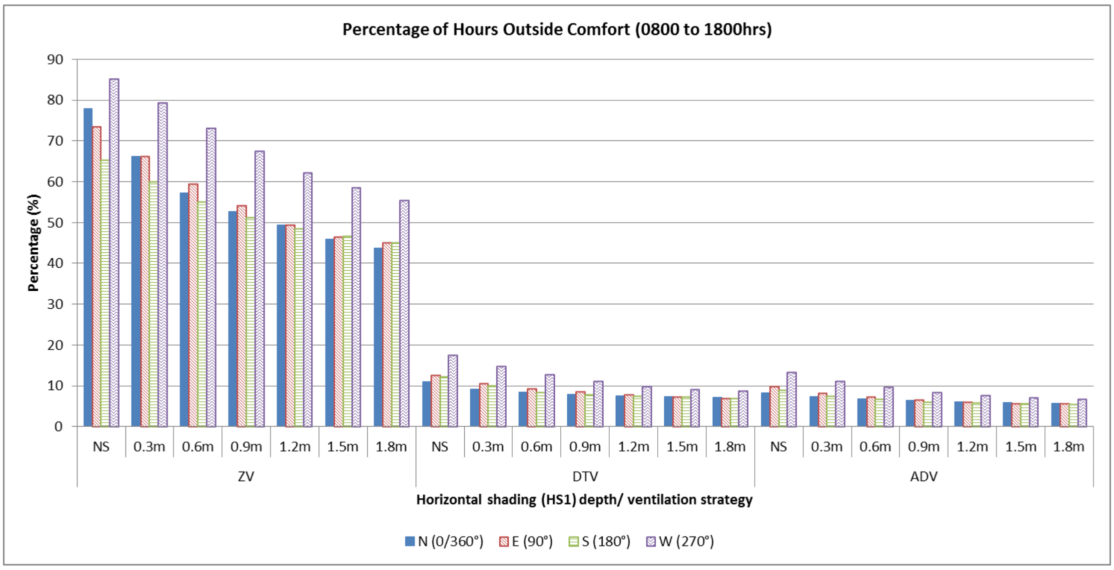


Figure 6-12 Reduction in discomfort hours due to application of various horizontal shade (HS1) depths; under zero ventilation, day time ventilation and all day ventilation strategies.

Vertical shading had less of an impact in the reduction of discomfort hours for all orientations when compared to horizontal shading elements. In particular, zones orientated to the west and the east showed the highest reduction in percentage discomfort hours (Figure 6-13). This was explained to be due to their ability to reduce the amount of solar heat gain due to low angle sun in the mornings (east) and the afternoons (west). Next to the west and the east, the north oriented zone was found to perform better than the south zone.

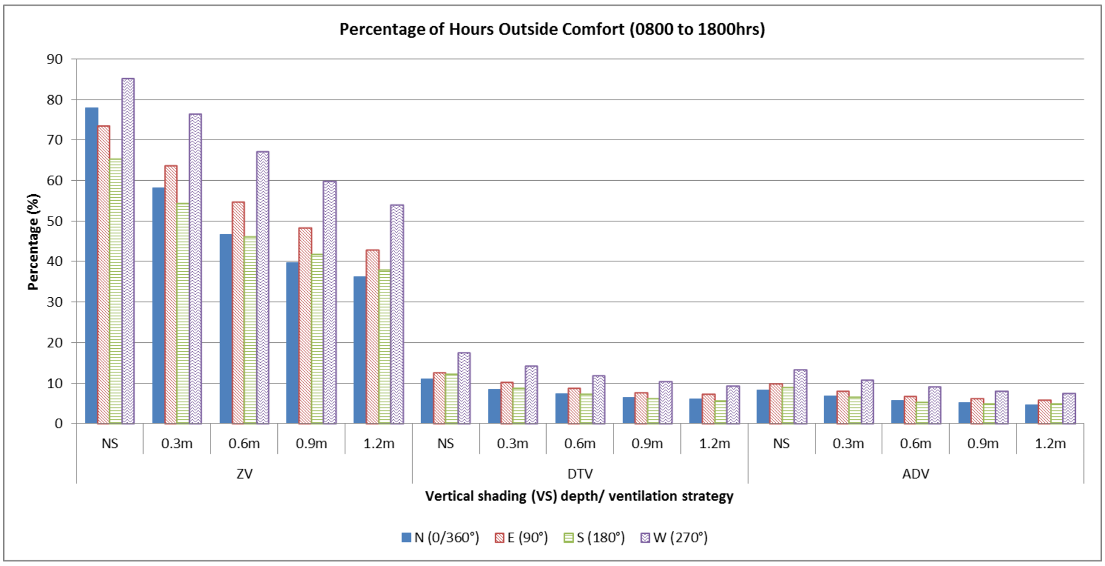


Figure 6-13 Reduction in discomfort hours due to application of various vertical shading (VS) depths; under zero ventilation, day time ventilation and all day ventilation strategies.

The use of egg crate shading significantly narrowed down the gap in the percentage of discomfort hours for all orientations (Figure 6-14). It was also found to be highly effective for significantly smaller shading depths. In fact, it was noted that a combined horizontal and vertical shade depth of more than 0.1m did not significantly reduce the number of discomfort hours. In terms of orientation, the west and east orientated zones did not perform as well as the north and south orientated zones when egg crate shading was applied.

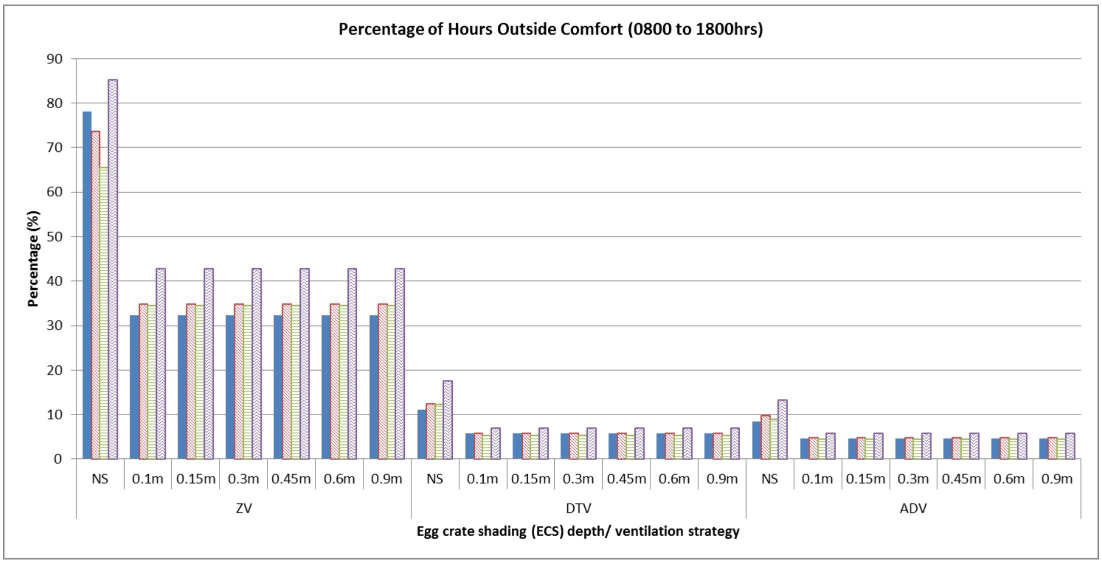


Figure 6-14 Reduction in discomfort hours due to application of various egg crate shading (ECS) depths; under zero ventilation, day time ventilation and all day ventilation strategies.

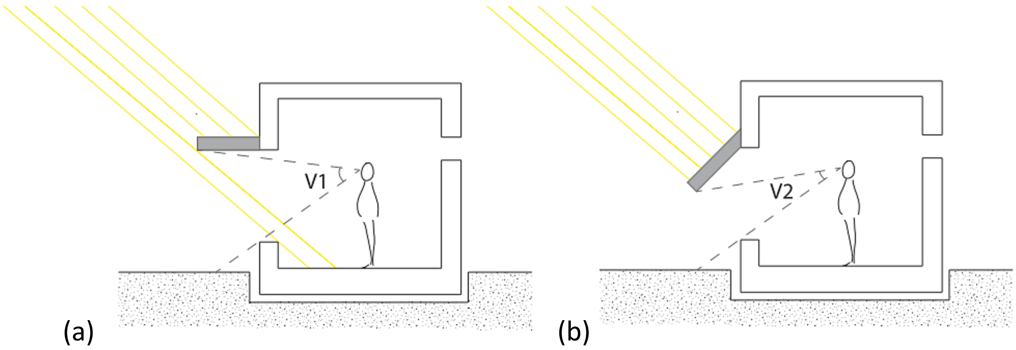
Through these performance analysis studies, external shading devices were shown to have a significant impact on improving internal thermal conditions and as a result, extending comfort conditions in office buildings of the local region. In general, in terms of orientation, the zone exposed to the west was found to experience the highest levels of solar gain. Naturally, it was the worst affected by the lack of sun shading and had the highest percentage of discomfort hours even when shaded with similar sized elements to other orientations.

Horizontal shades were found to be most effective when the sun was on the opposite side of the building facade considered and at a high angle – a condition common to north and south facing orientations. For east and west facades which are prone to low angle sun, it was determined that this type of device would have to be tilted to shelter the window completely. However, in addition to significantly blocking outward views, this would also result in reduced natural lighting levels. Overall, it was concluded that horizontal shades had the greatest impact on north, south, east, and west orientated zones, respectively.

Vertical shades were found to be most effective when the sun was to one side of the elevation, such as an eastern or western orientation. These devices were also found to be most effective when the sun was opposite to the building facade considered and almost completely sheltering the whole window *i.e.* tilted. Overall, mainly due to their ability to block low angled sun that affects these orientations, vertical shades were found to have the greatest impact on the west and east facades, respectively.

Egg crate shades were found to be the most effective in decreasing the number of discomfort hours when applied to any orientation and for relative low PF ratios. This was suggested to be due to their configuration (a combination of horizontal and vertical elements that if used together result in a complex shading mask) which helped block solar radiation from varied sun angles.

Generally, other than increasing shading depth/PF ratio, it was determined that the only option to improve the shading performance of either shading type especially in the west and east oriented zones would be to use tilted elements. Essentially, tilted shading elements work by decreasing the area of glazing surface area exposed to solar radiation. However, these elements were found to often have the disadvantage of blocking views to the outside, reducing visible light transmission (which can result in high lighting requirements and subsequently lead to increased energy demand for lighting) and may even result in making the building appear unsightly (Figure 6-15).



(a) (b)

Figure 6-15 In comparison to perpendicular shading devices (a), tilted devices (b) can result in blocking views and reduction in visible light transmission.

A summary of guidelines derived from simulation set 'A' are illustrated in Figure 6-16.

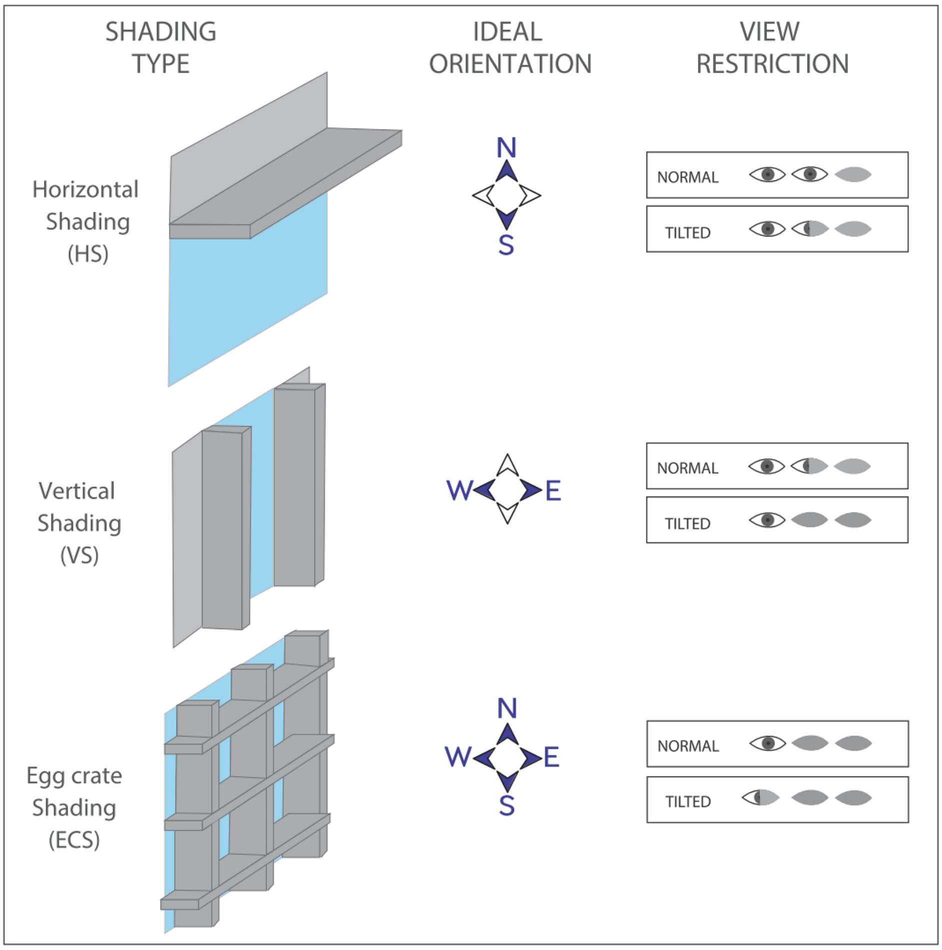


Figure 6-16 Shading selection guidelines (Latitude 4°S)

6.3 Simulation B results

Guided by the results of the initial simulations results, the subsequent stage of the simulation study involved the derivation of SHGC values due to external shading. Specifically, the results presented in this section were derived from simulations run for the selected typical office building under its existing orientation. As the existing building is offset by approximately 20° off the north-south axis, the four selected zones were found to represent building facade orientations of 20° (N20°E), 110° (S80°E), 200° (S20°W) and 290° (N70°W).

To begin with, the SHGC of horizontal shades were calculated and presented for selected PF ratios in Table 6-5. From this, it was observed that the difference between the SHGC values of horizontal shades applied to different facade orientations was relatively small. It was suggested that this might be explained by the significantly high levels of diffuse solar radiation experienced in the region. Climate analysis in Chapter 1 revealed this to be a common occurrence in humid regions. Similarly, a review of the Mombasa weather data file showed this to be the case locally (Chapter 1). For clarity, colour coding was used to correlate the selected orientations, and their respective curve fit graphs.

Table 6-5 SHGC of horizontal shades based on PF ratio (Simulation B).

PF (Horizontal)	0	0.2	0.4	0.6	0.8	1	1.2
SHGC N20°E	1	0.84	0.72	0.63	0.56	0.51	0.47
SHGC S80°E	1	0.84	0.72	0.62	0.55	0.50	0.46
SHGC S20°W	1	0.84	0.72	0.64	0.57	0.52	0.48
SHGC N70°W	1	0.85	0.73	0.63	0.56	0.51	0.47

In addition to the table of SHGC values, curve fits (Figure 6-17) and their respective equations (Table 6-6) were presented for various PF ratios for different orientations. Given the highly positive correlation factors indicated by the R^2 values, it was suggested that this information provided very close estimates of the SHGC value from any PF values (horizontal shading) applied to the simulation typical office building. This was further validated by comparing the SHGC values derived using the equations and those derived from running further simulations.

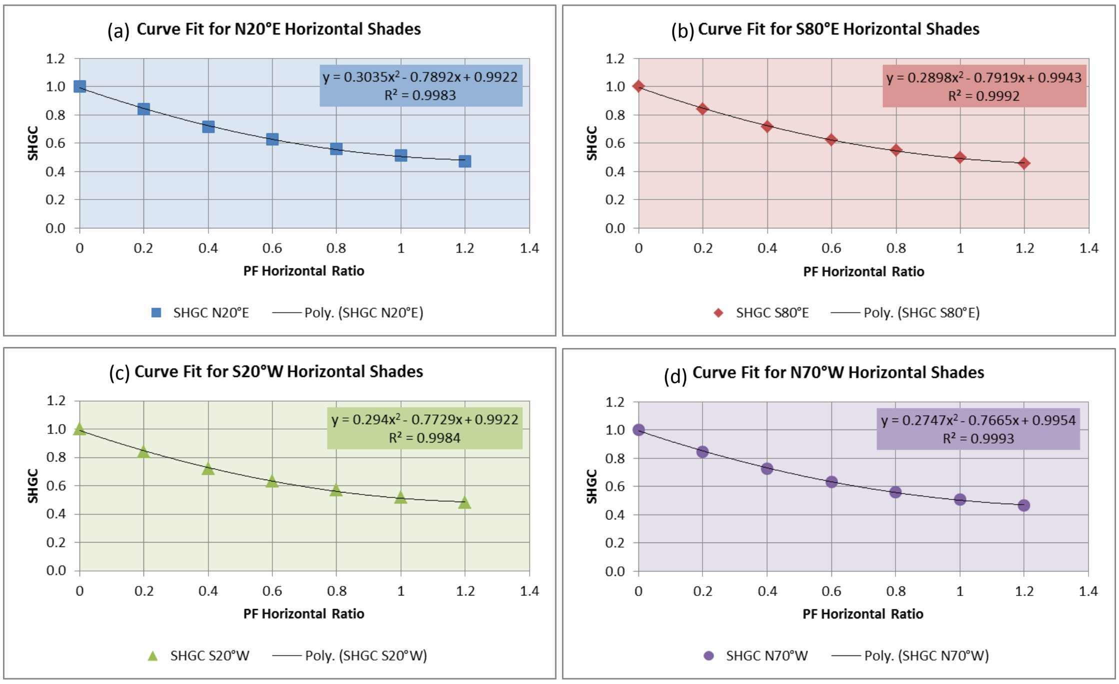


Figure 6-17 (a) to (d) SHGC Curve Fits for horizontal shades for N20°E, S80°E, S20°W and N70°W orientations.

Table 6-6 SHGC Curve Fit Equation for N20°E, S80°E, S20°W and N70°W, where 'x' is the PF ratio and 'y' is the SHGC.

Orientation	SHGC Curve Fit Equation	R^2
N20°E	$y = 0.3035x^2 - 0.7892x + 0.9922$	0.9983
S80°E	$y = 0.2898x^2 - 0.7919x + 0.9943$	0.9992
S20°W	$y = 0.294x^2 - 0.7729x + 0.9922$	0.9984
N70°W	$y = 0.2747x^2 - 0.7665x + 0.9954$	0.9993

It has already been explained in Section 6.1 that SHGC gives an indication of reduction in solar heat gain due to the application of external shading elements. Similarly, these reductions would reflect a reduction of discomfort attributed to a reduction in this gain. In terms of comfort performance, the SHGC results were found to be a reflection of the performance analysis carried out in Section 6.2.1 where it was noted that the comfort improvement was significantly higher on N70°W and S80°E. Additionally, it was found that in as much as comfort improvement was higher on the aforementioned facades due to higher levels of solar heat radiation received, the SHGC indicated that the horizontal shading was more effective when used in N20°E and S20°W.

Next, the SHGC of vertical shades were derived for the four orientations and presented for selected PF ratios in Table 6-7. Unlike the previous results obtained from the horizontal shades analysis, more variation was observed in the SHGC of vertical shades derived for the different facade orientations. The SHGC values were found to be highest in the N70°W. This was explained to be due to the fact that former facade was more exposed to the west orientation, which has been shown to be the most prone to solar heat gain (Chapter 1 and 2).

Table 6-7 SHGC of vertical shades based on PF ratio.

PF (Vertical)	0	0.1	0.2	0.3	0.4
SHGC N20°E	1	0.70	0.50	0.38	0.30
SHGC S80°E	1	0.74	0.56	0.44	0.36
SHGC S20°W	1	0.84	0.72	0.64	0.57
SHGC N70°W	1	0.85	0.73	0.63	0.56

As with the horizontal shading, curve fits (Figure 6-18) and their respective equations (Table 6-8) were presented for various PF ratios for different orientations. This information was found to give close estimates of the SHGC value for any PF values for vertical shading applied to the simulation typical office building. This was confirmed by a review of the high positive correlations derived for the curve fits (R^2 values) and a comparison of SHGC values derived from the equations and those obtained from further simulations.

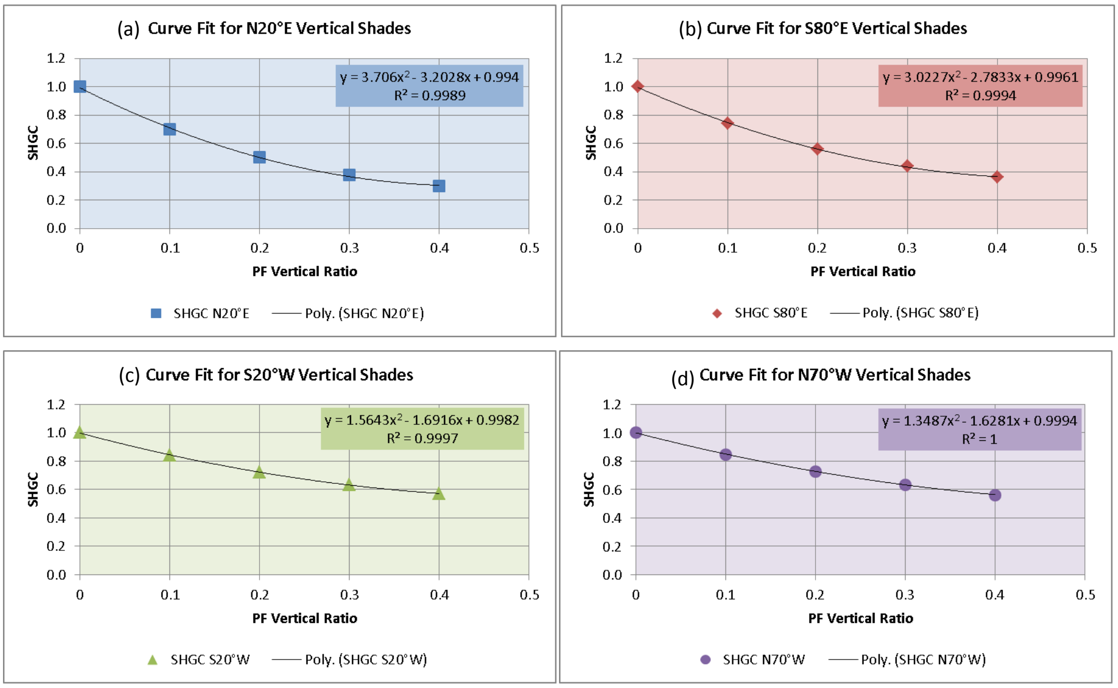


Figure 6-18 (a) to (d) SHGC Curve Fits for vertical shades for N20°E, S80°E, S20°W and N70°W orientations.

Table 6-8 SHGC Curve Fit Equations for N20°E, S80°E, S20°W and N70°W, where ‘x’ is the PF ratio and ‘y’ is the SHGC.

Orientation	SHGC Curve Fit Equation	R^2
N20°E	$y = 3.706x^2 - 3.2028x + 0.994$	0.9989
S80°E	$y = 3.0227x^2 - 2.7833x + 0.9961$	0.9994
S20°W	$y = 1.3487x^2 - 1.6281x + 0.9994$	1
N70°W	$y = 1.5643x^2 - 1.6916x + 0.9982$	0.9997

The SHGC results indicated that comfort improvement was higher on the N70°W and S80°E orientations on the application of vertical shades. Further, the SHGC of egg crate shades were derived for the four main orientations and the selected PF ratio results presented in Table 6-9. As with the results obtained from the horizontal shades analysis, little variation (ranging from 0.01 to 0.03) was observed in the SHGC values for different orientations. Additionally, the SHGC of egg crate shades were significantly low irrespective of orientation. This may be explained by the high efficiency of egg crate shading brought on by the complex shading masks it creates.

Table 6-9 SHGC of egg crate shades based on PF ratio.

PF (Horizontal)	0	0.2	0.4	0.6
PF (Vertical)	0	0.1	0.2	0.3
N20°E	1	0.23	0.23	0.23
S80°E	1	0.24	0.24	0.24
S20°W	1	0.22	0.22	0.22
N70°W	1	0.25	0.25	0.25

Furthermore, the individual horizontal and vertical curve fits (Figure 6-19 and Figure 6-20) and their respective equations (Table 6-10) were derived to allow for the derivation of SHGC values for other PF ratios. Given the high positive correlation factors (over 0.9), they provided very close estimates of the SHGC for egg crate shading applied to the simulation typical office building. This was confirmed by a review of the high positive correlations (R^2 values) and a comparison of derived SHGC values with further simulation results.

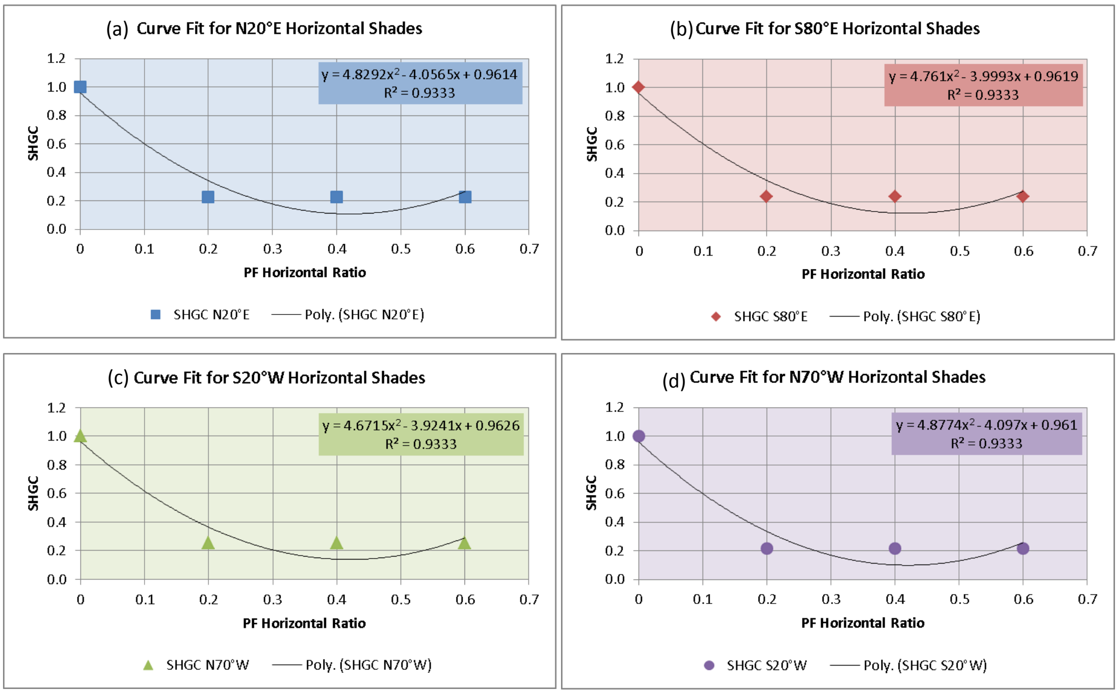


Figure 6-19 (a) to (d) SHGC Curve Fits for egg crate shades (horizontal) for N20°E, S80°E, S20°W and N70°W orientations.

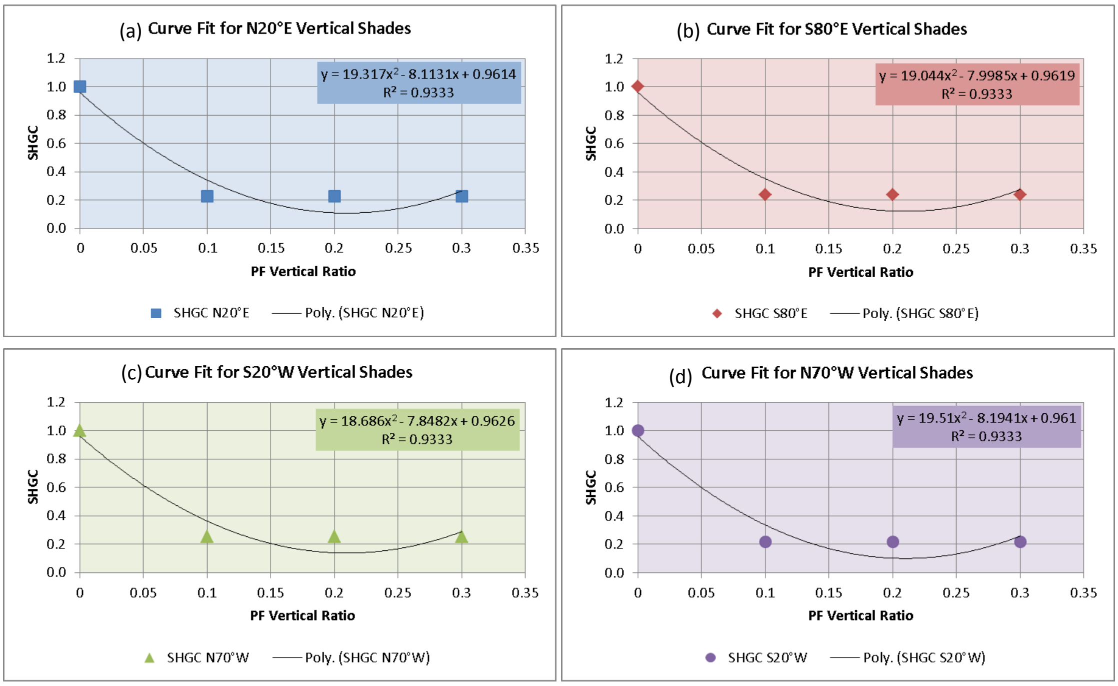


Figure 6-20 (a) to (d) SHGC Curve Fits for egg crate shades (vertical) for N20°E, S80°E, S20°W and N70°W orientations.

Table 6-10 SHGC Curve Fit Equation for N20°E, S80°E, S20°W and N70°W, where 'x' is the PF ratio and 'y' is the SHGC.

Horizontal Shades			Vertical Shades		
Orientation	**SHGC Curve Fit Equation**	**R^2**	**Orientation**	**SHGC Curve Fit Equation**	**R^2**
N20°E	$y = 4.8292x^2 - 4.0565x + 0.9614$	0.9333	**N20°E**	$y = 19.317x^2 - 8.1131x + 0.9614$	0.9333
S80°E	$y = 4.761x^2 - 3.9993x + 0.9619$	0.9333	**S80°E**	$y = 19.044x^2 - 7.9985x + 0.9619$	0.9333
S20°W	$y = 4.8774x^2 - 4.097x + 0.961$	0.9333	**S20°W**	$y = 19.51x^2 - 8.1941x + 0.961$	0.9333
N70°W	$y = 4.6715x^2 - 3.9241x + 0.9626$	0.9333	**N70°W**	$y = 18.686x^2 - 7.8482x + 0.9626$	0.9333

The significantly low SHGC values derived for egg crate shading suggested that comfort discomfort levels would be significantly lower due to applying this shading type compared to other shading types. This confirmed the findings of the performance analysis carried out in section 6.2.1 that found egg crate shading to be the most effective irrespective of orientation.

Overall, the results of this study were found suitable for predicting the impact of various shading types on typical office buildings. Consequently, it was suggested that the results of this exercise could serve as a useful reference for designers during the early design stages to help them predict the potential impact of the SHGC external on reducing solar heat gain and consequently reduce the need for cooling energy in typical office buildings at the latitude of 4°S.

6.4 Simulation C results

Following the derivation of SHGC values for the selected typical office building under its existing orientation, the next step involved the derivation of the SHGC values for simulations run using the selected typical office building under 'true' north-south orientation. Results were derived for N – 0/360°, NNE – 22.5°, NE - 45°, ENE – 67.5°, E - 90°, ESE – 112.5°, SE - 135°, SSE -157.5°, S - 180°, SSW – 202.5°, SW- 225°, WSW – 247.5°, W - 270°, WNW – 292.5°, NW - 315° and NNW – 337.5° orientations. This was done to allow for the transferability of the research outcomes to similar type buildings for a variety of building facade orientations. Additionally, to establish the impact of SHGC reduction on indoor thermal comfort, these results were also correlated to the reduction of discomfort hours.

The data derived from these simulations was also found to offer a reasonable estimate of energy saved due to the reduction of SHGC. Therefore, based on information derived for the glazing area, orientation of the window and the PF ratio, estimates of the energy reduction resulting from the use of external shading devices were derived for the selected orientations. Unlike the previous studies within this research, the upper thermal comfort range for the energy use simulations was adjusted to 26.7°C as was derived using the PMV comfort model as defined in ASHRAE Standard 55 (ASHRAE, 2013a). This was in keeping with the Chapter 1 findings that suggested the PMV model to be more suitable for predicting comfort for buildings that use mechanical conditioning.

The SHGC values of horizontal shades applied to the sixteen main orientations were calculated and presented in Table 6-11. It was noted that an increase in the PF ratio (due to an increase in shading depth) resulted in a reduction in the SHGC that indicated a reduction in the total solar heat gain. For all the orientations, it was found that the solar heat gain could be reduced by almost 50% when using an effective horizontal shading depth similar to the height of the selected window (PF ratio of 1). Additionally, it was observed that the difference in the SHGC values from the use of horizontal external shades was relatively small for different orientations and for similar PF ratios. This was attributed to high levels of diffuse radiation, especially during morning hours. For clarity, colour coding was used to correlate the selected orientations, and their respective curve fit graphs.

Table 6-11 SHGC of horizontal shades for N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW based on PF ratio.

