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THERMAL COMFORT IN A HOT-HUMID CLIMATE THROUGH PASSIVE COOLING IN LOW-INCOME RESIDENTIAL BUILDINGS IN ABUJA, NIGERIA

by

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy in Architecture

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ABSTRACT

The research investigates the thermal performance of residential buildings in Abuja, Nigeria during the dry and rainy seasons. A field study was conducted to understand the real and preferred conditions of thermal comfort in low-income residential buildings, which represent the largest single housing sector. Knowing the temperatures people are experiencing in their houses and the limits that residents can tolerate is a first step to proffer passive solutions to reduce discomfort and energy demand and then satisfy the energy demand passively. During the survey, 222 people responded to a post occupancy questionnaire and for the ten selected case study dwellings, a comfort survey questionnaire was used. Physical measurements were taken simultaneously during the comfort survey in both air-conditioned and naturally ventilated residential buildings. The ASHRAE and air flow sensation scales were chosen as voting scales. This survey further looked at possible barriers to the implementation of more sustainable approaches that would enhance passive solutions in Nigeria, since the conventional means of cooling in this hot-humid climate is becoming expensive and less satisfactory.

The results from the study showed that during the dry season monitoring period, the average and maximum temperatures in the air-conditioned case studies were 32°C and 34°C; and 31°C and 36°C for the naturally ventilated buildings. This compares with the external average and maximum air temperatures of 31°C and more than 40°C. Dynamic simulation modelling was used to reveal the sensitivity of the cooling loads to various thermal interventions (e.g. insulation and shading) in the case study buildings. The optimum passive cooling intervention (involving roof and wall insulation and shading) proved to be effective in reducing the indoor maximum temperatures by more than 5°C for naturally ventilated cases and the cooling load. This translates to a monthly cost saving in the air-conditioned model of N8,110 (£16.97) which is significant compared to the Nigerian National Minimum Wage of N18,000 (£37.66).

This study makes a significant contribution to understanding the real and ideal thermal conditions occupants experience in low and middle income residential buildings in Abuja and demonstrates the effectiveness of passive interventions in reducing indoor temperatures and cooling loads.

DEDICATION

I dedicate this research to the
Almighty God, my Creator, my Helper, my strength, my Father, and my
All in All.

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LIST OF PUBLICATIONS

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v. Michael U. Adaji, Richard Watkins and Gerald Adler. "An Investigation into Thermal Comfort in Residential Buildings in the Hot-Humid Climate of Sub-Saharan Africa: A Field Study in Abuja-Nigeria." The 31st International PLEA Conference, Bologna, Italy 9th – 11th September 2015.

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CHAPTER 1

Thesis introduction

CHAPTER 1: Thesis introduction

1.1 Introduction to chapter 1

Dry season temperatures in residential buildings in tropical regions like Nigeria are becoming a major concern. High levels of solar radiation influence the heat produced in this region, which increases the heat intensity felt by residents within buildings. The resulting indoor temperatures can be a health hazard and can be life threatening to occupants. In addition, global temperatures are expected to rise, because of greenhouse gas emissions and this together with local pressures of rural urban migration, industrial process and deforestation are highly likely to exacerbate the problem of these high indoor temperatures (Adunola, 2012).

The current indoor temperatures experienced in residential buildings, especially those in the big cities like Abuja in Nigeria are thermally uncomfortable for a substantial period (Adunola and Ajibola, 2012). Unfortunately, the housing condition in the country is of extreme worry as it is largely of inferior quality and standard in both rural and urban centres. The increased focus on quantity of housing rather than quality and quantity needs is one of the reasons that has led to a major and evident concern about the quick deterioration of the current housing stock leading to a shortage of housing units (Olayiwola et al., 2005). Hence, because of the rush to meet demand, builders tend to focus more on quantity rather than quality therefore compromising standards and indoor comfort. This in turn creates buildings with poor thermal properties that cannot last for longer periods before they start deteriorating. Consequently, most occupants now rely on mechanical cooling, fans and air conditioning, to try to achieve thermal comfort.

Mechanical cooling is largely dependent on electricity in Nigeria of which the residential buildings sector consumed 53.3% of electricity generated as seen in the Federal Government of Nigeria's vision 2020 report released in 2009 in (Oyedepo, 2014); (Adaji et al., 2015). However, due to the lack of a reliable and continuous power supply from the national grid, mechanical cooling systems in residential buildings cannot be relied on to provide cooling. In addition, cooling mechanisms like air-conditioning require lots of energy to run and maintain, which many cannot afford. Hence, the continuous running of air-conditioning is not feasible and sustainable (Adaji et al., 2015). In addition, because of the lack of a constant power supply, people tend to turn to generators as a back-up power supply for their electrical appliances, especially for mechanical cooling.

Consumption of energy in buildings varies by activity, climate and habitation, temperature change through the various hours of the day, weather conditions and seasons, (Shaahid and Elhadidy, 2008). With global warming, depletion of our oil and gas reserves (Shaahid and Elhadidy, 2008), greenhouse effects, rising energy and gas bills are becoming a major concern. It has become imperative to look for sustainable solutions like exploring methods of reducing energy use and reliance on fossil fuel to generate power. A significant amount of fossil fuel energy used by the residential housing sector produces a significant percentage of greenhouse gas emissions that contribute to global warming and climate change. According to the Energy Performance of Buildings Directive (EPBD), buildings accounts for 40% of the total energy used in the European Union (EU, 2010) and in related reports by the US Department of energy (2010), and the National Bureau of Statistics of China (2010), they showed the energy consumption figures for the housing sector of 41% and 25% respectively, (Visa et al. 2014). In Nigeria, an investigation carried out by Uyigue et al. (2010), showed that 65% of electricity generated was consumed in the residential building sector, 20% for the commercial sector and 10% for the industrial sector.

Alternative ways of reducing energy consumption that do not rely on or eliminate the need for mechanical cooling in households are encouraged by researchers. Passive cooling strategies can reduce energy use, increase comfort, and encourage the health of occupants in a building. Furthermore, they also respond to climate and site conditions while saving energy (Taleb, 2014). Adoption of passive cooling techniques for new and existing buildings is increasing awareness of the need to reduce the emission greenhouse gases, caused by fossil fuels used to power the heating and cooling requirements of buildings.

Passive design techniques have been brought back in to the limelight owing to the current high cost of energy alongside the concern about greenhouse gas emissions. The third world countries like Nigeria that have vast natural resources and a population that comprises mostly low-income earners living below $2.00 per day (World Bank, 2012) are beginning to view the economic benefits of these techniques as a more cost-effective way of facing the high cost of energy and uncertain energy supply. For example, the low-cost housing scheme introduced by the Nigerian government to support the vast low-income earners eventually led to the construction of houses with poor thermal qualities that failed in complementing the environment in which they were built and occupants who eventually lived in such buildings experienced high temperature and poor indoor thermal conditions.

Abuja is undergoing a gradual change in microclimate, which could be related to the rate of increase in the size of built up area. ‘Other contributing factors to temperature increase could be traced to high population density and exclusion of nature, since the natural vegetation has been cleared for construction and consequently an alteration of biodiversity’ (Gidley et al., 2010 in Alabi, 2012).

Similar issues have also been documented in other parts of the world, where there is a considerable change in the global climate with tremendous health, economic and environmental consequences (Monjur, 2011 in Alabi, 2012).

The study area Abuja lies at latitude 9° 04’ N and longitude 7° 29’ E, at an elevation of 840 m (2760 ft.) above sea-level. The area now designated the Federal Capital Territory (F.C.T.), Abuja, Nigeria’s capital, falls within the Savannah Zone vegetation of the West African sub region with patches of rain forest. As in the tropics, the FCT experiences two weather conditions annually; the rainy season (the equivalent of winter in a temperate region) which begins in April and ends in October and the dry season (the equivalent of summer in a temperate climate) which begins in October and ends in April. However, within this period, there is a brief interlude of harmattan, a period when the North-East Trade Wind moves in with the main feature of dust haze, intensified coolness, and dryness. Fortunately, the high altitudes and undulating terrain of the FCT act as a moderating influence on the weather of the territory. The maximum daytime air-temperature ranges from 28° C to 35°C and a minimum night-time temperature ranging from 18°C-23°C (World climate guide, 2014). The housing situation in Abuja is very severe, as many people in the city cannot afford the low-cost houses provided by the government, owing to inaccessible housing mortgages and the desire of private developers who are now the main housing providers to maximise their profit, no matter the social cost. The problem of insufficient housing also manifests itself where people that have migrated from the rural areas now have to form squatter settlements just to find a resting place in the city.

1.2 Aims and objectives of the research

The aim of this research is to understand indoor thermal conditions of residential buildings in Abuja. The study will explore low-income cooling strategies to improve the indoor thermal conditions and reduce the energy demand in low-income residential buildings in Abuja, a city in the hot-humid climate of sub-Saharan Africa.

Objectives:

1. Review literature to understand the thermal discomfort in the tropical regions.
2. Investigate thermal conditions of occupants in residential buildings in low-income/ low-middle income areas in Abuja, Nigeria.
3. Undertake environmental monitoring and surveying of selected residential buildings in various locations in Abuja to understand the environmental thermal conditions in real life situations.

4. Assess the possibility of appropriate applications of passive cooling techniques that could be used to enhance the thermal performance of dwellings in the hot humid climate of Abuja.
5. Study the behaviour of buildings in their current and modified form.
6. Model the energy performance of selected residential buildings and provide predictive energy data for different variables in achieving the best scenarios.
7. Identify possible barriers to implementing passive cooling strategies in residential housing and proffer viable solutions.
8. Assess the cost effectiveness of modifying the dwellings in the context of Abuja.

1.3 Statement of problem

Nigeria, a country with numerous resources and a population of over 168 million, which is expected to exceed 230 million by 2030, has 63% of its electricity generated from natural gas, 21% from hydro plants and 16% from oil (World Bank, 2012). Around 56% of electricity generated goes to residential housing, 25% goes to commercial activities and street lighting while 18% goes to industrial consumption (Central Bank of Nigeria 2010). However, over the past two decades, electricity generation, transmission and distribution have been poor due to poor maintenance of power plants, corruption, inadequate funding, and lack of energy mixture among many factors (Emovon et al., 2010). The current electricity supply cannot meet demand and is therefore hampering economic activities and development (Sambo, 2008).

The current typical design of houses does not provide a comfortable indoor climate in Abuja without air-conditioning. The lack of insulation in the building envelopes, thermal considerations like orientation and shading devices on windows in the design of residential buildings in Nigeria, all contribute to increased heat stress and discomfort in buildings. There is a great need for the indoor environment to be cooled, but instead of turning to more sustainable ways of cooling, developers and occupants of residential buildings have chosen air conditioning, which in turn is often backed up with generators to supplement the poor power supply experienced in the country.

An evaluation by Somefun (2015) shows that only about 40% of Nigerians are connected to the national energy grid. This percentage of Nigerians who have electric power supplied to them still experience irregular electric power supply around 60% of the time (Aliyu et al., 2013). The generating systems must be supplemented with constant fuel and maintenance to keep them running when there is no power, and all this costs money.

Given the unreliability of power from the grid, and the expense of the cost of generator, Nigeria needs to look more at the concept of sustainable, low energy cooling approaches and alternatives that have the potential of making the indoor environment more comfortable for occupants and reducing energy consumption. Research into viable solutions to the problems associated with indoor discomfort have shown that passive cooling approaches are environmentally more benign, less expensive, reduce energy use and improve the indoor environment (Santamouris et al., 2007a; Santamouris et al., 2007b), especially in hot humid climates like Abuja, Nigeria. The prospects of reducing active energy consumption for cooling building interiors in hot-humid climates can be seen in passive approaches and strategies; they also can reduce rising energy demands and the effect of greenhouse gases on our environment (Ojebode and Gidado, 2008).

In summary, Nigeria is a country with numerous resources but cannot provide constant power to the domestic sector because of a variety of factors, including pervasive mismanagement and corruption. Designers and builders are also responsible. They construct buildings with little or no regard for the local climate and thermal comfort considerations. There is no effective shield or insulation between the outdoor environment and the building interior and consequently a high level of solar gain enters the building through its opaque fabric e.g. through the typical uninsulated metal roof. This causes thermal discomfort to the occupants, as the building envelope can neither reflect sunlight away nor prevent the heat absorbed being transmitted to the interior. Sustainable passive design approaches should be encouraged to reduce energy consumption for cooling since most occupants are now relying on air conditioning systems as the best way to improve thermal comfort, increasing bills along the way.

1.4 Research Questions

Proposed research questions:

1. Are passive cooling approaches suitable for solving the problem of thermal discomfort in such a hot-humid climatic region as Abuja?
2. If passive cooling is a possible solution to thermal discomfort, can low-income earners afford the strategy in Abuja, Nigeria?
3. What barriers might inhibit the acceptance of passive solutions and how might these be overcome?

1.5 Research hypotheses

The research looks at three hypotheses to help answer the research questions, and they are as follows:

1. There is a significant difference in thermal comfort of residents in Abuja with different socio-economic status.
2. The indoor temperature in naturally ventilated buildings can be reduced by applying interventions such as insulation and shading to reduce heat gain.
3. The indoor cooling loads in air-conditioned buildings can be reduced by applying interventions such as insulation and shading to reduce heat gain.

1.6 Justification

With the advent of global warming, temperatures will continue to rise, creating more discomfort and increasing stress levels especially in lower income households. As occupants seek to bring the internal temperatures down, more air conditioning is used, increasing energy bills. In developed countries, there is considerable interest and government intervention (building regulations, financial incentives) in improving building design to maintain comfort at a lower energy cost. Recommendations are barely implemented and there is little awareness of the negative of global warming on the people and the environment. There is unfortunately no drive to promote awareness on the advantages of sustainable low energy approaches like passive cooling.