PF (Horizontal)	0	0.2	0.4	0.6	0.8	1	1.2
SHGC North (N)	1	0.84	0.71	0.62	0.56	0.51	0.47
SHGC NNE	1	0.84	0.72	0.63	0.57	0.52	0.48
SHGC NE	1	0.84	0.72	0.63	0.56	0.51	0.47
SHGC ENE	1	0.84	0.72	0.62	0.55	0.50	0.46
SHGC East (E)	1	0.84	0.72	0.62	0.55	0.50	0.45
SHGC ESE	1	0.84	0.72	0.62	0.55	0.50	0.46
SHGC SE	1	0.84	0.72	0.63	0.56	0.51	0.47
SHGC SSE	1	0.84	0.73	0.64	0.57	0.52	0.49
SHGC South (S)	1	0.84	0.72	0.64	0.57	0.53	0.49
SHGC SSW	1	0.84	0.73	0.64	0.57	0.52	0.48
SHGC SW	1	0.85	0.73	0.64	0.57	0.52	0.47
SHGC WSW	1	0.85	0.73	0.64	0.57	0.52	0.47
SHGC West (W)	1	0.85	0.73	0.64	0.57	0.52	0.47
SHGC WNW	1	0.85	0.73	0.64	0.57	0.51	0.47
SHGC NW	1	0.85	0.72	0.63	0.56	0.51	0.47
SHGC NNW	1	0.84	0.72	0.63	0.56	0.51	0.48

In addition to the SHGC values, curve fits (Figure 6-21 and Figure 6-22) and their respective equations (Table 6-12) were presented for the selected orientations. The highly positive correlation factors (R^2 values) indicated that they provided very close estimates of the SHGC values for any PF value for horizontal shading applied to the selected orientations. The curve fits were further validated by comparing SHGC values derived using dynamic simulations and those derived using the curve fits, and found to be accurate.

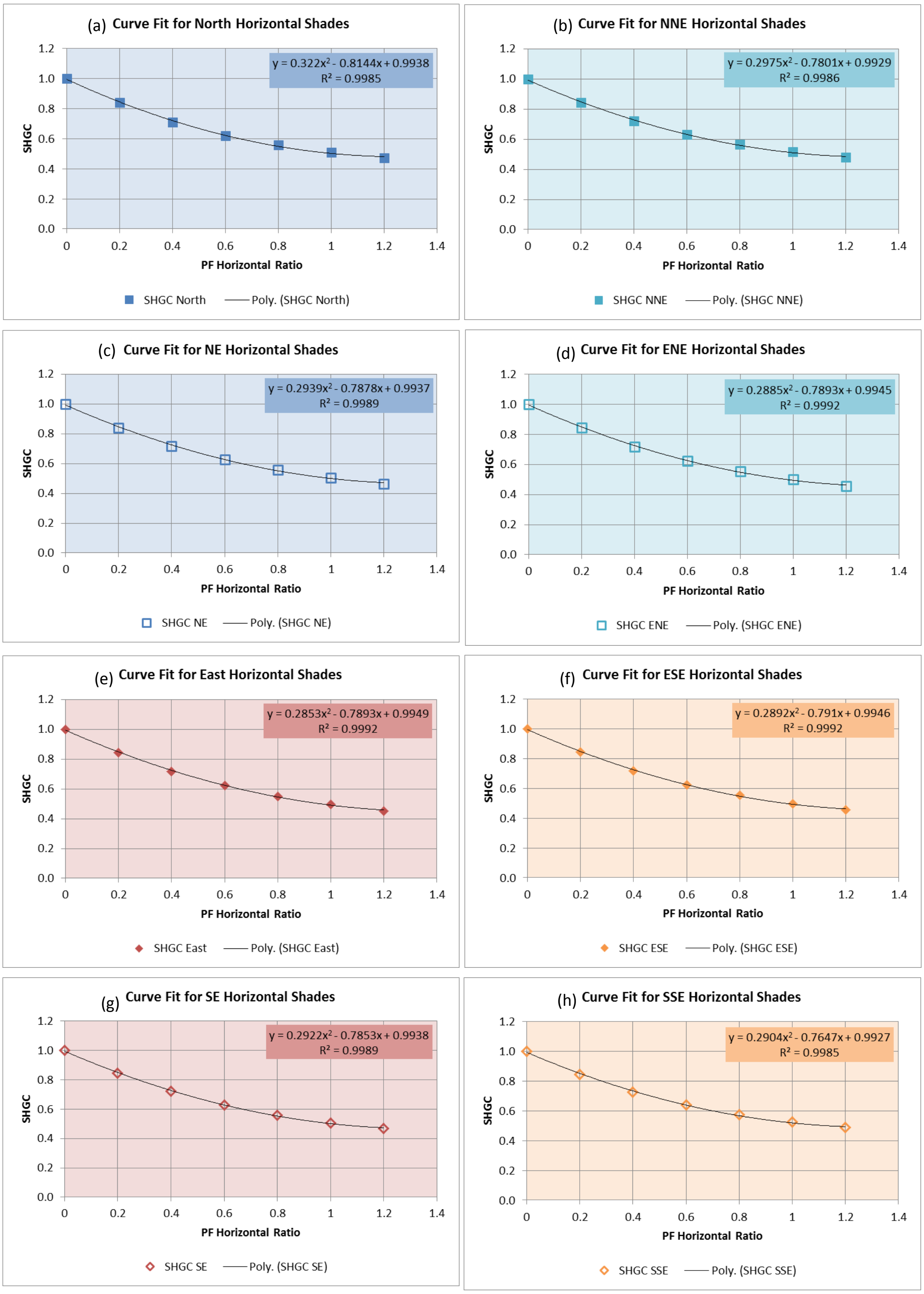


Figure 6-21 (a) to (h) SHGC Curve Fits for horizontal shades for N, NNE, NE, ENE, E, ESE, SE and SSE orientations.

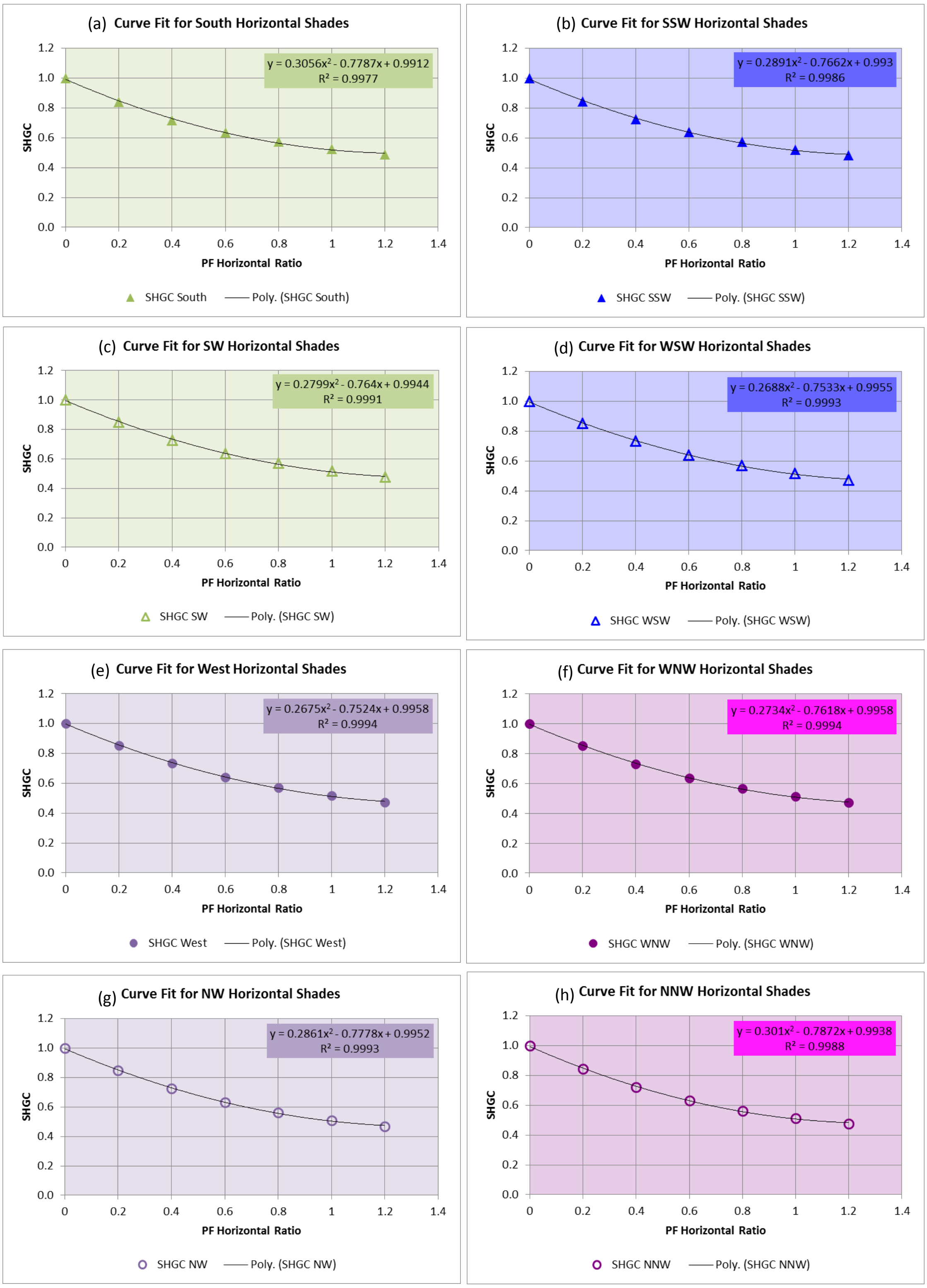


Figure 6-22 (a) to (h) SHGC Curve Fits for horizontal shades for S, SSW, SW, WSW, W, WNW, NW and NNW orientations.

Table 6-12 SHGC Horizontal Curve Fit Equation for N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW, where 'x' is the PF ratio and 'y' is the SHGC.

Orientation	SHGC Curve Fit Equation	R^2
North (0°)	$y = 0.322x^2 - 0.8144x + 0.9938$	0.9985
NNE (22.5°)	y = 0.2975x2 - 0.7801x + 0.9929	0.9986
NE (45°)	$y = 0.2939x^2 - 0.7878x + 0.9937$	0.9989
ENE (67.5°)	y = 0.2885x2 - 0.7893x + 0.9945	0.9992
East (90°)	$y = 0.2853x^2 - 0.7893x + 0.9949$	0.9992
ESE (112.5°)	y = 0.2892x2 - 0.791x + 0.9946	0.9992
SE (135°)	$y = 0.2922x^2 - 0.7853x + 0.9938$	0.9989
SSE (157.5°)	y = 0.2904x2 - 0.7647x + 0.9927	0.9985
South (180°)	$y = 0.3056x^2 - 0.7787x + 0.9912$	0.9977
SSW (202.5°)	y = 0.2891x2 - 0.7662x + 0.993	0.9986
SW (225°)	$y = 0.2799x^2 - 0.764x + 0.9944$	0.9991
WSW (247.5°)	y = 0.2688x2 - 0.7533x + 0.9955	0.9993
West (270°)	$y = 0.2675x^2 - 0.7524x + 0.9958$	0.9994
WNW (292.5°)	y = 0.2734x2 - 0.7618x + 0.9958	0.9994
NW (315°)	$y = 0.2861x^2 - 0.7778x + 0.9952$	0.9993
NNW (337.5°)	y = 0.301x2 - 0.7872x + 0.9938	0.9988

To put into perspective, the impact of SHGC reductions on indoor thermal comfort, SHGC values were correlated to the subsequent percentage discomfort hours and the results presented in Figure 6-23 and Figure 6-24. The review indicated that the SHGC reductions led to significant reductions in discomfort hours. Percentage discomfort for selected facade orientations varied from 10% to 4% for western orientated facades and northern orientated facades, respectively. Interestingly, in as much as the SHGC values were similar for corresponding PF ratios for different orientations, the percentage discomfort hours tended to show more variation. This was attributed to varying solar gain received on each facade; in Section 6.2.2 it was found that higher the solar gain resulted in higher corresponding discomfort hours.

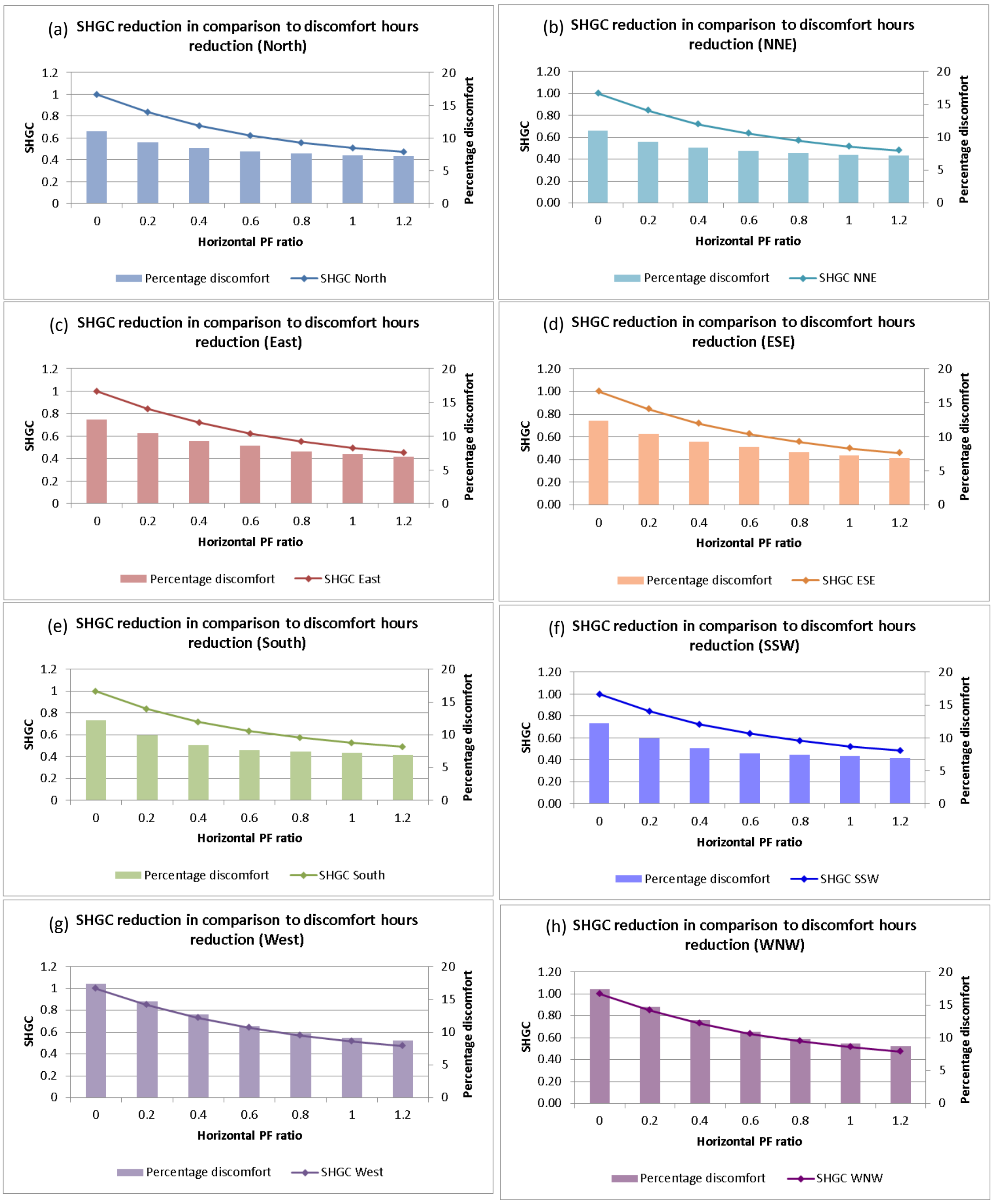


Figure 6-23 (a) to (h) SHGC horizontal reduction impact on comfort for N, E, S, W, NNE, ESE, SSW and WNW orientations.

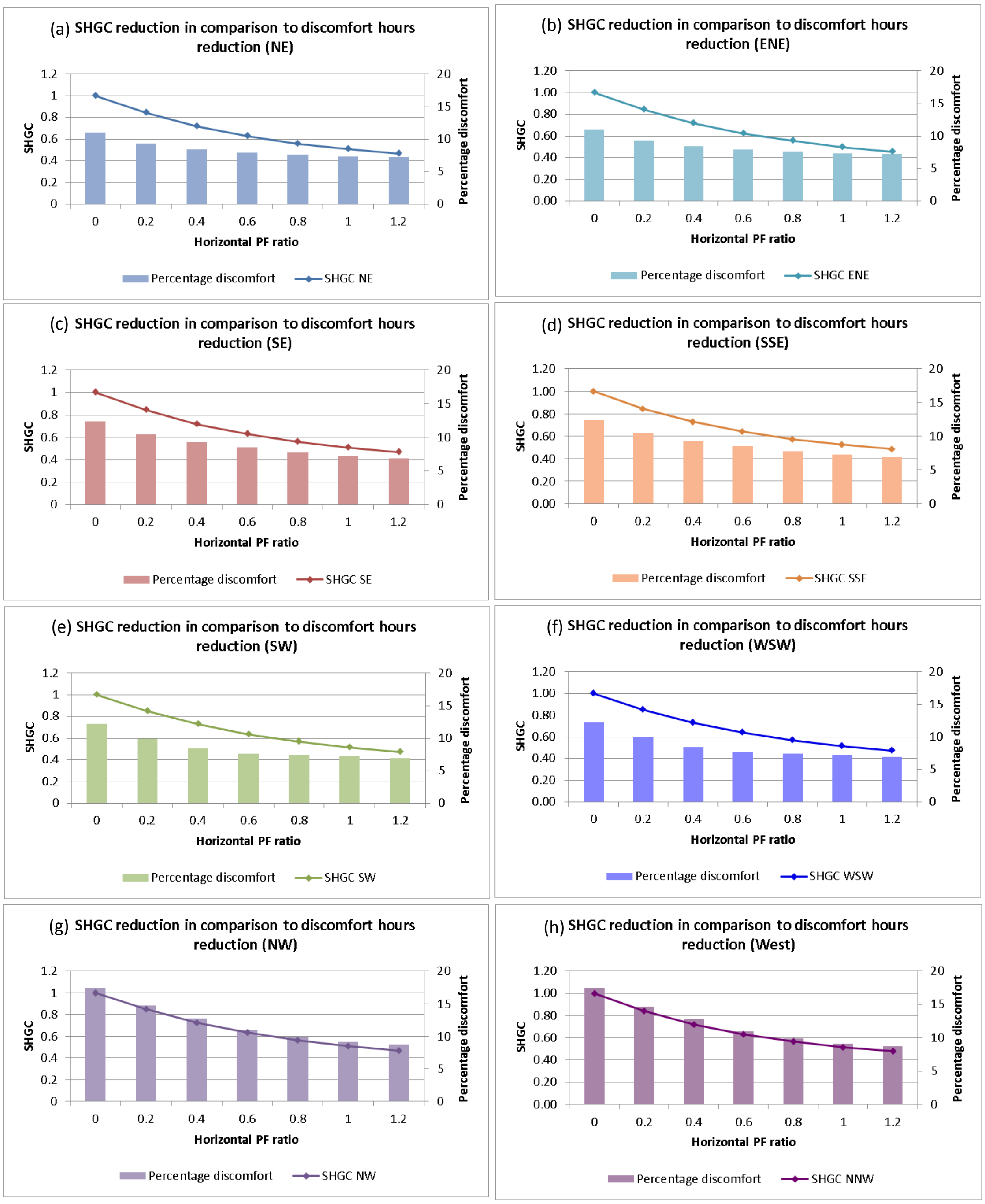


Figure 6-24 (a) to (h) SHGC horizontal reduction impact on comfort for NE, SE, SW, NW, ENE, SSE, WSW and NNW orientations.

Subsequently, the potential energy reductions due to the application of horizontal shading to each of the selected orientations were calculated and the results presented in Figure 6-25. Energy reductions were found to be significantly higher in the west, east, north and south facades, respectively. The same trend was observed in western, eastern, northern and southern orientations, respectively. Additionally, it was revealed that although the previously derived SHGC values for the selected orientations were found to be relatively similar for the same PF ratios, the energy reductions showed greater variation. In both cases, the notably higher variations in energy reduction were attributed to the corresponding solar gain. Previously in Section 6.2, it was determined that the solar gain varied with different orientations with the western orientations being the most prone to solar heat gain and the south being the least prone to solar heat gain. Therefore, given that the orientations with higher reductions also received higher levels of solar radiation, it was deemed rational to expect them to have a reduction proportional to their gain.

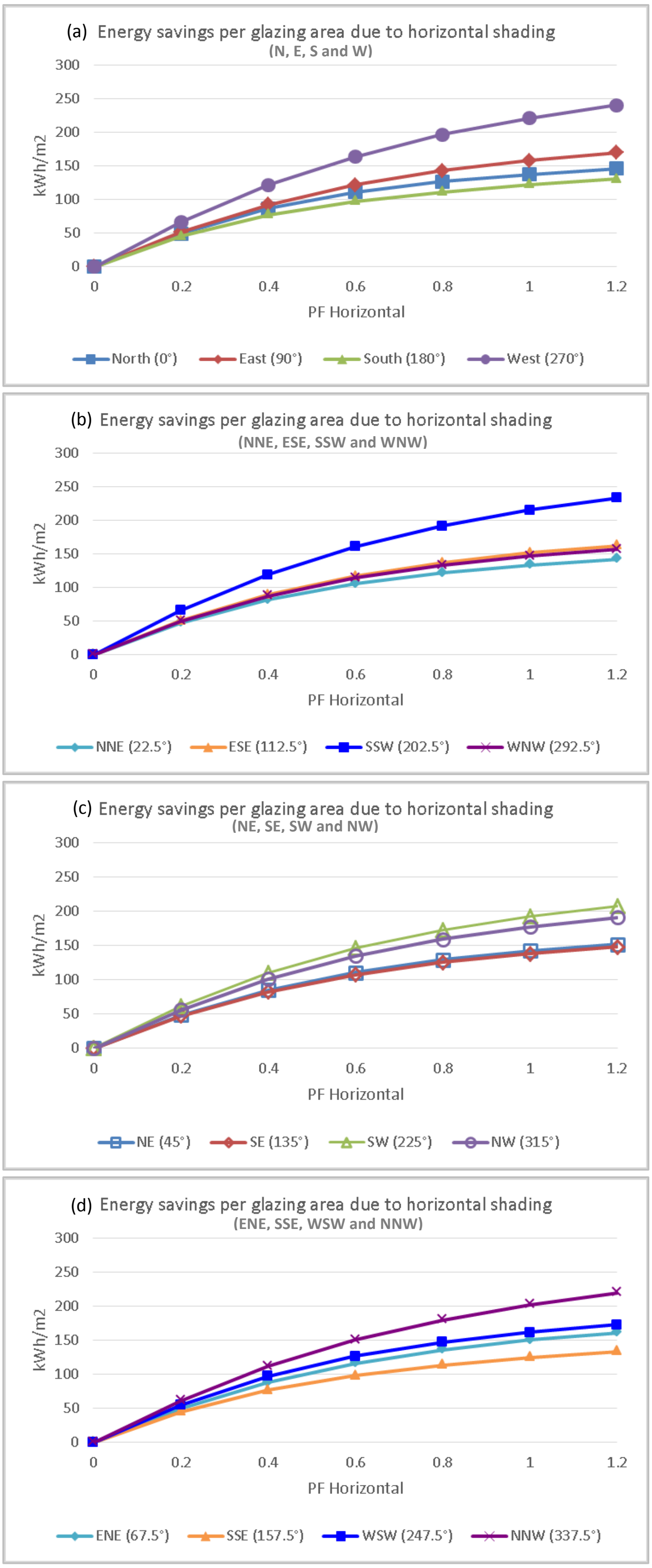


Figure 6-25 (a) to (d) Energy savings per glazing area due to the provision of horizontal shading devices (N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW orientations).

Next, the SHGC values of vertical shades applied to the sixteen main orientations were calculated and presented in Table 6-13. Unlike the results obtained from the horizontal shades analysis, more variation was observed in the SHGC values for different orientations and with similar PF ratios. This variation was found to be grouped in terms of north and south (lower SHGC values) and east and west facades (higher SHGC values). The higher SHGC values indicated that the vertical shading type was more effective in reducing solar heat gain in the respective orientation. This confirms previous findings that found vertical shading to be more suitable for west and east facing facades. The SHGC values were found to be higher in the western facing orientations and lower in the northern facing orientations.

Table 6-13 SHGC of vertical shades for N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW based on PF ratio.

PF (Vertical)	0	0.1	0.2	0.3	0.4
SHGC North (N)	1	0.67	0.48	0.36	0.29
SHGC NNE	1	0.70	0.51	0.38	0.30
SHGC NE	1	0.71	0.52	0.40	0.32
SHGC ENE	1	0.73	0.54	0.42	0.34
SHGC East (E)	1	0.74	0.57	0.45	0.36
SHGC ESE	1	0.74	0.56	0.44	0.36
SHGC SE	1	0.72	0.53	0.41	0.33
SHGC SSE	1	0.71	0.52	0.40	0.32
SHGC South (S)	1	0.68	0.49	0.38	0.30
SHGC SSW	1	0.68	0.48	0.36	0.29
SHGC SW	1	0.69	0.49	0.37	0.29
SHGC WSW	1	0.73	0.55	0.42	0.34
SHGC West (W)	1	0.76	0.60	0.48	0.39
SHGC WNW	1	0.75	0.58	0.46	0.37
SHGC NW	1	0.72	0.52	0.40	0.32
SHGC NNW	1	0.70	0.50	0.37	0.30

In addition, curve fits (Figure 6-26 and Figure 6-27) and their respective equations (Table 6-14) were derived for the selected orientations. Given the highly positive correlation factors (R^2 values), this information was found to provide very close estimates of the SHGC value for vertical shading applied to the selected orientations. These curve fits were further validated by comparing SHGC values derived using dynamic simulations and those derived using the curve fits, and found accurate.

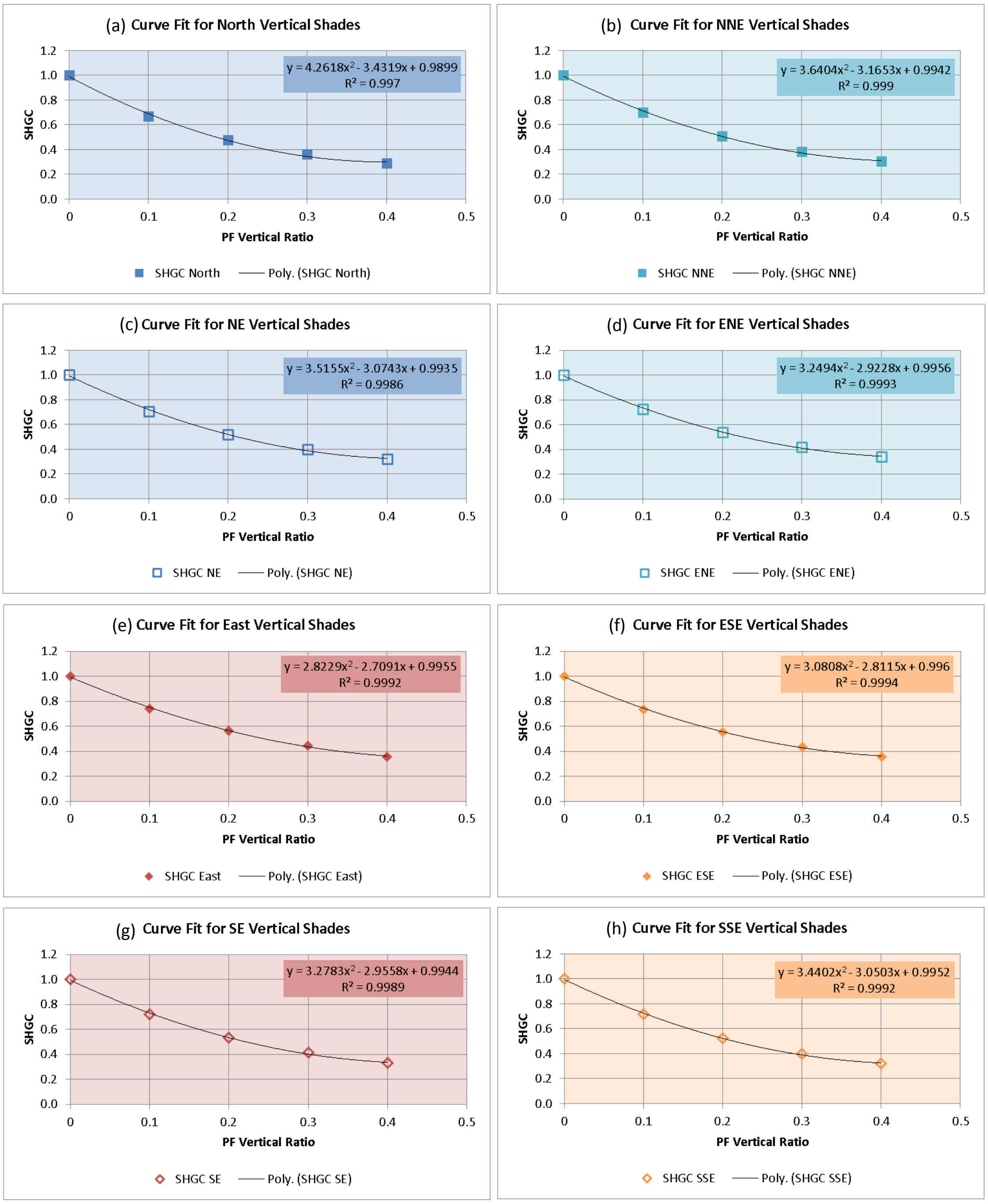


Figure 6-26 (a) to (h) SHGC Curve Fits for vertical shades for N, NNE, NE, ENE, E, ESE, SE and SSE orientations.

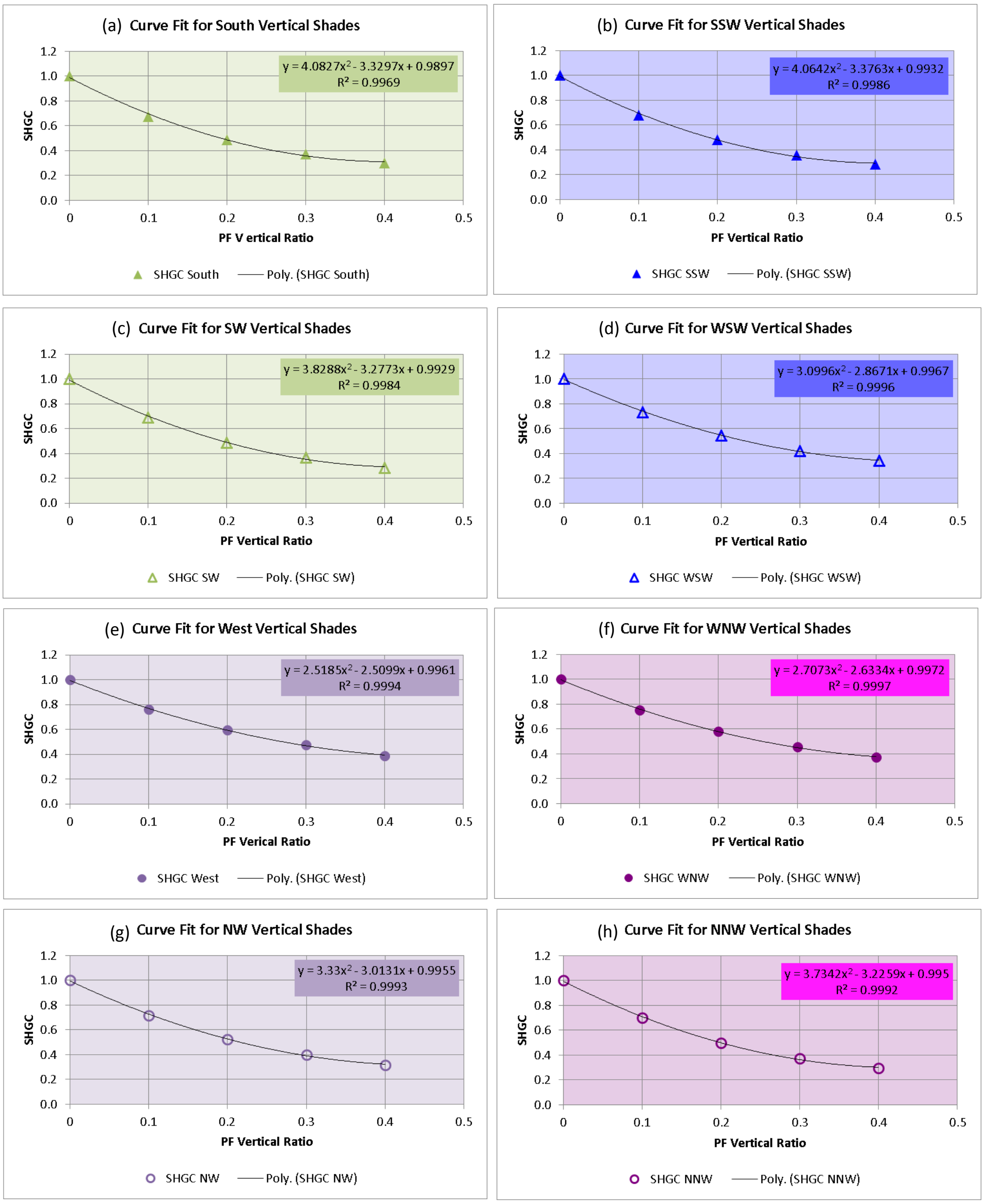


Figure 6-27 (a) to (h) SHGC Curve Fits for vertical shades for S, SSW, SW, WSW, W, WNW, NW and NNW orientations.

Table 6-14 SHGC Vertical Curve Fit Equation for N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW, where 'x' is the PF ratio and 'y' is the SHGC.

Orientation	SHGC Curve Fit Equation	R^2
North (0°)	$y = 4.2618x^2 - 3.4319x + 0.9899$	0.997
NNE (22.5°)	$y = 3.6404x^2 - 3.1653x + 0.9942$	0.999
NE (45°)	$y = 3.5155x^2 - 3.0743x + 0.9935$	0.9986
ENE (67.5°)	$y = 3.2494x^2 - 2.9228x + 0.9956$	0.9993
East (90°)	$y = 2.8229x^2 - 2.7091x + 0.9955$	0.9992
ESE (112.5°)	$y = 3.0808x^2 - 2.8115x + 0.996$	0.9994
SE (135°)	$y = 3.2783x^2 - 2.9558x + 0.9944$	0.9989
SSE (157.5°)	$y = 3.4402x^2 - 3.0503x + 0.9952$	0.9992
South (180°)	$y = 4.0827x^2 - 3.3297x + 0.9897$	0.9969
SSW (202.5°)	$y = 4.0642x^2 - 3.3763x + 0.9932$	0.9986
SW (225°)	$y = 3.8288x^2 - 3.2773x + 0.9929$	0.9984
WSW (247.5°)	$y = 3.0996x^2 - 2.8671x + 0.9967$	0.9996
West (270°)	$y = 2.5185x^2 - 2.5099x + 0.9961$	0.9994
WNW (292.5°)	$y = 2.7073x^2 - 2.6334x + 0.9972$	0.9997
NW (315°)	$y = 3.33x^2 - 3.0131x + 0.9955$	0.9993
NNW (337.5°)	$y = 3.7342x^2 - 3.2259x + 0.995$	0.9992

A review of the impact of SHGC reduction on indoor thermal comfort was undertaken and the results presented in Figure 6-28 and Figure 6-29. The review indicated that the SHGC reductions led to significant reductions in discomfort hours. Percentage discomfort for selected facade orientations varied from 9% to 5% for western orientated facades and northern orientated facades, respectively.

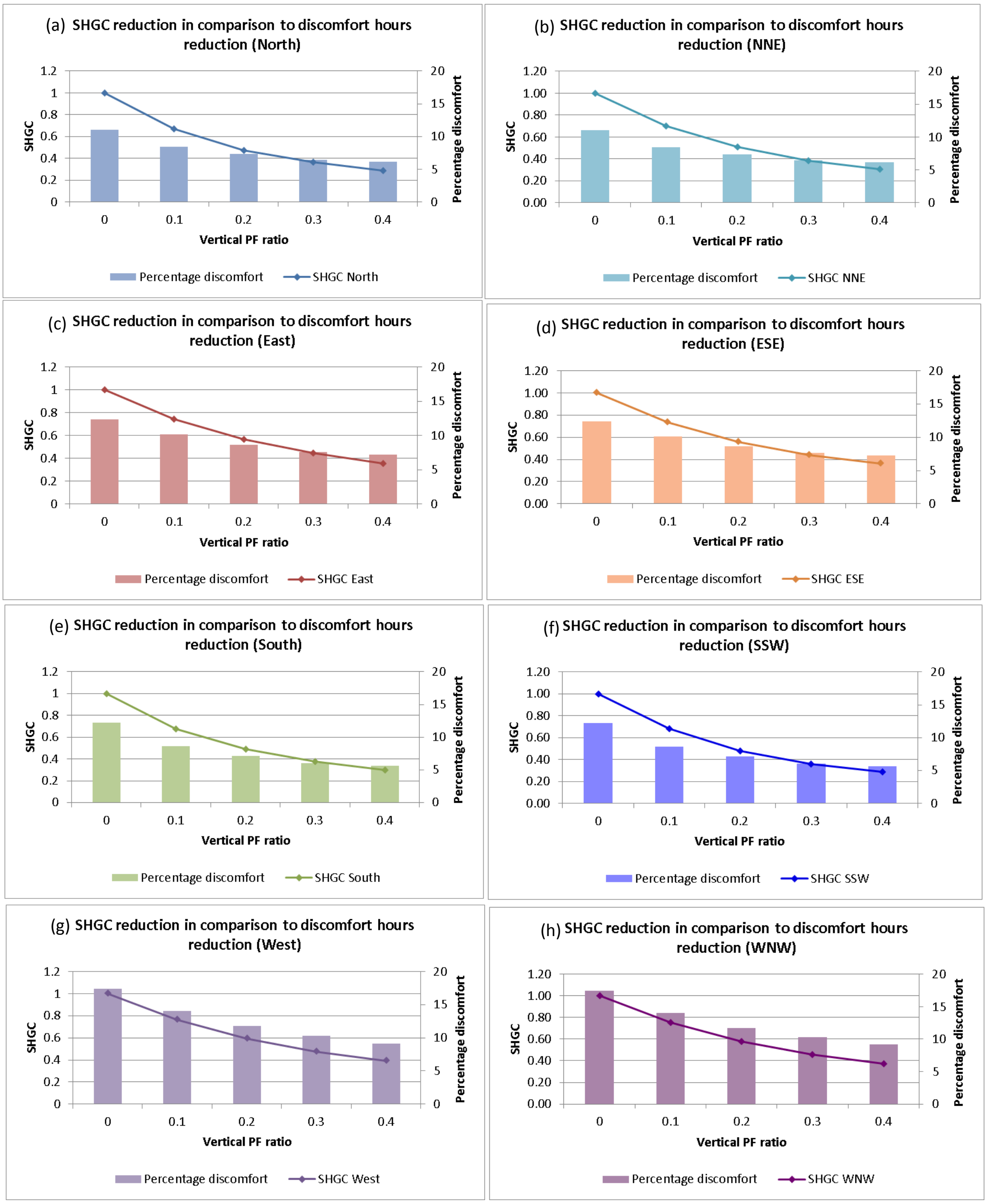


Figure 6-28 (a) to (h) SHGC vertical reduction impact on comfort for N, E, S, W, NNE, ESE, SSW and WNW orientations.

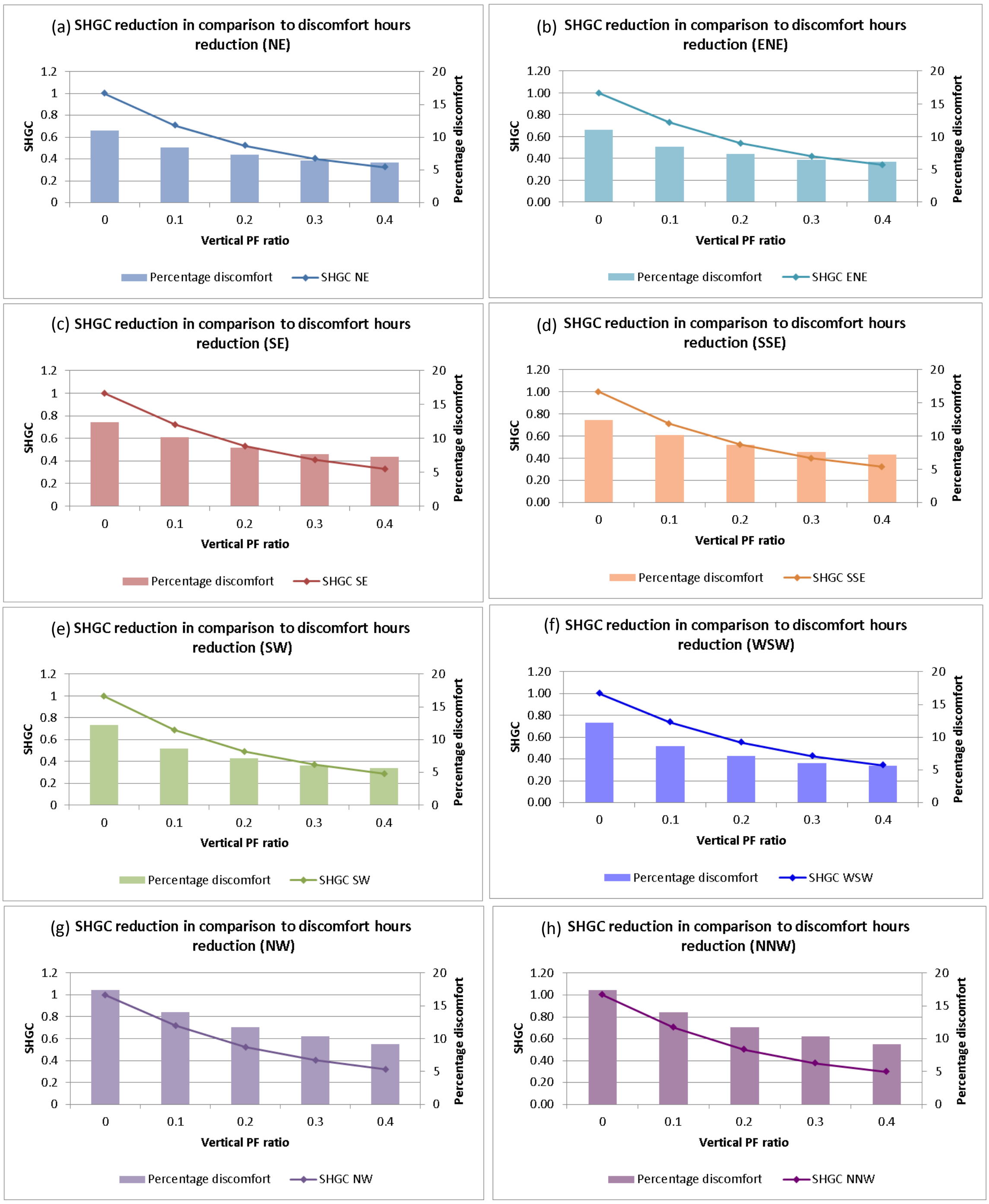


Figure 6-29 (a) to (h) SHGC vertical reduction impact on comfort for NE, SE, SW, NW, ENE, SSE, WSW and NNW orientations.

Further to this, the predicted energy reductions due to the application of vertical shading to each of the selected orientations were calculated and presented in Figure 6-30. The results indicated that although the SHGC values were lower on the northern and southern facades in comparison to the eastern and western facades, little variation was noted in energy reduction values for similar PF ratios. This was attributed to the corresponding lower solar heat gain received on northern and southern facing facades compared to the higher solar heat gain received on the western and eastern facades.

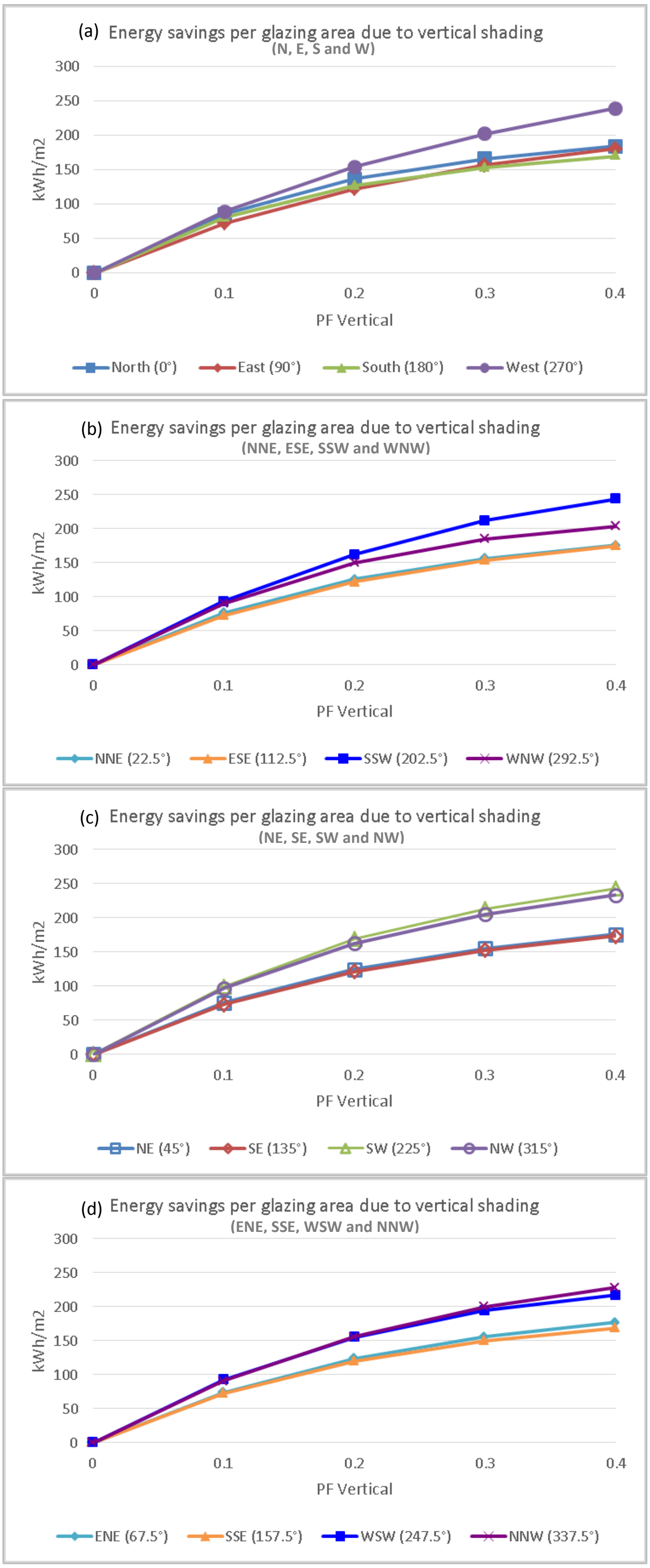


Figure 6-30 (a) to (d) Energy savings per glazing area due to the provision of vertical shading devices for N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW orientations.

Further, the SHGC values of egg crate shades applied to the sixteen main orientations were calculated and presented in Table 6-15. Little variation was observed in the SHGC values for different orientations. This was attributed to the high shading efficiency of egg crate shading. Although SHGC values showed little variation irrespective, they were higher in the western orientations and lower in the southern orientations; reflecting where the shading was most and least effective.

Table 6-15 SHGC of egg crate shades for N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW based on PF ratio.

PF (Horizontal)	**0**	**0.20**	**0.40**	**0.60**
PF (Vertical)	**0**	**0.10**	**0.20**	**0.30**
SHGC North (N)	1	0.22	0.22	0.22
SHGC NNE	1	0.23	0.23	0.23
SHGC NE	1	0.23	0.23	0.23
SHGC ENE	1	0.24	0.24	0.24
SHGC East (E)	1	0.24	0.24	0.24
SHGC ESE	1	0.24	0.24	0.24
SHGC SE	1	0.23	0.23	0.23
SHGC SSE	1	0.24	0.24	0.24
SHGC South (S)	1	0.24	0.24	0.24
SHGC SSW	1	0.22	0.22	0.22
SHGC SW	1	0.22	0.22	0.22
SHGC WSW	1	0.24	0.24	0.24
SHGC West (W)	1	0.27	0.27	0.27
SHGC WNW	1	0.25	0.25	0.25
SHGC NW	1	0.22	0.22	0.22
SHGC NNW	1	0.21	0.21	0.21

Curve fits (Figure 6-31, Figure 6-32, Figure 6-33 and Figure 6-34) and their respective equations (Table 6-16) were presented for the different orientations. As with the horizontal and vertical shading reviews, the highly positive correlation factors (R^2 values) indicated that this information provided very close estimates of the SHGC values for the outlined PF values for the application of egg crate shading.

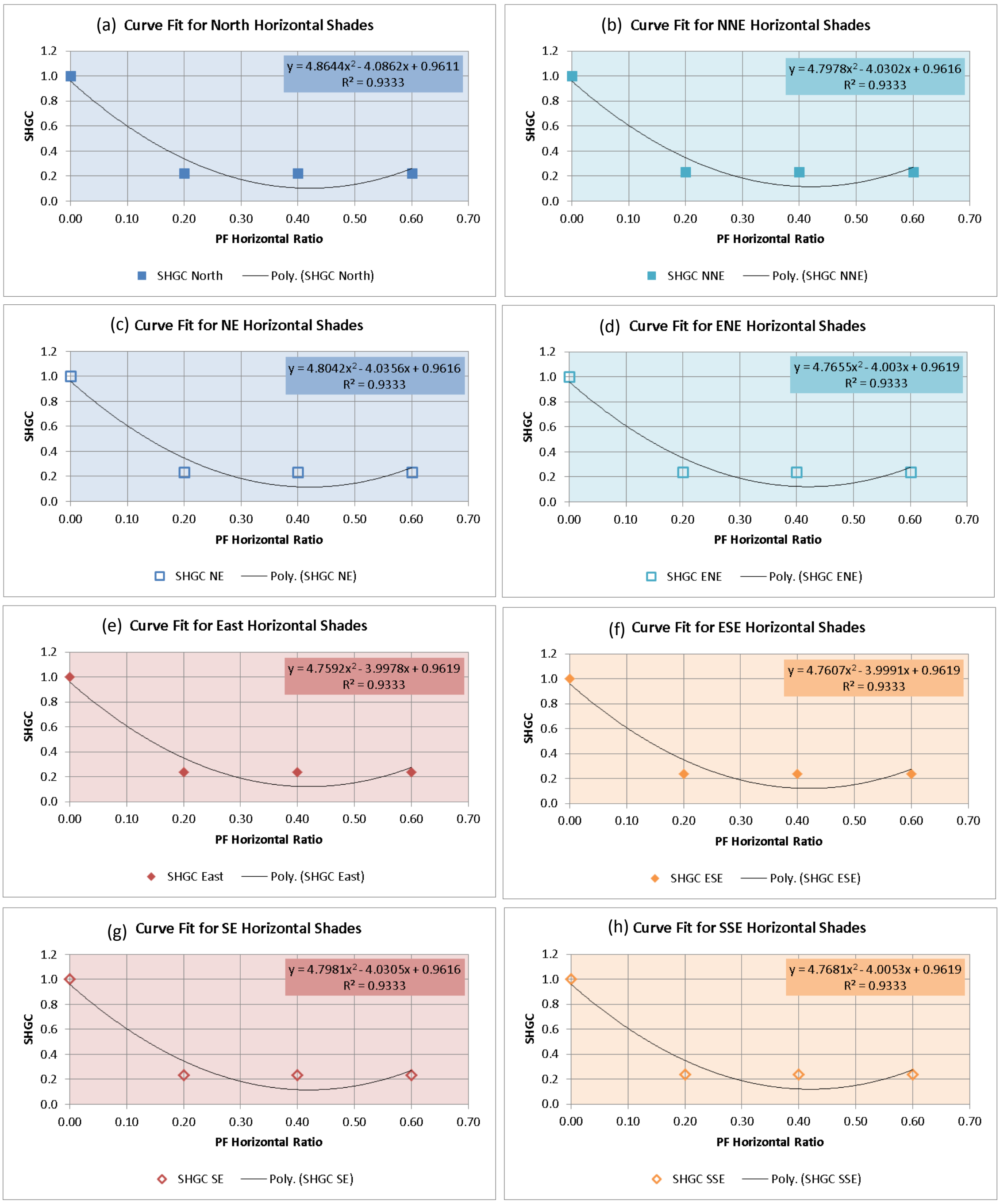


Figure 6-31 (a) to (h) SHGC (horizontal) Curve Fits for egg crate shades for N, NNE, NE, ENE, E, ESE, SE and SSE orientations.

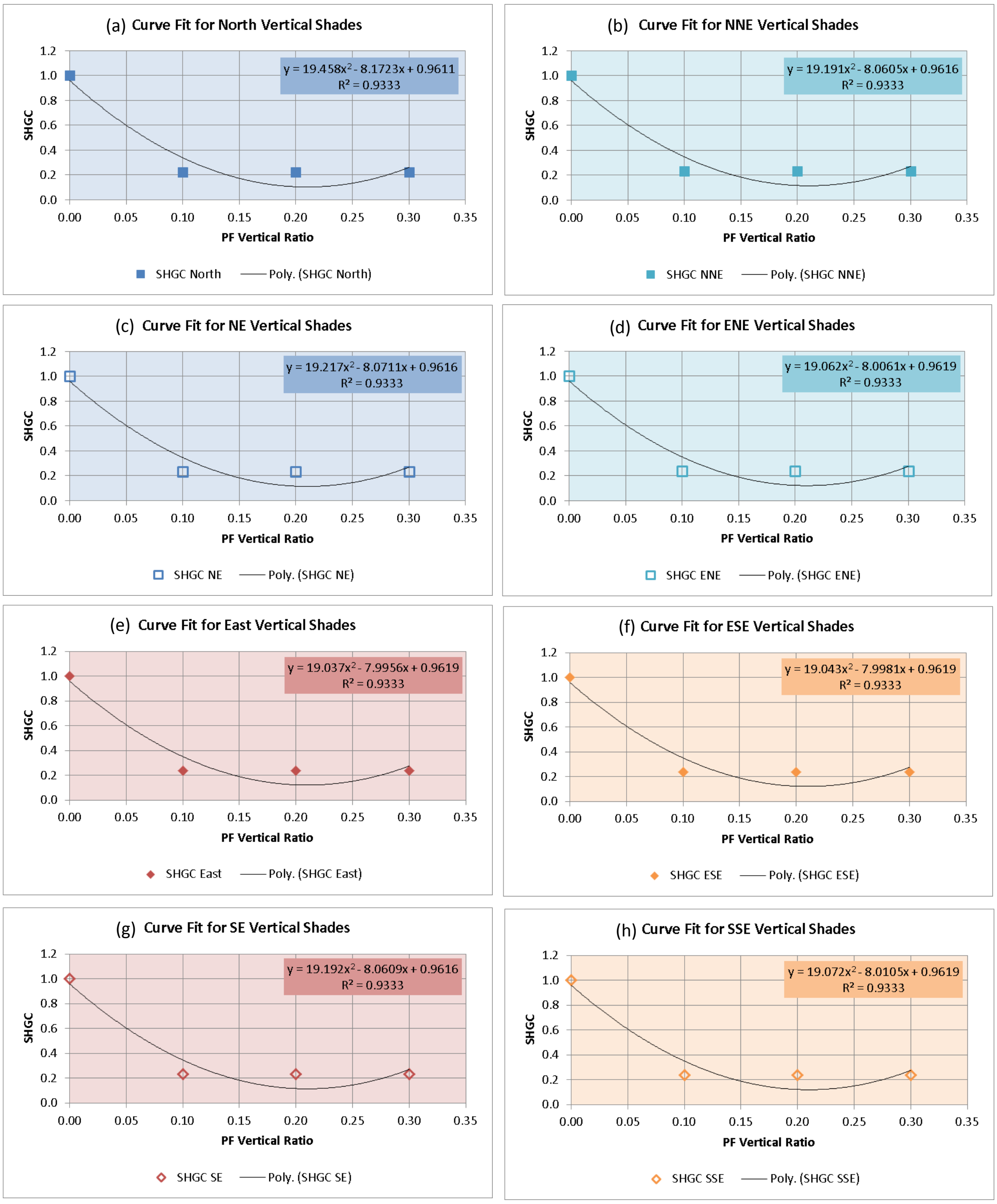


Figure 6-32 (a) to (h) SHGC (vertical) Curve Fits for egg crate shades for N, NNE, NE, ENE, E, ESE, SE and SSE orientations.

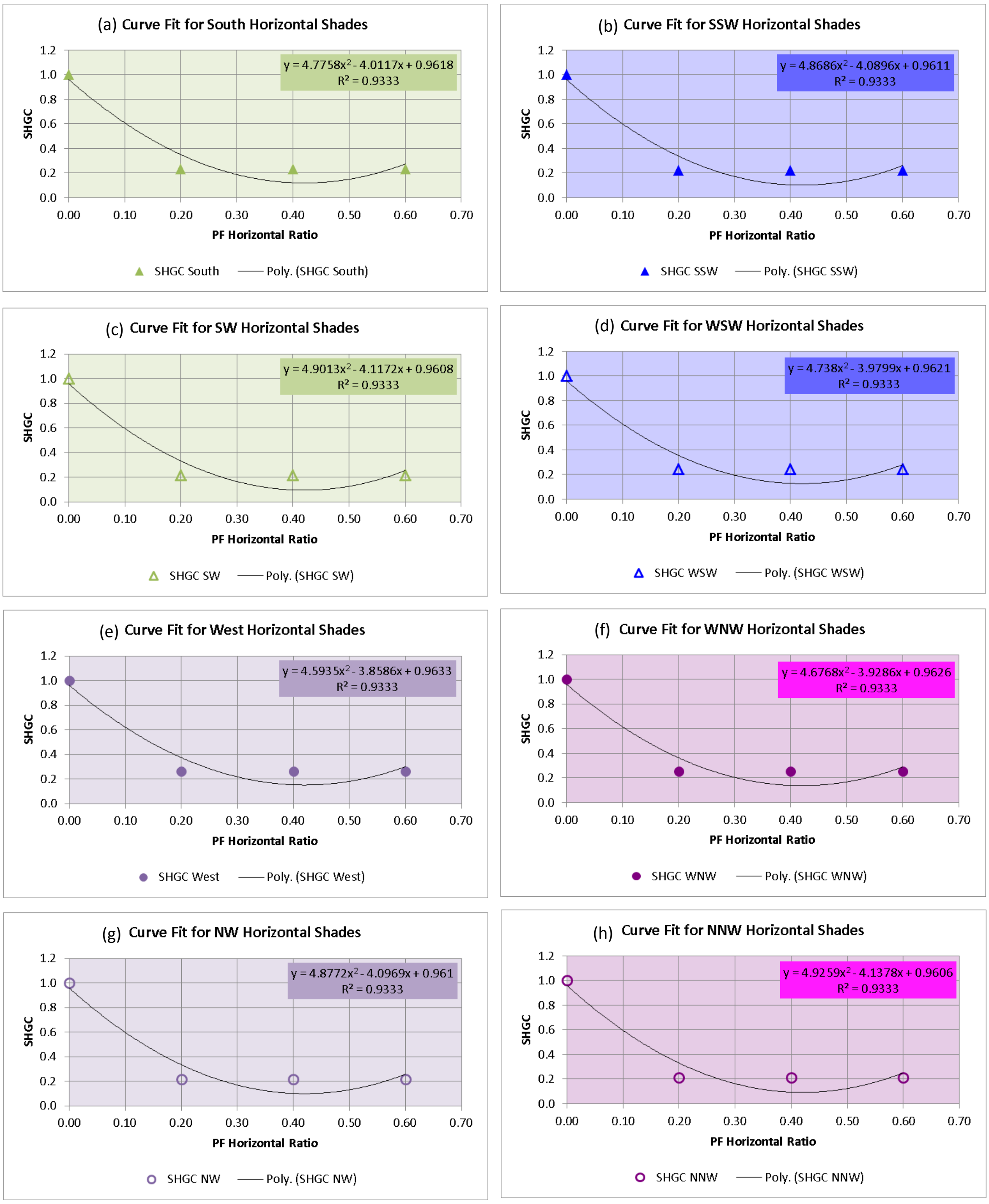


Figure 6-33 (a) to (h) SHGC (horizontal) Curve Fits for egg crate shades for S, SSW, SW, WSW, W, WNW, NW and NNW orientations.

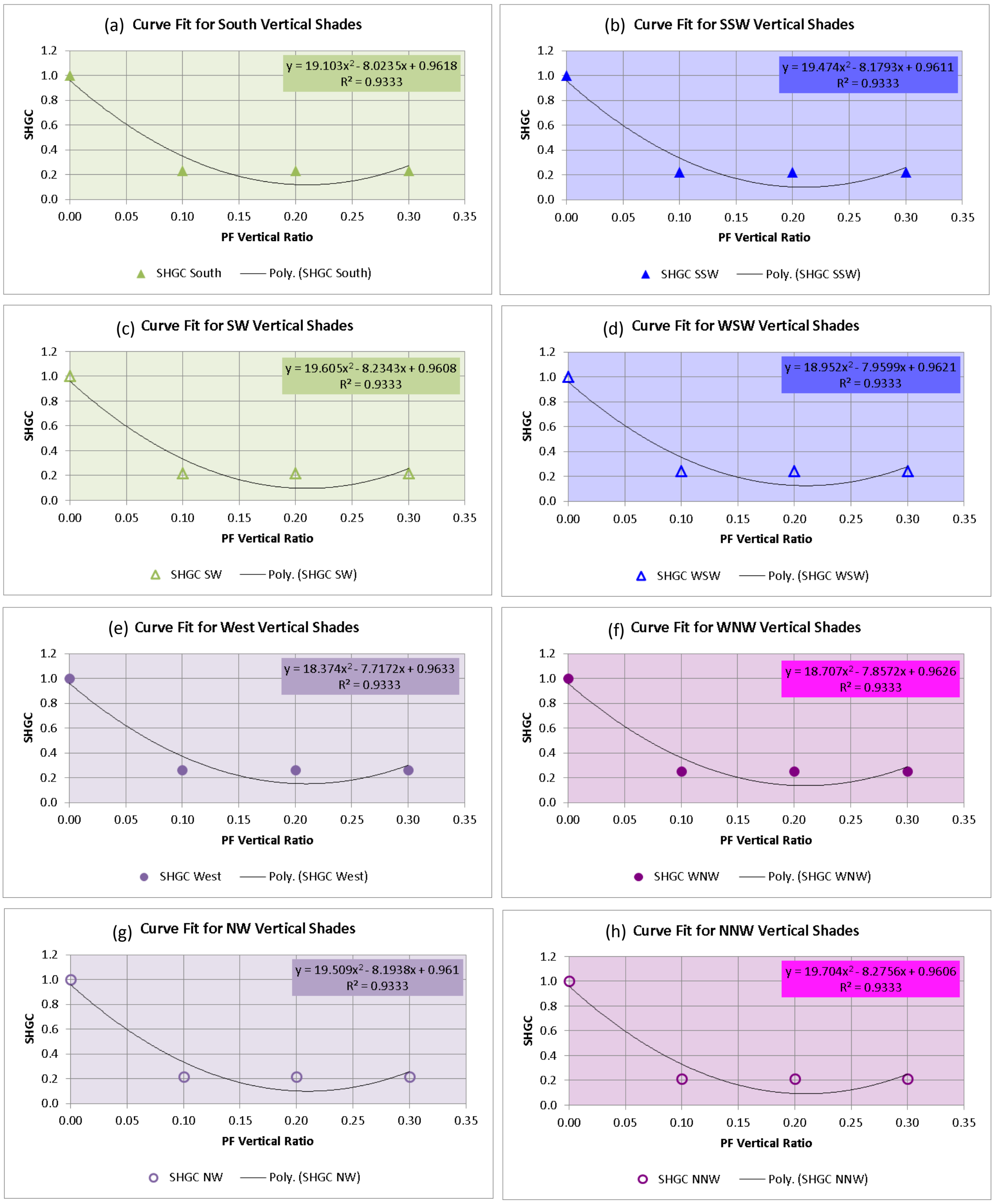


Figure 6-34 (a) to (h) SHGC (vertical) Curve Fits for egg crate shades for S, SSW, SW, WSW, W, WNW, NW and NNW orientations.

Table 6-16 SHGC egg crate Curve Fit Equation for N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW, where 'x' is the PF ratio and 'y' is the SHGC.

Horizontal Shades			Vertical Shades		
Orientation	**Curve Fit Equation**	**R^2**	**Orientation**	**Curve Fit Equation**	**R^2**
North (0°)	$y = 4.8644x^2 - 4.0862x + 0.9611$	0.93	**North (0°)**	$y = 19.458x^2 - 8.1723x + 0.9611$	0.93
NNE (22.5°)	$y = 4.7978x^2 - 4.0302x + 0.9616$	0.93	**NNE (22.5°)**	$y = 19.191x^2 - 8.0605x + 0.9616$	0.93
NE (45°)	$y = 4.8042x^2 - 4.0356x + 0.9616$	0.93	**NE (45°)**	$y = 19.217x^2 - 8.0711x + 0.9616$	0.93
ENE (67.5°)	$y = 4.7655x^2 - 4.003x + 0.9619$	0.93	**ENE (67.5°)**	$y = 19.062x^2 - 8.0061x + 0.9619$	0.93
East (90°)	$y = 4.7592x^2 - 3.9978x + 0.9619$	0.93	**East (90°)**	$y = 19.037x^2 - 7.9956x + 0.9619$	0.93
ESE (112.5°)	$y = 4.7607x^2 - 3.9991x + 0.9619$	0.93	**ESE (112.5°)**	$y = 19.043x^2 - 7.9981x + 0.9619$	0.93
SE (135°)	$y = 4.7981x^2 - 4.0305x + 0.9616$	0.93	**SE (135°)**	$y = 19.192x^2 - 8.0609x + 0.9616$	0.93
SSE (157.5°)	$y = 4.7681x^2 - 4.0053x + 0.9619$	0.93	**SSE (157.5°)**	$y = 19.072x^2 - 8.0105x + 0.9619$	0.93
South (180°)	$y = 4.7758x^2 - 4.0117x + 0.9618$	0.93	**South (180°)**	$y = 19.103x^2 - 8.0235x + 0.9618$	0.93
SSW (202.5°)	$y = 4.8686x^2 - 4.0896x + 0.9611$	0.93	**SSW (202.5°)**	$y = 19.474x^2 - 8.1793x + 0.9611$	0.93
SW (225°)	$y = 4.9013x^2 - 4.1172x + 0.9608$	0.93	**SW (225°)**	$y = 19.605x^2 - 8.2343x + 0.9608$	0.93
WSW (247.5°)	$y = 4.738x^2 - 3.9799x + 0.9621$	0.93	**WSW (247.5°)**	$y = 18.952x^2 - 7.9599x + 0.9621$	0.93
West (270°)	$y = 4.5935x^2 - 3.8586x + 0.9633$	0.93	**West (270°)**	$y = 18.374x^2 - 7.7172x + 0.9633$	0.93
WNW (292.5°)	$y = 4.6768x^2 - 3.9286x + 0.9626$	0.93	**WNW (292.5°)**	$y = 18.707x^2 - 7.8572x + 0.9626$	0.93
NW (315°)	$y = 4.8772x^2 - 4.0969x + 0.961$	0.93	**NW (315°)**	$y = 19.509x^2 - 8.1938x + 0.961$	0.93
NNW (337.5°)	$y = 4.9259x^2 - 4.1378x + 0.9606$	0.93	**NNW (337.5°)**	$y = 19.704x^2 - 8.2756x + 0.9606$	0.93

Next, the impact of SHGC reduction was correlated to the subsequent reduction in discomfort hours and the results presented in Figure 6-35 and Figure 6-36. The review indicated that the SHGC reduction lead to significant reductions in discomfort hours. These reductions were found to be the most significant when compared to lone SHGC horizontal and vertical reductions. Additionally, although SHGC values were found to show little deviation for different facade orientations, the variation in the reduction of percentage discomfort was more noticeable. Percentage discomfort for selected facade orientations varied from 11% to 6% for western orientated facades and northern orientated facades, respectively. As was the case with the previous shading configurations, this was also attributed to varying solar gain received on each facade.