1.7 Scope of Research

Time, finance, security issues and human resources always place constraints on research projects, forcing trade-offs between coverage and level of detail. It was vital that logistic problems usually associated with field studies and data collection were kept to the minimum, hence the choice of a familiar region, city and area. Given the limited resources and time available for the study. To minimise the impact of these constraints, the study has been limited to occupants' indoor thermal comfort, occupants' adaptation in residential buildings and environmental monitoring in five neighbourhood centres in Abuja, namely Lugbe, Mpape, Kubwa, Dutse Alhaji and Bwari during the dry and rainy seasons.

1.8 Original contribution to the body of knowledge

Previous studies have tended to employ a limited number of tools. The preferred approach to the study's multi-criteria, integrated assessment will also contribute to the ongoing debate on thermal comfort and passive cooling energy strategies in low-income residential buildings in a hot-humid climate.

The study is intended to provide an original contribution on human adaptation in residential buildings in Nigeria, methods to reduce energy demands and satisfy the energy demand passively by providing insights and recommendations of theoretical and practical value for decision support in environmental designs and sustainable energy building policy within the sub Saharan Africa and tropical regions. Regarding human thermal comfort, there has been much documented material worldwide from physiological, adaptive and social hypotheses but throughout sub-Saharan Africa, especially the tropic regions, there is a paucity of literature on the comfort of occupants and the residential thermal environment. The tropics may require a different level of comfort parameter in the Standard; current standards are almost all based on experiments across a variety of climatic zones including temperate, hot-humid and cold regions. Furthermore, there is little, or no literature reported on indoor comfort for residential occupants, nor a 24-hr indoor residential survey in Abuja.

This research is aimed at filling this gap by investigating the indoor thermal comfort for occupants and their thermal environment during the dry and rainy seasons.

1.9 Research Methodology

The methodology for this research included environmental monitoring, post-occupancy and comfort surveys, dynamic thermal simulation, and interviews. The surveys were aimed at obtaining a comprehensive understanding of occupants' thermal comfort sensation, occupants' adaptation within the buildings, occupant's energy loads, demands and use and applications of passive strategies as a solution to improving the indoor thermal environmental conditions of occupants in residential buildings.

Methodology: The ANSI/ASHRAE standard 55-2010 involving the ASHRAE sensation scale of (1 to 7), [(-3 to +3)] for thermal comfort was adopted for this research, because it incorporates evaluative methods which are based on an adaptive approach. This approach covers thermal comfort and indoor environment parameters. It also allows occupants in naturally ventilated buildings and mixed mode (hybrid) buildings to be studied with a wider range of thermal comfort parameters which included a psychological (acclimatization) approach i.e. shivering, vasoconstriction, thermal perception of cold, physiological (expectations) approach and behavioural approach i.e. opening and closing of windows, the use of fans, cultural and social backgrounds.

HOBO data loggers were used to measure indoor temperature and relative humidity of the air and were installed at a height of 1.1 m above the floor level. The height was considered the average height of the head region of occupants seated and the mid-region (waist) of participants carrying out standing activities. Temperatures and relative humidity were measured continuously at 15-minute intervals for one week. Thermal comfort questionnaires were issued to respondents. Indoor monitoring was carried out in 10 houses, with two houses per neighbourhood monitored in Abuja. The sensors were mounted on the internal walls to measure the air temperature and relative humidity experienced by the occupants in two spaces in the building: the living room and the (master) bedroom. These two spaces are the most occupied. For the daytime and evening time, the living room is the most occupied and for the night time, the bedroom is the most occupied. The outdoor environmental conditions measured were air temperature and relative humidity using Tiny Tag T/RH sensors inside a radiation shield. The solar radiation was also measured using a Kipp and Zonen Pyranometer. Data was recorded every 15 minutes.

The data collected from the field study was analysed using the statistical programme SPSS (Statistical Package for Social Sciences) to reveal information about the real-life conditions of occupants in residential buildings, occupant adaptation and domestic energy demand and use within the region. Measured environmental data was used in a building energy performance simulation model and the results compared to the recordings made during the field studies. The research concludes with comments on the overall findings of the study and proposes a framework for future studies on domestic energy demand and use. It also identifies areas for further research, especially with regards to the use of existing energy tools and models.

1.10 Thesis structure

The thesis consists of nine chapters, whose content is described briefly below:

Chapter 1: This chapter gives an overview of the whole research, research methodology and its significance.

Chapter 2: This chapter reviews the literature on thermal comfort, passive cooling and housing in Nigeria. The chapter gives an idea of what thermal comfort is, and the various comfort models and applications around the world. It also looks at how passive cooling can be used to achieve comfort through various research and the latest advancements in the research area. The review gives a guide to the current environmental performance of residential buildings and identifies where improvements are needed especially for those in the low-income bracket.

Chapter 3: The protocol for data and information collection, and analysis is discussed in this chapter.

Chapter 4: This chapter describes the case study area, Abuja. It gives a vivid description of the location, climate, case study selection criteria and the architecture and building construction.

Chapter 5: This chapter presents a statistical analysis of the post-occupancy, environmental monitoring of case study dwellings and thermal comfort surveys carried out during the dry and rainy season.

Chapter 6: This chapter uses dynamic thermal simulation to determine the thermal performances of selected case study houses.

Chapter 7: This chapter looks at the passive cooling interventions that reduce the need for cooling using dynamic thermal simulation.

Chapter 8: This chapter discusses the likely energy savings from using the proposed passive interventions and the possible barriers to implementing these.

Chapter 9: This chapter summarizes the findings and provides general conclusions and recommendations for passive solutions in Nigeria. It also outlines the limitations and potential future extensions of this work through new research.

CHAPTER 2

Literature review

CHAPTER 2: Literature review

The literature review falls into two parts: Part-A reviews the context of housing in Nigeria and looks at the income status and the provision of housing in the country. Part-B considers comfort theories and passive design strategies.

PART-A

Housing Context and Provision of Housing in Nigeria

2.1 Contextual background to housing provision in Nigeria.

Nigerian cities have grown to look like many western urban centres with the influx of oil revenues and foreigners, cities like Lagos, Ibadan and Abuja are massive and overcrowded, filled with congested vehicular traffic, theatres, department stores, restaurant, and supermarkets. Little urban planning was used to plan these cities as most Nigerian cities grew out of much older towns and eventually expanded into larger metropolitan cities. The strain on many services such as housing, power and transportation was caused by the huge rural-urban migration where people left the villages to the state capitals for greener pastures. Inconsistent power distribution, power cuts and interruptions of the telephone service are not uncommon, (Sambo, 2008; Emovon et al., 2010). The tropical location of Nigeria presents a hot climate problem, (Akande, 2010; Akande and Adebamowo, 2010; Allu, 2014; Daniel, 2015) which creates indoor discomfort due to the high temperatures experienced by occupants who now commonly rely on air-conditioning for cooling. Unfortunately, due to the lack of a constant power supply, residents have turned to generators for back-up power for their air-conditioners which in turn increase energy costs, greenhouse gas emissions from generator fumes and considerable noise and air pollution. All these have had a negative impact on indoor comfort.

The main concepts of traditional architecture that contributed to a naturally cooler interior have been abandoned in modern buildings in Nigeria. Current housing designs and construction do not really relate to their immediate climatic environment or take natural indoor cooling as a priority, which if adopted can reduce indoor temperature, improve comfort, and reduce the energy load (Akande, 2010; Akande and Adebamowo, 2010; Adebamowo and Sangowawa, 2013; Allu, 2014; Daniel, 2015). The ability to own, use air-conditioning and even use it extensively for cooling relies on the income status of residents. In Nigeria, living in a well-planned and constructed residential settlement is often based on income status or designated income location. The next section, i.e. Socio-economic status, and housing in Nigeria, will give an insight into the relationship between income status, indoor comfort and residential settlements in Nigeria. It will also explain the construction methods, housing design and procurements process in Nigeria.

2.2 Socio-economic status and housing in Nigeria.

The levels of household income may be classified as: the lower, lower-middle, middle and the high-income earners. These are examined next in relation to the type of dwelling typically associated with each class.

1) *Lower income earners*

Lower-income earners in Nigeria can be classified as a group of people who on average earn money or reward for their corresponding labour. The lower-income group, according to the National housing policy of 2002, were defined as all employees or self-employed persons whose annual income as of the year 2001 was N100, 000 (£360.00) or below. They make up the largest group of people in Nigeria. In this context, lower-income earners include individuals in civil, public, and private employment services or are self-employed, and their income cannot guarantee credit for home acquisition (Jolaoso et al., 2012). Lower-income earners can also be defined as a group of people who at least earn the national minimum wage of N18, 000.00 per month (GBP 45.00) where GPB 1 = N400 (Ekong and Onye, 2013) or $1-3 per day. Low income groups earn less than N216,000 but most people earn less than N100,000

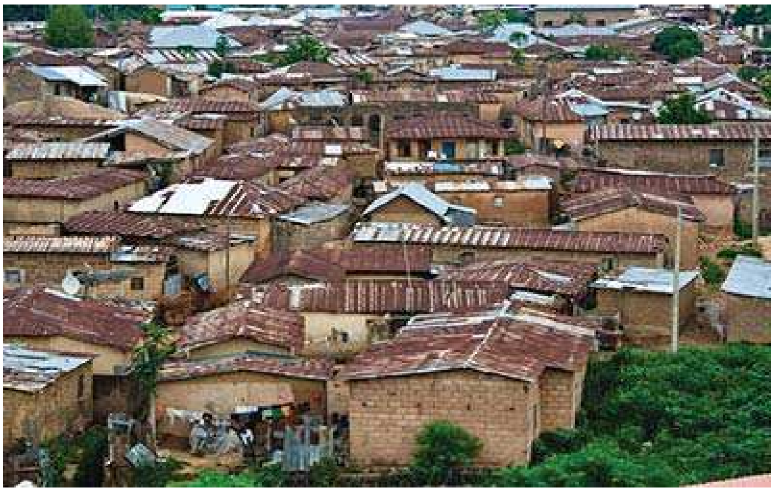


Figure 2.1: Typical lower-income area in Jos, Nigeria, constructed by the inhabitants of the area, Source: Google/images

This group comprises self-employed, semi and unskilled manual workers. They live mostly in the outskirts of cities and in areas associated with poor planning and a high crime rate. Houses built in the lower-income areas are typically built with sandcrete blocks (manufactured from a mixture of natural sand, water and a binder usually cement or Rice Husk Ash) or clay bricks for walling material (Oyelola and Abdullahi, 2006; Sholanke, et al., 2015) (see Figure 2.1). The residential buildings here have poor thermal performance with occupants always experiencing high indoor temperatures and discomfort. They are roofed with galvanized steel which tend to rust over time (see Figure 2.1). The roofs are not ventilated, and some do not have ceilings. Roof overhangs are usually in the range of 400mm – 600m and the floor to ceiling height is 2.5m - 3.0m. They are mostly designed and built by the inhabitants of these areas with little or no supervision and approval from the local housing authorities.

2) *Lower-middle income earners*

This group comprises supervisory, clerical, junior managerial, administrative, or professional workers who earn between $15-30 per day. They can be defined as people who earn four times the national minimum wage i.e. N72, 000 (GBP 180.00), (Ekong and Onye, 2013). Most people in this income bracket tend to have more than one job and save over time to build or rent better houses. Therefore, the façade of some of these houses might look like those meant for the middle-income areas, but most often, they are not usually built to the recommended standard set by the housing authorities in Abuja (see Figure 2.2). They also live on the outskirts of the city but in well-developed estates and carefully planned areas.

Figure 2.2: Typical lower-middle income housing estate in Abuja Nigeria, Source: Google/images

Figure 2.3: Typical low-middle income housing unit in Nigeria, Source: Google/images

Houses for this income group are usually of better quality compared to the low-income group (see Figure 2.3). They use standard vibrated sandcrete blocks of 450mm x 230mm x 230mm for external walls and 450mm x 150mm x 230mm for internal partition walls like toilets and bathrooms and are roofed with galvanized steel or aluminium sheets. Roof overhangs are usually in the range of 500mm – 700m and a floor to ceiling height of 3.0m - 3.2m. The houses are designed and supervised by professionals i.e. architects and approved by the local and federal housing authorities (Federal Capital Development Authority, F.C.D.A. and the Federal Housing Authority, F.H.A.) who often check the progress of work done on the building construction. They are usually built by local tradesmen living around the area.

3) Middle income earners

This group consists of intermediate managerial, administrative, or professional workers and earn between $35-50 per day, approximately N15, 000. They live close to or in the cities. Their living quarters are well-developed and built according to the building regulations of the local authority (Figure 2.4).

Figure 2.4: Typical middle-income housing unit in Nigeria, Source: Google/images

Figure 2.5: Typical middle-income area in Nigeria, Source: Google/images

This income group boasts of higher quality houses compared to the previous income groups. They have the resources to buy and maintain generators. The houses are constructed with standard vibrated sandcrete or concrete blocks and are roofed with cement-based tiles (Figure 2.4) and aluminium sheets (Figure 2.5). Roof overhangs are usually in the range of 600mm – 700mm and a floor to ceiling height of 3.0m - 3.5m. These houses usually have larger indoor spaces and a luxury of small gardens and a large entrance space. They are designed and supervised by professionals and approved by the local housing authorities (F.C.D.A.). They are usually built by local contractors who employ tradesmen from all over the region.