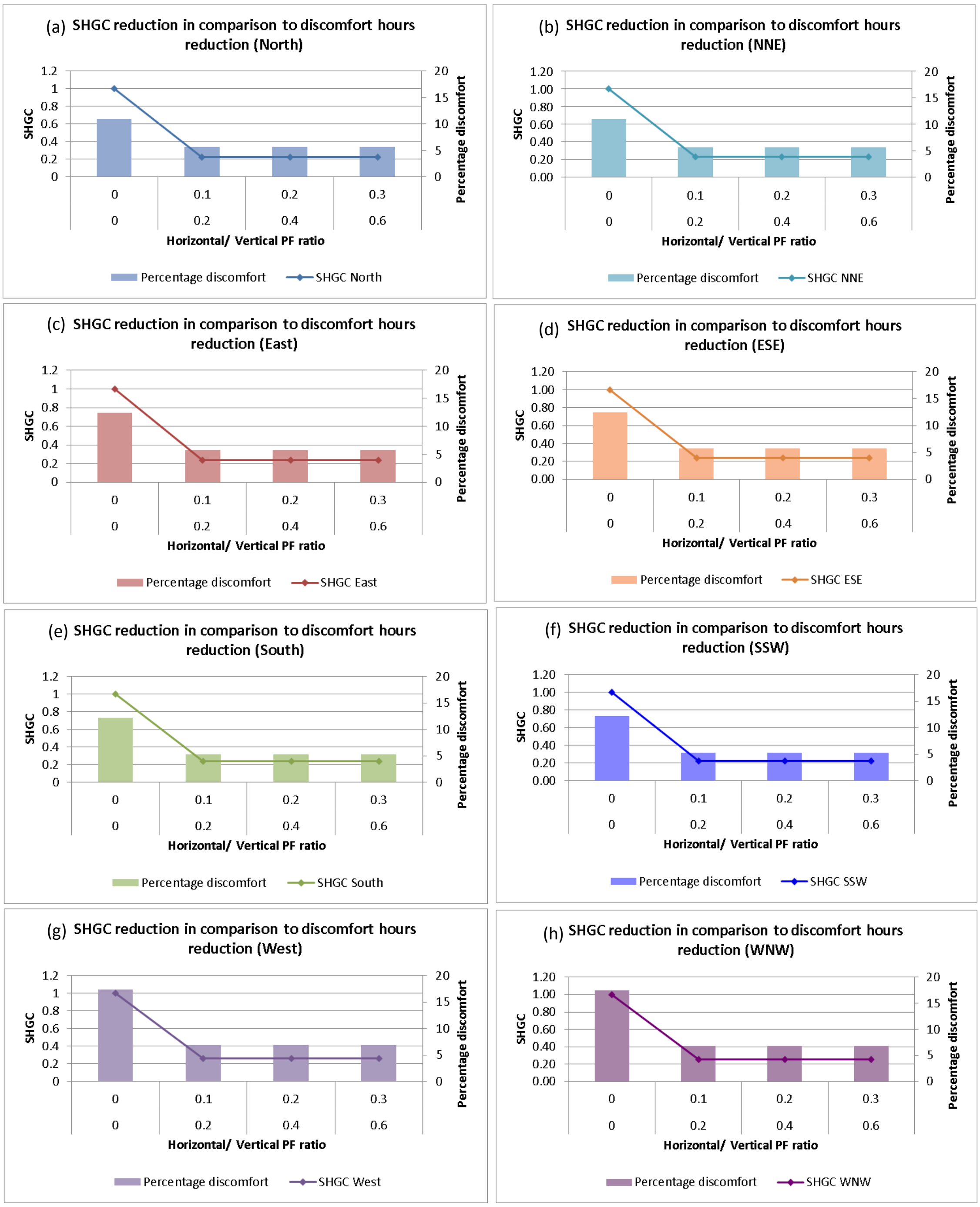


Figure 6-35 (a) to (h) SHGC egg crate reduction impact on comfort for N, E, S, W, NNE, ESE, SSW and WNW orientations.

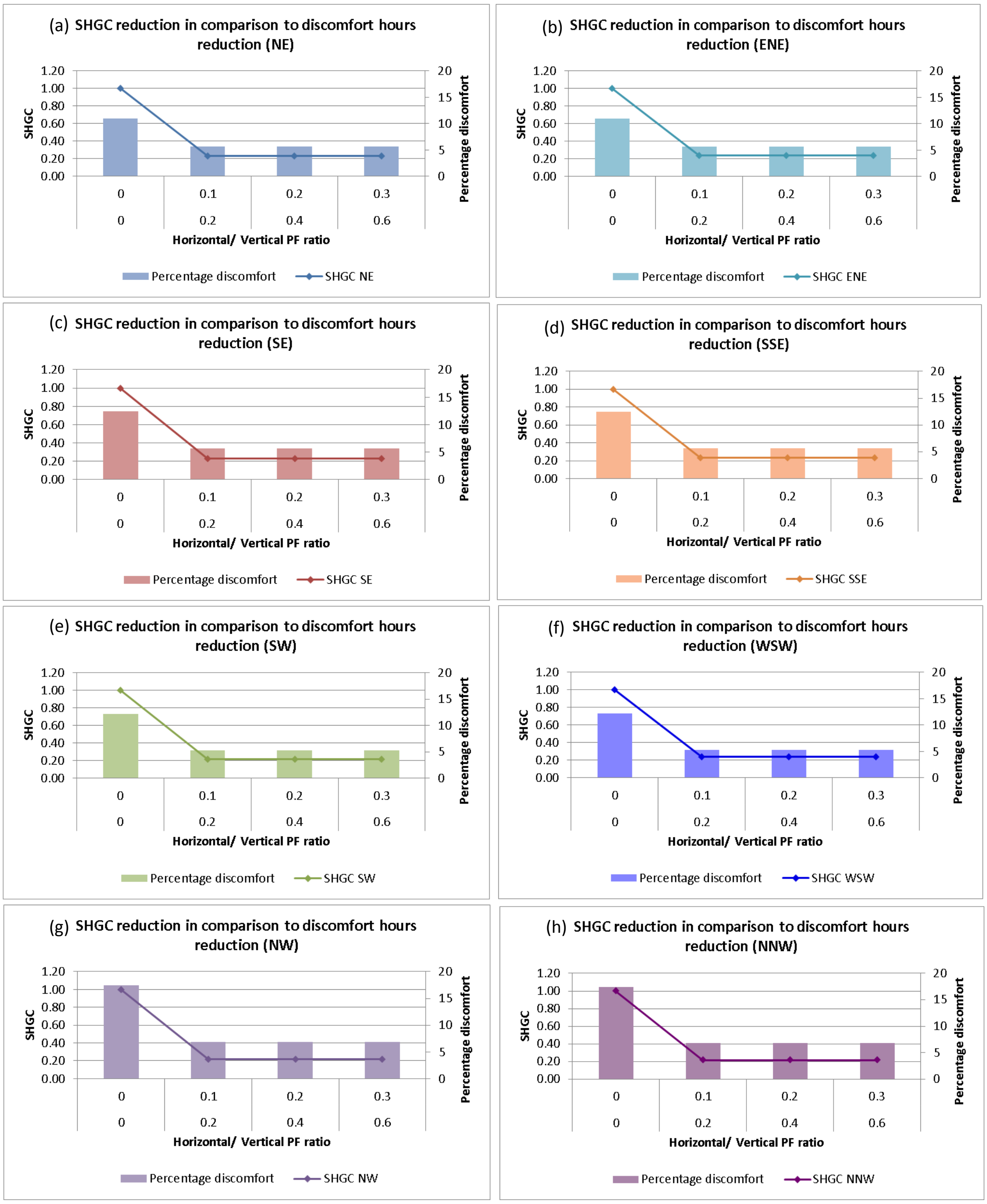


Figure 6-36 (a) to (h) SHGC egg crate reduction impact on comfort for NE, SE, SW, NW, ENE, SSE, WSW and NNW orientations.

In addition to resulting in the highest levels of comfort performance in comparison to horizontal and vertical shading devices, egg crate shading was found to give the greatest energy savings for relatively low corresponding PF ratios. For instance for the west facing facade, a PF ratio of 0.2 was found to give energy savings of 306.8kWh/m^2 using egg crate shading compared to 154.05kWh/m^2 and

66.81kWh/m^2 for vertical and horizontal shading, respectively. This translated into annual savings of up to 58.5%, 29.4% and 12.7% for egg crate, vertical and horizontal shading, respectively. This trend was found to be similar for other orientations where egg crate shading allowed for higher savings compared to both horizontal and vertical shading.

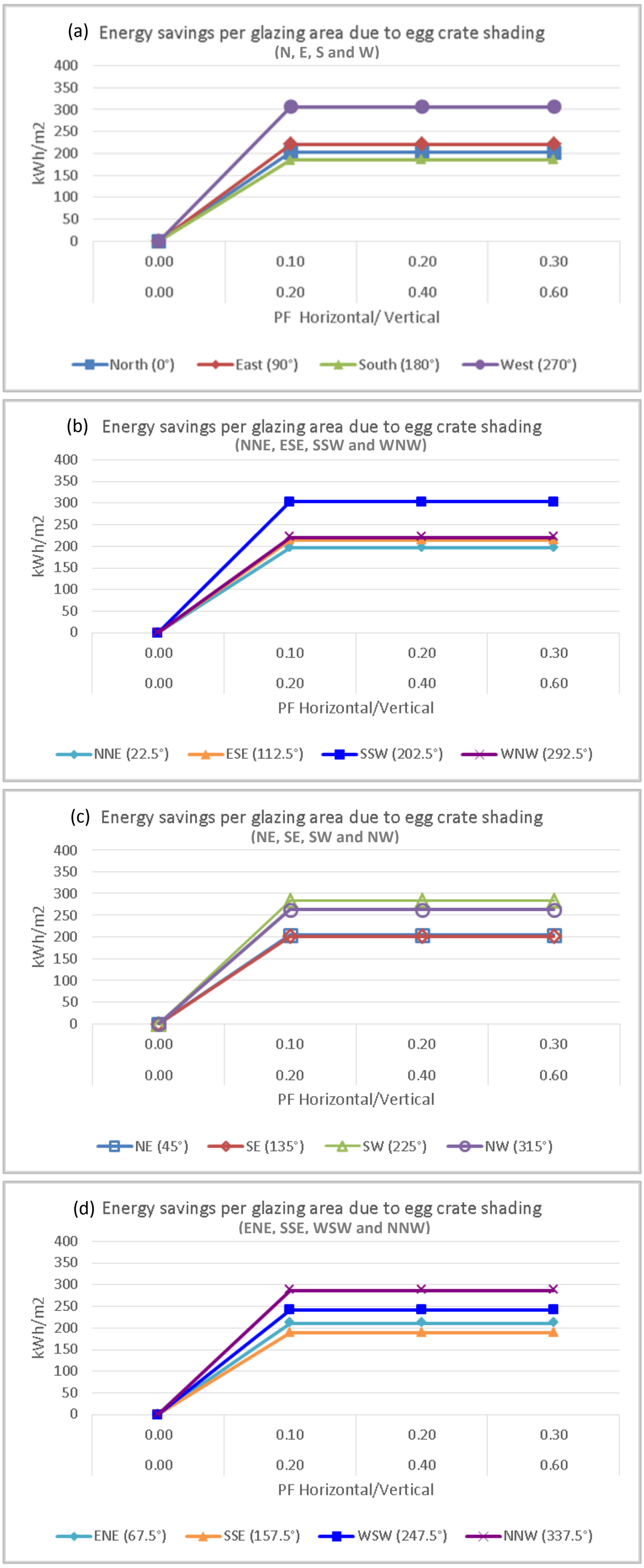


Figure 6-37 (a) to (d) Energy savings per glazing area due to the provision of egg crate shading devices for N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW orientations.

6.5 Conclusions

This chapter was focused on determining and categorising the performance impact of external shading elements as applied to typical office buildings found on the local latitude of 4°S. This was guided by earlier findings presented in previous chapters that found the application of external shading devices suitable for the reduction of the impact of solar radiation on glazed surfaces and consequently the reduction of the risk of overheating which contributes substantially to energy consumption.

The initial performance analysis outcomes revealed that external shading played a significant role in the improvement of indoor comfort conditions. Of the shading types investigated, egg crate shading was found to perform significantly better than both external horizontal or vertical shading elements. For the shading depths examined, the application of egg crate shading led to reduction in the hours outside comfort (discomfort hours) by 42.5% (under zero ventilation), 10.5% (under day time ventilation) and 7.5% (under all day ventilation). On the other hand, the application of horizontal shading led to a reduction in the hours outside comfort (discomfort hours) by 31.3% (under zero ventilation), 8.7% (under day time ventilation) and 6.6% under all day ventilation). Of all the three shade types, the application of vertical shades had the least significant impact. The application of this shade type led to a reduction in the hours outside comfort (discomfort hours) by 30% (under zero ventilation), 8.2% (under day time ventilation) and 5.8% under all day ventilation).

In addition, egg crate shading was found to be highly effective for low PF ratios and for all orientations. For a low PF ratio of 0.3, egg crate shading had approximately half the amount of hours outside comfort showcased by both horizontal shading and vertical shading with a similar PF ratio in the north, east, south and west orientations. Additionally, horizontal shading was found to be more appropriate for northern and southern orientations (up to 3% less discomfort hours than when using vertical shading). On the other hand, vertical shading was found to be more suitable for western and eastern orientations (up to 3% less discomfort hours than when using horizontal shading).

Further to this, solar data derived from dynamic simulations was used to develop solar heat gain coefficients (SHGC). These coefficients were used to categorise the impact of applying shading types of various PF ratios to avoid unnecessarily large solar gains through glazing surfaces in similar type office buildings. To allow for the transferability of these results by determining the performance of shading in similar types office buildings, these SHGC values were derived for sixteen cardinal compass orientations. Further to this, curve fits and their respective equations were derived to facilitate the derivation of SHGC values for higher projection factor ratios that may be considered by designers. The curve fits and their equations were further validated by comparing their results with other simulations and proved accurate in their SHGC predictions.

A review of the reduction of SHGC values with respect to comfort performance indicated that a low SHGC value of 0.5 was a general indication of a low percentage in discomfort hours of less than 10%. Similarly, a moderately low SHGC value of 0.7 was a general indication of a moderately low percentage in discomfort hours of less than 15%. This considered, it was also noted that the reduction in discomfort hours was largely influenced by facade orientation. This explained why seemingly similar SHGC values applying to different orientations would result in a variety of reductions in discomfort: up to 11% (egg crate shading), 10% (horizontal shading) and 9% (vertical shading) in the west, compared to 6% (egg crate shading), 4% (horizontal shading) and 5% (vertical shading) in the north.

Additionally, energy simulations based on data derived from the glazing area, orientation of the window and the PF ratio, were conducted to derive the potential energy savings achievable using various shading types. The findings indicated that annual energy savings of up to 58.5% (egg crate shading), 12.7% (horizontal shading) and 29.4% (vertical shading) were achievable. Further simulations proved these predictions to be good approximations.

As the study findings were aimed for use during early design stages, it was deemed unnecessary to delve into more complex shading systems as part of this investigation. This was based on the conclusion that these complex shading systems are more often than not a variant or combination of the simpler horizontal and or vertical shading types that tend to apply to individual cases. Even so, based on the methodology of this study, it was noted that it would still be possible to derive the SHGC values if one took into account the effect the combination of shading elements and their respective PF ratios (as was done for egg crate shading types).

Further, it was noted that although it is often advisable to resolve shading early in the design stages, it is not always possible do so. Nonetheless, the data that was presented in this study was still considered useful in the derivation of SHGC values and indeed potential energy savings as a result of shading applied after construction.

Given that the study findings were aimed to inform designers, the next chapter delved into the application of these findings to two other typical office buildings located in Mombasa. The first was found to be within the early design stages whereas the second had been built and recently occupied. The aim of this process was to demonstrate that the summarised correlation of the SHGC tables, curve fits and their respective equations and energy saving estimates presented in this chapter are useful when considered under general conditions for similar type office buildings on latitude 4°S.

From this, a guidance document setting out a methodical approach demonstrating how a designer can quantify the effect of applying external shading elements on thermal comfort and energy use was prepared and presented in APPENDIX D.

7 APPLYING THE DESIGN GUIDELINES TO TYPICAL OFFICE BUILDINGS

Following the derivation of solar heat gain coefficients and energy saving estimates in Chapter 6, this chapter is focused on examining how these guidelines can be applied to typical office buildings in Mombasa. For the cases reviewed, a step by step procedure is presented to show how the findings from the previous studies can be used to inform decision making at the early stages of the design process when considering the application of external shading. To test the validity of these findings, dynamic simulations of the selected buildings were carried out and the results were compared.

7 APPLYING THE DESIGN GUIDELINES TO TYPICAL OFFICE BUILDINGS

Much of this study has been focused around a practical approach to suitable design strategies for office buildings in warm humid climates. One of the main aims of adopting this approach was to enable the application of the selected design strategies to similar building types in Mombasa. In the previous chapters, it was noted that whereas local designers are encouraged to adopt climate-responsive strategies, few specific and workable guidelines had been provided. Having identified external shading as one of the most suitable design strategies, it was considered useful to provide access to readily-available and practical design information to the designers so that they would be encouraged to apply appropriate shading devices to office buildings.

With this in mind, the use of the solar heat gain coefficient (SHGC) tables, curve fits and the energy estimates derived in Chapter 6 was examined by using two typical office buildings in Mombasa, Kenya as test cases. The first building, Olem House, had recently been retrofitted (to add more floor levels and to introduce air conditioning) at the time of this study. On the other hand, the design of the second building, Combrook House, was in its early design stages (scheme design level). During this case study selection process it was noted that it is not uncommon to find external shading being implemented as part of a retrofit solution. However, as issues such as structural support and impact on facade design are often considered during the installation of external shades, it was recommended that shading requirements are reviewed and discussed during the early stages of the design process. Nonetheless, given that it is not always possible to integrate external shading early in the design process, the method and guidelines proposed in this study were aimed to cater for both scenarios.

This being a simple manual method of determining the thermal performance and energy use impact of external shading devices on a typical office building, only a selected number of design parameters are required for data input purposes. This is because a number of assumptions which represent good practice and/or national regulation minimums have already been made as was outlined in Chapter 5 and 6. It is worth noting that these guidelines were developed for and limited to preliminary comparative studies. This is largely based on the fact that the predictions assume that both the occupants and the building systems function in an optimum mode. As such, these guidelines could be used for testing and comparing the relative performance of a number of design options so that overall trend and workable design solutions can be identified.

For ease of use, a guidance document presented in APPENDIX D was developed. The steps in the guidance document explained how designers could use the proposed method and guidelines as a means of selecting suitable external shading devices.

These steps are elaborated on next:

1. On a plan of your building, divide it into passive (naturally ventilated) and/or non-passive (artificially ventilated) zones.
2. Determine the glazing area and glazing orientation of each zone.
3. Identify the most suitable shading type for each orientation and proceed with the next step – refer to Figure 6-16 or the guidance document in APPENDIX (for example, horizontal shading for North and South facades and vertical shading for east or west facades). Alternatively, proceed with the next step to compare various shading types' performance.
4. Calculate the base case $SHGC_{total}$ using a $SHGC_{external}$ value of 1 (refer to Equation 6-4 or the guidance document in APPENDIX D).
5. Calculate the $SHGC_{total}$ using a $SHGC_{external}$ value of 0.5. This value gives an indication of low discomfort hours.
6. Calculate the $SHGC_{total}$ using a $SHGC_{external}$ value of 0.7. This value gives an indication of moderately low discomfort hours.
7. Using the $SHGC_{external}$ tables or the relevant curve fits; substitute the base case $SHGC_{external}$ value of 1 with the given value of the shading type of interest and for various PF ratios.

8. Analyse the results by comparing them with the SHGC $_{total}$ for low and moderately low discomfort hours to determine the most effective shading PF ratio/ shading depth.

   For naturally ventilated zones, skip to step 10. For artificially ventilated zones, proceed with step 9.
9. Estimate the potential energy savings per glazing area (kWh/m^2).
10. Make an informed decision on shading design based on results obtained from step 8 and step 9.

A trial run of the use of this method by 20 local Kenyan architects and architectural students, using the guidance document presented in APPENDIX D, was undertaken during the final stages of this study to determine their ease of use. Feedback received by the researcher indicated that users found the method straightforward and easy to use. Even those with a minimal environmental design background noted that they found the descriptions provided clear and the method easy to apply. Although the sample used to carry out this initial analysis was small, it was suggested that it still gave a good indication of the usability of the method. Further testing of the method is planned as part of the further work as highlighted in Chapter 8.

Using this step-by-step approach, the application of this method and guidelines was demonstrated in the testing of for Olem House and Combrook House next.

7.1 Olem House (Retrofit)

In this section, the use of the SHGC data and energy saving estimates were examined for an existing building located in the warm humid city of Mombasa. From this, the potential improvement of building thermal performance due to the application of selected shading types was predicted.

7.1.1 Building information – Olem House

Olem House is located on Mombasa Avenue, one of the busiest roads in the central business district of Mombasa (Figure 7-1). Comprising of a total built up area of 1,216 m^2, the building serves primarily commercial uses. Office spaces are allocated to the top five floors and whereas shops spaces are found on the ground floor (see Figure 7-2, Figure 7-3 and Figure 7-4). Similar to a significant number of older office buildings located in the city centre, it was recently retrofitted in the year 2012 to meet the increasing demand for modern office space in the city.

Figure 7-1 Olem House (highlighted) location plan (author-modified from Google Maps).

Figure 7-2 Front perspective view of Olem House.

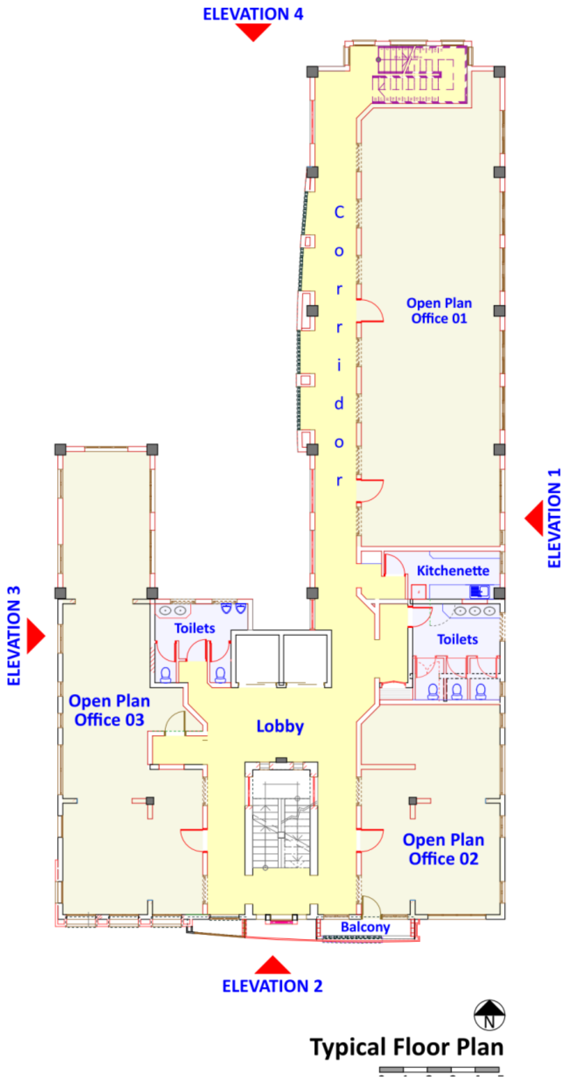


Figure 7-3 Olem House, typical floor plan (author-modified from A.D. Design Architects).

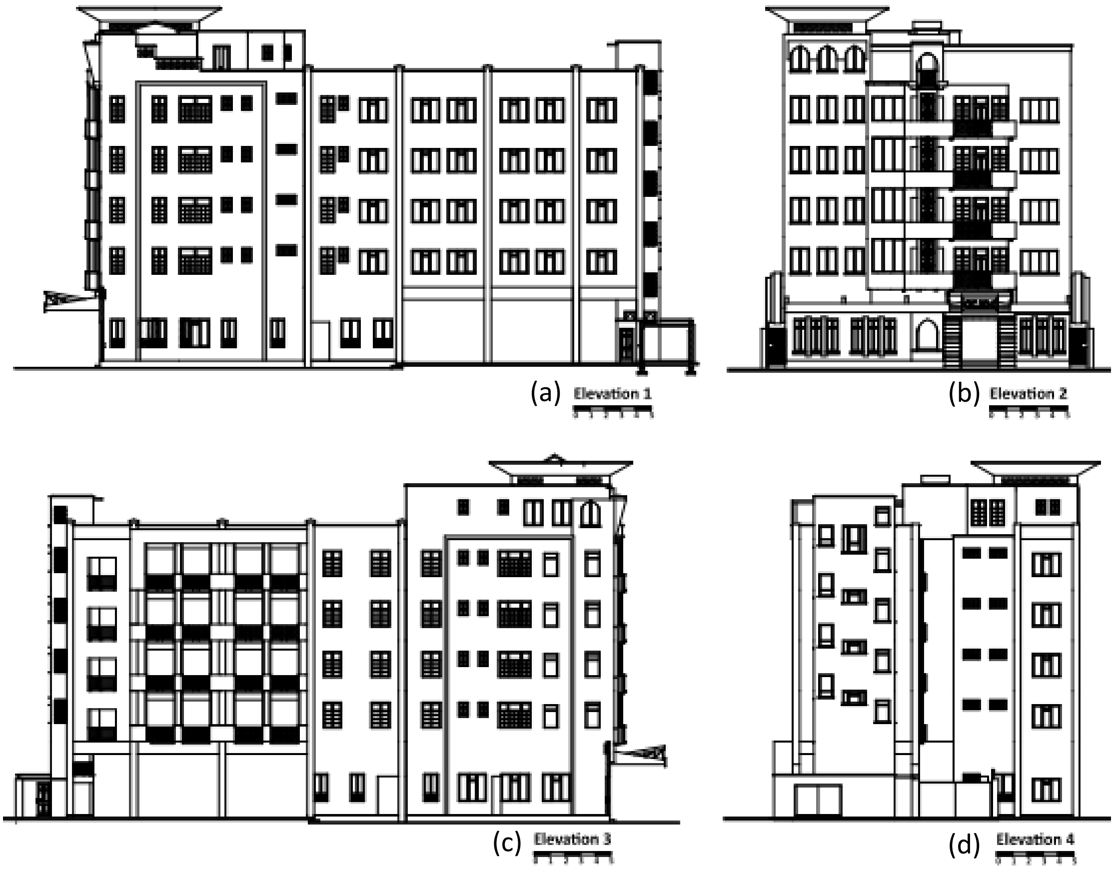


Figure 7-4 (a) to (d) Olem House main elevations (author-modified from A.D. Design Architects).

The main construction materials used in the building were listed in Table 7-1. A review of these materials found them to be typical to a significant number of office buildings found in the city (Chapter 1).

Table 7-1 Olem House construction materials.

Main frame	**Reinforced concrete**
Floor/ ceiling	Ground floor: Concrete ground floor slab (Admittance: 3.45W/m^{2}K) Suspended floors: 150mm Lightweight reinforced concrete slab (Admittance: 4.33W/m^{2}K)
Walls	External: 200mm Lightweight concrete (Admittance: 3.54W/m^{2}K) Internal: Chipboard on studs (Admittance: 2.67W/m^{2}K)
Roof	Concrete tile finish on hollow block slab (Admittance: 3.95W/m^{2}K)
Windows	10mm thick glazing, in aluminium frame.

As with a growing number of office buildings in Mombasa, Olem House was found to depend almost entirely on an air-conditioning system for ventilation and cooling. A discussion held with the architect in charge of the recent retrofit revealed that the client was keen on introducing active measures so as to compete with other “modern” office spaces across the city.

Site analysis that included a review of its siting and form (longer along the north-south axis) revealed that little could be done to maintain adequate natural ventilation or natural lighting levels in the long open plan office spaces without having openings in the west and east facades. Further, due to the nature of the project, reorganisation of the building layout and glazing orientation to cut down on the solar exposure to east and west facades was not an option. Instead, the use of external shading devices was considered.

7.1.2 Olem House shading analysis

For purposes of this analysis, three main non-passive zones (office spaces only) within a typical floor plan were defined as is indicated in Figure 7-5. In this case, only habitable spaces were considered. In addition, the glazing orientation and glazing area of each zone was extracted and presented in Table 7-2.

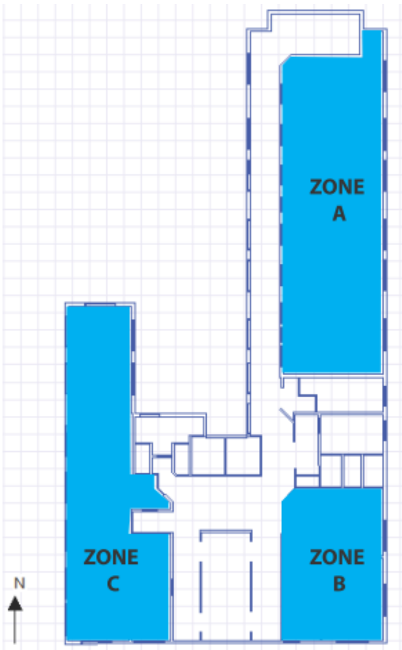


Figure 7-5 Selected non-passive zones for shading analysis, Olem House.

Table 7-2 Glazing orientation and glazing area of the selected zones – Olem House.

Zone	Glazing orientation	Glazing area (m^2)
A	East	16.2
B	South	4.6
	East	5.4
C	North	2.7
	East	5.4
	South	5.4
	West	18.9

A quick review of this information revealed that majority of the glazing area lay on the east and west facades. Previously in Chapter 6, Figure 6-16, vertical and egg crate shades were found to be particularly effective when applied to these facades due to their ability to block out low angle sun. Nonetheless, all the basic three shading types were examined as part of this exercise. This is an optional approach; in other situations, the designer may choose to analyse only the recommended type if preferred.

Next, the $SHGC_{total}$ of the base case was calculated. As was highlighted in Chapter 6, Section 6.1.2, the total SHGC of a fenestration system (SHGC total) is influenced by the three variables illustrated in Equation 6-4. This includes the SHGC external which is the solar heat gain coefficient of external shading devices (1, if no external shading device is used); the SHGC glazing which is the solar heat gain coefficient of the glazing and the SHGC internal which is the solar heat gain coefficient of internal shading devices (1, if no internal shading device is used). As no shading was considered for the base case, the $SHGC_{external}$ and $SHGC_{internal}$ values remained constant at a value of 1. Additionally, the $SHGC_{glazing}$ was set at 0.86 as per the properties of clear single glazing (ASHRAE, 2013b, p. 17.5). This gave the base case $SHGC_{total}$ of 0.86.

Following this, the reduction in the $SHGC_{total}$ values of the selected zones were estimated taking into account the effect of the application of external shading devices of varying configuration and depth *i.e.* a reduction in $SHGC_{external}$. For these calculations, SHGC $_{external}$ values for various PF ratios were extracted from Table 6-11 (horizontal shading – HS), Table 6-13 (vertical shading – VS) and Table 6-15 (egg crate shading – ECS) in Chapter 6. The estimated SHGC $_{total}$ values were presented in Table 7-3 (HS), Table 7-4 (VS) and Table 7-5 (ECS). In addition, the SHGC $_{total}$ reduction values were given to highlight the percentage reduction of the base case SHGC $_{total}$.

In Chapter 6, the findings suggested that low SHGC $_{external}$ values of under 0.5 gave an indication of low discomfort hours. Similarly, a SHGC $_{external}$ of 0.7 was found to give an indication of moderately low discomfort hours. Applied here, the SHGC $_{external}$ of 1 was substituted with values of 0.5 and 0.7 resulting in approximate SHGC total values of 0.43 and 0.6, respectively. These values were then used to give an indication of the suitability of the external shading types applied to Olem House.

Table 7-3 Estimated SHGC $_{totals}$* as a result of using horizontal shading – Olem House.