4) *Higher income earners*

This group is made up of higher managerial, administrative, or professional workers who earn $50-150, approximately N35, 000 per day. In some cases, they go above the $150 per day threshold. They live in the cities and can afford the high housing rent and cost of living. This income group have the highest quality of built houses. They are built with vibrated standard sandcrete or concrete blocks. They are roofed with aluminium sheets or shingles sheets (see Figure 2.6 and 2.7). The roofs usually have a steep pitch, and some are ventilated. Roof overhangs are usually in the range of 600mm – 700m and a floor to ceiling height of 3.0m - 6.0m.

Figure 2. 6: Typical high-income housing unit in Nigeria, Source: Google/images

Figure 2.7: Typical high-income housing unit in Nigeria, Source: Google/images

Some of the building materials used, like roofing sheets, tiles and paints are imported. These houses usually have larger indoor spaces and a luxury of small gardens and large entrance space. They are designed and supervised by professionals and approved by the local housing authorities (F.C.D.A.). They are usually built by big construction companies and skilled tradesmen and professionals from all over the region.

2.3 Building environmental performance in Abuja

The influence of the hot-humid climate in Abuja on high temperatures experienced in both outdoor and indoor environments cannot be dismissed. Today's modern buildings in Nigeria have deep plans with low ceilings, are highly glazed and are constructed of lightweight materials and finishes while most houses in the rural settlements on the outskirts of Abuja have smaller windows and poorly constructed building fabric. Occupants of these buildings experience over-heating and discomfort unless mechanical cooling is provided. Unfortunately, the latter usually leads to very high-energy consumption. According to Edwards (1998), the main heat gains that create overheating are the result of direct sunlight on the uninsulated building fabrics. Heat transfer through the walls is not regulated or controlled and therefore a large amount of heat is transferred into the indoor space.

Urbanization has been going on in Nigeria for the past one hundred years (Olotuah and Adesiji, 2005a; Jolaoso et al., 2012) causing a rapid growth of people in the urban area and creating new ones in the process (Jolaoso et al., 2012). Seemingly, this has resulted in relentless rural-urban migration and tremendous growth in the size of the urban settlements. The need to increase the quantity of housing has led to a major and evident concern about the quick deterioration of current housing stock leading to a shortage of housing units (Olayiwola et al., 2005). Hence, because of the rush to meet demand builders tend to focus more on quantity than quality therefore compromising standards.

2.4 Housing situation in Nigeria

Most people live in poor quality housing and unsanitary conditions in Nigeria. The rapid rate of urbanisation and economic growth has led to the problem of inadequate housing in urban areas. These problems include unplanned population growth, exaggerated real estate values, inflow of immigrants and lack of planning are all the main complications of housing which has far more grave consequences for low income earners.

Deep inadequacies in the housing condition of Nigeria, in particular for those people who are low income earners (Olotuah and Fasakin, 2003; Olotuah and Aiyetan, 2006), show that over the years there has not been any significant improvement in the quality of buildings meant for low-income earners who constitute the vast majority of the population of Nigeria (Olotuah and Ajenifujah, 2009). The massive rural-urban migration has been caused by the lack of rural development, government's bias towards the location of public infrastructure in the cities and the rural dwellers living in poor economic circumstances. Over the years, the population in the cities has been growing steadily, through the increase in size of urban households in Nigeria. In the 1930's, only 7% of Nigerians lived in cities, the number gradually increased in 1950 to 10% and 20%, 27% and 35% in 1970, 1980 and 1990 respectively (Okupe, 2002; Olotuah and Ajenifujah, 2009).

According to a report by tradingeconomics.com (2018) more than 48% of Nigerians live in cities. Because of this population explosion in the urban centres, overcrowding and inadequate dwellings are now a serious problem, with over 60% of According to a report on urban migration by the Federal Government of Nigeria, the population explosion in the urban centres, overcrowding and inadequate dwellings are now a serious problem, with over 60% of Nigerians said to be without a home or a place they could call home (Federal Government of Nigeria, 2004). Apart from the issue of overcrowding in the current housing stock, there is a high emergence of temporary dwellings that are lacking the minimal structural and standard quality, caused principally by the rural-urban migrations. These areas are poorly maintained, sanitary conditions are non-existent, there is a lack of power supply and good air quality, and privacy does not really exist at all. High density, severe sanitary problems, air pollution, surface water and solid waste contamination are characteristics of urban centres in Nigeria as previous research has revealed (Filani 1987; Agbola, 1998; Olotuah and Ajenifujah, 2005).

Housing deficiencies are the noticeable consequence of the rapid urbanisation taking place in Nigerian cities. The inferior quality of current housing units, the massive scale of housing needs, the construction of these houses without regard to location or climate is a clear expression of this phenomenon (Olotuah and Ajenifujah, 2005). According to research by Olotuah and Ajenifujah, (2005), an estimated 2.3 million urban dwelling units are below the housing standard, only 33% can be considered physically sound and to bring the remaining houses up to standard, 44% would require minor repairs while 19% of these houses would require major repairs. There is a gross inadequacy of sanitary facilities and public services like clean water and electricity supply in most urban centres (Olotuah, 2002a; Olotuah and Ajenifujah, 2005).

2.5 Housing procurement and ownership in Nigeria

The main components of the Nigerian housing sector, public and private, will be discussed in this section. The historical trend of the major housing programmes and policy evolution in the country is presented to set the context within which both the private and public housing sectors operate and are shaped in Nigeria. The cultural, social, and economic principles of a society reflect its housing and the people’s ability to meet their needs for shelter in the context of their communities. There are two routes in housing procurement and ownership in Nigeria: through the public housing sector and through the private housing sector. These are described below.

2.5.1 Public housing sector

There are two main types of public housing in Nigeria: the government owned housing provided mainly for government and public officials, civil servants, and public employees and the mass public housing for the public.

a) Government owned housing

Government housing consists of residential houses allotted to civil servants and government employees of certain grades and category of staff usually owned by the federal government, state government or rented by them for their employees. A small fixed amount is usually deducted from their monthly salaries as rent payment. This type of housing provides accommodation for around 25% of civil servants in Nigeria (Talba, 2004). According to Mba (1993), there are two distinctive types of government owned housing, namely that of the government residential areas (GRAs) and the low-income staff housing. These GRAs originated from the British colonial administration and can be found nearly all over the major cities in Nigeria. The British brought in this concept of building European quarters to accommodate large number of colonial administrators and key executives of commercials firms and companies in the late 1920s. They normally consist of western style single-family housing units with open space and large plot sizes. The GRAs were in low-density urban housing areas, usually one housing unit per two hectares but vary slightly between cities (Ndubueze, 2009). With Nigeria's independence in 1960, many British citizens and companies left the country and therefore the government turned the GRAs into subsidised luxurious housing to provide accommodation for high-ranking government officials.

The second government owned housing type is provided mainly for the low/middle income earners of government workers. Its purpose is to provide basic affordable housing for employees close to their place of work. This type of housing, compared to GRAs, is smaller and less fashionable. The dwellings normally consist of one or two-bedroom flats in detached, semi-detached, or terraced housing on small plot sizes (Ndubueze, 2009). High-density neighbourhoods are usually associated with this type of housing and basic amenities and utilities like roads, electricity and water supply are provided making them comparatively better for accommodation compared to other low-income, high density neighbourhoods. They are more affordable at a subsidised cost to the worker that is lucky to benefit from this housing scheme.

However, the federal government later had a shift in policy from the National Housing fund of 1992 to the Housing and Urban Development policy in 2002 (Festus and Amos, 2015). At this point, affordable housing was to be provided through a monetisation programme in which the government owner or rented houses were sold to the highest bidder to about 25% of civil servants at subsidized rates. Owing to this policy, every Civil servant is now responsible for his or her accommodation. The accommodation will be funded as a form of accommodation allowance depending on the Government structure from 50% - 75% of their annual basic salary (Talba, 2004). The Federal Government had argued that the policy enables civil servants to acquire houses at affordable prices and provide housing for all Nigerians. Nonetheless, critics tend to disagree; their argument is that these houses are in fact sold at current market prices therefore making them too expensive and difficult to buy. Most civil servants already occupying these houses eventually sell their houses and move on to a more affordable lower standard accommodation but in less desirable locations (Talba, 2004).

b) Mass public housing

This is a government programme intended to provide housing for the public. It is designed and built by the government agencies at federal and state levels, although private companies and building contractors who have won such contracts from the appropriate government agencies carry out the construction of these houses. Houses built under this programme are rented or sold to the public at all levels of income at a subsidised rate. Applicants for the programme are selected by a raffle draw. Unfortunately, this housing programme remains a symbol of a failed attempt by the federal government to provide affordable housing to most Nigerians and intervene directly in the urban housing market. The allocation process is frequently abused and manipulated therefore denying those that properly merit these houses and allocating them to those that essentially schemed their way into getting the houses illegitimately.

Owing to the failure of the programme, the current rationale of the government is that housing programmes should be privately led not government led. This represents a major shift in the government's approach to mass housing implementation in Nigeria. However, many states in the country can still embark on direct housing delivery as stated by the housing provision (Federal Government of Nigeria, 2002), where the appropriate designated ministry in each state shall provide low-income housing (Ndubueze, 2009).

2.5.2 Private housing sector

Housing development by the private sector has been the dominant factor even with government policies stressing the need for mass public housing. The public housing stock provided by the government during the implementation of the housing policies was too limited to have any meaningful impact on the provision of housing to all in the country (Ozo, 1990). According to the Nigerian Housing Policy (FGN, 2002), over 90 per cent of the current housing stock is provided by the private sector. This sector is a blend of individuals, small-scale builders, commercial estate/ agencies, banking and non-banking financial intermediaries, industrial and commercial organisations, and non-governmental organisations. The main motivation for the private sector is to invest into housing development to make a profit. This sector is divided into these three groups as follows:

a) Individual and households

More than 70 per cent of the total housing stock in Nigeria is provided by individuals or households, therefore making it the most dominant sub-sector of the private sector which is mostly owner occupier or rental housing (UNHCS, 1993b). This sub-sector is responsible for the bulk of rented housing in the country largely for personal profit. All the different income groups can be found in this sub-sector, from the low end substandard houses in the low-income group to the luxurious houses of the high-income group. Within the housing market, most of the urban households consist of low-income and middle-income earners. Extra apartments or rooms are usually rented out by many home owners to supplement their household income and recover their investments. Property and land owners also tend to build or rent out additional houses for commercial purposes. Most landlords, after moving to a middle or higher income neighbourhood tend to develop land and properties usually in areas they have lived or are familiar with to build houses for financial gains. This is often evident in low-income housing neighbourhoods and informal housing settlements.

The financing of these projects by urban household developers is usually from personal savings. The culture of financing home ownership is firmly rooted in the traditional rural housing provision system, a practical influence by urban areas (Ndubueze, 2009).

b) Private profit-oriented firms

This type of house delivery concept has been increasing in role and scale in recent years. This sub-sector comprises three categories namely the traditional large-scale construction firms, multinational co-operations, and the small and medium scale property development firms.

The large-scale construction firms like Julius Berger, G. Cappa, Setraco Nigeria Limited, Reynolds Construction Company, Dantata and Sawoe Construction Company, Ascot Africa Limited, Costain West Africa, Chinese Civil Engineering Construction Company etc. embark on large scale exclusive housing developments on serviced lands provided by the government. Their target users are the high-income earners and largely around major cities like Abuja, Lagos and Port Harcourt etc. This income housing schemes usually benefit the high income private housing sub-markets and staff housing estates.

The Big-Multinationals such as Shell Oil Company, Mobile Telecommunication Company (MTN), Nigerian National Petroleum Company (NNPC), United Africa Company (UAC), British American Company PLC, NICON Insurance and the big Nigerian banks such as First Bank, Zenith Bank, Guarantee Trust Bank etc., form the next group of developers. They engage in staff housing schemes and commercial rental housing ventures. A government policy, the Special Provisions Decree No. 54 of 1979 (as Amended) was established to encourage employers to provide adequate accommodation for their staff at different level of income from low to high income earners. However, in reality the cooperation's inclined to provide housing only for the middle-high level staff leaving the low-income group to sort out their accommodation themselves.

The small and medium scale property developers form the last group of private firms. They usually provide houses mainly for the upper-middle to the high-income group in the urban areas of the country. These houses usually come in the form of gated housing estates and there is currently an increase in gated small and medium scale residential estate in the big cities around the country these include, Trade Moore estate in Abuja, Mayfair Gardens in Lagos, and Ogbonah Layout in Port Harcourt. The emergence of these housing developments is evidence of the increasing influence of this sub-sector on urban areas in the country. The most common property developers at this group are: Abuja Property Development (APDC), Grants Property, Crown Realities, Cornerstone Nigeria Limited (Ojenagbon, 2004), Cachez Property Limited etc.

The housing developments to date of this sub-sector do not cater and meet the housing needs of most people in the country especially those in the low-income group. Although the upper-middle and high-income group can afford the high prices in this sub-group, the low-income majority cannot and are therefore deprived of descent housing accommodation (Ndubueze, 2009).

c) NGO's, CGO's, and Cooperatives

The Non-Governmental Organisations (NGO's) are gradually seen as a feasible substitute to providing non-profit housing for the low-income earners in Nigeria though this group has insignificant impact on the development of the housing sector. They tend to complement the effort of the government and assist vulnerable targets groups in the process of development. Most NGO's provide rudimental social services thus are no more than social clubs and voluntary agencies (Agbola, 1994). Little has been done by the government or those within official circles to promote and provide the necessary attention to programmes such as cooperative housing scheme and the sub-sector in general. However, it is important to bear in mind that cooperative housing concept is not new to Nigeria, they are very traditional means of providing housing in many rural areas through cooperation and self-help housing. How to this into an effective urban housing delivery tool is often seen as a big challenge. The growth of the cooperative housing is really struggling and does not have much effect because little work has been done in the urban delivery framework to create a favourable environment.

The Community-based Organisations/ associations (CBO's) have also recorded limited success though it has been a significant innovative effort. This sub-group constitutes mostly local grass root organisations which has played a more significant role in housing delivery in rural areas. The CBO's are more effective because they offer community cohesion at high levels within rural areas. CBO's offer great opportunity for project housing delivery at the grass root level in rural communities and forging partnership that would benefit the communities and develop housing programmes. The high level of community cohesion within the rural areas, the CBO's are more effective in these areas in providing community-based housing project delivery. According to Ndubueze (2009), he noted that government policies has done little to encourage housing delivery in the private sector apart from the tax exemptions and capital allowances granted in the 1990's and 2002 housing policies for cooperative developers. Therefore, whether these incentives are significant enough to stimulate the mass enthusiastic response and participation is doubtful (Ndubueze, 2009).

PART-B

Comfort Theories and Passive Strategies

Thermal comfort is linked to the need to maintain an almost constant internal body temperature, irrespective of the rate at which heat is generated within our bodies or what environment we are in. This stable core body temperature of around 37°C is essential for our health and well-being. The thermal interaction with the environment is directed towards maintaining this stability in a process called 'thermoregulation.' The opportunities available to us for such interactions are numerous and complex and are the subject of a great deal of research (Nicol et al. 2012). Thermal physiologists study how we produce and use heat. The next section will look at human behaviour and thermal comfort.

2.6 Human behaviour and thermal comfort

It is important to note that behaviour plays a significant role in the occupants' thermal interaction with the environment. Parsons (2003) suggested that behaviour is a powerful form of human thermoregulation, i.e. taking off or putting on clothing, changing posture, moving, taking shelter etc. All the approaches to our thermal interactions with the environment listed above have in effect assumed that we are acted upon by the environment and react to it in a passive way.

Nicol et al. (2012) noted that these are deliberate actions to control the environment and augment the unconscious physiological reactions already referred to. Time is important for behavioural interactions. Consequently, there are four typical time periods for these effects:

- Immediate – the change of clothing in anticipation of a thermal change; for example, putting on a coat before going out
- Within-day – the clothing changes, changes of posture or environmental adjustments we use to cope with changing environments within a day.
- Day-to-day – we learn from one day to the next how to cope with changing conditions such as the weather.
- Longer term – seasonal changes in clothing, in the use of buildings, activities learned over a longer period.

The total findings are drawn from physics and physiology, but will change with climate, place and time in a dynamic and interactive way. The next section considers the theoretical basis for thermal comfort.

2.7 Mathematical modelling of heat exchanged between human body and its environment

Heat production in a body is the result of the metabolism process through which components derived from digested foods are oxidized in cells, releasing energy required for the functions of various organs in the body (i.e. the contraction of muscles during work, the involuntary activities of the internal organs: heart, respiration, digestion) and maintaining the body temperature stable. It is unusual if more than 5-10% of this energy production is used for mechanical work done by the muscles (Nishi, 1981). Hence metabolic activities result in heat that must be continuously dissipated and regulated to maintain normal body temperatures (ASHRAE, 2009). Even when the body is completely at rest and in warm surroundings, its heat production does not fall below a certain minimum level – the basal metabolism – usually taken as about 85W for an average person. Various sources do not always agree on the exact formulation of the human heat balance equation. For this study, information from Parsons (2003), the ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) Handbook of Fundamentals, (2009) and Djongyang et al., (2010) was used to discuss the metabolic rate of work (see below) and the thermal effects contributing to heat exchanges.

2.7.1 The DuBois area

The total metabolic rate of work produced within the human body is dissipated to the environment through the skin surface. The most useful measure of nude body surface area is given by the following formula known as the DuBois area (A_d):

$$A_d = 0.2025m^{0.425}l^{0.725} \qquad (2.1)$$

where m (kg) is the body mass and l (m) is the body height.

2.7.2 Thermal effects contributing to heat exchanges

Six main thermal effects contribute to the heat exchanges between the human body and its environment: conductive, convective, radiative, moisture, clothing and metabolic effects which are discussed in this section.

2.7.2.1 Conductive effect

Although the human body exchanges heat by conduction (K), only a small surface area is concerned. When a greater body area is in contact, for example with furniture (e.g. chair, armchair, sofa, bed, etc.), thermal equilibrium rapidly occurs. The body area in contact with the furniture is insulating toward the environment. Generally, in the steady state, the body's temperature and direct conductive effects are neglected and then included within the convective exchanges instead.

2.7.2.2 Convective effect

The global convective heat flux exchanged (C) between the human body and its environment is:

$$C = h_c\,(T_a - \dot{T}_{sk})\ A_cF_{cl} \qquad (2.2)$$

where h_c is the convective heat transfer coefficient, T_a is the ambient air temperature and $\dot{T}_{sk}$ is the mean skin temperature, A_c is the effective convection body area (taken to be equal almost to the DuBois area A_d), F_{cl} is the clothing area factor ($F_{cl} = 1$ when there is no clothing insulation and ≈ 0 for high clothing insulation). The convective heat transfer coefficient is given by:

$$hc = 3.5 + 5.2\upsilon_{ar}\text{for } \upsilon_a \leq 1 \text{ m/s} \qquad (2.3)$$

$$hc = 8.7\upsilon^{0.6}{}_{ar} \qquad \text{for} > 1 \text{ m/s} \qquad (2.4)$$

Where υ_a is the air velocity, υ_{ar} is the resultant air velocity considering the ambient air velocity and that due to activities and displacement of the person:

$$\upsilon_{ar} = \upsilon_a + 0.0052(M - 58) \qquad (2.5)$$

Where *M* is the metabolic heat production defined in section 2.7.2.5 with the supplementary condition *M* = 200 W/m^2 when M is found greater than 200 W/m^2, to limit the second term of Equation (2.2) to 0.7.

2.7.2.3 **Radiative effect**

The radiative heat lost from the skin (R) is given by:

$$R = h_r (\dot{T}_r - \dot{T}_{sk}) A_r F_{cl} \tag{2.6}$$

Where hr is the radiative heat transfer coefficient, $\dot{T}_r$ is the mean radiant temperature and $\dot{T}_{sk}$ is the mean skin temperature, A_r is the effective radiation area of the body, F_{cl} is the clothing area factor. The radiative heat transfer coefficient hr is given by:

$$h_r = 4\sigma\varepsilon_{sk} (\dot{T}_r - \dot{T}_{sk}/2)^3 \tag{2.7}$$

Where $\sigma = 5.67 \text{ x } 10^8 \text{ W/m}^2 \text{ K}^4$ is the Stefan-Boltzmann coefficient and $\varepsilon_{sk} = 0.97$ is the emissivity of the skin. The effective radiation area of the body (Ar) is not easy to be evaluated. It can be written as a fraction of the Dubois area:

$$A_r = (A_r/A_d) A_d \tag{2.8}$$

Where the ratio A_r/A_d = 0:67 for a squatting person; 0:70 for a sitting person; 0:77 for a standing person:

The mean radiant temperature ($\dot{T}_r$) can be evaluated using the empirical formula:

$$\dot{T}_r = [(T_g)^4 + 2.5 \text{ x } 10^8 \upsilon_a^{0.6} (T_g - T_a)]^{1/4} \tag{2.9}$$

Where T_g is the inside globe temperature (defined in ISO 7726).

Beshir and Ramsey (1988) in Djongyang et al. (2010) proposed a more simplified formula as:

$$\dot{T}_r = T_g + 1.8 \sqrt{\upsilon_a} (T_g - T_a) \tag{2.10}$$

2.7.2.4 **Moisture effect – evaporative cooling**

The effect moisture has on heat transfer is due to the dampness of some organs like the lips, eyes or respiratory tract. However, at that level the transfers are relatively small. At the level of the skin, regulatory sweating creates an important evaporative heat loss (E) given by:

$$E = h_e (P_{aH_2O} - P_{skH_2O}) A_e F_{pcl} \tag{2.11}$$

where h_e ($h_e = kh_c$ with k = 16.7 K/kPa) is the evaporative heat transfer coefficient at the surface, P_{aH2O} is the water vapour pressure in ambient air, $PskH_2O$ is the water vapour pressure in saturated air at T_{sk}, Ae is the evaporative surface, F_{pcl} is the clothing permeability factor. The evaporative surface can be rewritten as: $Ae = (Ae/A_d) A_d = wA_d$. The ratio $w = A_e/A_d$ is known as the skin wettedness. The skin wettedness is a derived physiological index defined as the ratio of the actual sweating rate to the maximum rate of sweating that would occur if the skin were completely wet, and skin temperature.

Skin wettedness, w is important in determining evaporative heat loss. It ranges from about 0.06 caused by the evaporative heat loss due to moisture diffusion through the skin alone (i.e. with no regulatory sweating) for normal conditions, to '1' when theoretically a skin surface is totally wet with perspiration, a condition that occurs rarely in practice. For large values of the possible maximum evaporative heat loss or long exposures to low humidity, the value of w may drop to as low as 0.02, since dehydration of outer skin layers alters their diffusive characteristics (Lin and Deng 2008). Figure 2.8 presents the relationship between the wettedness and thermal constraint.

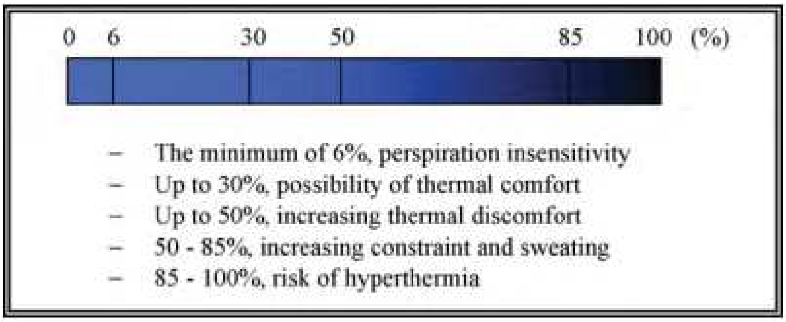
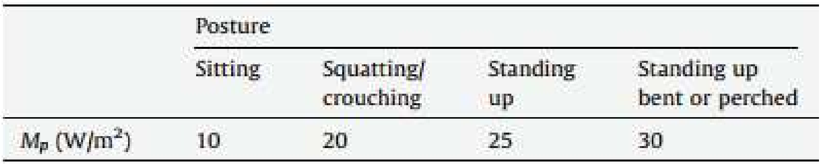


Figure 2. 8: Wettedness and thermal constraint (source: Djongyang et al. 2010).

2.7.2.5 **Metabolic effect**

The production of metabolic heat is the reflection of the cellular life that results from the consumption of oxygen (O_2) and rejection of carbon dioxide (CO_2). In the steady state, the quantity of the metabolic heat produced may be deduced from the consumption of oxygen, calculated from the rate of ventilated air and the difference of concentration between the inspired and expired air. In normal conditions, when a body is at rest and in nutritional equilibrium, the global respiratory ratio is $m_{CO_2}/m_{O_2} = 0.83$. For that value, the consumption of a litre of oxygen per hour produces approximately 5.57 W. Since a person at rest consumes oxygen, he produces approximately 104 W (58 W/m^2 = 1met for a standard person of 1.8 m^2 surface area): this is the metabolic heat at rest (M_r) (a sitting person, thermoneutrality in clothing, no external influence) Djongyang et al. (2010).



	Posture			
	Sitting	Squatting/ crouching	Standing up	Standing up bent or perched
M_p (W/m^2)	10	20	25	30

Figure 2.9: Metabolic heat of posture (source: Djongyang et al. 2010).

In the condition of activity (in the office, at school, at home), the quantity of the metabolic heat produced may not be deduced from the consumption of oxygen (it is difficult to be evaluated), but from the type of the activity practised (Figure 2.9). An approximation consists to use the formula:

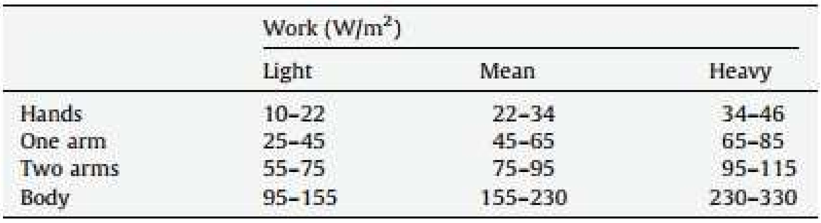
$$M = M_b + M_p + M_a \qquad (2.12)$$

where M is the metabolic heat produced, $M_b = 45\ W/m^2$ is the basal or minimal metabolic heat (nude body lying down in the case of thermoneutrality), M_p is the metabolic heat of posture whose values are given in Figure 2.9, M_a is the metabolic heat of activity whose values are given in Figure 2.10.

Metabolism as any other chemical reaction is accelerated with increasing temperature if the higher temperature does not lead to the inhibition of the metabolic process. The temperature dependence can be written as:

$$M = 1.1^{\Delta T} M_b \qquad (2.13)$$

where M_b is the basal metabolic heat production rate and ΔT is the temperature increase. Goto et al. (2002) noted that ‘‘activity level is probably one of the least well-described parameters of all the parameters that affect thermal sensation, comfort and temperature preferences indoors’’.



	Work (W/m²)		
	Light	Mean	Heavy
Hands	10–22	22–34	34–46
One arm	25–45	45–65	65–85
Two arms	55–75	75–95	95–115
Body	95–155	155–230	230–330

Figure 2.10: Metabolic heat of activity (source: Djongyang et al. 2010).