PF ratio		**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.2**
Zone A (East)	SHGC $_{total}$	0.86	0.72	0.62	0.53	0.47	0.43	0.39
	SHGC $_{total}$ reduction	0	0.14	0.24	0.33	0.39	0.43	0.47
Zone B (South)	SHGC $_{total}$	0.86	0.72	0.62	0.55	0.49	0.46	0.42
	SHGC $_{total}$ reduction	0	0.14	0.24	0.31	0.37	0.40	0.44
Zone B (East)	SHGC $_{total}$	0.86	0.72	0.62	0.53	0.47	0.43	0.39
	SHGC $_{total}$ reduction	0	0.14	0.24	0.33	0.39	0.43	0.47
Zone C (North)	SHGC $_{total}$	0.86	0.72	0.61	0.53	0.48	0.44	0.40
	SHGC $_{total}$ reduction	0	0.14	0.25	0.33	0.38	0.42	0.46
Zone C (East)	SHGC $_{total}$	0.86	0.72	0.62	0.53	0.47	0.43	0.39
	SHGC $_{total}$ reduction	0	0.14	0.24	0.33	0.39	0.43	0.47
Zone C (South)	SHGC $_{total}$	0.86	0.72	0.62	0.55	0.49	0.46	0.42
	SHGC $_{total}$ reduction	0	0.14	0.24	0.31	0.37	0.40	0.44
Zone C (West)	SHGC $_{total}$	0.86	0.73	0.63	0.55	0.49	0.45	0.40
	SHGC $_{total}$ reduction	0	0.13	0.23	0.31	0.37	0.41	0.46

* SHGC $_{total}$ = SHGC $_{external}$ (varies) x SHGC $_{glazing}$ (0.86) x SHGC $_{internal}$ (1)

Column showing an approximate SHGC $_{total}$ of 0.43

Column showing an approximate SHGC $_{total}$ of 0.60

The results indicated that significant SHGC $_{total}$ reductions of up to 47% could be achieved from the use of reasonably sized external horizontal shades (up to 1.2m). In addition, it was found that the application of a minimum PF ratio of 1 resulted in approximate SHGC $_{total}$ values of 0.43, signifying low percentage discomfort hours. Similarly, the application of a minimum PF ratio of 0.4 resulted in approximate SHGC

$_{total}$ values of 0.6, signifying moderately low discomfort hours. The SHGC $_{total}$ reductions for similar PF ratios were found to be fairly similar irrespective of zone orientation. However, given that zone C had a total glazing area of 32.4m^2 (the majority of which was in the solar-prone west facade) compared to 16.2m^2 in zone A and 8.1m^2 in zone B, this did not imply similarity in solar heat gain. Instead, it was attributed to high diffused radiation levels (Chapter 6).

Table 7-4 Estimated SHGC $_{totals}$* as a result of using vertical shading – Olem House.

PF ratio		0	0.1	0.2	0.3	0.4
Zone A (East)	SHGC $_{total}$	0.86	0.64	0.49	0.39	0.31
	SHGC $_{total}$ reduction	0	0.22	0.37	0.47	0.55
Zone B (South)	SHGC $_{total}$	0.86	0.58	0.42	0.33	0.26
	SHGC $_{total}$ reduction	0	0.28	0.44	0.53	0.60
Zone B (East)	SHGC $_{total}$	0.86	0.64	0.49	0.39	0.31
	SHGC $_{total}$ reduction	0	0.22	0.37	0.47	0.55
Zone C (North)	SHGC $_{total}$	0.86	0.58	0.41	0.31	0.25
	SHGC $_{total}$ reduction	0	0.28	0.45	0.55	0.61
Zone C (East)	SHGC $_{total}$	0.86	0.64	0.49	0.39	0.31
	SHGC $_{total}$ reduction	0	0.22	0.37	0.47	0.55
Zone C (South)	SHGC $_{total}$	0.86	0.58	0.42	0.33	0.26
	SHGC $_{total}$ reduction	0	0.28	0.44	0.53	0.60
Zone C (West)	SHGC $_{total}$	0.86	0.65	0.52	0.41	0.34
	SHGC $_{total}$ reduction	0	0.21	0.34	0.45	0.52

* SHGC $_{total}$ = SHGC $_{external}$ (varies) x SHGC $_{glazing}$ (0.86) x SHGC $_{internal}$ (1)

Column showing an approximate SHGC $_{total}$ of 0.43

Column showing an approximate SHGC $_{total}$ of 0.60

The next set of results indicated that the application of vertical shading devices showed greater potential for solar heat gain reductions (of up to 61%) compared to horizontal shading devices, and for significantly lower PF ratios. Given that majority of the glazing areas in Zones A, B and C were located on the east and west facades, and taking into account the suitability of vertical shading fins for these orientations (Chapter 6); this kind of performance was anticipated.

The findings indicated that a minimum PF ratio of 0.2 (north and south facing zones) and 0.3 (east and west facing zones) resulted in suitably low $SHGC_{total}$ values of 0.43 and below. On the other hand, a minimum PF ratio of 0.1 (north and south facing zones) and 0.2 (east and west facing zones) resulted in moderately low $SHGC_{total}$ values of 0.6 and below.

Table 7-5 Estimated SHGC $_{totals}$* as a result of using egg crate shading – Olem House.

PF ratio		0	0.2/0.1	0.4/0.2	0.6/0.3
Zone A (East)	SHGC $_{total}$	0.86	0.21	0.21	0.21
	SHGC $_{total}$ reduction	0	0.65	0.65	0.65
Zone B (South)	SHGC $_{total}$	0.86	0.21	0.21	0.21
	SHGC $_{total}$ reduction	0	0.65	0.65	0.65
Zone B (East)	SHGC $_{total}$	0.86	0.21	0.21	0.21
	SHGC $_{total}$ reduction	0	0.65	0.65	0.65
Zone C (North)	SHGC $_{total}$	0.86	0.19	0.19	0.19
	SHGC $_{total}$ reduction	0	0.67	0.67	0.67
Zone C (East)	SHGC $_{total}$	0.86	0.21	0.21	0.21
	SHGC $_{total}$ reduction	0	0.65	0.65	0.65
Zone C (South)	SHGC $_{total}$	0.86	0.21	0.21	0.21
	SHGC $_{total}$ reduction	0	0.65	0.65	0.65
Zone C (West)	SHGC $_{total}$	0.86	0.23	0.23	0.23
	SHGC $_{total}$ reduction	0	0.63	0.63	0.63

* SHGC $_{total}$ = SHGC $_{external}$ (varies) x SHGC $_{glazing}$ (0.86) x SHGC $_{internal}$ (1)

Column showing approximate SHGC $_{total}$ of 0.43 and less

Of the three types examined, egg crate shading showed the greatest reductions in SHGC $_{total}$ values of up to 67% and for relatively low PF ratios. This good performance was previously attributed to complex shading patterns (Chapter 6). The findings indicated that combined low horizontal and vertical PF ratios of 0.2 and 0.1 gave a SHGC $_{total}$ of under 0.21. This was well below the recommended SHGC $_{total}$ value of

0.43 and indicated significantly low discomfort hours. At this stage, this information was deemed useful in determining the following:

a) The most suitable shading type in order of effectiveness: egg crate, vertical and horizontal shading, respectively.
b) The approximate sizing of the selected shading type required to give significant improvement to comfort: minimum PF ratios of 1 (HS), 0.2 for north and south facades and 0.3 for east and west facades (VS) and 0.2/0.1 (ECS), respectively.
c) The approximate sizing of the selected shading type required to give moderate improvement to comfort: minimum PF ratios of 0.4 (HS), 0.1 for north and south facades and 0.2 for east and west facades (VS) and 0.2/0.1 (ECS), respectively.

With this information, a designer would have useful information with which they could weigh out the pros and cons of applying either option. A similar exercise was undertaken for Olem House and highlighted in Table 7-6.

Table 7-6 Shading selection appraisal for selected zones of Olem House.

Zone	Type	Strengths	Weaknesses
Zone A (East exposure only)	HS	• Minimal view restrictions • Good natural lighting levels	• Relatively lower SHGC reduction with high PF ratios (greater depths)
	VS	• High SHGC reductions for low PF ratios • Suitable for low angle sun experienced in the east facade.	• Two shading fins required for each window • Relatively high view restrictions • Reduced natural lighting levels
	ECS	• Highest SHGC reductions for relatively low PF ratios	• High view restrictions • Reduced natural lighting levels
Zone B (South and East exposure)	HS	• Relatively similar significant SHGC reductions for similar PF ratios on both facades (promotes uniformity that might be considered aesthetically pleasing) • Minimal view restrictions • Good natural lighting levels	• High PF ratios
	VS	• High SHGC reductions for low PF ratios • Suitable for low angle sun experienced in the east facade.	• Higher number of shading elements required • Relatively high view restrictions • Reduced natural lighting levels
	ECS	• Highest SHGC reductions for low PF ratios	• High view restrictions • Reduced natural lighting levels
Zone C (North, East, South and West exposure)	HS	• Relatively similar significant SHGC reductions for similar PF ratios for different orientations (allows for • Minimal view restrictions • Good natural lighting levels	• Higher material use as a result of high PF ratios
	VS	• High SHGC reductions for low PF ratios • Suitable for low angle sun experienced in the east and west	• Higher number of shading elements required • Relatively high view restrictions • Reduced natural lighting levels
	ECS	• Highest SHGC reductions for very low PF ratios irrespective of orientation	• High view restrictions • Reduced natural lighting levels

It was noted that in cases where artificial lighting is or will be in use for a significant amount of time, the option of using shading elements that work well to reduce a significant amount of solar heat gain but also restrict natural lighting might be worth considering.

Following this analysis, it was suggested that a designer would be better placed to select the shading configuration that would best fit their requirements, be they aesthetic, economic or environmental. Most importantly, they would be able to do so with regard to their impact on solar heat gain control and subsequent comfort.

To validate this method of obtaining SHGC total values from the SHGC data tables presented in Chapter 6, the predicted values were compared to $SHGC_{total}$ values derived from Tas simulations conducted for a simplified model of Olem House (Figure 7-6). These results were presented in Figure 7-7, Figure 7-8 and Figure 7-9 for horizontal, vertical and egg crate shading, respectively.

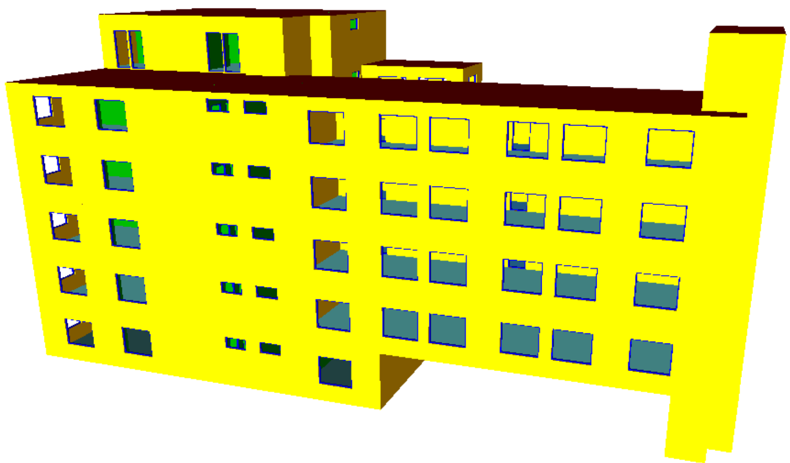


Figure 7-6 Perspective view of the Olem House Tas model.

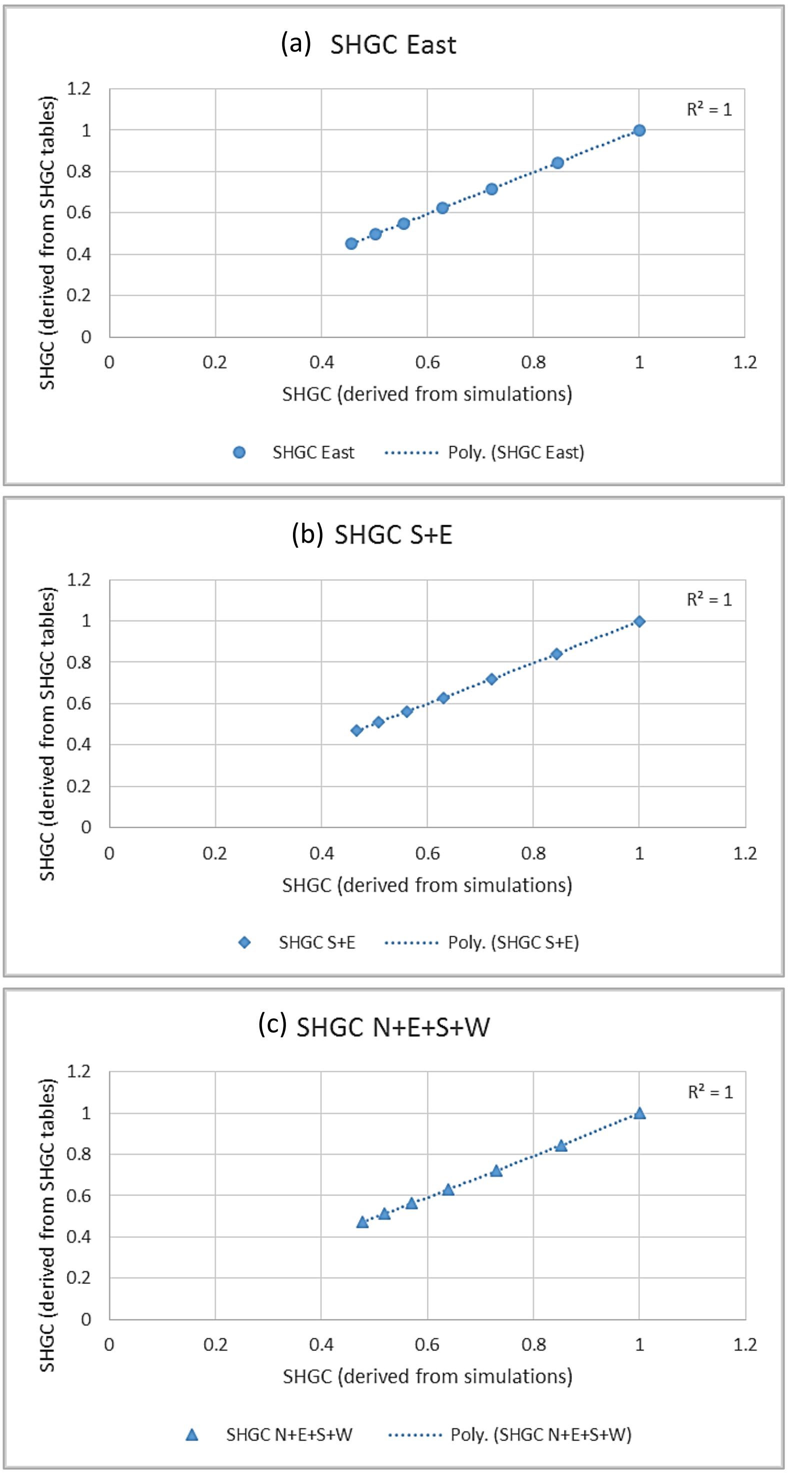


Figure 7-7 (a), (b) and (c) SHGC data comparison for horizontal shades applied to Olem House.

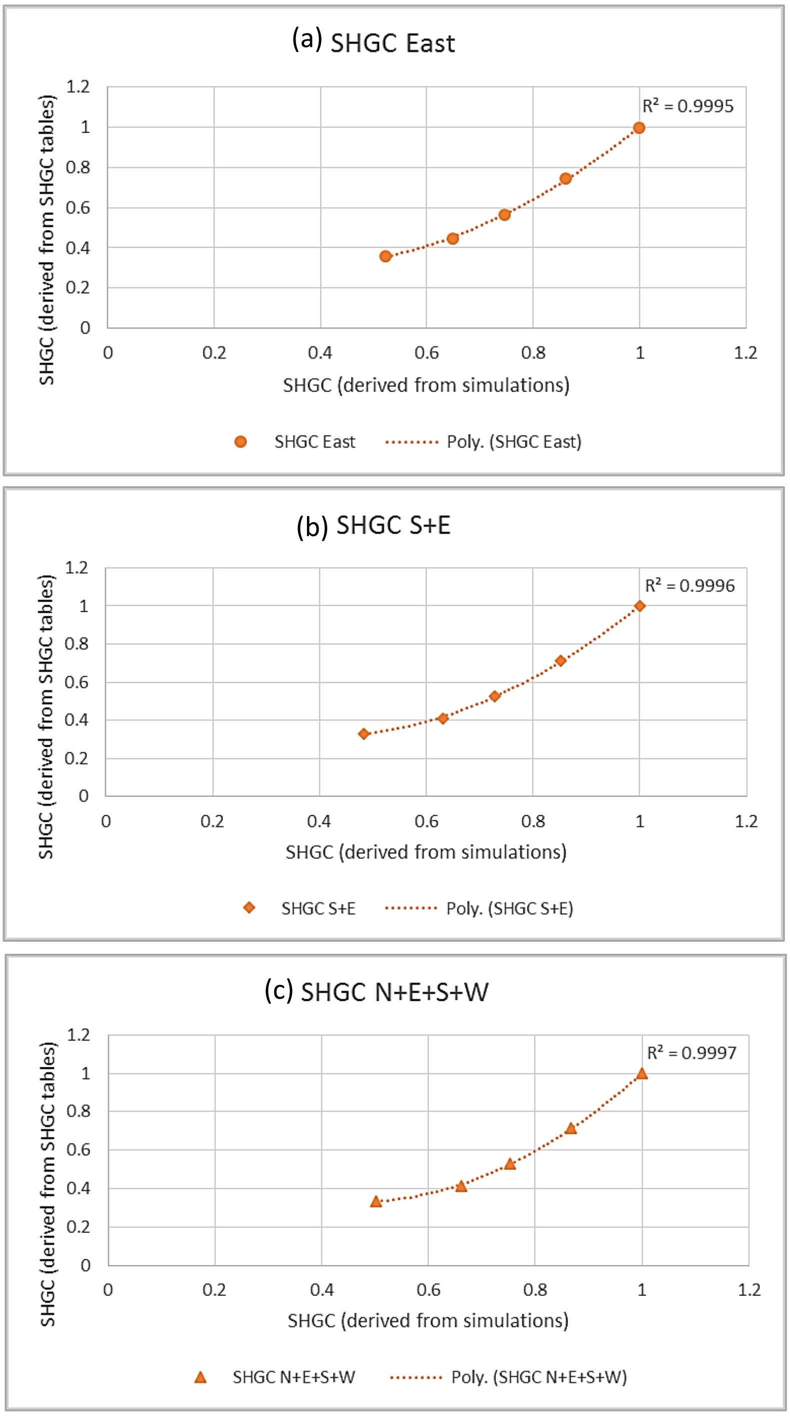


Figure 7-8 (a), (b) and (c) SHGC data comparison for vertical shades applied to Olem House.

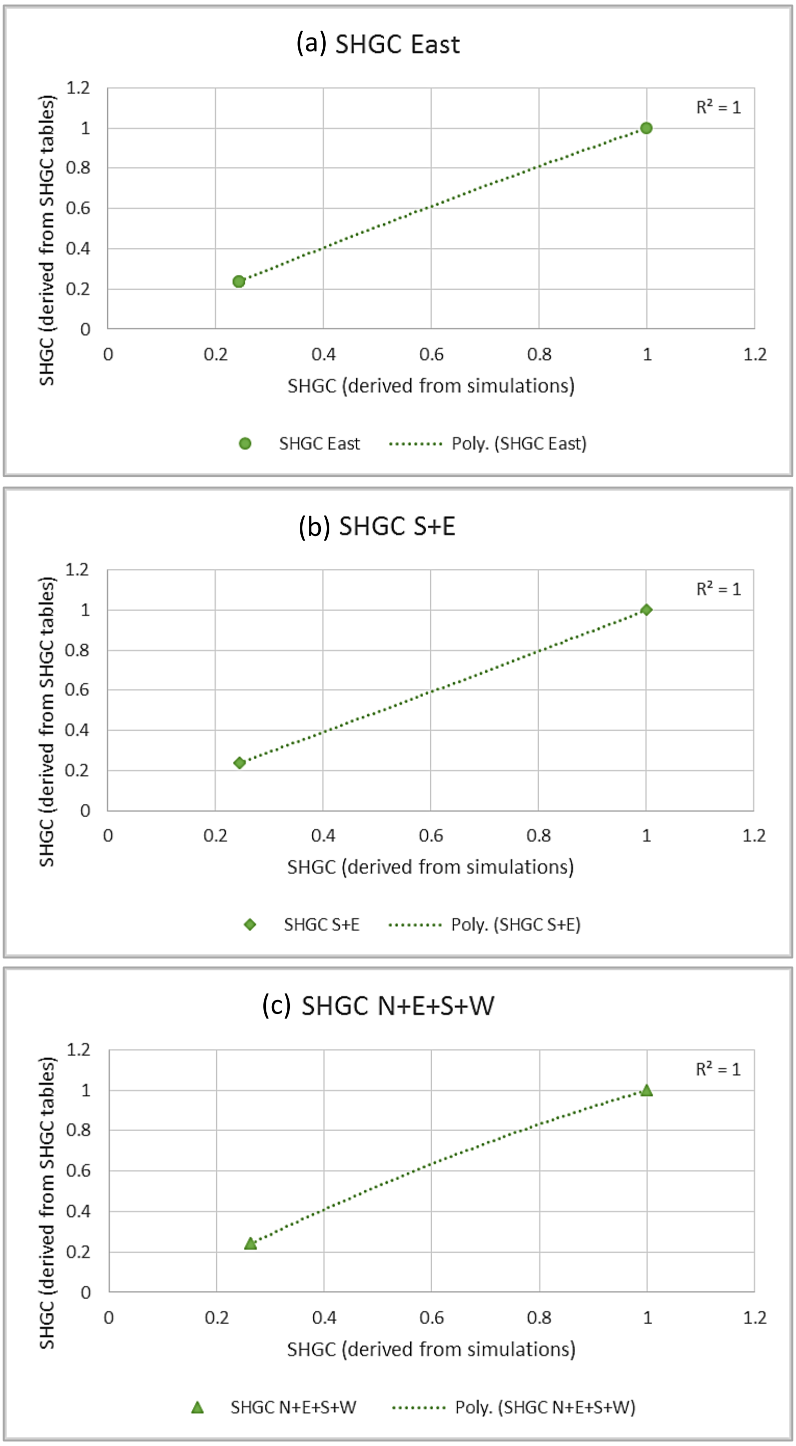


Figure 7-9 (a), (b) and (c) SHGC data comparison for egg crate shades applied to Olem House.

In this comparison analysis, the R^2 value represented the coefficient of determination, and signified the degree of correlation between the variables. The R^2 value ranges between 0 and 1 (0 being no relationship and 1 being strong correlation). For the data analysed, R^2 values ranged between 0.9 and 1. This indicated a strong positive correlation between the two sets of data for each shading type and demonstrated the reliability of the SHGC tables for similar calculations. Specifically, the horizontal and egg crate $SHGC_{total}$ values were found to be slightly more accurate in their predictions as they gave a higher R^2 value of 1 compared to 0.9 for vertical shading. This was suggested to be possibly due to the uneven glazing distribution in different orientations in the spaces that were analysed and the ability of vertical shading to control solar gain. Nonetheless, the results still indicated that the $SHGC_{total}$ tables gave good estimates and meaningful design messages for early stage design.

The next step of this shading evaluation process involved the estimation of potential energy savings. This stage is primarily intended to be performed for buildings with non-passive zones as was the case with Olem House. Approximations were made from the energy savings estimates presented in Figure 6-25 (horizontal shading), Figure 6-30 (vertical shading) and Figure 6-35 (egg crate shading) in Chapter 6; and the results presented in Table 7-7.

Table 7-7 Predicted energy savings per glazing area (kWh/m^2) – Olem House.

Horizontal shading PF ratio	0	0.2	0.4	0.6	0.8	1	1.2
Zone A	0	52.1	92.7	121.7	143.1	158.1	169.8
Zone B	0	48.9	85.2	109.5	127.3	140.2	150.1
Zone C	0	53.5	94.7	123.6	144.6	159.8	171.8
Vertical shading PF ratio	**0**	**0.2**	**0.3**	**0.5**	**0.7**	**-**	**-**
Zone A	0	108.3	168.9	184.3	154.4	-	-
Zone B	0	110.3	166.3	170.4	122.8	-	-
Zone C	0	121.5	187.1	198.6	156.2	-	-
Egg crate shading PF ratio	**0/0**	**0.2/0.1**	**0.4/0.2**	**0.6/0.3**	**-**	**-**	**-**
Zone A	0	220.4	220.4	220.5	-	-	-
Zone B	0	202.8	202.8	202.8	-	-	-
Zone C	0	228.6	228.6	228.6	-	-	-

Predicted energy savings for PF ratios which give an approximate SHGC $_{total}$ of 0.43 and less (red shading)

Predicted energy savings for PF ratios which give an approximate SHGC $_{total}$ of 0.6 and less (green shading)

The results indicated that significant energy savings could be made from the application of external shading devices of varying PF ratios. For recommended PF ratios that gave approximate SHGC $_{total}$ values of 0.43 and below, energy savings of up to 159.8kWh/m^2, 187.1kWh/m^2 and 228.6kWh/m^2 were predicted for horizontal, vertical and egg crate shading, respectively. As expected, for energy savings for PF ratios that gave higher SHGC $_{total}$ values of 0.6, lower energy savings of up to 94.7kWh/m^2, 121.5kWh/m^2 were predicted for horizontal and vertical shading, respectively. Given the high efficiency of egg crate shading with low PF ratios, it was deemed unnecessary to consider a SHGC $_{total}$ of 0.6.

Separate energy simulations conducted using Tas indicated that these predicted energy savings represented significant reductions in energy use of between 7.4% to 54.7% for the PF ratios considered (see Table 7-8).

Table 7-8 Potential annual percentage energy savings (%) – Olem House.

Horizontal shading PF ratio	0	0.2	0.4	0.6	0.8	1	1.2
Zone A	0	9.1	16.5	21.8	25.8	28.6	30.8
Zone B	0	9.1	16.3	21.3	25.0	27.7	29.8
Zone C	0	11.8	21.5	28.7	34.3	38.3	41.5
Vertical shading PF ratio	0	0.2	0.3	0.5	0.7	-	-
Zone A	0	7.4	13.5	18.5	22.7	-	-
Zone B	0	7.9	14.4	19.6	23.7	-	-
Zone C	0.0	9.8	17.9	24.7	30.2	-	-
Egg crate shading PF ratio	0/0	0.2/0.1	0.4/0.2	0.6/0.3	-	-	-
Zone A	0	40.2	40.2	40.2	-	-	-
Zone B	0	40.1	40.1	40.1	-	-	-
Zone C	0	54.7	54.7	54.7	-	-	-
Percentage energy savings for PF ratios which give an approximate $SHGC_{total}$ of 0.43 and less Percentage energy savings for PF ratios which give an approximate $SHGC_{total}$ of 0.6 and less							

Subsequently, to test the validity of the energy savings estimates, a comparison was made between the results extracted from the energy savings estimates presented in Table 7-7 and those derived from Tas energy simulations conducted for Olem House. The summarised results of this process were presented in Figure 7-10, Figure 7-11 and Figure 7-12.

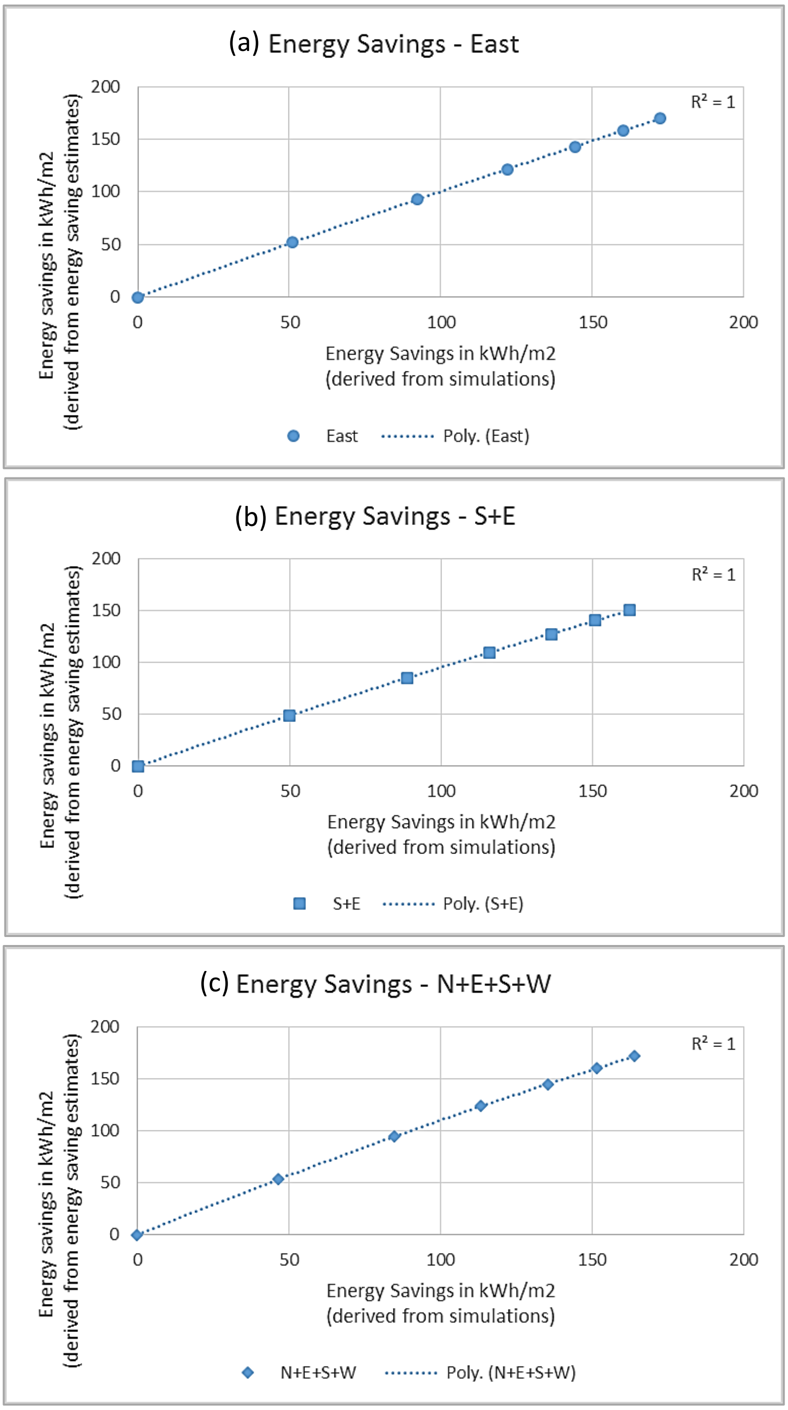


Figure 7-10 (a), (b) and (c) A comparison of energy savings predictions due to horizontal shading – Olem House.

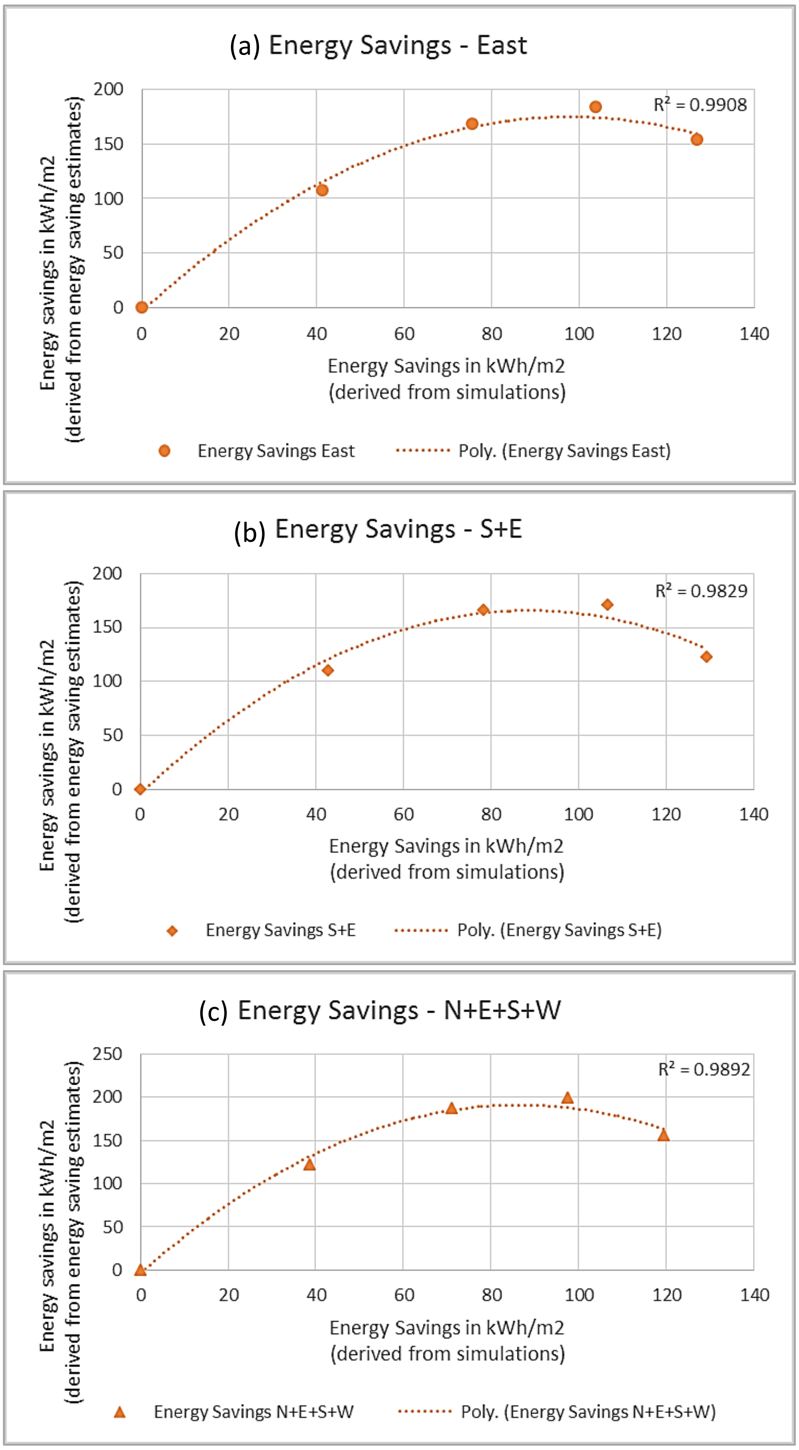


Figure 7-11 (a), (b) and (c) A comparison of energy savings predictions due to vertical shading – Olem House.