2.8 The heat balance approach to defining thermal comfort

One generally accepted definition of thermal comfort is that of ASHRAE:

> *‘that state of mind which expresses satisfaction with the thermal environment’.*

Several researchers have set out to build models that mimic the physics and physiology of thermal comfort and a considerable number of thermal indices have resulted. Auliciems and Szokolay (2007) have listed some 20 major examples with others having identified as many as 80. This suggests the task is non-trivial.

Some models are based on a survey of people’s response to the environment using statistical analysis from field surveys looked at further in this chapter. They are sometimes called ‘empirical’ models. But, despite the definition of comfort given above being centred on a ‘state of mind’, the most common type of model is built on physics and physiology. These are sometimes called ‘rational’ or ‘heat balance’ models and the best known among them are the Predicted Mean Vote (PMV) (Fanger, 1970 in Djongyang et al., (2010)) and Standard Effective Temperature (SET) (Gagge et al., 1986 in Djongyang et al., 2010). The PMV model is particularly important because it forms the basis for most national and international comfort standards which will be discussed further in this chapter.

There is a necessary balance between the heat produced by the body and the heat lost from it, to maintain the body temperature. One can imagine situations in which balance would occur, but which might not be considered comfortable. For instance, a person with a warm head and cold feet may be in thermal balance but is not necessarily comfortable. Thus, it is possible to be in thermal balance but still feel too cold or hot. The determination of comfort conditions is therefore in two stages: first, finding the conditions for thermal balance and then, second, determining which of the conditions so defined are consistent with comfort.

2.8.1 The heat balance approach

As seen in section 2.7, equations can be derived for all the individual contributions to the heat balance equation, and they can be evaluated if the metabolic rate, the clothing resistance, and the environmental parameters are known.

This approach is concerned with studying the steady states; it investigates thermal comfort models in climate chambers (Djongyang et al., 2010; Taleghani et al., 2013). In this type of study, various climatic parameters such as air temperature, radiant temperature and humidity are varied to suit certain results; personal variables such as clothing insulation and metabolic rate are fixed.

In the model that underlies PMV, the condition for thermal comfort for a given person is that their mean skin temperature and sweat secretion must have a certain value at a given metabolic rate. The formulae for determining the conditions for comfort simply assume a required ‘optimum’ value for these two physiological variables. The data to establish optimal skin temperatures and sweat rates used in PMV were obtained entirely from climate chamber experiments. In the classic climate chamber, experiments subjects are dressed in standard clothing and given a task to do that may involve physical or mental work. Their comfort votes were then polled at intervals over periods of some hours (Nicol et al., 2012).

During the experiments, sweat rates and skin temperatures were measured for people at various metabolic rates who considered themselves comfortable. Optimal conditions for thermal comfort were expressed by regression lines relating skin temperature and sweat rate to the metabolic rates from data in these experiments. In this way, an expression for optimal thermal comfort was deduced from metabolic rate, clothing insulation and experimental conditions. The final equations for optimal thermal comfort are complex (Nicol et al., 2012). They are available in ISO 7730 (2005). The solution to the equation has been computed and the results presented in the form of diagrams from which optimal comfort conditions (in terms of air temperature, mean radiant temperature and humidity, at different values of the air speed) can be found if the metabolic rate and clothing insulation of the desired population are known.

The other most commonly used model is the SET* model (standard effective temperature). SET* is a comfort index that was developed based upon a dynamic two-node model (2NM) of the human temperature regulation (ASHRAE, 1997; Gagge et al., 1971; Gagge et al., 1986; Ye et al., 2003), which is different from Fanger's steady-state model. It also uses skin temperature as one of its limiting conditions but uses skin wettedness (w) rather than sweat rate for the other building limiting condition. A transient energy balance states that the rate of heat storage is equal to the net heat gain minus the heat loss. The thermal model is described by two coupled heat balance equations, one applied to each compartment:

$$S_{cr} = M - W - (C_{res} + E_{res}) - (t_{cr} - t_{sk}) \times (5{:}28 + 1{:}163 \times \text{skbf}) \quad (2.14)$$

$$S_{sk} = (t_{cr} - t_{sk}) \times (5{:}28 + 1{:}163 \times \text{skbf}) - (C + R + E_{sk}), \quad (2.15)$$

where S_{cr} is the rate of heat storage in the core node (W/m^2); S_{sk} the rate of heat storage in the skin node (W/m^2); C_{res} the rate of convective heat loss from respiration (W/m^2); E_{res} the rate of evaporative heat loss from respiration (W/m^2); t_{cr} the temperature of core node; t_{sk} the temperature of skin node; skbf the peripheral blood flow (L/h m^2); C the sensible heat loss from skin by convection (W/m^2); R the sensible heat loss from skin by radiation (W/m^2); E_{sk} the total of evaporative heat loss from the skin (W/m^2).
The rate of heat storage in the body equals to the rate of increase in internal energy. The rate of storage can be written separately for each compartment in terms of thermal capacity and time rate of change of temperature in each compartment:

$$S_{cr} = (1 - \alpha)\, mcp_{,b}(dt_{cr}/d\Theta)/A_D, \quad (2.16)$$

$$S_{sk} = \alpha mc_{p,b}(dt_{sk}/d\Theta)/A_D, \quad (2.17)$$

where α is the fraction of body mass in skin compartment; m the body mass (kg); $c_{p,b}$ the specific heat capacity of the body (kJ/kg); Θ the times (s); A_D the Dubois surface area (m^2).

The ASHRAE's SET* Index is defined as the equivalent temperature of an isothermal environment at 50% Relative Humidity (RH) in which a subject, while wearing clothing standardized for the activity concerned, would have the same heat stress (skin temperature, tsk) and thermoregulatory strain (skin wettedness, w) as in the actual test environment (Gagge et al., 1986). The values for T_{sk} and w are derived from the 'Pierce two-node' model of human physiology developed at the John B. Pierce Foundation in the United States (Gagge et al., 1970). Isothermal environment refers to the environment at sea level, in which the air temperature is equal to the mean radiant temperature, and the air velocity is zero. If H_{sk} is defined as the heat loss from skin, that is the thermal load of skin, then it can be expressed as Equation 2.18.

$$\mathrm{H}_{sk} = h_s(t_{sk} - \mathrm{SET}^*) + wh_{s,e}(p_{s,sk} - 0.5p_{\mathrm{SET}^*}), \qquad (2.18)$$

where h_s is the standard heat transfer coefficient ($\mathrm{W/m^2 \cdot {}^\circ C}$); $h_{s,e}$ the standard evaporative heat transfer coefficient ($\mathrm{W/m^2kPa}$); w the fraction of the wetted skin surface; $p_{s,sk}$ the water vapor pressure at skin, normally assumed to be that of saturated water vapor at t_{sk} (kPa); $_{\mathrm{pSET}^*}$ the saturated water vapor pressure at SET* (kPa), (G. Ye et al., 2003).

The ‘two nodes’ are the body’s core and its peripheral tissues. This model was also calibrated in climate chamber experiments. The SET* relates the real conditions to an ‘effective temperature’ that would give the same physiological response in people in standard clothing (0.5 clo) and metabolic rate (1.0 met) and relative humidity of 50 percent. This standard effective temperature can then be related to subjective response. SET was used as a thermal index in past editions of the ASHRAE Standard 55, but recent editions have used PMV rather than SET* as an indicator of indoor comfort.

2.8.1.1 **Predicted mean vote (PMV) and predicted percentage dissatisfied (PPD)**

The PMV approach goes beyond the provision of a thermal index. The index is not related to an ‘effective temperature’ as is done in SET but sets out to predict the mean comfort vote on the ASHRAE scale (Table 2.1) of a group of people based on six variables: the air temperature, the radiant temperature, the air speed, the humidity, the clothing insulation, and the rate of metabolism.

Table 2.1: Two seven-point scales commonly used in thermal comfort work

ASHRAE Scale		**Bedford scale**	
Descriptor	Number	Descriptor	Number
Hot	+3	Much too warm	7
Warm	+2	Too warm	6
Slightly warm	+1	Comfortably warm	5
Neutral	0	Comfortable – neither cool nor warm	4
Slightly cool	-1	Comfortably cool	3
Cool	-2	Too cool	2
Cold	-3	Much too cool	1

Source: Nicol et al. 2012.

The assumption behind the model is that the sensation expressed through the ASHRAE scale is caused by the ‘physiological strain’ caused by the environment. The strain is defined as ‘the difference between the internal heat production and the heat loss to the actual environment for a person kept at the comfort values for the skin temperature and the sweat production level' (Fanger, 1970). It has been noted that this criterion for comfort is consistent with fixed ranges of sweat rate and skin temperature only for a fixed value of clothing insulation (Humphreys and Nicol, 1996). The vote predicted is the mean to be expected from a group of people, and PMV has been extended to predict the proportion of the group who would be dissatisfied with the environment. Dissatisfaction was defined in terms of the comfort vote. Those who voted outside the central three points on the ASHRAE scale (votes +3, +2, -2, and -3 in table (2.1) were counted as dissatisfied. PPD expresses this as a percentage and its value is calculated from the PMV value. However, work based on field studies suggests PPD does not reliably predict the discomfort caused by deviations from the comfort temperature in real-life circumstances of diverse activity and clothing (Humphreys and Nicol 2002). It revealed that occupants' responses in terms of thermal discomfort are subjective while responses regarding thermal sensation is objective and mentioned that thermal comfort of occupants are influenced by environmental, subjective and objective factors.

The PMV-PPD model of Fanger is now widely used and approved in some international/national standards (CIBSE, 1999; ASHRAE, 2004; ISO, 2005; CEN, 2007). Since the PMV-PPD model relies on the experimental data from comfort surveys in controlled environments, the model was proved to be quite reliable in an air-conditioned (AC) building under steady-state conditions. However, in naturally ventilated (NV) buildings and under hot conditions, the predictions of the PMV-PPD model showed significant bias, compared with the actual mean thermal sensation vote (de Dear & Brager, 2002; Nguyen et al., 2012). Although there have been some efforts to revise the PMV-PPD model to overcome this limitation, none of them reaches a feasible solution (Nicol et al., 2012).

2.8.2 Problems with the analytical approach

The heat balance approach has been much recommended, particularly for separating out the effects of the various aspects of the thermal environment such as air movement, humidity clothing and activity. However, possible sources of error in the use of these models in practice need to be noted. Errors are essentially of two kinds: formulation errors and measurement errors (Humphreys and Nicole, 2002). Formulation errors are those coming from the approximations in the way in which the environmental variables are expressed and combined to predict the comfort response. The complexity of the interaction between people and buildings leaves a lot of scope for interpretation. The model itself has been built from a mixture of theory and measurement using a mixture of experimental approaches, both statistical and analytical (Humphreys and Nicole, 2002).

Measurement errors are those coming from the measurement process, and are particularly evident when the environment, and the people's response to it are changeable. To predict conditions for optimal comfort requires knowledge of the thermal insulation of clothing and the metabolic rate of a group of individuals (G. Ye et al., 2003). Both clothing insulation and metabolic rate are difficult to assess accurately. The measurement of the temperature and humidity can be made accurately enough, but air speeds can vary widely through time, and from place to place, so it can be hard to determine the best value. Nicol et al. (2012) noted that for environmental designers who use PMV to decide what temperature to provide in a space, the model poses many problems. What clothing will the building occupants wear? What activity will they be engaged in (particularly where many activities are taking place in the same space)?

Field studies show that people worldwide accept a much more diverse set of thermal environments than laboratory-based indices lead us to expect, because people have adapted to their own climate. If this is true, then the thermal environment standards derived from the laboratory-based models will typically only be applicable in highly serviced buildings that can produce tightly controlled indoor climates in a wide range of outdoor temperatures. The variability of the indoor temperatures in a building with no mechanical heating or ventilation renders the method difficult to use (Nicol et al., 2012). Without mechanical control, the temperature will change continually with time. The inhabitants will open or close windows, open or close blinds, or change their clothing or their activity to make themselves comfortable. The PMV is of reduced value in these varying circumstances because it uses a steady-state model.

A heat exchange approach, as used in the PMV method, should ideally predict the outcome of a field survey, yet comfort temperatures computed from field studies are often difficult to reconcile with those calculated using the indices based on heat balance assumptions and experiments in the chambers. From the point of view of the adaptive approach, the climate chamber is a special case of a room where the participants are unfamiliar with the space they occupy and usually lack any ability to control their conditions. If there is a behavioural element to the way people deal with discomfort, then the lack of control will affect their response to the thermal environment of a group of the people and the temperature predicted using PMV (Nicol et al., 2012).

2.9 Adaptive approach to field survey

Humphreys (1995) suggested if we want to know how people feel in a situation, there is no better way to find out than to ask them. This is the method of the field survey which is a basic tool in the adaptive approach. It is impossible, using only a simple theoretical model to understand the complex working of a local comfort system that involves people, buildings, and climates. A method was therefore needed to record and analyse local conditions and behaviours, and so provide an effective model to help design for site-specific comfort and practical application. The behaviour, climate, culture, and context are unique to any place, so also are the comfort needs and expectations of its inhabitants (Nicol et al., 2012). Further review of adaptive approaches like field surveys, Post occupancy and comfort surveys, together with environmental monitoring and overheating criteria will be discussed in the next section

2.9.1 Field surveys of thermal comfort

A field survey of thermal comfort is an in-situ poll of comfort (Table 2.1) among a given population (e.g. residents in a dwelling) together with simultaneous measurements of the environmental conditions. In the field surveys, participants wear their normal clothing and go about their usual work. There has been a continuing stream of thermal comfort field surveys which are analysed statistically to estimate the temperature at which the average survey participant will be comfortable, usually called 'the comfort temperature' or the 'neutral temperature'. It can also be termed the temperature at which the largest number of participants in a survey will be comfortable (Humphreys, 1995; Nicol et al., 2012). Together with the field studies are laboratory-based heat balance models of thermal comfort described in section

Field surveys have been used to develop empirical, statistically based indices of thermal comfort. Examples of these indices include Bedford's Equivalent Temperature (Bedford, 1935 in Nicol et al., 2012) and Sharma and Ali's tropical Summer Index (Sharma and Ali, 1986 in Nicol et al., 2012). Such indices share the objective of the theoretical heat balance indices to estimate the conditions which people find comfortable. However, they suffer the limitation that they apply only to the conditions and context of the field survey on which they are based, and it is virtually impossible to accurately extrapolate those results to fit the conditions that exist in another location and site.

2.9.2 Environmental monitoring

Physical measurement of environmental parameters helps to assess indoor environmental conditions (Wang et al., 2011; Sakka et al., 2012). It provides a range of internal and external temperature variations at which indoor occupants find comfortable (Akande and Adebamowo, 2010). There are three different heights (0.1m, 0.6m and 1.1m) above floor level at which indoor environmental parameter measurements can be taken during environmental monitoring for sitting activities, while measurements can be taken at 0.6m, 1.1m and 1.7m above floor levels when occupants are carrying out non-sitting activities (ASHRAE, 2004). Some previous investigations have taken measurements of variables at 0.6m height (Wang et al., 2011), at 1.1m height (Han et al., 2007; Akande and Adebamowo, 2010; Indraganti and Rao, 2010; Adekunle and Nikolopoulou, 2014), at 1.7m height (Ghisi and Massignani, 2007) above floor level for sitting and non-sitting activities; while other studies have considered measurements of variables at the three heights above floor level concurrently (Wang, 2006; Honjo et al., 2012; Limbachiya et al.,

2012) for sitting activities. Few studies have also considered measurements of environmental variables at different heights not mentioned by ASHRAE (2004) for sedentary and non-sedentary activities. For example, environmental variables were measured at 0.3m above the floor level considered to be centre of gravity for occupants seated on the floor (Ealiwa et al., 2001), at 1.0m level (Hong et al. 2009; Cao et al., 2011), while measurement of variables at 2.10m above the floor to enable participants carry out their everyday routines undisturbed (Gomez-Amador et al., 2009). All the measurements at various heights are considered to ensure that the sensors are placed in the right position with minimum or no interference during the period of monitoring and the occupants are not limited to carry out their daily tasks within the indoor spaces. For this study, measurements at 1.1m (then average height of the head-region of occupants seated) will be considered as recommended by ASHRAE (2004).

2.9.3 Post-occupancy surveys

Another type of survey, the Post-Occupancy Evaluation (POE) is essentially concerned with the individual building in which the survey is being conducted (Nicol and Roaf, 2005). It is also called Building Performance Evaluation by some practitioners (Preiser and Vischer, 2004). The evaluation may be concerned with energy use and the effectiveness of any energy saving technologies, as well as whole building performance. The normal post-occupancy questionnaire will ask building occupants about their experience of the building, e.g. whether it gets too hot in summer or too cold in winter. The results from these surveys can be used to assess the relative success of the design in relation to its overall environmental performance. Post-occupancy studies have identified that occupants are more ‘forgiving’ of, and work more efficiently in a building they like. They may be the result of a popular management system, or a quiet, peaceful building, or very often one that affords them more control over their own environment (Leaman and Bordass, 1997; Nicol et al., 2012). These studies highlight the importance of occupant behaviour and perceptions, as well as the performance of the building, on the overall comfort experience of people in the building.

A survey questionnaire can be extended to include, e.g. the sex, age and weight of the participant or the time of the day at which they are surveyed, so that the effect of these factors on the resulting comfort temperature can be evaluated. Many recent survey questionnaires have also included the ways in which the participants interact with the building they occupy, such as when they are in the building, when they open and close windows, turn on or off the heating or cooling, shade the windows and so on. Questions in this survey may also include if the building is air-conditioned or naturally ventilated. It is often a part of a comprehensive survey of the environment that includes noise, lighting, humidity, and air quality (Nicol et al., 2012).

A combination of different methods during field studies provides feedback for professionals in the built environment to evaluate and improve on the building's performance (Bordass and Leaman, 2005). Also, evaluation of occupants' thermal comfort, physical measurements of environmental variables in different seasons can be carried out during field studies (Gossauer and Wagner, 2007). The information gathered during field studies is very crucial to understand indoor environmental conditions and cannot be collected at the construction stage of the building. The studies also help to gather comments and recommendations for professionals in building industry to know how different building design features, materials and technologies affect indoor occupants' comfort, satisfaction, and overall well-being. Comfort field studies were considered for this investigation over climate chamber tests to understand actual occupants' different behavioural actions and how they adjust to their thermal environment as well as their understanding of the differences in occupants' responses during comfort survey which suggested that expectation and sensation differ from one occupant to another (Raja et al., 2001).

Due to difficulties of field studies to cover a long duration, thermal comfort in dwellings using thermal modelling and simulation can also be investigated (Hacker et al. 2008; Peacock et al., 2010; Mavrogianni et al., 2012). Dynamic thermal simulation is a valuable technique for evaluating thermal performance of buildings with the ability to save time and costs which are associated with post-occupancy survey, environmental monitoring, and comfort survey (Pereira and Ghisi, 2011). It does not only overcome difficulties of carrying out rigorous calculation of huge data that is lengthy and time taking (Ralegaonkar and Gupta, 2010; Pereira and Ghisi, 2011) but also provides designers the means of working with all necessary information required for achieving effective decisions about design (Pereira and Ghisi, 2011). This suggested that the application of dynamic simulation provides a better understanding of how the building performs in different seasons in both current and future situations. It can capture more data than other methods and a combination of different methods provides different sets of data for analysis and comparison (Lomas and Kane, 2012). For this study, application of comfort field studies and dynamic simulations were pursued.

2.9.4 Comfort and indoor temperature: the basic adaptive relationship

Outside a range of mean operative temperatures of 20°C to 25°C, matching of comfort temperature to mean operative temperature is not exact (Nicol et al., 2012). In hotter climates, the comfort temperature is generally lower than the mean operative temperature, suggesting that people are frequently slightly warmer than they would like to be and in colder climates they are frequently slightly cooler. However, the values of neutral temperature in this analysis are calculated for still air. In fact, most offices and homes in hot climates have fans which has the capacity to bring down the operative temperature by 2K (Nicol, 2004).

2.9.5 Outcomes: indoor comfort and outdoor temperature

Humphreys (1976) found that there was a strong relationship between indoor comfort temperature and the outdoor temperature. This allows the effect of climate on comfort temperature to be estimated. Humphreys (1978) collected data from reports of field surveys from all over the world and produced the well-known graphs in Figure 2.11 and 2.12. It was found that the comfort temperature in free-running buildings varies linearly with the outdoor temperature whilst that of heated buildings shows a more complex curvilinear relationship. Few data were available at that time for the comfort in cooled buildings in hot climates and it was assumed that they would continue the trend of the heated or cooled building.

The relationships between monthly mean outdoor temperatures and the neutral comfort temperatures shown (Figure 2.11) can explain the difference observed between comfort temperatures in buildings in the heated and in the free-running mode. The indoor temperature in free-running buildings is coupled to the outdoor temperature through the fabric of the building while that of a building in cooled or heated mode is decoupled by the closed skin of the building and the operation of the heating and cooling systems within it. People indoors in a free-running building are effectively adapting to the external temperature around the building mediated through its walls and operable windows, and through roofs and floors.

The range of comfort temperatures at any one outdoor temperature is real, and not just a scatter of 'errors' about a mean. It suggests that there is a range of about 4K of the mean temperatures that people find comfortable.

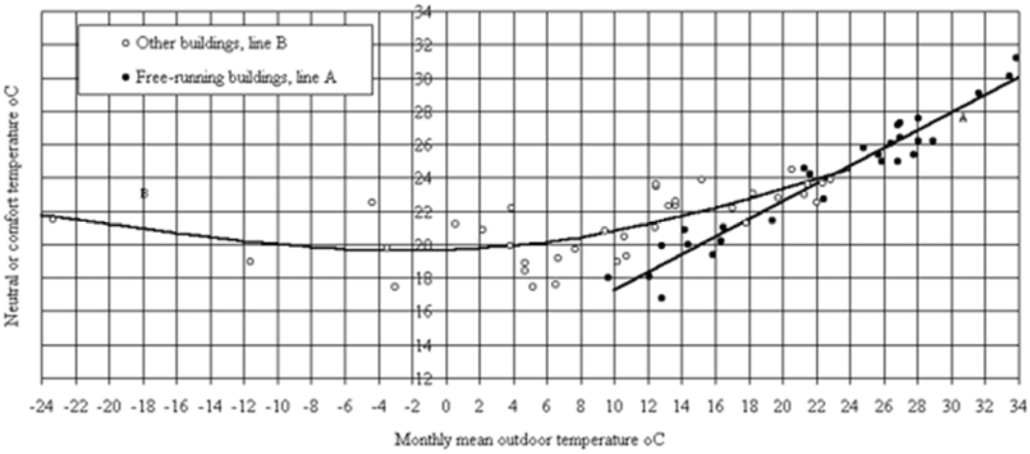


Figure 2.11: Comfort temperature change with monthly mean outdoor temperature. Source: Humphreys, 1978

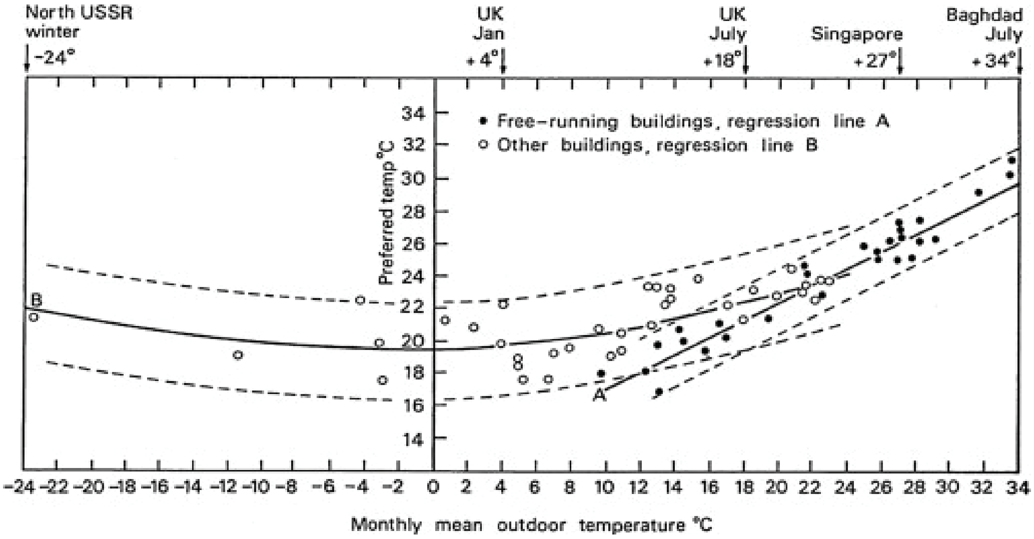


Figure 2.12: Comfort temperature change with monthly mean outdoor temperature. Source: Humphreys, 1978

It has been observed that through adaptation mechanisms, occupants' comfort may be achieved over a wide range of indoor temperature, from 17 – 31°C (Humphreys and Nicol 1998). In Naturally ventilated (NV) buildings, the prime driver of occupants' adaptation is the internal temperature which is usually correlated well with outdoor conditions. Based on data from surveys performed

Humphreys et al. (2010) reported that the mean comfort temperature range for any given outdoor temperature has risen by 2K in buildings in both free-running and in heated and cooled modes (Figure 2.11 and 2.12). This is possibly because buildings have become warmer, and people have adapted to these higher indoor temperatures. It also suggests that more recent building types may provide less protection against summer heat or be better insulated and that, in general, free-running buildings are running hotter because of this. However, too much should not be made of this increase, since the surveys in the meta-analyses on which this finding was based were done in buildings that were not selected on a strictly representative basis.

The range of the comfort temperatures at any given outdoor temperature in the heated and cooled building remains much the same but in the free running buildings it has increased from about 4K in pre-1978 buildings to about 7K. The strong relationship between indoor and outdoor temperature has thus been the basis of adaptive standards for indoor temperatures (Humphreys et al., 2010).

2.9.6 The basics of the adaptive model: using surveys to understand comfort

Human beings are comfort-seeking animals who will, given the opportunity, interact with the environment in ways that secure comfort (Levins and Lewontin, 1985). Nicol and Humphreys (1973) in

Nicol et al. (2012) suggested a feedback approach to interpreting the results of field surveys of thermal comfort. Unpleasant sensations prompt reactions from people and cause them to make changes in the comfort control system (e.g. air-conditioners and heating devices) itself. In addition to the automatic physiological response of the body, people's conscious behavioural actions might alter their relationship to the world around them, ultimately helping to safeguard the core temperature of the body. The greater the difference between the core temperature and the environmental temperature, the greater the task of the comfort control system.