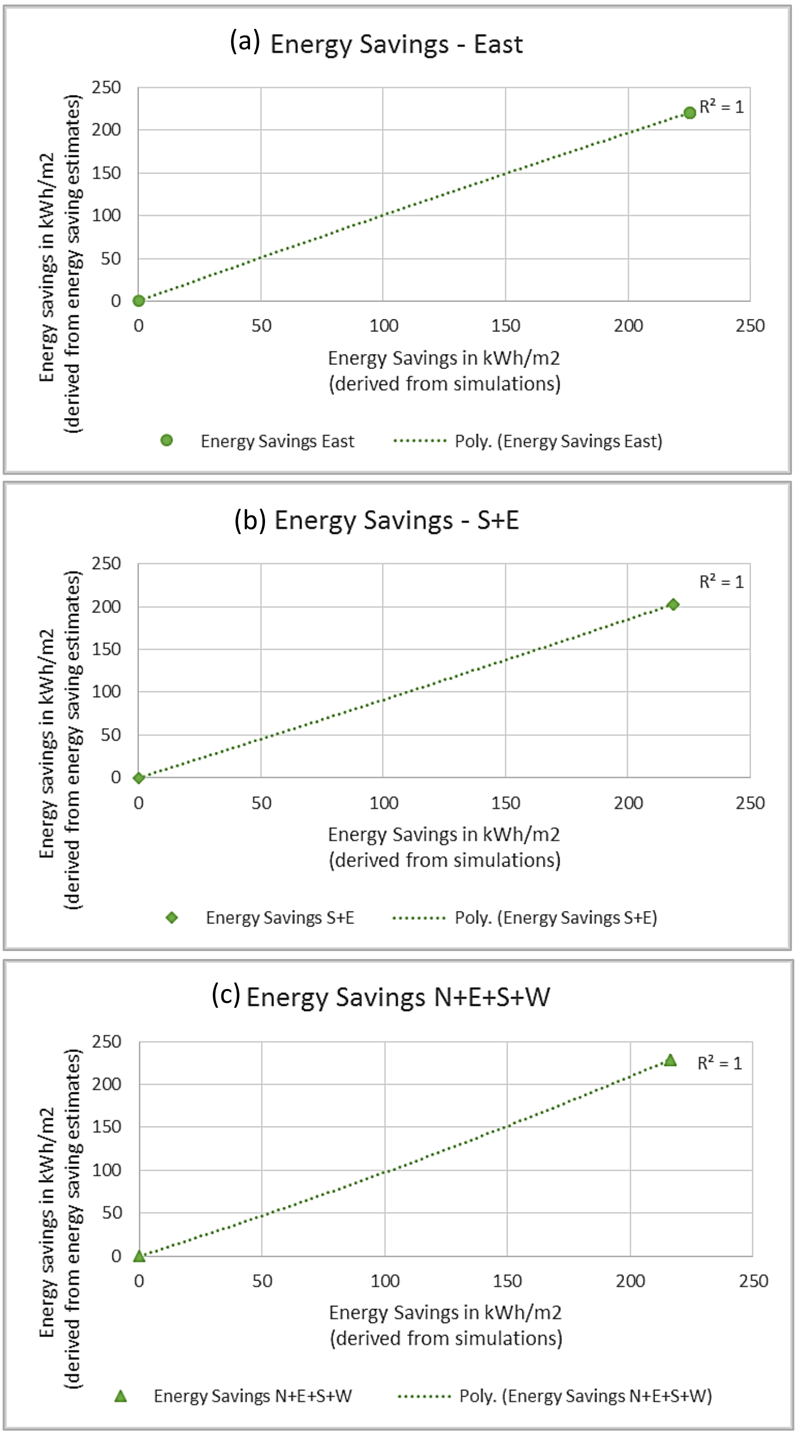


Figure 7-12 (a), (b) and (c) A comparison of energy savings predictions due to egg crate shading – Olem House.

The results indicated that the predictions presented close estimates of the energy saved from a reduction in SHGC $_{total}$ values. This was indicated by the high R^2 values between 0.9 and 1. As was the case in the previous comparison of the SHGC data, the energy savings correlation results indicated that the estimates due to a reduction in horizontal and egg crate SHGC values were slightly more accurate in their predictions than those derived for vertical shading which showed an overestimation of energy savings values for low PF ratios only. This performance was attributed to uneven glazing distribution in various orientations (especially where glazing in the east and west is greater as was the case in Olem House) and the subsequent solar gain of the selected zones. It was suggested that vertical shades were more influenced by this factor due to their inability to cut off the direct solar radiation component when the sun was at high altitudes. Nonetheless, the results normalised for higher PF ratios.

All considered, the energy savings analysis revealed that the designer could have opted for one of the following external shading design solutions:

a) Use of egg crate shading to obtain the greatest energy savings per glazing area of up to 228.6 kWh/m^2 (54.7% cooling energy savings per annum). However, this has the disadvantage of obstructed views and low natural lighting levels.
b) Use of horizontal shading of higher PF ratios to get lower but still significant energy savings of up to 159.8kWh/m^2 (38.3% cooling energy savings per annum). Also, this would allow for better natural lighting levels and less view obstruction. To avoid the use of shades of unnecessarily large depth, they could be broken down into multiple horizontal elements that achieve similar energy savings per annum.
c) Use a combination of horizontal (north and south facades) and vertical shading (the east and west facades) to maximise the energy saving potential of each shading type.

7.2 Combrook House (New build)

In this section, the SHGC values and energy saving estimates were applied to a building project at scheme design level; from this recommendations were made based on the optimum solutions.

7.2.1 Building information – Combrook House

The proposed site of Combrook House lies along Meru Road, off Mombasa Avenue (Figure 7-13); where a smaller commercial building is set to be demolished to accommodate the new build. This was found to be quite common in older sections of the city centre where dated buildings were often retrofitted or demolished to meet the increasingly high demand for modern commercial spaces. Consisting of five floor levels, the proposed office building is intended to cover a total built up area of 2,591.814sqm (see Table 7-14 and Table 7-15).

Figure 7-13 Combrook House Proposed Location Plan (author-modified from Google Maps).

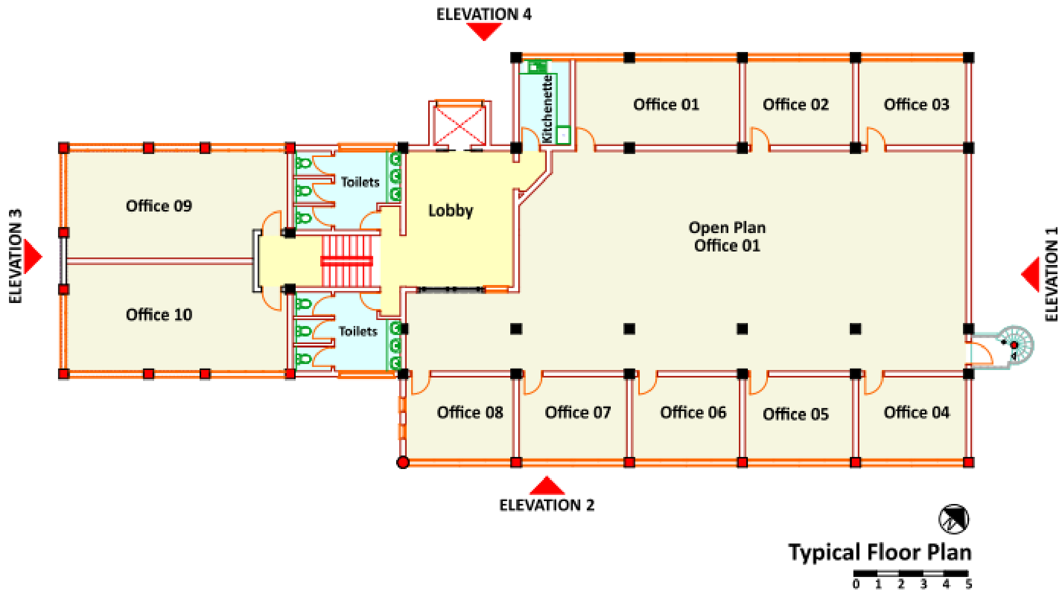


Figure 7-14 Combrook House, proposed typical floor plan (author-modified from A.D. Design Architects).

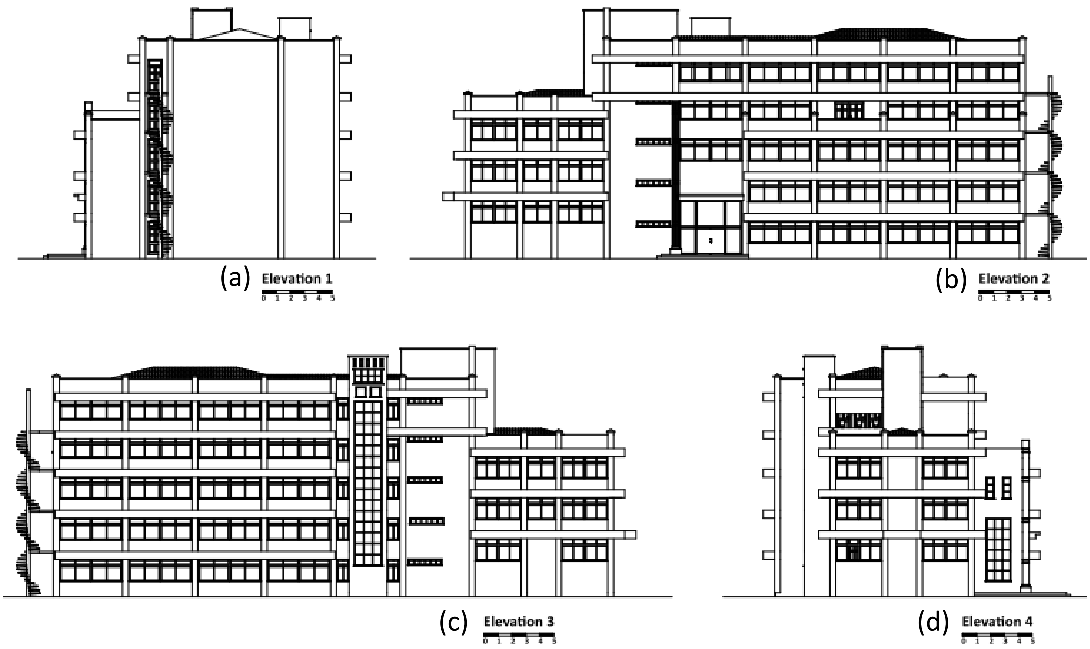


Figure 7-15 (a), (b) and (c) Combrook House proposed elevations (author-modified from A.D. Design Architects).

The proposed construction materials for Combrook House were typical to a significant number of recent buildings found in the city (Table 7-9).

Table 7-9 Combrook House proposed construction materials.

Main frame	Reinforced concrete
Floor/ ceiling	Ground floor: Concrete ground floor slab (Admittance: 3.45W/m^2K) Suspended floors: 150mm Lightweight reinforced concrete slab (Admittance: 4.33W/m^2K)
Walls	200mm Lightweight concrete (Admittance: 3.54W/m^2K)
Roof	Concrete tile finish on hollow block slab (Admittance: 3.95W/m^2K)
Windows	10mm thick glazing, in aluminium frame.

As was the case in Olem House, the introduction of an air conditioning system was selected for ventilation and cooling purposes as per client requirements. To reduce overheating that would in turn minimise the cooling load, the potential of the application of external shading devices was examined.

7.2.2 Combrook House shading analysis

Due to the similarities in glazing area and glazing orientation (of the office zones with glazed external walls), only two zones within a typical floor plan were selected for purposes of this analytical study as is indicated in Figure 7-16.

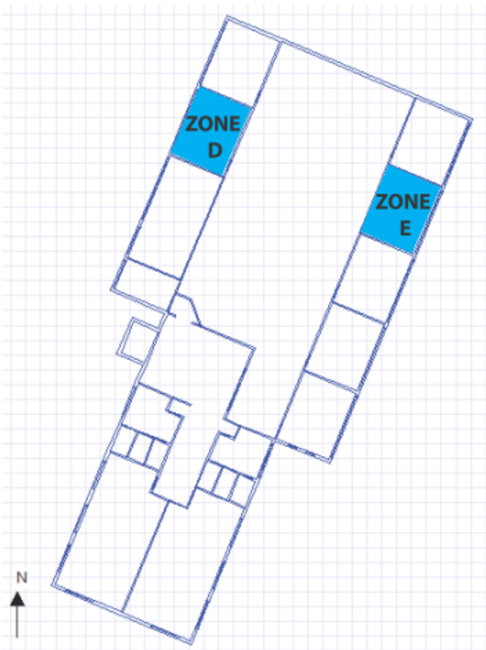


Figure 7-16 Selected zones for shading analysis, Combrook House.

For each zone, the glazing orientation and glazing area was extracted and presented in Table 7-10.

Table 7-10 Glazing orientation and glazing area of the selected zones – Combrook House.

Zone	Glazing orientation	Glazing area (m^2)
D	North-west (NW)	6.75
E	South-east (SE)	6.75

To begin with, the base case SHGC $_{total}$ of each zone of was calculated using Equation 6-4. No shading was considered for the base case; consequently, both the SHGC $_{external}$ and SHGC $_{internal}$ values remained constant at 1. In addition, the SHGC $_{glazing}$ was set at 0.86 as per the properties of clear single glazing (ASHRAE, 2013b, p. 17.5). This gave the base case a SHGC $_{total}$ of 0.86 which was later used to evaluate the SHGC $_{total}$ reduction as a result of the application of shading.

Low SHGC $_{external}$ values of under 0.5 have previously been suggested to be good indicators of low discomfort hours. Similarly, moderately low SHGC $_{external}$ values of under 0.7 have been suggested to be indicators of moderately low discomfort hours. Substituting the base case SHGC $_{external}$ of 1 with 0.5 and later 0.7 resulted in SHGC $_{total}$ values of 0.43 and 0.6, respectively. As was the case in Olem House, these SHGC $_{total}$ values were used to give an indication of the efficacy of the external shading types analysed.

Next, taking into account the application of external shading devices and the consequent reduction in SHGC $_{external}$, a series of SHGC $_{total}$ values were estimated and the results presented in Table 7-11 (HS), Table 7-12 (VS) and Table 7-13 (ECS). For estimation purposes, the SHGC $_{external}$ values applicable to various PF ratios were extracted from Table 6-11 (HS), Table 6-13 (VS) and Table 6-15 (ECS). A review of the scheme design details revealed that the designer had chosen to apply a horizontal shading canopy of 0.6m depth. Given the typical window height of 1.5m, this translated into a horizontal PF ratio of 0.4. The suitability of this shading type and depth was also examined as part of this exercise.

Table 7-11 Estimated SHGC $_{totals}$* as a result of using horizontal shading – Combrook House.

PF ratio		**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.2**
Zone D (NW)	SHGC $_{total}$	0.86	0.73	0.62	0.54	0.48	0.44	0.40
	SHGC $_{total}$ reduction	0	0.13	0.24	0.32	0.38	0.42	0.46
Zone E (SE)	SHGC $_{total}$	0.86	0.72	0.62	0.54	0.48	0.44	0.40
	SHGC $_{total}$ reduction	0	0.14	0.24	0.32	0.38	0.42	0.46

* SHGC $_{total}$ = SHGC $_{external}$ (varies) x SHGC $_{glazing}$ (0.86) x SHGC $_{internal}$ (1)

Column showing efficacy of proposed horizontal shading of PF ratio 0.4 which also has an approximate SHGC total value of 0.6

Column showing approximate SHGC $_{total}$ of 0.43

A review of the performance of the proposed horizontal shading with a PF ratio of 0.4 (also representative of an approximate SHGC $_{total}$ value of 0.6) revealed that the application of horizontal shading of this depth could result in a significant SHGC $_{total}$ reduction of 24%. However, to achieve the recommended low SHGC $_{total}$ of 0.43 (and significant SHGC reductions of up to 46%), a higher PF ratio of 1 and above was required.

Table 7-12 Estimated SHGC $_{totals}$* as a result of using vertical shading – Combrook House.

PF ratio		**0**	**0.1**	**0.2**	**0.3**	**0.4**
Zone D (NW)	SHGC $_{total}$	0.86	0.62	0.45	0.34	0.28
	SHGC $_{total}$ reduction	0	0.24	0.41	0.52	0.58
Zone E (SE)	SHGC $_{total}$	0.86	0.62	0.46	0.35	0.28
	SHGC $_{total}$ reduction	0	0.24	0.40	0.51	0.58

* SHGC $_{total}$ = SHGC $_{external}$ (varies) x SHGC $_{glazing}$ (0.86) x SHGC $_{internal}$ (1)

Column showing an approximate SHGC $_{total}$ of 0.43

Column showing an approximate SHGC $_{total}$ of 0.60

The application of vertical shading devices to the selected zones indicated that they help to reduce solar heat gain by up to 58% for the appropriately sized shading elements. This performance was significantly better than that of horizontal shading, and for lower PF ratios. This revealed the suitability of vertical shading over horizontal shading for use in the selected zones. The findings indicated that a minimum PF ratio of 0.3 resulted in suitably low SHGC $_{total}$ values of under 0.43 (52% SHGC $_{total}$ reduction). It was also suggested that a PF ratio of 0.2 would also be adequate as it gave fairly low SHGC $_{total}$ values of 0.45 (zone D) and 0.46 (zone E).

Table 7-13 Estimated SHGC $_{totals}$* as a result of using egg crate shading – Combrook House.

PF ratio (HS/VS)		**0**	**0.2/0.1**	**0.4/0.2**	**0.6/0.3**
Zone D (NW)	SHGC $_{total}$	0.86	0.19	0.19	0.19
	SHGC $_{total}$ reduction	0	0.67	0.67	0.67
Zone E (SE)	SHGC $_{total}$	0.86	0.20	0.20	0.20
	SHGC $_{total}$ reduction	0	0.66	0.66	0.66

* SHGC $_{total}$ = SHGC $_{external}$ (varies) x SHGC $_{glazing}$ (0.86) x SHGC $_{internal}$ (1)

Column showing approximate SHGC $_{total}$ of 0.43 and less

Egg crate shading had the greatest reduction in SHGC $_{total}$ values and for relatively low PF ratios. This was achieved using the low combined horizontal and vertical PF ratio of 0.2 and 0.1 which gave a SHGC $_{total}$ value of under 0.20.

At this stage, the following could be determined:

a) The shading types in the order of the most effective: egg crate, vertical and horizontal shading, respectively.
b) The approximate sizing of the selected shading type required to give significant improvement to comfort (based on approximate SHGC $_{total}$ values of 0.43): minimum PF ratios of 1 (HS), 0.3 (VS) and 0.2/0.1 (ECS), respectively.
c) The approximate sizing of the selected shading type required to give moderate improvement to comfort (based on approximate SHGC $_{total}$ values

of 0.6): minimum PF ratios of 0.4 (HS), 0.2 (VS) and 0.2/0.1 (ECS), respectively.

Next, to examine the validity of the results presented, the SHGC $_{total}$ values derived from SHGC $_{external}$ tables were compared to SHGC $_{total}$ values derived from Tas simulations conducted for a simplified model of Combrook House (Figure 7-17). The results were presented in Figure 7-18, Figure 7-19 and Figure 7-20 for horizontal, vertical and egg crate shading, respectively.

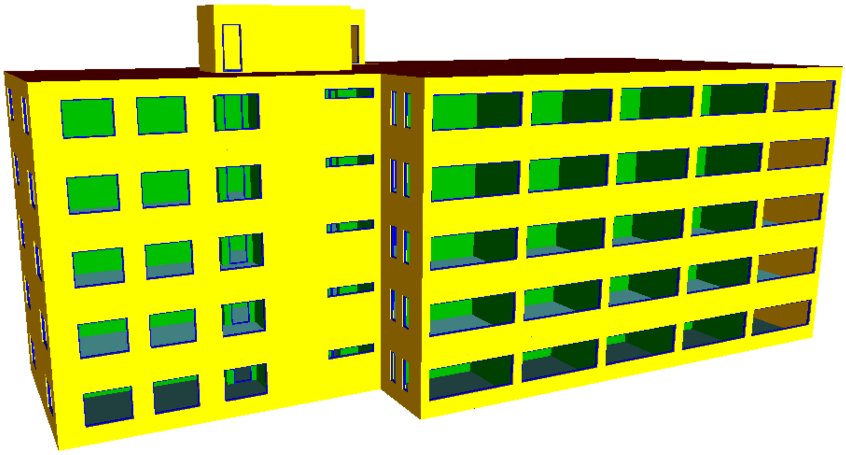
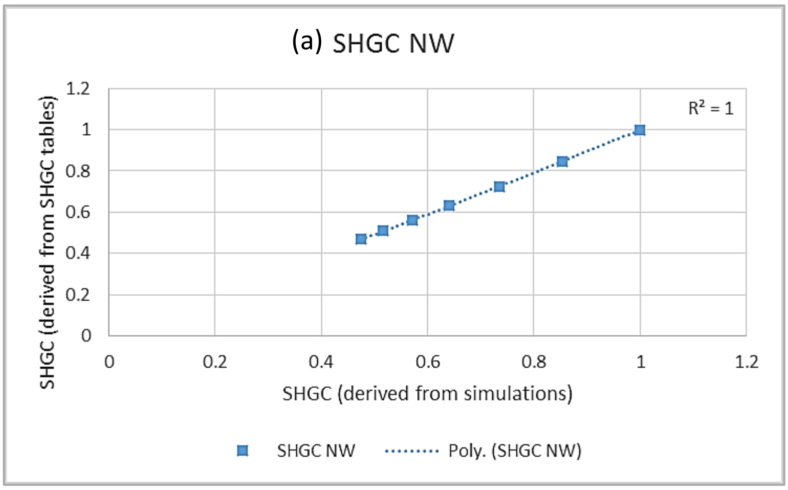


Figure 7-17 Perspective view of the Olem House Tas model.



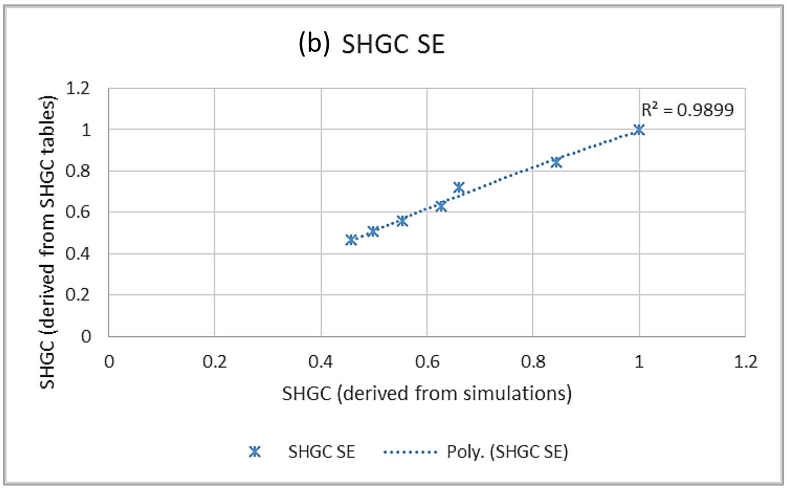
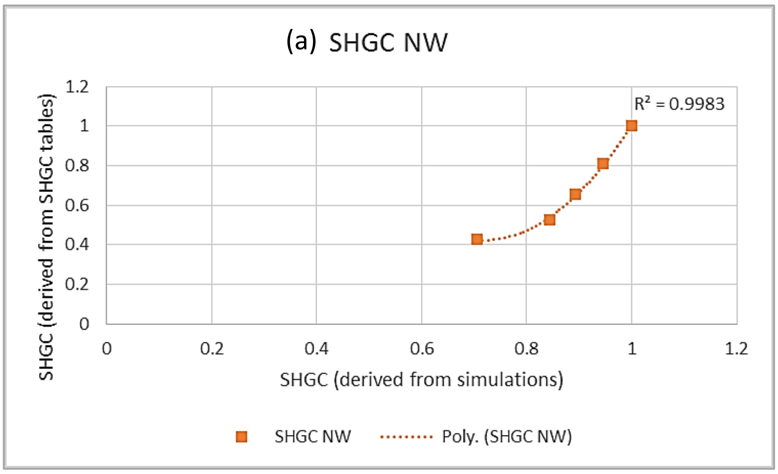


Figure 7-18 (a) and (b) SHGC data comparison for horizontal shades applied to Combrook House.



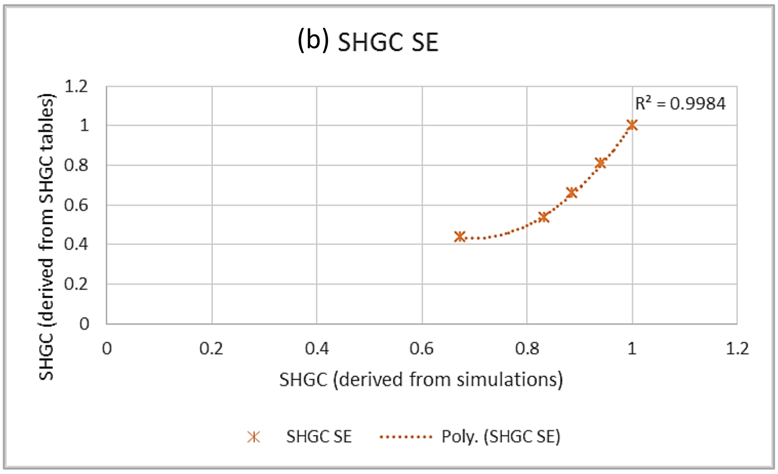


Figure 7-19 (a) and (b) SHGC data comparison for vertical shades applied to Combrook House.

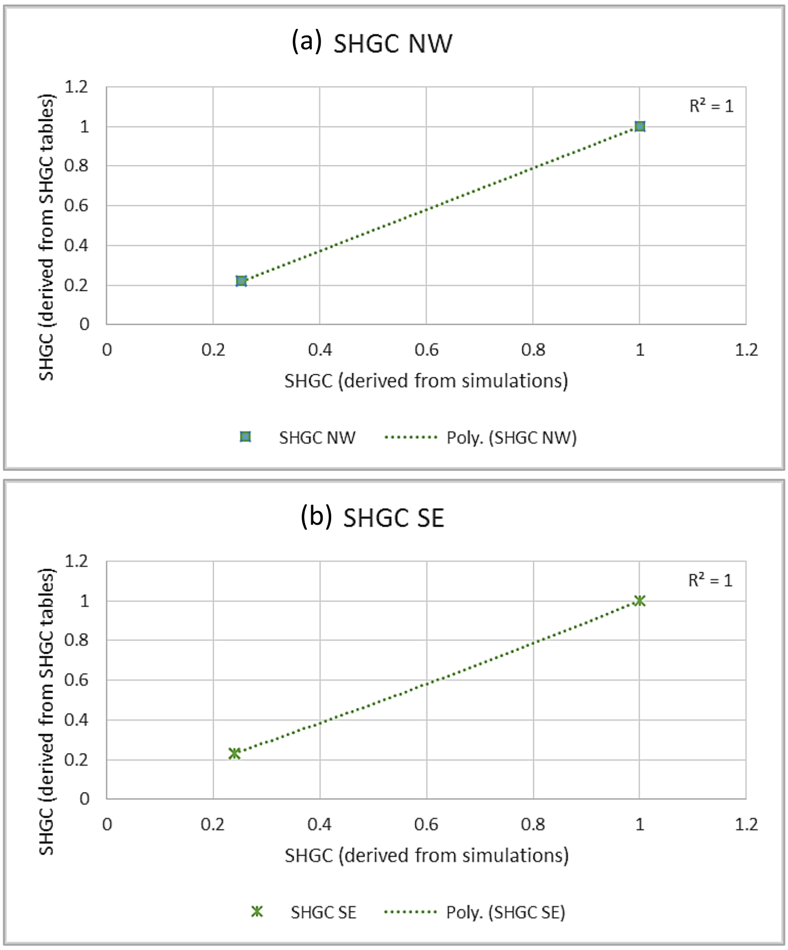


Figure 7-20 (a) and (b) SHGC data comparison for egg crate shades applied to Combrook House.

A comparison of the SHGC $_{total}$ data obtained using the estimation method and the Tas simulations indicated that the R^2 values ranged between 0.9 and 1. These highly positive correlations demonstrated the reliability of the SHGC tables for similar calculations in obtaining estimates. In addition, it was noted that both the horizontal and egg crate SHGC $_{total}$ values were found to be slightly more accurate in their predictions than vertical shading as they gave a higher R^2 value of 1. Nonetheless, the results still indicated that the SHGC $_{total}$ tables gave good estimates for early design stage design.

Following the extraction and subsequent review of SHGC $_{total}$ values, the potential cooling energy savings were derived from the estimates presented in Figure 6-25 (a) to (d) Energy savings per glazing area due to the provision of horizontal shading devices (N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW orientations). Figure 6-25 (HS), Figure 6-30 (VS) and Figure 6-37 (ECS) and the results presented in Table 7-14.

Table 7-14 Predicted energy savings per glazing area (kWh/m^2) – Combrook House.

Horizontal shading PF ratio	0	0.2	0.4	0.6	0.8	1	1.2
Zone D	0	56.6	101.3	134.7	159.1	177.3	191.0
Zone E	0	47.6	82.8	107.7	125.6	138.3	147.8
Vertical shading PF ratio	**0**	**0.2**	**0.3**	**0.5**	**0.7**	**-**	**-**
Zone D	0	141.9	218.4	231.1	180.0	-	-
Zone E	0	106.1	162.5	170.6	130.5	-	-
Egg crate shading PF ratio	**0/0**	**0.2/0.1**	**0.4/0.2**	**0.6/0.3**	**-**	**-**	**-**
Zone D	0	262.3	262.3	262.3	-	-	-
Zone E	0	201.5	201.5	201.5	-	-	-

Predicted energy savings for PF ratios which give an approximate SHGC $_{total}$ of 0.43 and less (red)
Predicted energy savings for PF ratios which give an approximate SHGC $_{total}$ of 0.6 and less (green)

The findings indicated that the application of the initially proposed horizontal shading (PF ratio 0.4 and SHGC $_{total}$ of 0.6) could result in significant energy savings of up to 101.3kWh/m^2 and 82.8kWh/m^2 for Zone D and E, respectively. However, the application of higher PF ratios of 1 (HS), 0.3 (VS) and 0.2/0.1 (ECS) for approximate SHGC $_{total}$ values of 0.43 resulted in higher energy savings of up to 177.3kWh/m^2, 218.4kWh/m^2 and 262.3kWh/m^2, respectively.

Separate energy simulations conducted using Tas for Combrook house indicated that these results represented energy savings of between 8.2% and 61% for the PF ratios considered (Table 7-15).

Table 7-15 Potential annual percentage energy savings (%) - Combrook House.

Horizontal shading PF ratio	**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.2**
Zone D	0	12.4	22.9	31.2	37.5	42.4	46.1
Zone E	0	13.1	23.4	31.1	36.6	40.7	43.7
Vertical shading PF ratio	**0**	**0.2**	**0.3**	**0.5**	**0.7**	**-**	**-**
Zone D	0	4.3	8.2	12.0	15.5	-	-
Zone E	0	4.6	8.9	12.8	16.5	-	-
Egg crate shading PF ratio	**0/0**	**0.2/0.1**	**0.4/0.2**	**0.6/0.3**	**-**	**-**	**-**
Zone D	0	61.1	61.1	61.1	-	-	-
Zone E	0	58.2	58.2	58.2	-	-	-

Percentage energy savings for PF ratios which give an approximate $SHGC_{total}$ of 0.43 and less (red)
Percentage energy savings for PF ratios which give an approximate $SHGC_{total}$ of 0.6 and less (green)

To test the validity of these energy savings estimates, a comparison was made between the results extracted from the energy savings estimates presented in Table 7-14 and those derived from Tas energy simulations conducted. The results were presented in Figure 7-21, Figure 7-22 and Figure 7-23.

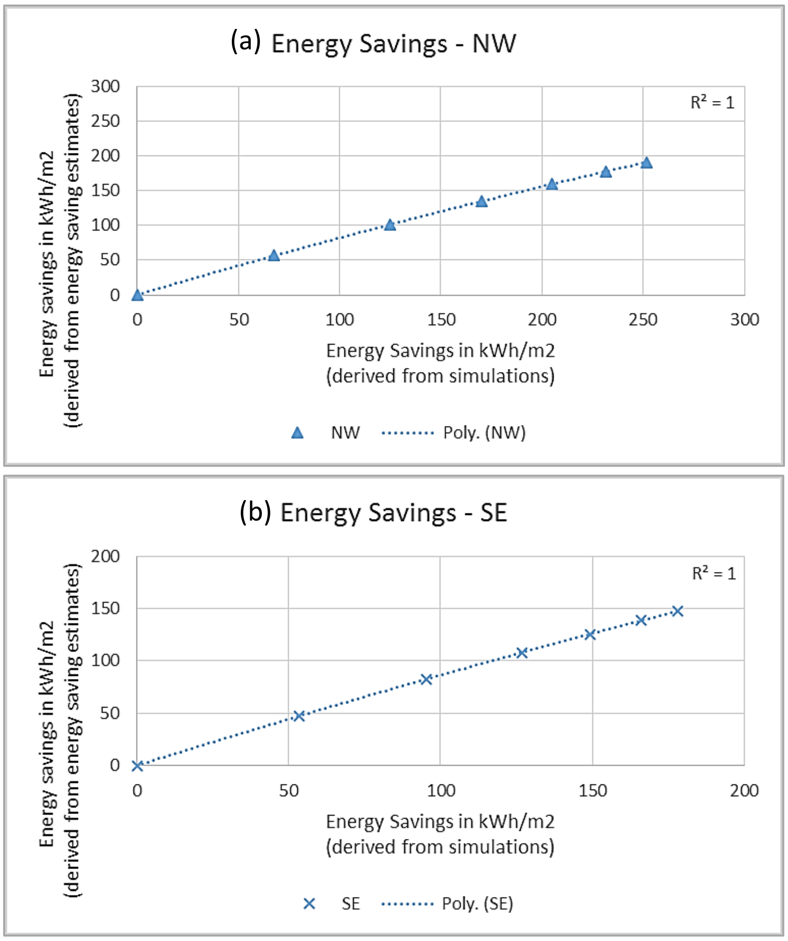


Figure 7-21 (a) and (b) A comparison of energy savings predictions due to horizontal shading – Combrook House.

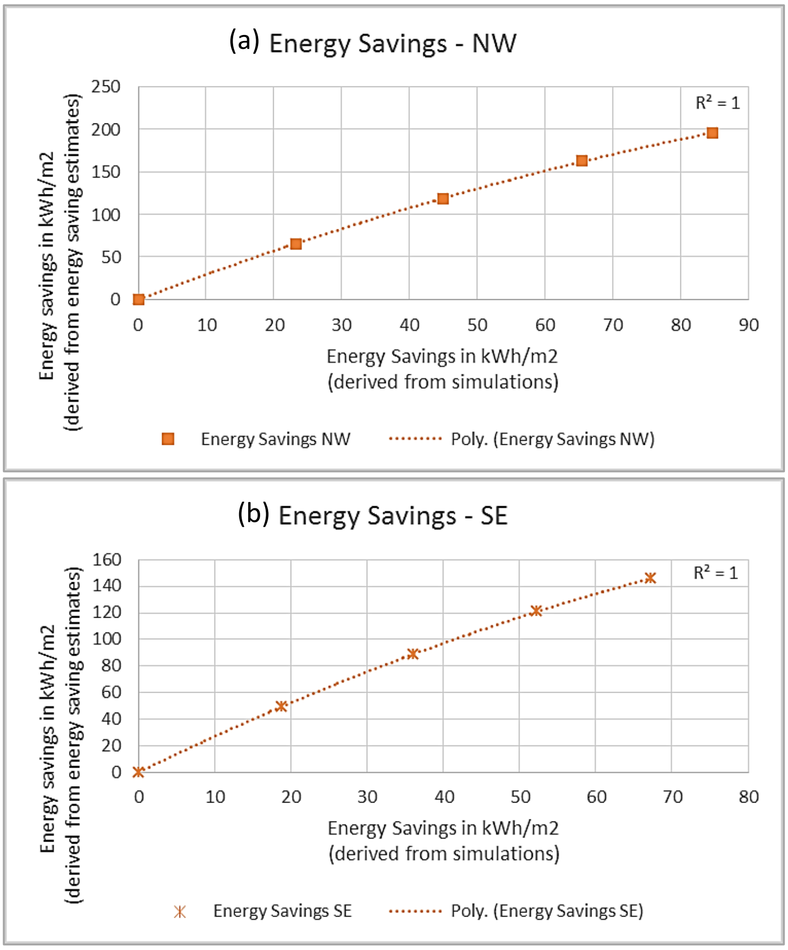
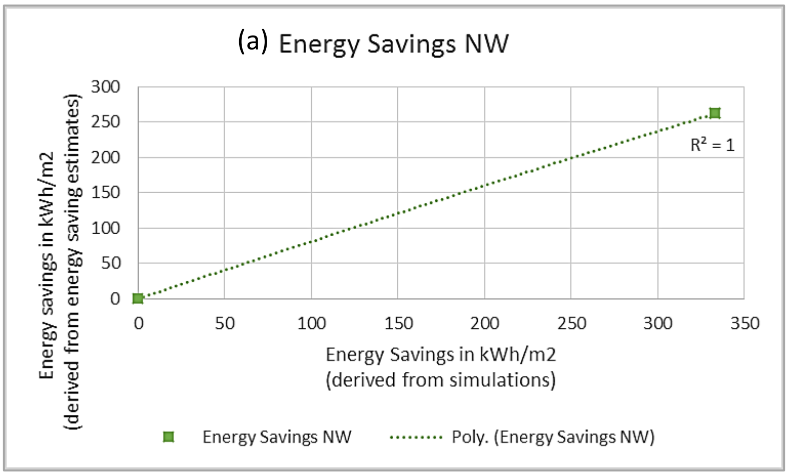


Figure 7-22 (a) and (b) A comparison of energy savings predictions due to vertical shading – Combrook House.



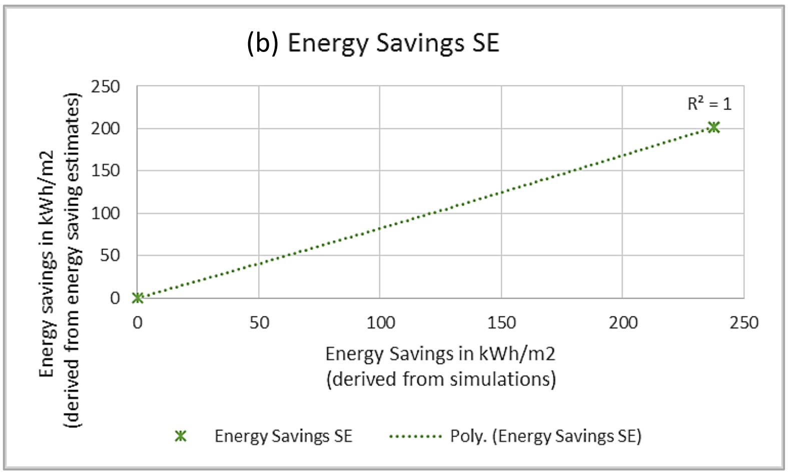


Figure 7-23 (a) and (b) A comparison of energy savings predictions due to egg crate shading – Combrook House.

The results showed that the predictions gave close estimates of the energy saved from a reduction in SHGC values. This was indicated by the high R^2 values between 0.9 and 1. As was the case in the previous comparison of the SHGC data, the energy savings correlation results indicated that the estimates due to a reduction in horizontal and egg crate SHGC values were slightly more accurate in their predictions than those derived for vertical shading which showed an overestimation of energy savings values for low PF ratios only. However, this was found to normalise for higher PF ratios. As with the previous analysis of Olem House, this performance was attributed to the large direct solar component experienced in the western and eastern exposed facades.

Following this review, it was suggested that the designer would have adequate information to opt for one of the following external shading design solutions:

a) Maintain the proposed solution (horizontal shading of PF ratio 0.4) with reduced energy savings per glazing area of up to 101.3kWh/m^2 (22.9% cooling energy savings per annum) for moderate discomfort hours.
b) Increase the PF ratio of the horizontal shading to maintain a similar aesthetic and get almost double the amount of energy savings of up to 177.3kWh/m^2 (42.4% cooling energy savings per annum) and for lower discomfort hours. This had the added advantage of better natural lighting levels and less view obstruction.
c) Use of egg crate shading to obtain the maximum energy savings of up to 262.3kWh/m^2 (61.1% cooling energy savings per annum). However, this had the disadvantage of obstructed views and low natural lighting levels.

7.3 Conclusions

This chapter has examined the application of the study findings highlighted in Chapter 6 to two local office buildings. A step by step approach has been adopted to demonstrate how a designer can quantify the effect of applying external shading elements on thermal comfort and energy use. As a result, workable solar control strategies can be developed. Initial testing has indicated that the proposed users of the method find it easy to use. To illustrate the application of the proposed method, two office buildings in Mombasa were selected and analysed. In both cases, the application of external shading devices was considered as a means of mitigating solar heat gain. The main focus of this design intervention was to significantly reduce discomfort hours and in so doing increase energy savings.

The first building, Olem House, was a retrofit project where one of the main retrofitting objectives was the introduction of air-conditioning for cooling and ventilation purposes. Early on, it was detected that the building layout and orientation made it particularly prone to solar heat gain that could lead to overheating. The second building, Combrook House, was a new build project. In as much as this project offered greater design flexibility that may have precluded the need for air conditioning, it was still required as part of the client project brief. However, unlike Olem House which appeared devoid of passive design interventions, the use of horizontal shading of had been proposed for Combrook House. The impact of this proposal was also examined.

To begin with, $SHGC_{total}$ values were estimated and compared to the base case $SHGC_{total}$ value of 0.86. These values gave an indication of the amount of solar heat gain passing though the glazing area and into the respective zones. Using the recommended low $SHGC_{external}$ value of 0.5, a $SHGC_{total}$ of 0.43 was derived to give a good indication of low discomfort hours. Similarly, using the recommended $SHGC_{external}$ value of 0.7 for moderately low discomfort hours, a $SHGC_{total}$ of 0.6 was derived.

Using a $SHGC_{total}$ of 0.43 as a reference point, suitable PF ratios of 1 for horizontal shading, 0.3 for vertical shading and 0.2/0.1 for egg crate shading were established for both buildings. It was also found that a $SHGC_{total}$ reduction of over 50% was achieved as a result of applying these PF ratios. Alternatively, using a $SHGC_{total}$ of 0.6 as a reference point, suitable PF ratios of 0.4 for horizontal shading and 0.2 for vertical shading were derived for both buildings. In this case, a $SHGC_{total}$ reduction of between 21% and 28% was obtained from using these PF ratios. Further, it was noted that the reference $SHGC_{total}$ values of 0.43 and 0.6 were similar for both buildings due to similarities in $SHGC_{glazing}$ type used in the base case $SHGC_{total}$ calculations. Nonetheless, due to differences in actual shading depths and window dimensions, variances in energy savings for both buildings were noted in later findings.

Of the shading types considered, egg crate shading was found to be the most effective in both cases. This was because this type enabled the greatest reduction in $SHGC_{total}$ values for significantly lower PF ratios with highs of up to 67% compared to 47% and 41% for vertical and horizontal shades, respectively.

To validate the predicted $SHGC_{total}$ results, the derived values were compared to the $SHGC_{total}$ values extracted from a series of Tas simulations conducted for both buildings. R^2 values of 0.9 to 1 indicated that these values showed strong positive correlations and demonstrated the reliability of the $SHGC_{external}$ values derived for horizontal, vertical and egg crate shading.

The next step of this evaluation process involved the estimation of potential energy savings as a result of applying external shades. From this, the findings indicated that energy savings of up to 228.6 kWh/m^2 and 262.3kWh/m^2 were predicted for Olem House and Combrook House, respectively. This represented a significant energy savings of 55% and 61% for Olem House and Combrook House, respectively. Overall, the shading analysis revealed that energy savings ranging between 15% and 61% could be achieved from the application of suitably sized horizontal, vertical and egg crate shading devices to Olem House and Combrook House.

As with the validation of SHGC values, the predicted energy savings estimates were compared with the data derived from energy simulations conducted for both buildings. In both cases, highly positive R^2 values ranging from 0.9 to 1 indicated that the estimates provided good approximations. The energy estimates due to a reduction in horizontal and egg crate SHGC values were the most accurate of those extracted with consistent R^2 values of 1. Estimates for vertical shading were found to be slightly less accurate and gave R^2 ratios of 0.9; however, higher levels of accuracy were recorded for higher PF ratios.

In summary, the findings of the analysis presented in this chapter validated the use of the derived SHGC values and energy estimates in office buildings in similar latitudes. It was suggested the SHGC and predicted energy savings data provided useful references that designers could use to carry out quick and simple calculations that would enable them to determine the most suitable and/or effective shading type. It was suggested that this type of information would encourage designers to use external shading devices as a method of maintaining thermal comfort and conserving energy in office buildings situated in the local region. It was further suggested that these energy savings values could be multiplied by the current commercial tariffs to get an idea of the potential annual savings. This could further be compared against the cost of the selected shading type to get an idea of the payback period.

8 CONCLUSIONS AND FURTHER WORK

8 CONCLUSIONS AND FURTHER WORK

Growing concern over issues of climate change and fast-dwindling natural resources have prompted the Kenyan government to cut down on energy consumption and reduce carbon emissions. To meet this challenge, the Kenyan government has set ambitious targets to develop and enforce national codes for energy efficiency and conservation in buildings by 2030. In addition, the government is committed to promote the design and retrofit of buildings that offer reductions in energy use. Whilst this is a positive step, the lack of adequate and specific guidance in existing regulations reveals that there is a significant amount of work that needs to be done to meet these goals within the time frame provided.

In the meantime, contemporary office buildings in the warm humid region of Kenya continue to show a predominance of highly glazed lightweight buildings that are prone to overheating, and rely on costly and unsustainable active climate control systems. In fact, climate control systems in warm climate regions account for approximately 70% of building energy consumption. This substantial amount of energy consumption is attributed to heavy reliance on active climate control measures which are used to solve climate related comfort issues induced by poor design. In the midst of growing energy demand and a potential deficit in supply, the influx of these poorly-designed buildings has intensified the need to explore viable climate-responsive design alternatives suitable to local conditions.

Taking this into account, this research was set out to explore ways of improving thermal comfort and energy efficiency in response to climate considerations and for parameters typical to office buildings in the warm humid city of Mombasa, Kenya. The strategic study aim was further supported by the following objectives:

- To gain an understanding of local climate conditions and related comfort considerations.
- To review the design strategies recommended for office buildings in similar hot and warm humid regions.

- Using the selected case study buildings as a research vehicle, to identify suitable design strategies for office buildings in warm humid regions of Kenya.
- Guided by research outcomes, to give recommendations for the incorporation of minimum standards in building regulations.

It is clear that the key to mitigating environmental design problems that lead to significant energy consumption lies in a design response to climate. In the warm humid region of Kenya, the main environmental issues of concern stem from the relatively high temperature and humidity levels and instances of high solar radiation. This explains why local highly glazed office buildings - and especially those that are unprotected against the elements - would be prone to overheating. As such, to ensure that an office building works well within its local climate, it is essential for designers to effectively address key environmental concerns by way of appropriate design strategies.

Besides identifying the main climate concerns, it is also necessary to establish how long it would be possible to run an office building using suitable passive design strategies in a typical year. With this information, a designer can anticipate for which part of the year mechanical controls would be necessary to restore comfort and design accordingly. Where naturally ventilated buildings are concerned, this would likely cut down on the provision of active measures and enable focus on passive controls.

When considering the adaptive comfort model under the climate conditions of Mombasa, typical office buildings can be kept comfortable for up to 74% of the year without the need for active control systems. Collaborated by field studies carried out as part of this work, this gives credence to the fact that designers could indeed implement passive design strategies to promote desirable indoor conditions for the majority of the year. Importantly, the knock-on effect of applying these design strategies to local office buildings would led to a significant reduction in the need for active controls and in so doing reduce rampant energy use in office buildings in Kenya.

Generally, passive design strategies recommended for office buildings in warm humid climates fall into two classifications: heat gain control measures and the provision for cooling. Of the heat gain controls, external shading is the most significant. This is largely because shading works by blocking out solar radiation, which is the greatest source of heat gain in buildings. This explains why external shading is highly recommended by notable researchers and specified in energy efficiency regulations for hot and warm humid regions as one of the main structural controls applied to curb poor thermal conditions in buildings. In addition, given the ongoing proliferation of the number of highly glazed and unshaded buildings in Kenya, it is clear to see why there would be increased concern regarding the poor thermal performance of these buildings with respect to thermal comfort and energy efficiency.

Where heat gain control measures have been applied and the ambient conditions are still deemed unsatisfactory, cooling strategies can be implemented to offer occupants the chance to remedy indoor conditions without the need for active control. In this case, natural ventilation strategies tend to be the most effective. Using naturally driven air movement, a building could be cooled down when the outdoor temperatures are cooler than those indoors. Similarly, occupants could benefit from physiological cooling provided by sensible air movement. However, to avoid ventilation gains, the effectiveness of this method is usually limited to periods when outdoor temperatures are cooler than those indoors.

Often, lessons learnt from vernacular architecture offer significant insights into solving climate-related problems. This is because these buildings have been tried and tested for many years under local conditions and been found suitable. Vernacular Swahili architecture is the predominant vernacular type found in the warm humid city of Mombasa in Kenya. Whereas the typical Swahili building looks more suited to hot dry climates, the highly shaded typology still demonstrates a suitable and workable architectural and environmental response to the local context and climate. Accordingly, it serves as a suitable precedent for the design of local office buildings.

The climate responsiveness of a typical vernacular Swahili building is attributed to a series of design elements and strategies that include:

- Building orientation and positioning: Buildings and their openings are laid out to encourage the channelling of breezes for cooling. Additionally, the close proximity of buildings enables them to mutually shade each other from solar radiation thereby reducing heat gain.
- Outdoor 'living rooms': The extension of living spaces outdoors encourages occupants to take full advantage of the cooling breezes for physiological cooling.
- Balconies: Besides shading the main building fabric from solar radiation, the porous nature of the balconies encourages rather than hinders air movement into indoor spaces.
- Screened window openings: Windows with screens such as shutters give occupants greater adaptive opportunities by enabling them to control shading (including the control of solar ingress, indoor natural lighting levels and glare) and ventilation (determining the direction and rate of air flow).
- Thick walls with significant thermal mass and ventilation: The external walls are notably thick with a significant amount of thermal mass to curb solar heat gain. These walls are punctuated by relatively few very well shaded fenestration openings and porous balconies that facilitate efficient cross ventilation and shading.
- Ventilated roof attic: Given that the sun is almost always overhead in this latitude, the use of a ventilated roof attic can be used to temper the impact of solar radiation from the zenith and reduce the amount of heat gain transmitted into living spaces below.

In comparison to a typical vernacular Swahili building, the typical modern office building in Mombasa is tall and isolated, heavily glazed, poorly shaded and lightweight. To curb overheating, these buildings are often sealed up for air conditioning and left with few adaptable opportunities for occupants. This considered, the aforementioned Swahili-inspired design strategies show potential for transfer to typical office buildings. In particular, the application of thermal mass, suitable ventilation strategies and external shading show good potential for the improvement of thermal comfort and a reduction in cooling energy use.

Thermal mass is mainly useful in reducing indoor temperatures and maintaining fairly steady indoor temperatures (in comparison to outdoor temperatures), delaying peak temperature times (until periods after an office building is unoccupied) and increasing comfort hours. Further, a combination of day time ventilation and night time ventilation (where windows are opened for ventilation during the day and later for night cooling) can result in a significant improvement to indoor comfort conditions. In this study, it was shown that the combination of thermal mass and night cooling works well to store coolth for cooling during occupancy periods. This finding contributed to the ongoing debate that seeks to determine the suitability of thermal mass in warm humid climates. In this case it was shown to work adequately, and especially if combined with night cooling.

It is widely accepted that external shading plays a major role the alleviation of solar heat gain in warm climates. Even so, little by way of design information specific to the local region is available to designers for the review of external shading solutions. To address this challenge, the study was focused on determining and categorising the effect of applying external shading devices to typical office buildings in Mombasa. In so doing, this work addressed the challenge of providing design guidance for local practitioners.

Usually, external shading is defined based on three basic configurations, *i.e.* horizontal, vertical and egg crate shades. Of these shading types, egg crate shading is the most effective irrespective of glazing orientation. This is the case even when low PF ratios (the ratio of the depth of the shading projection to the height or width of the window) are used. The high effectivity of egg crate shades is mainly attributed to its complex shading mask which helps to block solar radiation from varied sun angles. On the other hand, horizontal shading is most effective when used to cut out high angle sun - mainly in the northern and southern facing facades - whereas vertical shading is most effective when used to cut out low angle sun - experienced mainly in the eastern and western facing facades.

Save for knowing the most suitable shading type for each orientation, it is also useful to quantify the potential impact of various shading types in terms of solar gain reduction. This estimation can usually be portrayed by way of solar heat gain coefficients. Solar heat gain coefficients (SHGC) are indices that are developed to categorise the impact of applying shading types of various PF ratios to typical office buildings as a means of reducing solar gain.

The potential impact of a reduction in SHGC values can be interpreted in terms of comfort (for naturally ventilated buildings) or energy use (for actively ventilated buildings). In the SHGC values presented for Mombasa, a reduction of SHGC values with respect to comfort shows that a low SHGC value of 0.5 is a general indication of a low percentage in discomfort hours of less than 10%. Similarly, a moderately low SHGC value of 0.7 is a general indication of a moderately low percentage in discomfort hours of less than 15%. On the other hand, energy savings of up to 60% are achievable using practicably sized external shading elements.

Given the high level of accuracy showcased by the SHGC values derived for Mombasa, the values are considered good indicators of predicted solar gain. In addition, the external shading guidance document (APPENDIX D) used to compile these findings presents a methodical approach that demonstrates how a designer can quantify the effect of applying external shading elements on indoor thermal comfort and energy consumption. Overall, the method is considered simple and easy to apply by the intended users – architects and architectural students, all of whom would have a basic background in environmental design. Even where one has little technical knowledge, it is anticipated that the step-by-step approach adopted coupled by the highlighted definitions presented in the guidance would be useful in explaining the concept of the method.

As global warming brought on by climate change continues to take hold, the environmental design strategies proposed for climate control need to be examined for their endurance. For Kenya, the greatest concern for office buildings running under future climate change scenarios is from rising indoor temperatures. Although a rise in average outdoor temperatures of up to 3°C is anticipated, the average outdoor temperatures is expected to remain below 31.5°C (the calculated adaptive comfort upper limit for Mombasa) until the year 2100 (under the worst case emissions scenario). Therefore, as all the main study analyses conducted in this thesis are based on this comfort limit, the proposed strategies would still be valid. However, it was noted that the added risk of a rise in minimum outdoor temperatures might compromise the impact of strategies such as natural ventilation and thermal mass, which depend on significant temperature differences.

Overall, this research serves to contribute to the urgent need for the exploration of viable climate-responsive alternatives in buildings as a means of meeting energy efficiency and conservation targets set by the Kenyan government. The practical approach employed in the execution of this work has enabled easy translation of the major study findings into the local building and construction industry. Much like the energy efficiency assessment methods covered in this thesis, this structured method steps away from the generalised standards common to Kenyan building regulations, and provides specific guidelines based on minimum recommended shading performance indices. These guidelines can provide useful references for designers and help in the determination of effective shading types as a means of maintaining thermal comfort and conserving energy use in office buildings.

Efforts are currently underway to carry out further testing of the external shading guidance by a larger sample of anticipated users in Kenya. The feedback obtained from this process will be used to review the method as necessary. Additionally, reporting documentation based on the study findings is expected to be presented to the Environmental Design Chapter of the Architectural Association of Kenya (the chapter plays an advisory role building regulation review process) as well as in other forums. It is suggested that this will help to disseminate the findings to relevant stakeholders.

Besides further testing and revision of the guidance document (based on user feedback), there are a number of areas where further work is necessary. This could involve the extension of the analytical and experimental approach used within this work to a wider number of buildings so that the sensitivities of various other parameters can be greater understood. In addition, a review of the application of insulation to office buildings, although not commonly used in Kenya, might be useful in determining its potential impact on heat gain reduction.

Furthermore, given that the field study period for this research was relatively short, it would be useful to have more site-based investigation into the actual performance of local office buildings. This could enable a higher level of accuracy in the estimation process, and reduce any observed divergence between theoretical and measured thermal performance and resultant comfort.

One of the main limitations of this study was time. Whereas the use of the case study approach was exciting, it was also time-consuming. This was primarily due to the lack of precedent research work applicable to the Kenyan context and climate, and the absence of documented building information. Consequently, the researcher was required to collect a significant amount of empirical data for analysis purposes. On the part of the researcher, this necessitated a more thorough review of the overall study topic and the case study buildings and allowed for a large amount of learning and experience. Fortunately, this extensive work enabled the publication of a series of papers that will serve to the encourage availability of high quality research on the study topic.

Unless significant changes are made, the infiltration of highly glazed and poorly designed buildings in the warm humid region of Kenya will continue to lead to the use of costly climate control systems and increased energy consumption. The Kenyan government's commitment to meeting energy and carbon emissions reduction targets and the lack of research that can be applied to local office buildings necessitates a review of the existing situation and the development of suitable solutions. Environmental design strategies can assist in the mitigation of overheating and the improvement of overall comfort conditions for a significant part of year. Ultimately, the application of guidelines derived from similar studies that seek to understand and implement the principles of environmental design is essential.

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APPENDIX A

Technical data sheets (Chapter 3 and Chapter 4).

i) Tinytag View 2 Temperature/Relative Humidity Logger (Tinytag, 2014b).

Gemini DATA LOGGERS

Tinytag View 2 Temperature/Relative Humidity Logger (-25 to +50°C/0 to 100% RH)

TV-4500

Issue 6 : 17th October 2014 (E&OE)

Features

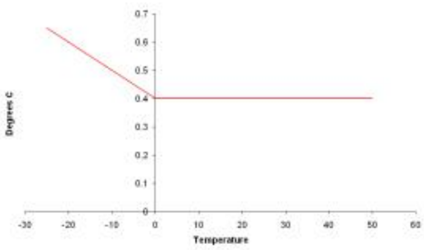
Total Reading Capacity	30,000 readings
Memory type	Non Volatile
Display	4 digits + indicators
Display Modes	°C or °F / %RH
Display Refresh Rate	Every 2 seconds (alternating temperature/humidity)
Trigger Start	Magnetic Switch
Delayed Start	Relative / Absolute (up to 45 days)
Stop Options	When full After n Readings Never (overwrite oldest data)
Reading Types	Actual, Min, Max
Logging Interval	1 sec to 10 days
Offload	While stopped or when logging in minutes mode
Alarms	2 fully programmable; latchable

Reading Specification

Temperature

Reading Range	-25°C to +50°C (-13°F to 122°F)
Sensor Type	10K NTC Thermistor (Integral)
Response Time	10 mins to 90% FSD in moving air
Logger Resolution	0.02°C or better
Display Resolution	0.1°C or 0.1°F

Logger Accuracy



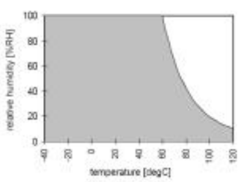
Relative Humidity

Reading Range	0 to 100% RH
Sensor Type	Capacitive (Integral)
Accuracy	±3.0% RH at 25°C / 77°F
Reading Resolution	Better than 0.3% RH
Response Time	40 seconds to 90% FSD (current data loggers, from SN 612487)
Display Resolution	0.1% RH

RH Sensor Working Range

The working range for the RH sensor is shown in terms of relative humidity / temperature limits.

Although the sensor will not fail beyond these limits, the accuracy will deteriorate.



Physical Specification

IP Rating	IP65 splash proof (see notes)
Operational Range*	-25°C to +70°C
Case Dimensions	
Diameter	60mm / 2.36"
Length	90mm / 3.54"
Width	65mm / 2.56"
Depth	35mm / 1.38"
Weight	85g / 3oz

*The Operational Range indicates the physical limits to which the unit can be exposed, not the reading range over which it will record.

Notes

Battery Type	Tekcell SBAA02P; SAFT LS14250 or LST14250

The logger will operate with other ½AA 3.6V Lithium (Li-SOCl2) batteries but performance cannot be guaranteed.

Replacement Interval Annually

Before replacing the battery the data logger must be stopped.

After removing an old battery from a logger, wait five minutes before inserting the new one.

Data stored on the logger will be retained after a battery is replaced.

The clarity of the display may change at extremes of temperature.

If used at low temperatures the data logger should be allowed to warm to room temperature before it is opened to avoid condensation forming inside the unit.

The IP65 rating is valid only when the unit's connector cap is securely fitted.

The coated sensor used on this unit (current product, SN 612487 and above) provides good protection from moisture and condensation, but in some cases - where the sensor becomes saturated - readings may become unpredictable. Once the sensor has dried out, and provided no residue is left behind, the unit should return to normal reading within 30 minutes.

Any dust, salts or residue that is allowed to build up on the RH sensor will affect the unit's reading accuracy.

The sensor may be cleaned with de-ionised water but not with pure isopropanol or abrasive detergents, as these may damage the coating on the sensor and effect its accuracy.

The RH sensor will resist small amounts of the following chemicals: formaldehyde, ammonia, carbon monoxide, sulphur dioxide, ethylene oxide, hydrogen chloride, hydrogen fluoride, hydrogen peroxide, nitrogen dioxide, methyl chloride, chlorine, freon, methanol, ethanol, isopropanol and ozone.
It also offers resistance to ultraviolet rays.

Calibration

This unit is configured to meet Gemini's quoted accuracy specification during its manufacture.

We recommend that the calibration of this unit should be checked every six months against a calibrated reference meter.

A certificate of calibration, traceable to a national standard, can be supplied for an additional charge either at the point of purchase, or if the unit is returned for a service calibration.

data sheet

www.tinytag.info sales@tinytag.info

ii) Tinytag Ultra 2 Temperature/Relative Humidity Logger (Tinytag, 2014a)

Gemini
DATA LOGGERS

Tinytag Ultra 2 Temperature/Relative Humidity Logger (-25 to +85 ℃/0 to 95% RH)

TGU-4500

Issue 10 : 17th October 2014 (E&OE)

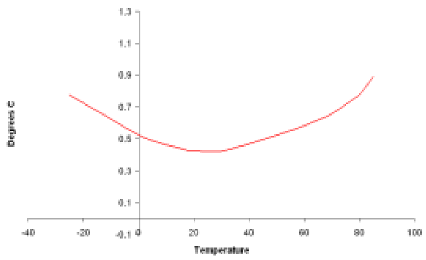
Features

Total Reading Capacity	32,000 readings
Memory type	Non Volatile
Trigger Start	Magnetic Switch (from SN 602211)
Delayed Start	Relative / Absolute (up to 45 days)
Stop Options	When full After n Readings Never (overwrite oldest data)
Reading Types	Actual, Min, Max
Logging Interval	1 sec to 10 days
Offload	While stopped or when logging in minutes mode
Alarms	2 fully programmable; latchable

Reading Specification

Temperature

Reading Range	-25 ℃ to +85 ℃ (-13 ℉ to +185 ℉)
Sensor Type	10K NTC Thermistor (Internally mounted)
Response Time	20 mins to 90% FSD in moving air
Reading Resolution	0.01 ℃ or better
Accuracy	

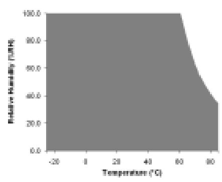


Relative Humidity

Reading Range	0% to 95% RH
Sensor Type	Capacitive
Accuracy	±3.0% RH at 25 ℃ / 77 ℉
Reading Resolution	Better than 0.3% RH
Sensor Location	Externally mounted
Response Time	10 seconds to 90% FSD

RH Sensor Working Range

The working range for the RH sensor is shown in terms of relative humidity / temperature limits.



Physical Specification

IP Rating	IP53 splash proof (see notes)
Operational Range*	-40 ℃ to +85 ℃ (-40 ℉ to +185 ℉)
Case Dimensions	
Height	72mm / 2.83"
Width	60mm / 2.36"
Depth	33mm / 1.30"
Weight	55g / 1.94oz

*The Operational Range indicates the physical limits to which the unit can be exposed, not the reading range over which it will record.

Notes

Battery Type	SAFT LS14250 or LST14250; Tekcell SBAA02P

The logger will operate with other ½AA 3.6V Lithium (Li-SOCl2) batteries but performance cannot be guaranteed.

Replacement Interval	Annually

Before replacing the battery the data logger must be stopped.

When replacing the battery, wait at least one minute after removing the old battery before fitting the new one.

Data stored on the logger will be retained after a battery is replaced.

If used at low temperatures the data logger should be allowed to warm to room temperature before it is opened to avoid condensation forming inside the unit.

The IP53 rating is valid only when the unit's connector cap is fitted and the unit is orientated with it's hanging tab uppermost.

If moisture forms on the unit's RH sensor readings will become unpredictable. Once the sensor has dried out, and provided no residue is left behind, the unit should return to normal reading within 30 minutes.

Any dust or residue that is allowed to build up on the RH sensor will affect the unit's reading accuracy.

The sensor may be cleaned with de-ionised water or pure isopropanol, but not with abrasive detergents, as scratches or residue will affect the accuracy.

The RH sensor will resist small amounts of the following chemicals: formaldehyde, ammonia, carbon monoxide, sulphur dioxide, ethylene oxide, hydrogen chloride, hydrogen fluoride, hydrogen peroxide, nitrogen dioxide, methyl chloride, chlorine, freon, methanol, ethanol, isopropanol and ozone.
It also offers resistance to ultraviolet rays.

Salt solutions may cause permanent damage as crystals forming within the porous layers affect moisture levels there.

Trigger Start

The trigger start option allows a unit to be set up as required and then started at a later time with a magnet. The position of the unit's trigger start switch is indicated by the • • • label on the back of the logger. When the "Wait until trigger event" option is selected in the Tinytag Explorer software, the green LED on the unit will flash once every eight seconds, indicating that the unit is waiting to log. When a magnet passed over the label, the green LED will light briefly to indicate that the unit has been activated. Once activated, the green LED will flash every four seconds to indicate that the logger is recording.

data sheet

www.tinytag.info sales@tinytag.info

iii) Testo 425 - Compact Thermal Anemometer (Testo, 2012)

Technical data / Accessories

testo 425

testo 425, thermal anemometer with permanently attached flow probe (Ø probe head 7.5 mm), incl. temperature measurement and telescopic handle (max. 820 mm), battery and calibration protocol

Part no. 0560 4251

General technical data

Oper. temp.	-20 to +50 °C
Storage temp.	-40 to +85 °C
Battery type	9V block battery, 6F22
Battery life	20 h
Dimensions	182 x 64 x 40 mm
Weight	285 g
Material/Housing	ABS
Warranty	2 years

Sensor types

	Thermal	NTC
Meas. range	0 to +20 m/s	-20 to +70 °C
Accuracy ±1 digit	±(0.03 m/s +5% of mv)	±0.5 °C (0 to +60 °C) ±0.7 °C (remaining range)
Resolution	0.01 m/s	0.1 °C

Accessories

Accessories	Part no.
Accessories for measuring instrument	
Case for measuring instrument and probes	0516 0210
TopSafe, protects from impact and dirt	0516 0221
Transport case for meas. instr. and probes (405 x 170 x 85 mm)	0516 0201
Recharger for 9V rechargeable battery, for external recharging of 0515 0025 battery	0554 0025
9V rech. battery for instrument, instead of battery	0515 0025
ISO calibration certificate velocity hot wire, vane anemometer, Pitot tube; calibration points 1; 2; 5; 10 m/s	0520 0004
ISO calibration certificate velocity hot wire, vane anemometer, Pitot tube; calibration points 5; 10; 15; 20 m/s	0520 0034

iv) Testo 540 – Pocket-sized light metre (Testo, 2013)

testo 540

We measure it. testo

Technical data / Accessories

testo 540

testo 540 handy Lux meter incl. protection cap, batteries and calibration protocol

Part no. 0560 0540

Sensor type	Silicone photodiode
Measuring range	0 to 99999 Lux
Accuracy ±1 digit	±3 Lux or ±3 % of mv (compared to reference Class B, DIN 5032 Part 7)
Resolution	1 Lux (0 to 19999 Lux) 10 Lux (remaining range)

General technical data	
Measurement rate	0.5 s
Storage temperature	-40 to +70 °C
Protection class	IP40
Operating temperature	0 to +50 °C
Battery type	2 AAA micro batteries
Battery life	200 h (average, without display illumination)
Dimensions	133 x 46 x 25 mm
Weight	95 g (incl. batteries and protective cap)
Warranty	2 years

0981 9794/msp/A/08.2013

Accessories	Part no.
Accessories for measuring instrument	
ISO calibration certificate/light Calibration points 0; 500; 1000; 2000; 4000 Lux	0520 0010

Subject to change without notice.

www.testo.com

APPENDIX B

Semi-structured interview guidance (Chapter 3 and Chapter 4).