This way of interpreting thermal comfort has become generally known as the adaptive Model and is governed by the adaptive principle:

> *'If a change occurs such as to produce [discomfort], people react in ways which tend to restore their comfort.' (Humphreys and Nicol 1998)*

As mentioned earlier in section 2.8.2, considerable discrepancies between the predictions given by heat balance-based comfort models (e.g. PMV-PPD model) and field measurements have been observed. Particularly in naturally ventilated (NV) buildings, other simple comfort models which use a simple predictor (e.g. air or operative temperature) were found more accurate (Nicol and Humpheys, 2002). This discrepancy can be explained by the results of a feedback between subjects' comfort and their behaviours (Nicol and Humphreys, 1973), resulting in considerable changes in thermal perception. Understanding these changes and their consequences is the objective of increasing research in "adaptive comfort theory." Adaptive thermal comfort models often predict comfort (or neutral) temperature in an environment by assuming a direct relationship between comfort temperature and a predictor, usually the mean outdoor temperature of a prevailing period. The basis of the adaptive theory is that, if changes occur in the thermal environment to produce discomfort, then people will generally change their behaviour and act in a way that will restore it (Nicol and Humpheys, 2002).

An alternative approach termed the 'adaptive model' suggests that an active role is played by people in creating their own thermal preferences through unconscious acclimatisation, expectation and conscious adaptive behaviours mostly shaped by demographics and the cognitive process, (deDear et al., 1997 in Ogbonna 2008). This means that people tend to adapt themselves to the context they are living in to maintain thermal comfort. Adaptive actions can be categorized into three groups (Brager and de Dear, 2001 and Peeters et al., 2009):

i. Behavioural adaptation refers to deliberate changes of occupants, e.g. changing clothing, posture, controlling nearby windows or fans, adjusting activities. Behavioural adaptation provides occupants with the best opportunities to maintain their thermal comfort.
ii. Physiological adaptation (also known as acclimatization) refers to a biological response which result from prolonged exposure to a harsh environment, e.g. the increase of the sweating set point temperature of someone living in a hot climate.
iii. Psychological adaptation relates to the social aspect of thermal perception which depends on occupants' experiences, adaptations and expectations of the indoor environment.

2.9.7 Adaptive comfort and non-standard buildings

Whatever the type of building, adaptation itself is not a problem for the occupants so long as a there is a sufficient range of appropriate 'adaptive opportunity' (Baker and Standeven, 1995) to allow inhabitants to adapt to the indoor and outdoor temperatures experienced. There can still be problems when spikes of temperature are experienced, as in heatwaves, if it is not properly handled. It is well known that it is the 'shoulder months' of spring and autumn, during which the outdoor temperature can change quite rapidly, that are often the problem for comfort.

2.9.8 Deductions from adaptive models for achieving thermal comfort

Thermal adaptation is essentially dynamic. The control an occupant can exert over their environment will partly be decided by the design of the building they occupy but also by the management of the building, the environment surrounding it (the need to exclude noise, dust, etc.) and so on. The indoor temperature needed for comfort will also change with time and there are undoubtedly limits to the range of indoor climates that any group of people can adapt to over a certain period. The limits are related as much to their thermal experience as to their physiology, being affected by climate and the social, economic and cultural context.

A dynamic model for comfort requires a different approach to providing comfort from one that assumes a single temperature is best. Change and movement, typically within the context of well-understood patterns of behaviour, are the essence of the adaptive approach. Stasis, the existence of a static relationship between occupant and environment, is only achieved in circumstances where the indoor climate is highly regulated (Nicol and Roaf, 2005). To be successful, buildings need to allow people opportunities for adjustment and preferably using familiar technologies.

2.10 International comfort standards for the indoor environment

There are three well-known and widely used international standards that relate specifically to thermal comfort: ISO Standard 7730 (2005), ASHRAE Standard 55 (2004) and CEN Standard EN15251 (2007) which will be discussed in this section.

2.10.1 ISO 7730

The International Standards Organisation (ISO) is the overarching source of the standards, each of which becomes a national standard for its member states. ISO 7730 sets out the calculation and the use of the PMV/PPD index, but also includes some criteria for local comfort. In ISO 7730, the simplification is based on an operative temperature of 24.5 ◦C in summer and 22.0 ◦C in winter. These recommendations correspond to zero values of the PMV index, under standard assumptions on the metabolic rate (1.2 met, corresponding to sedentary activity), clothing level (0.5 clo in summer and 1 clo in winter), relative humidity (60% in summer and 40% in winter) and air velocity (as in Table 2.2). Three different comfort categories are introduced in ISO 7730 with varying ranges, corresponding to varying percentages of the PPD index: (i) Category A is recommended for buildings occupied by people with special thermal comfort requirements (e.g., young children, the elderly); (ii) Category B is suitable for most new buildings and renovations; and (iii) Category C is suitable for existing, less energy-efficient buildings, (Kontes et al., 2017)

Table 2.2: Acceptable operative temperature and operative temperature band for thermal comfort in office buildings based on ISO 7730, PPD, Predicted Percentage of Dissatisfied people; PMV, Predicted Mean Vote

Category	Thermal Comfort Indices		Operative Temperature		Max Air Velocity (m/s)	
	PPD (%)	PMV	Summer	Winter	Summer	Winter
A	≤6	-0.2 < PMV < +0.2	24.5 ± 1.0	22.0 ± 1.0	0.12	0.10
B	≤10	-0.5 < PMV < +0.5	24.5 ± 1.5	22.0 ± 2.0	0.19	0.16
C	≤<15	-0.7 < PMV < +0.7	24.5 ± 2.5	22.0 ± 3.0	0.24	0.21

Source: Kontes et al. (2017)

The standard has a table of measured values of the thermal insulation of various clothing items and ensembles but does not specify what clothing people should wear. It has a table of typical values for the metabolic rates of a variety of activities. The standard specifies 'classes' or 'categories' of building according to the range of PMV that occurs within them: so, Class A buildings maintain the indoor environment within ± 0.2 PMV (PPD ≤ 6 per cent), Class B ± 0.5 PMV (PPD ≤ 10 per cent) and Class C ± 0.7 PMV (PPD ≤ 15 per cent) (Table 2.3).

The other international standards use ISO 7730 as a model, so EN15251 contains a similar categorisation. The categories are not at present included in ASHRAE standard 55, but it is possible they will be included in future editions (Arens et al., 2010) because close control can increase energy use, the category system tends to favour high energy buildings.

Table 2.3: Class A, B and C building-category specifications in ISO 7730. (The Draft Rating has been dropped by ASHRAE 55, and PMV Class A is in question because of the difficulty of measuring small changes in PMV.)

Category	PPD	DR	Local discomfort	PMV
	Predicted percentage discomfort	Draft rating	(see Section 2.7.2)	Predicted mean vote
A	< 6%	< 10%	< 3 – 10%	-0.2 < PMV < +0.2
B	< 10%	< 20%	< 5 – 10%	-0.5 < PMV < +0.5
C	< 15%	< 30%	< 10 – 10%	-0.7 < PMV < +0.7

Source: Nicol et al. (2012)

2.10.2 ASHRAE 55

The American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) controls and sponsors ASHRAE Standard 55. Because the society has numerous branches outside the USA, and because the US air conditioning industry is dominant in the international market for mechanical cooling, the ASHRAE standard is in effect an international standard. Although the standard is co-sponsored by the America National Standard Institute (ANSI) it reflects the thinking and interests of the Heating, Ventilation, and Air Conditioning (HVAC) industry, which is represented on the drafting committee.

The standard is like ISO 7730 in being based on PMV. However, the ASHRAE standard was the first international standard to include an adaptive component. Following the extensive work of de Dear and Brager (2002) and using data collected in ASHRAE project RP884 (de Dear, 1998) an adaptive standard was developed that applies to 'naturally conditioned' buildings. The standard uses the relationship between the indoor comfort temperature and the outdoor temperature to delineate acceptable zones for indoor temperature in naturally conditioned buildings, i.e. buildings in which the principle means of control of indoor temperature is the use of windows (Figure 2.13). The standard defines zones within which 80 per cent or 90 per cent of building occupants might expect to find the conditions acceptable. The zones are based on the comfort equation for naturally conditioned buildings derived from the RP884 ASHRAE database:

$$T_{comf} = 0.31T_o + 17.8 \qquad (2.20)$$

T_{comf} is the optimal temperature for comfort and T_o is the mean outdoor temperature for the survey. T_o was not closely defined because surveys in the database obtained it from various sources (meteorological tables; measurements taken on site during the survey; and measurements at a nearby meteorological station during the survey).

$$T_{accept} = 0.31T_o + 17.8 \pm T_{lim} \tag{2.21}$$

Where T_{accept} gives the limits of the acceptable zones and T_{lim} is the range of acceptable temperatures (for 80 per cent or for 90 per cent of the occupants being satisfied). The given limits are T_{lim} (80) = 3.5K and T_{lim} (90) = 2.5K.

Standard 55 initially defined T_o as the monthly mean of the outdoor temperature but it is now defined as the prevailing mean outdoor temperature. In the latest revision of the standard the exact choice of the form of T_o is to some extent left to the user and can include different forms of running mean temperature. But the sudden 'jump' from one month to the next is difficult to allow for in dynamic thermal simulation. A historic monthly mean is also very insensitive to the variability of the weather from day to day and from one year to the next. There are still some questions of whether the same equation can be used irrespective of what measure of outdoor temperature is used (Nicol et al., 2012).

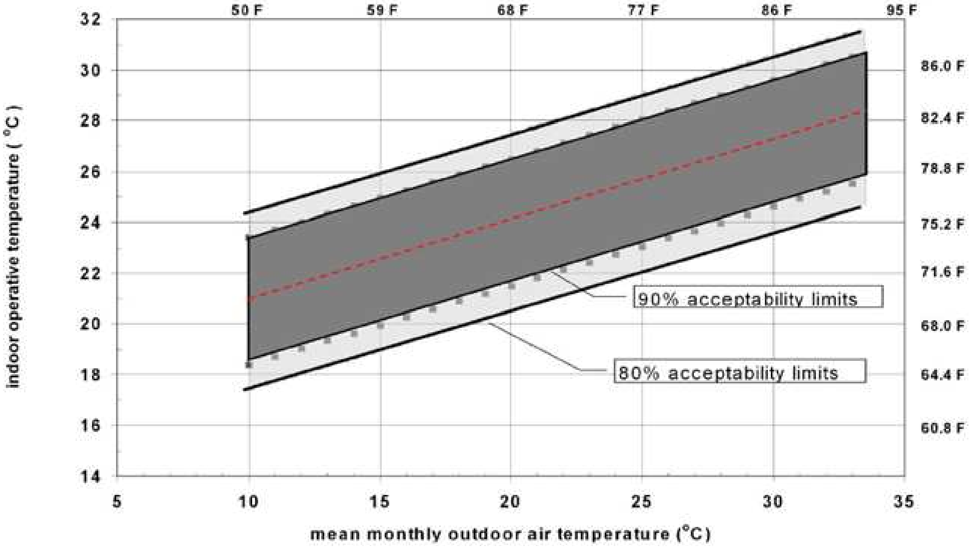


Figure 2.13: Acceptable operative temperature ranges for naturally conditioned spaces Source: ASHRAE 55, 2004

2.10.3 European standard EN15251

Standard EN15251 was developed by the Comité Européen de Normalisation (CEN) in response to calls from the European Union for standards to back up the Energy Performance of Buildings Directive (EPBD). The standard includes consideration of other aspects of the environment such as indoor air quality, lighting and acoustics effects on the energy use of a building. The major thrust of the standard is the definition of the thermal environment, the sections on other factors confining themselves largely to references to other standards (Nicol and Wilson, 2011). The standard follows the general lines of the ASHRAE standard having, as well as a consideration of mechanically ventilated buildings that use PMV, an adaptive standard to be used for assessing buildings in the free-running mode.

According to BSEN15251 (BSI, 2008), the Category I provides comfort for ‘high level of expectation and is applicable for spaces occupied by very sensitive and fragile persons with special requirements’ such as elderly occupants, disabled, sick and provides a temperature range of 4K. The Category II provides comfort for ‘normal level of expectation’. The Category III provides comfort for ‘an acceptable, moderate level of expectation and may be considered for existing buildings’ and provides a broader temperature range of 8K. The last category (Category IV) is not often used, which provides comfort for ‘values outside the criteria for the above categories and should only be accepted for a limited part of the year’ (Nicol and Wilson, 2011; Lomas and Giridharan, 2012; Olesen, 2012; Adekunle and Nikolopoulou, 2016).

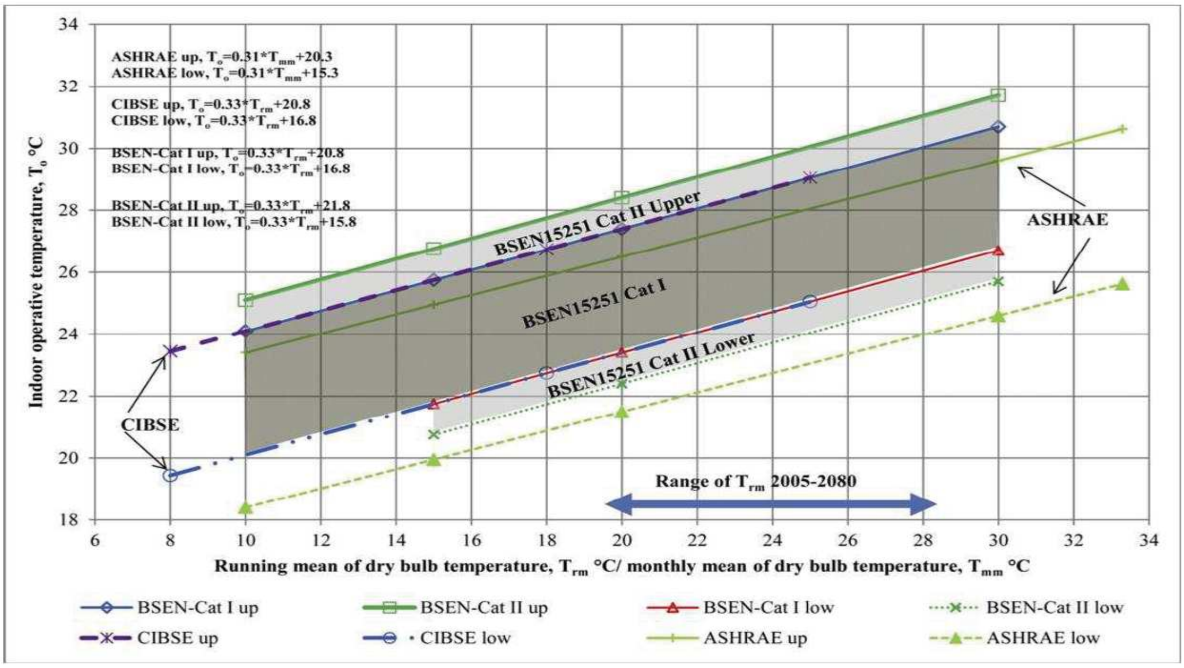


Figure 2.14: Adaptive thermal comfort standard’s comparison between different indicators (Lomas and Giridharan, 2012).