SEMI-STRUCTURED INTERVIEW GUIDANCE

Project: *Post occupancy Evaluation of select buildings in Mombasa City, Kenya.*

Building Name:

Date: **Time:**

Introduction

This interview is conducted with a building manager who has insight into the background issues that affect thermal performance of the building in question, during the post occupancy stage. It is anticipated that this interview will take place prior to or after a walkthrough session has been conducted.

This form provides guidance and a brief agenda to ensure areas of interest to the study are covered but also allows for other relevant information revealed in the course of the discussion to be recorded.

Agenda

The interview aims to cover these aspects:

1. Position and role
2. Building operation and usage patterns
3. System operation
4. Maintenance
5. Other controls and interfaces
6. Energy consumption
7. Other points of interest

Thank you for your help!

1. What is your position and role in the building?

2. Building operation and usage patterns

a) Are there any issues relating to building operation? (*This would include: time scheduling of HVAC systems; lights; blinds or other shading devices; occupancy schedules/room booking; and out of hour's settings*).

b) Other issues relating to building operation and usage patterns? (*Consider energy use data, building user feedback in the context of related issues/causes*).

3. System operation

a) Are there any issues relating to system operation? (*This would include: temperature settings; controlled ventilation openings such as motorised windows or manual openings/vents; local controls/switches; programmers; local fan controls; log books or building user manuals; and the general extent of automation*).

b) Other issues related to systems operation? (*Consider building user feedback and energy data to discuss possible related issues/causes*).

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Page **1** of **2**

4. Maintenance

a) Are you involved in maintenance of building services systems, and, if so, what are your main responsibilities?

b) Explain any issues relating to maintenance, reliability and reporting of breakdowns. Does the maintenance team have a help desk? Are actions logged in a record book or similar? Is maintenance: planned preventative; condition based; or on breakdown only? Do breakdowns affect building use and operation?

5. Other controls and interfaces

a) Do you have any particular issues with the control of lights – whether this is automated or simply conventional switches?

b) Can you explain your main issues with HVAC control systems? These could include: original installation/commissioning; ease of setting/adjustment; understanding of operation; accessibility; complexity of features/user interface/poor documentation; reliability; other issues such as remote controls.

6. Energy consumption

a) Do you have any involvement in energy management? If so, Can you explain the approach and any actions you take to meet targets? Do you have any views on how consumption management could be improved?

b) Can you explain any other issues that are affecting energy consumption?

7. Other points of interest

Please explain any other items not covered above which you feel may be relevant to a building performance study.

APPENDIX C

Building Use Studies (BUS) Questionnaire (Chapter 3 and Chapter 4).

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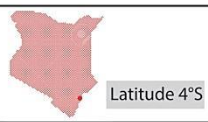
APPENDIX D

This section presents the external shading guidance document developed from the findings of the research work. It is mainly referred to in Chapters 6 and 7. The document outlines the method through which a designer can use the derived SHGC values and energy estimates to approximate the impact of applying external shading devices of various configurations to office buildings.

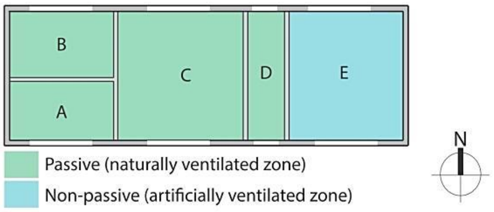
In this method, the first step involves the definition of the passive and non-passive zones in the selected office building to determine which areas will be or are naturally ventilated (thermal comfort impact) and actively ventilated (energy savings impact). Next, the glazing area and glazing orientation are established (to correlate the PF ratio and SHGC data). Subsequently, a suitable shading type can be selected for further review based on orientation and view recommendations. Alternatively, a review of the three basic shading configurations can be conducted. This involves the calculation of the base case $SHGC_{total}$, $SHGC_{total}$ for low discomfort hours and $SHGC_{total}$ moderately low discomfort hours. From this, one can determine the suitable PF ratios as corresponds to the potential discomfort for naturally ventilated zones. For actively ventilated spaces, the next step involves the selection of suitable PF ratios with respect to potential energy savings. From this one can make an informed decision based on the analysis results.

EXTERNAL SHADING DESIGN GUIDANCE

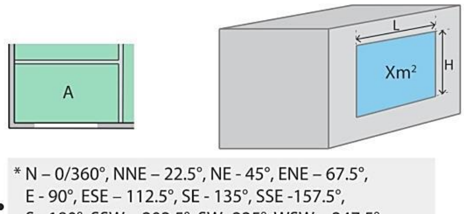
Project: ____________________ Date: _________________



STEP 01: On a plan of your building, divide it into passive (naturally ventilated) and/or non-passive (artificially ventilated) zones.

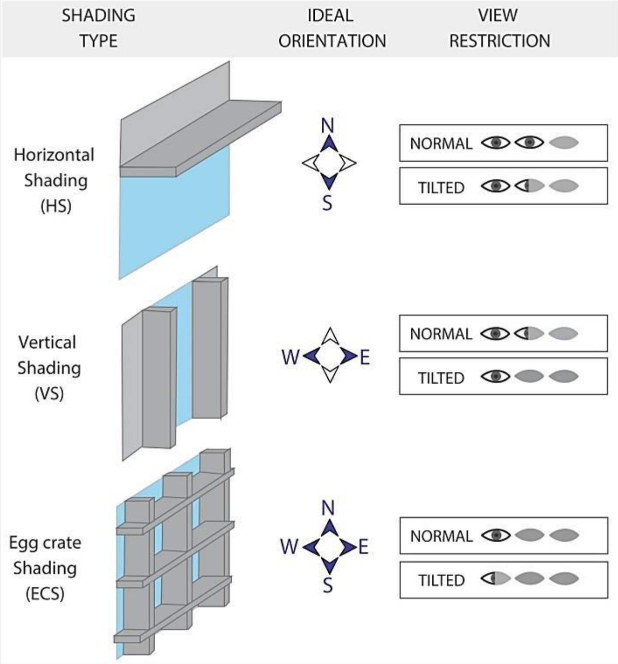


STEP 02: Determine the glazing area and glazing orientation* of each zone.



* N – 0/360°, NNE – 22.5°, NE - 45°, ENE – 67.5°, E - 90°, ESE – 112.5°, SE - 135°, SSE -157.5°, S - 180°, SSW – 202.5°, SW- 225°, WSW – 247.5°, W - 270°, WNW – 292.5°, NW - 315° and NNW – 337.5°

STEP 03: Identify the most suitable shading type for each orientation – refer to figure below. Alternatively, proceed with STEP 04 to compare various shading types' performance.



STEP 04: Calculate the base case SHGC $_{total}$ using a SHGC $_{external}$ value of 1(for no shading used).

STEP 05: Calculate the SHGC $_{total}$ using a SHGC $_{external}$ of 0.5. 0.5 is an indication of low discomfort hours.

STEP 06: Calculate the SHGC $_{total}$ using a SHGC $_{external}$ of 0.7. 0.7 is an indication of moderately low discomfort hours.

DEFINITIONS:

The SOLAR HEAT GAIN COEFFICIENT (SHGC) is the total amount of solar heat that passes through glazing:

$$SHGC_{total} = SHGC_{external} \times SHGC_{glazing} \times SHGC_{internal}$$

Where:

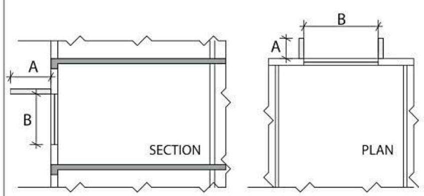
$SHGC_{total}$ = total solar heat gain coefficient of the fenestration system;
$SHGC_{external}$ = solar heat gain coefficient of external shading devices - 1, for none;
$SHGC_{glazing}$ = solar heat gain coefficient of the glazing;
$SHGC_{internal}$ = solar heat gain coefficient of internal shading devices - 1, for none.

The PROJECTION FACTOR (PF) ratio is given by the equation below:

$$PF\ ratio = A/B$$

Where:

$SHGC_{total}$ = total solar heat gain coefficient of the fenestration system;
$SHGC_{external}$ = solar heat gain coefficient of external shading devices - 1, for none;
$SHGC_{glazing}$ = solar heat gain coefficient of the glazing;
$SHGC_{internal}$ = solar heat gain coefficient of internal shading devices - 1, for none.



Horizontal Shading Vertical Shading

STEP 07:

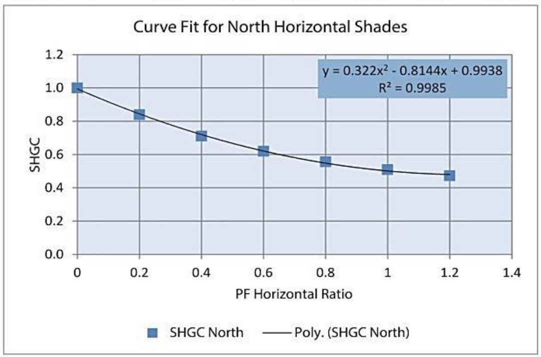
Using the SHGC $_{external}$ tables or the relevant curve fits, substitute the base case SHGC $_{external}$ value of 1 with the given value of the shading type of interest, and for various PF ratios.

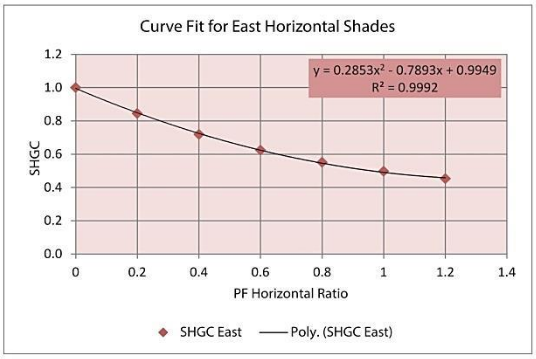
HORIZONTAL EXTERNAL SHADING: Design Estimates

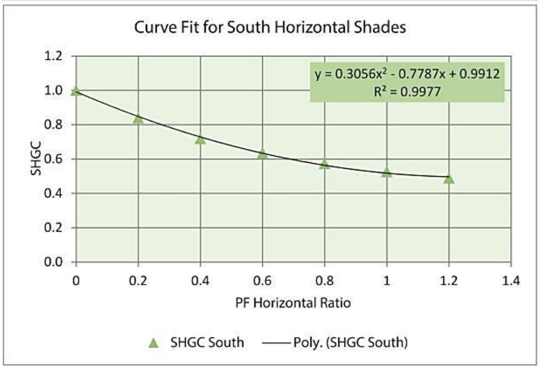
SHGC of horizontal shades for various orientations based on PF ratio

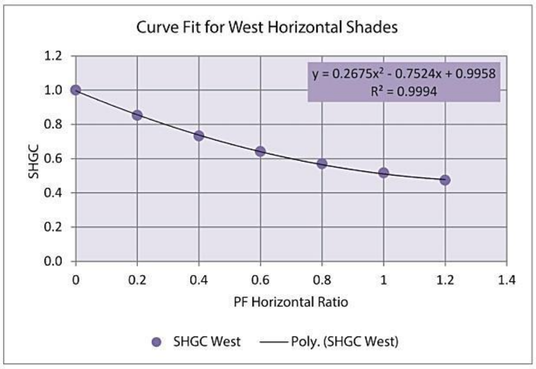
PF	0	0.2	0.4	0.6	0.8	1	1.2
N	1	0.84	0.71	0.62	0.56	0.51	0.47
NNE	1	0.84	0.72	0.63	0.57	0.52	0.48
NE	1	0.84	0.72	0.63	0.56	0.51	0.47
ENE	1	0.84	0.72	0.62	0.55	0.50	0.46
E	1	0.84	0.72	0.62	0.55	0.50	0.45
ESE	1	0.84	0.72	0.62	0.55	0.50	0.46
SE	1	0.84	0.72	0.63	0.56	0.51	0.47
SSE	1	0.84	0.73	0.64	0.57	0.52	0.49
S	1	0.84	0.72	0.64	0.57	0.53	0.49
SSW	1	0.84	0.73	0.64	0.57	0.52	0.48
SW	1	0.85	0.73	0.64	0.57	0.52	0.47
WSW	1	0.85	0.73	0.64	0.57	0.52	0.47
W	1	0.85	0.73	0.64	0.57	0.52	0.47
WNW	1	0.85	0.73	0.64	0.57	0.51	0.47
NW	1	0.85	0.72	0.63	0.56	0.51	0.47
NNW	1	0.84	0.72	0.63	0.56	0.51	0.48

Sketches and PF ratio calculations









SHGC Horizontal Curve Fit Equation for other orientations, where 'x' is the PF ratio and 'y' is the SHGC

Orientation	SHGC Curve Fit Equation	R^2
NNE (22.5°)	y = 0.2975x2 - 0.7801x + 0.9929	0.9986
NE (45°)	y = 0.2939x2 - 0.7878x + 0.9937	0.9989
ENE (67.5°)	y = 0.2885x2 - 0.7893x + 0.9945	0.9992
ESE (112.5°)	y = 0.2892x2 - 0.791x + 0.9946	0.9992
SE (135°)	y = 0.2922x2 - 0.7853x + 0.9938	0.9989
SSE (157.5°)	y = 0.2904x2 - 0.7647x + 0.9927	0.9985
SSW (202.5°)	y = 0.2891x2 - 0.7662x + 0.993	0.9986
SW (225°)	y = 0.2799x2 - 0.764x + 0.9944	0.9991
WSW (247.5°)	y = 0.2688x2 - 0.7533x + 0.9955	0.9993
WNW (292.5°)	y = 0.2734x2 - 0.7618x + 0.9958	0.9994
NW (315°)	y = 0.2861x2 - 0.7778x + 0.9952	0.9993
NNW (337.5°)	y = 0.301x2 - 0.7872x + 0.9938	0.9988

STEP 08:

Analyse the results by comparing them with the $SHGC_{total}$ for low discomfort hours,
where $SHGC_{external}$ = **0.50**
& moderately low discomfort hours,
where $SHGC_{external}$ = **0.70**

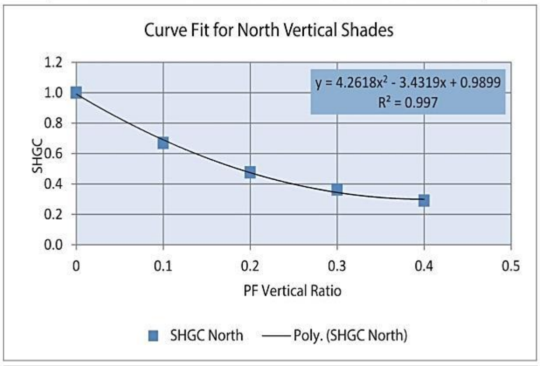
to determine the most effective shading PF ratio or shading depth.
For naturally ventilated zones, skip to STEP 10
For artificially ventilated zones, proceed with STEP 09

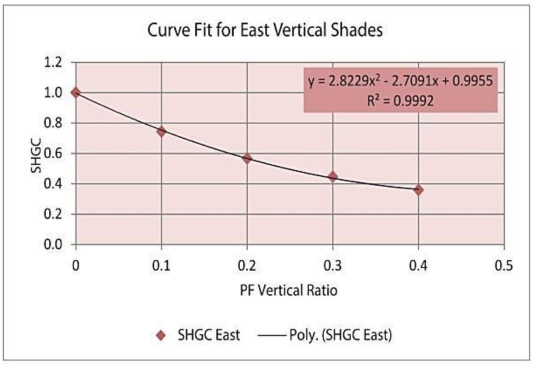
VERTICAL EXTERNAL SHADING: Design Estimates

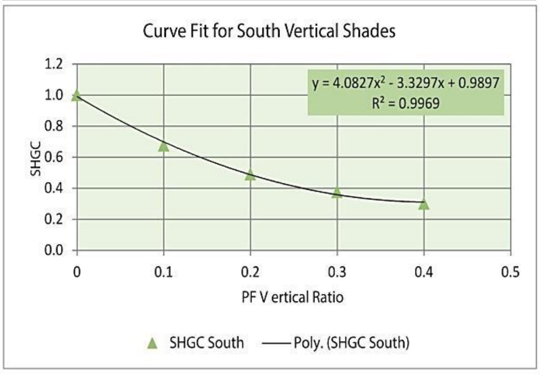
SHGC of vertical shades for various orientations based on PF ratio

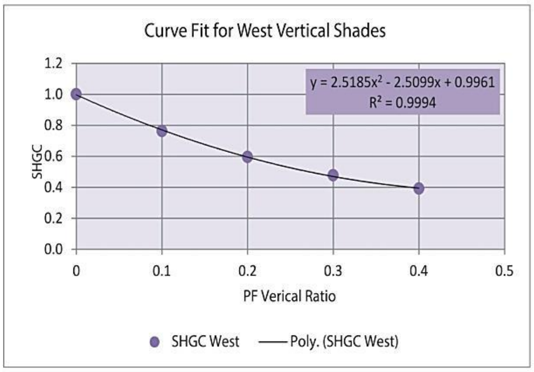
PF	0	0.1	0.2	0.3	0.4
N	1	0.67	0.48	0.36	0.29
NNE	1	0.70	0.51	0.38	0.30
NE	1	0.71	0.52	0.40	0.32
ENE	1	0.73	0.54	0.42	0.34
E	1	0.74	0.57	0.45	0.36
ESE	1	0.74	0.56	0.44	0.36
SE	1	0.72	0.53	0.41	0.33
SSE	1	0.71	0.52	0.40	0.32
S	1	0.68	0.49	0.38	0.30
SSW	1	0.68	0.48	0.36	0.29
SW	1	0.69	0.49	0.37	0.29
WSW	1	0.73	0.55	0.42	0.34
W	1	0.76	0.60	0.48	0.39
WNW	1	0.75	0.58	0.46	0.37
NW	1	0.72	0.52	0.40	0.32
NNW	1	0.70	0.50	0.37	0.30

Sketches and PF ratio calculations









SHGC Vertical Curve Fit Equations for other orientations, where 'x' is the PF ratio and 'y' is the SHGC

Orientation	SHGC Curve Fit Equation	R^2
NNE (22.5°)	y = 3.6404x2 - 3.1653x + 0.9942	0.999
NE (45°)	y = 3.5155x2 - 3.0743x + 0.9935	0.9986
ENE (67.5°)	y = 3.2494x2 - 2.9228x + 0.9956	0.9993
ESE (112.5°)	y = 3.0808x2 - 2.8115x + 0.996	0.9994
SE (135°)	y = 3.2783x2 - 2.9558x + 0.9944	0.9989
SSE (157.5°)	y = 3.4402x2 - 3.0503x + 0.9952	0.9992
SSW (202.5°)	y = 4.0642x2 - 3.3763x + 0.9932	0.9986
SW (225°)	y = 3.8288x2 - 3.2773x + 0.9929	0.9984
WSW (247.5°)	y = 3.0996x2 - 2.8671x + 0.9967	0.9996
WNW (292.5°)	y = 2.7073x2 - 2.6334x + 0.9972	0.9997
NW (315°)	y = 3.33x2 - 3.0131x + 0.9955	0.9993
NNW (337.5°)	y = 3.7342x2 - 3.2259x + 0.995	0.9992

STEP 08:

Analyse the results by comparing them with the SHGC $_{total}$ for low discomfort hours,
where SHGC $_{external}$ = **0.50**
& moderately low discomfort hours,
where SHGC $_{external}$ = **0.70**

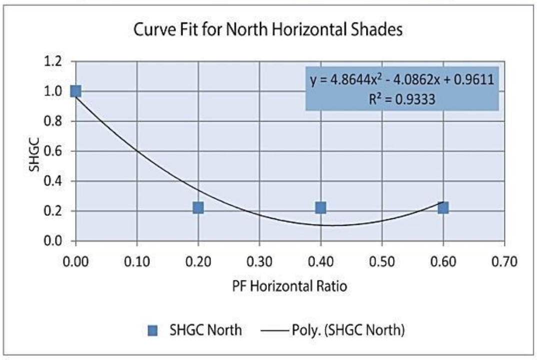
to determine the most effective shading PF ratio or shading depth.
For naturally ventilated zones, skip to STEP 10
For artificially ventilated zones, proceed with STEP 09

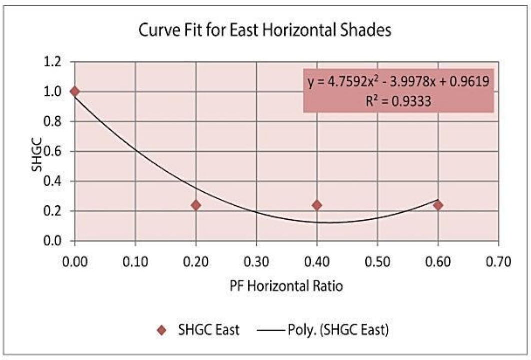
EGG CRATE EXTERNAL SHADING (Horizontal): Design Estimates 4/6

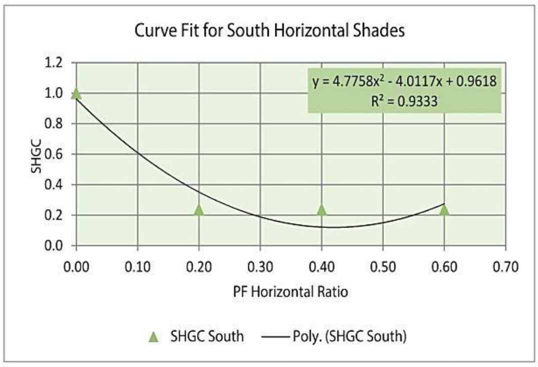
SHGC of egg crate shades for various orientations based on PF ratio

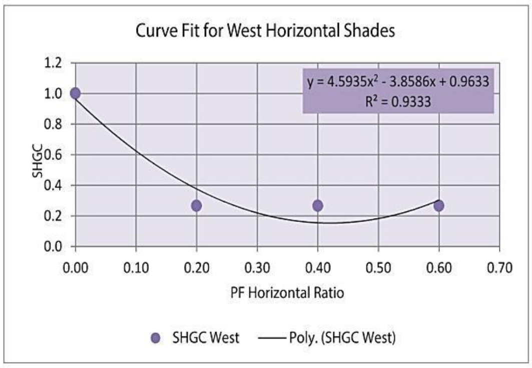
PF(H/V)	0	0.2/0.1	0.4/0.2	0.6/0.3
N	1	0.22	0.22	0.22
NNE	1	0.23	0.23	0.23
NE	1	0.23	0.23	0.23
ENE	1	0.24	0.24	0.24
E	1	0.24	0.24	0.24
ESE	1	0.24	0.24	0.24
SE	1	0.23	0.23	0.23
SSE	1	0.24	0.24	0.24
S	1	0.24	0.24	0.24
SSW	1	0.22	0.22	0.22
SW	1	0.22	0.22	0.22
WSW	1	0.24	0.24	0.24
W	1	0.27	0.27	0.27
WNW	1	0.25	0.25	0.25
NW	1	0.22	0.22	0.22
NNW	1	0.21	0.21	0.21

Sketches and PF ratio calculations









SHGC Egg crate Curve Fit Equations for other orientations, where 'x' is the PF ratio and 'y' is the SHGC

Orientation	SHGC Curve Fit Equation	R^2
NNE (22.5°)	y = 4.7978x2 - 4.0302x + 0.9616	0.93
NE (45°)	y = 4.8042x2 - 4.0356x + 0.9616	0.93
ENE (67.5°)	y = 4.7655x2 - 4.003x + 0.9619	0.93
ESE (112.5°)	y = 4.7607x2 - 3.9991x + 0.9619	0.93
SE (135°)	y = 4.7981x2 - 4.0305x + 0.9616	0.93
SSE (157.5°)	y = 4.7681x2 - 4.0053x + 0.9619	0.93
SSW (202.5°)	y = 4.8686x2 - 4.0896x + 0.9611	0.93
SW (225°)	y = 4.9013x2 - 4.1172x + 0.9608	0.93
WSW (247.5°)	y = 4.738x2 - 3.9799x + 0.9621	0.93
WNW (292.5°)	y = 4.6768x2 - 3.9286x + 0.9626	0.93
NW (315°)	y = 4.8772x2 - 4.0969x + 0.961	0.93
NNW (337.5°)	y = 4.9259x2 - 4.1378x + 0.9606	0.93

STEP 08:

Analyse the results by comparing them with the $SHGC_{total}$ for low discomfort hours,
where $SHGC_{external}$ = **0.50**
& moderately low discomfort hours,
where $SHGC_{external}$ = **0.70**

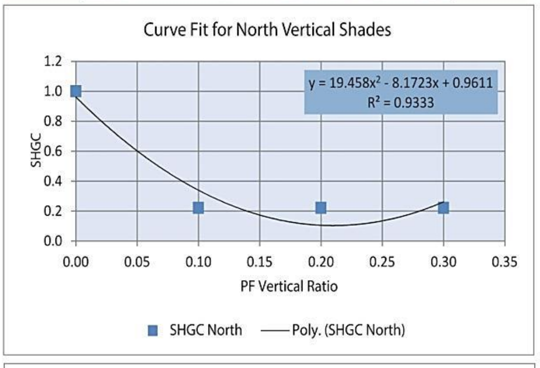
to determine the most effective shading PF ratio or shading depth.
For naturally ventilated zones, skip to STEP 10
For artificially ventilated zones, proceed with STEP 09

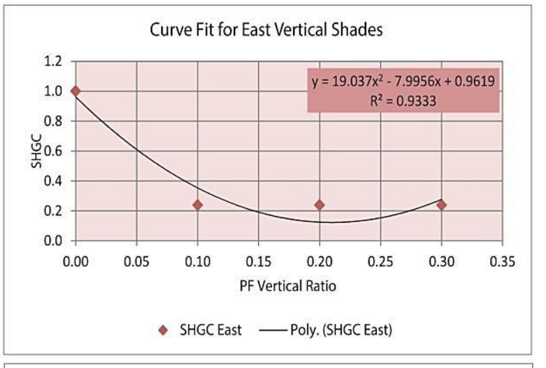
EGG CRATE EXTERNAL SHADING (Vertical): Design Estimates

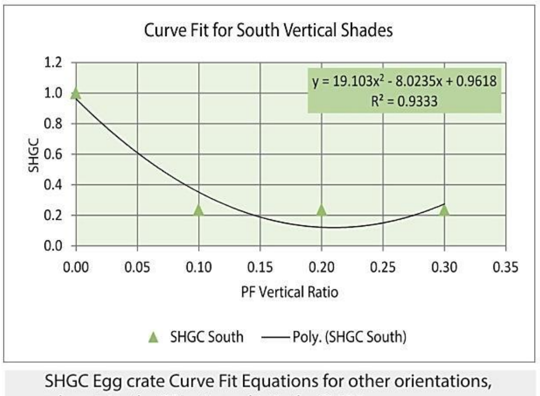
SHGC of egg crate shades for various orientations based on PF ratio

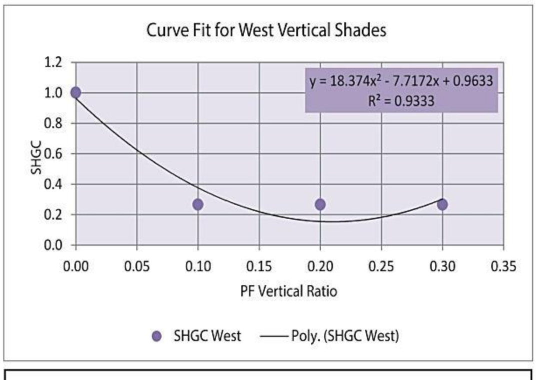
PF(H/V)	0	0.2/0.1	0.4/0.2	0.6/0.3
N	1	0.22	0.22	0.22
NNE	1	0.23	0.23	0.23
NE	1	0.23	0.23	0.23
ENE	1	0.24	0.24	0.24
E	1	0.24	0.24	0.24
ESE	1	0.24	0.24	0.24
SE	1	0.23	0.23	0.23
SSE	1	0.24	0.24	0.24
S	1	0.24	0.24	0.24
SSW	1	0.22	0.22	0.22
SW	1	0.22	0.22	0.22
WSW	1	0.24	0.24	0.24
W	1	0.27	0.27	0.27
WNW	1	0.25	0.25	0.25
NW	1	0.22	0.22	0.22
NNW	1	0.21	0.21	0.21

Calculated PF ratios and SHGC









SHGC Egg crate Curve Fit Equations for other orientations, where 'x' is the PF ratio and 'y' is the SHGC

Orientation	SHGC Curve Fit Equation	R^2
NNE (22.5°)	y = 19.191x2 - 8.0605x + 0.9616	0.93
NE (45°)	y = 19.217x2 - 8.0711x + 0.9616	0.93
ENE (67.5°)	y = 19.062x2 - 8.0061x + 0.9619	0.93
ESE (112.5°)	y = 19.043x2 - 7.9981x + 0.9619	0.93
SE (135°)	y = 19.192x2 - 8.0609x + 0.9616	0.93
SSE (157.5°)	y = 19.072x2 - 8.0105x + 0.9619	0.93
SSW (202.5°)	y = 19.474x2 - 8.1793x + 0.9611	0.93
SW (225°)	y = 19.605x2 - 8.2343x + 0.9608	0.93
WSW (247.5°)	y = 18.952x2 - 7.9599x + 0.9621	0.93
WNW (292.5°)	y = 18.707x2 - 7.8572x + 0.9626	0.93
NW (315°)	y = 19.509x2 - 8.1938x + 0.961	0.93
NNW (337.5°)	y = 19.704x2 - 8.2756x + 0.9606	0.93

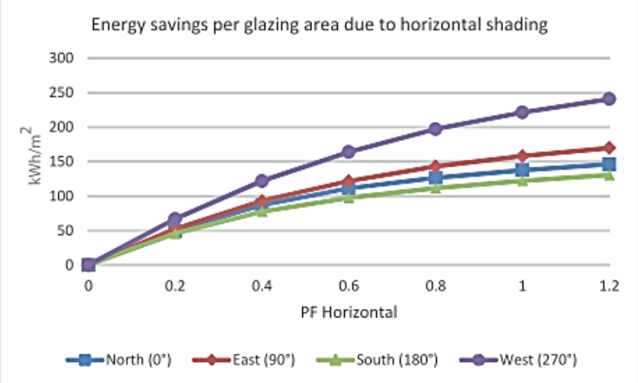
STEP 08:

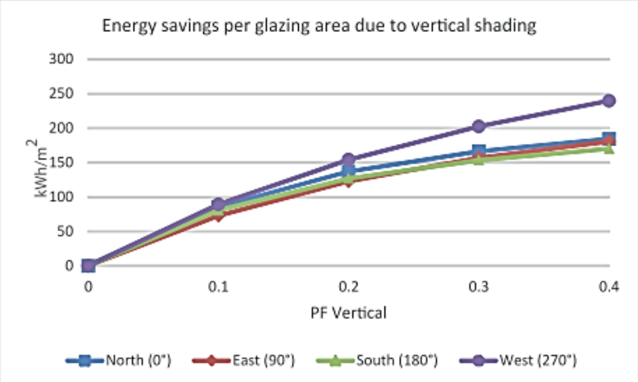
Analyse the results by comparing them with the $SHGC_{total}$ for low discomfort hours,
where $SHGC_{external}$ = **0.50**
& moderately low discomfort hours,
where $SHGC_{external}$ = **0.70**

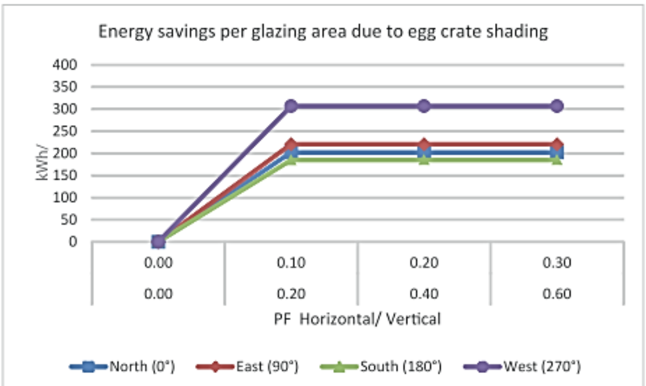
to determine the most effective shading PF ratio or shading depth.
For naturally ventilated zones, skip to STEP 10
For artificially ventilated zones, proceed with STEP 09

ENERGY SAVINGS PER GLAZING AREA: Design Estimates 6/6

STEP 09: Estimate the potential energy savings per glazing area (kWh/m²).







Calculations and results

STEP 10: Make an informed decision on shading design based on results obtained from STEP 08 and STEP 09

KIAMBA, L.N. (2016). *Optimising Environmental Design Strategies to Improve Thermal Performance in Office Buildings in Kenya,* University of Nottingham.