For the dynamic thermal comfort criteria, the Category II is employed, which provides comfort for ‘normal level of expectation and it is recommended to be used for new buildings and renovations’ with not more than 10% responses indicating dissatisfaction. The Category II applies for evaluating thermal comfort in non-residential and residential buildings and other similar buildings where rigorous tasks are not expected to be carried out and people can open or close windows and likely to adjust clothing insulation to meet the thermal conditions of their environment. The Category II applies to buildings that are not only naturally ventilated but also mechanically ventilated buildings. In summer, the buildings are likely to use unconditioned air with provision for individual means of regulating the indoor climate with use of night-time ventilation strategy, cooling fans and others that consume low energy and a major way of adjusting indoor thermal conditions will be through windows (opening and closing). The standard (BSEN15251) shows that the Cat. II applies to all spaces in free-running dwellings that are not occupied by the vulnerable people. The Category II provides a temperature range of 6K. The BSEN15251 standard provides no restriction on the acceptable limits of the category markers and 5% of hours over (warm discomfort) or lower (cold discomfort) the Category II limit will be considered as a benchmark in this study (Nicol and Wilson, 2011; Lomas and Giridharan, 2012; Olesen, 2012; Hashemi et al., 2015; Hashemi, 2016; Adekunle and Nikolopoulou, 2016).

Although EN15251 uses categories for buildings, they are defined by the nature of the building rather than referring directly to the quality of their indoor environment (Table 2.3). Mechanically conditioned and free-running buildings have the same category descriptions. Category II is recommended as the 'normal' criterion. The category descriptions in EN15251 (Figure 2.14), being according to the nature of the building are an attempt to overcome the tendency of the ISO 7730 classes to favour high-energy buildings.

The adaptive standard in EN15251 is like that in ASHRAE 55 but using data from the European SCATs (Smart Controls and Thermal Comfort) project that was collected from five European countries instead of the ASHRAE RP884 database. Although the SCATs database contains fewer sets of comfort data, they were all collected over the same period in the same manner and using a standard set of instruments. The graphical form of the adaptive standard is shown in Figure 2.14. EN15251 defines acceptable values of the indoor operative temperature according to their derivation from the comfort temperature by the equation:

$$T_{comf} = 0.33T_{rm} + 18.8 \qquad (2.22)$$

The comfort temperature is defined according to an exponentially weighted running mean of the outdoor temperature (T_{rm}) with the value of α of 0.8 (this is described further in this chapter) as this best describes the way in which comfort temperature changes with time (Nicol and Humphreys, 2012). The band of acceptable temperature around the comfort temperature is shown in the last column in Table 2.4.

Table 2.4: Category description and limits for mechanically conditioned (PMV) and free-running (K) building in EN15251 (after Tables 1 and A1 in EN15251)

Class/ category	Description	Limitation PMV	Limitation K
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements such as those with a disability, sick, very young children and elderly persons	± 0.2	± 2
II	**Normal level of expectation and should be used for new buildings and renovations**	**± 0.5**	**± 3**
III	An acceptable, moderate level of expectation and may be used for existing buildings	± 0.7	± 4

Source: Nicol et al, (2012)

2.10.4 Deductions from international standards

This section will review the strengths and weaknesses of existing standards, changing circumstances associated with climate change and fossil fuel depletion and how they affect approaches to the standards in the future.

2.10.4.1 Categories.

The introduction of building categories is recent. Olsen (2010) defends their use as follows:

‘The main idea behind the categories is to use them in designing buildings and HVAC systems when evaluating the yearly performance of buildings regarding the indoor environment.’ He noted that various categories may influence the size and dimensioning of HVAC systems, but not necessarily the energy consumption, which is regulated through building codes and energy certification (Figure 2.14).

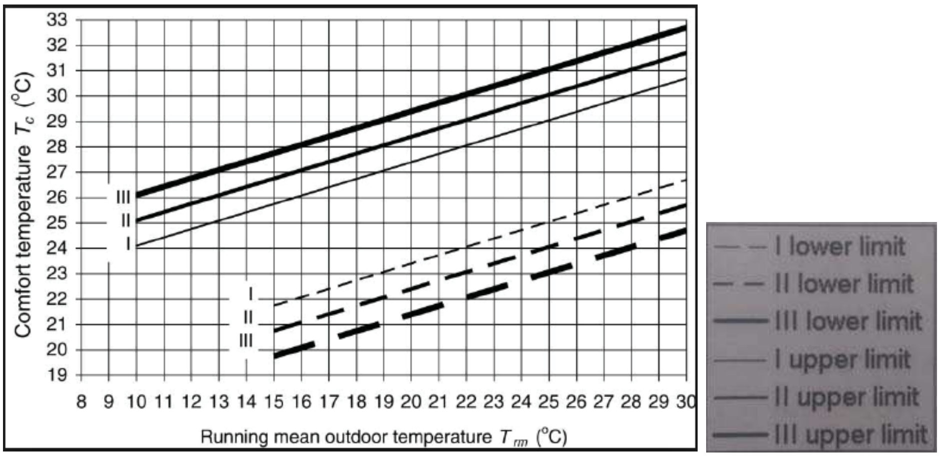


Figure 2.15: Acceptable operative temperature ranges for free-running naturally conditioned spaces (after standard EN15251). Source: Nicol et al., (2012)

There is an underlying assumption here that all buildings will have a mechanical climate conditioning system. A principal argument against the category system is that it discourages the design and construction of the building without mechanical conditioning. This is because without mechanical control, the indoor climate is unlikely to meet the more rigorous criteria for categories A or B (as seen in section 2.10.1) and hence in practice such buildings will be labelled inferior. Nicol et al. (2012) suggested that, it is the high-tech modern Class A buildings that can be less comfortable over a year compared to low-tech naturally ventilated alternatives in various climates. This is illustrated in overheating recorded in many modern schools designed with Class I/II standards. However, this problem was not experienced in Victorian schools in the warmer temperatures of recent decades (Telia et al., 2017).

2.10.4.2 **Local comfort criteria**

In addition to PMV, ISO 773 incorporates several local thermal comfort criteria that relate to discomfort problems as, for example, the Draught Risk (Table 2.5). For example, discomfort caused by localised air movement, possibly from an air diffuser in the air conditioning system. It addresses the real problem in mechanically conditioned buildings where complaints of draught are common. Draughts were a problem that was assumed to apply generally, but the assumption that air movement is a problem is based on a limited perception of the role of the air movement in the environment. However, in one study, most people when asked said they would prefer more air movement (Zhang et al., 2010) and the Draught Risk has been found not to correlate with discomfort in the field studies. It can be said ‘one person’s drought is another person’s cooling breeze’ (Nicol et al., 2012).

Because most of the experiments underlying the ‘rational approach’ to comfort were conducted in climate chambers in the developed world, culturally biased assumptions can creep in unnoticed and are then difficult to dislodge. The idea that people could be comfortable at an indoor temperature of 30°C or higher, as is implied by the adaptive lines of ASHRAE 55 or EN 15251, was just not considered a serious possibility, despite evidence from field studies in warm climates showing that people are indeed comfortable at these temperatures (Adebamowo, 2007; Dili, 2010). A problem for us all, as noted by Nicol et al. (2012), is that people do not know their own limits until they are crossed. International standards should be set by people with wide knowledge and experience of indoor temperature ranges common in climates around the world, not just those common in northern Europe or North America should their experience be confined to buildings that are air conditioned.

International Standards Agencies have been addressing the cultural biases by including many local styles of dress in ISO 9920 (2009). Comfort is a climate and culture specific phenomenon and different nations are indeed developing their own unique comfort standards. Japan, China and Malaysia apply different approaches to energy savings and comfort standards developed to meet the social, cultural and economic realities of their local markets.

2.10.4.3 **Mechanically cooled buildings**

The three international comfort standards use the PMV index to define acceptable internal environments. The PMV index combines the effect of four environmental (air temperature, radiant temperature, humidity, and air movement) and two personal (metabolic rate and clothing insulation) variables and this makes it difficult to use, because the specification of the required value of any one variable will entail the specification of the other five. The introduction of building categories has added another level of difficulty.

ISO 7730 and EN15251 both give examples of indoor temperature that will be suitable in each set of circumstances. For instance, in EN15251, it gives the design minimum indoor temperature in offices for winter (clothing insulation 1.0 clo) and maximum indoor temperature for summer (0.5 clo). Both assume a metabolic rate of 1.2 met. There are presumably assumptions about air movement rate (or still air) and relative humidity (50 per cent). And ‘temperature’ could mean the operative temperature or perhaps it is assumed that the air temperature is equal to the radiant temperature. The design temperature table shown in table 2.3 and the ranges for the categories in incorporates all hidden assumptions.

Nicol et al. (2012) noted that the advantage of such tables being included in standards is that they help the reader to judge the implications of the recommendations. The problem is that the examples can become, in effect, the accepted norm as the design temperatures. The theoretical superiority of an index that includes all the environmental and personal variables is lost because of the numerous assumptions that are made to reduce it to a room temperature.

2.10.4.4 **Naturally conditioned buildings**

The adaptive standards in ASHRAE 55 and EN15251 are derived from different databases. The ASHRAE standard used data from several countries and was compiled from 30 different building surveys conducted by different research teams using different instruments. The CEN standard used data from a single coordinated group of surveys in five European countries using a uniform experimental procedure and uniform instrumentation. In addition, different methods of analysis were used (de Dear and Brager. 2002; Nicol and Humphreys. 2010). Nevertheless, the two adaptive standards have almost the same comfort equation and a similar range of acceptable temperatures. It also reveals all equations predict similar neutral operative temperatures for hot–humid climate (Toe and Kubotaa, 2013). Currently, both the ASHRAE and EN15251 adaptive standards provide symmetrical limits of ±2.4C away from the comfort temperature for various categories of occupant accept ability or buildings (ASHRAE, 2010; BSI, 2008).

The difference in the mean outdoor temperature calculation method used in the two different standards is probably less important than it might seem. In the ASHRAE standard the outdoor temperature is expressed as the prevailing mean outdoor temperature, as previously explained, although it allows for running mean. While in the CEN standard the equation uses the exponentially weighted running mean temperature.

Nicol et al., (2012) noted two main deductions when using ASHRAE 55, ISO 7730 or EN15251, with respect to the prevailing mean and the exponentially weighted mean. Firstly, if one is to estimate a sensible temperature to aim for in each climate, the historical monthly mean is an appropriate choice. It is used to suggest climate – appropriate and comfortable indoor temperatures and to indicate the extent of the design challenges in achieving them in different climates.

Secondly, if however, the aim is to use building simulation to predict the indoor temperature and compare them with the limits in the standard, then the running mean is more useful. A criticism of the exponentially weighted mean is that people will be unfamiliar with it. However, the running mean is quite simple to explain and is easy to use. CIBSE has decided to include the exponentially weighted running mean in its standard range of weather data for simulations.

2.10.5 Overheating criteria in buildings

Overheating in buildings is considered as one of the major reasons causing occupants' discomfort and dissatisfaction in the thermal environment and avoiding overheating has been the motive for a considerable number of research projects (Lomas and Giridharan, 2012; Zhang et al., 2015; Adekunle and Nikolopoulou, 2016; Lomas and Porritt, 2017). ‘Overheating within a dwelling occurs when the actual indoor temperature for any given day is hot enough to make most people feel uncomfortable’ according to CIBSE (2010). Various indicators have been used for assessing overheating in dwellings. According to CIBSE (2006), for overheating not to occur within a dwelling, the temperature threshold (26°C for bedroom and 28°C for living room) should not be exceeded for more than a reasonable duration of hours (5% for the living room /1% for the bedroom) throughout the year.

In temperate climates like the UK, there has been a growing concern regarding the increase in summer period temperatures in dwellings (CIBSE, 2010; DCLG, 2012a), even as the climate is moderately warm, which is expected to occur regularly as global temperatures increase. Recent research has highlighted the problem with increasing summertime temperatures on the occupants’ comfort in the UK (Gupta and Gregg, 2013; Lomas and Kane, 2013; Adekunle and Nikolopoulou, 2014), as dwellings are built to meet improved regulations. As a result, they tend to be more likely to overheat and are more sensitive to potential summertime overheating than older houses (Gupta and Gregg, 2012, 2013). Similar issues have been identified in highly insulated passive houses in Europe (Mlakar and Strancar, 2010), where occupants are likely to experience high temperatures when such buildings are in a climatic region with hot summertime. Thermal mass is considered an important parameter to improve summertime thermal comfort (Holmes and Hacker, 2008) as it determines the capability of building fabrics to minimise temperature swing within indoor environments (Kendrick et al., 2012). This has led to increasing concerns about lightweight buildings, which potentially cannot cope with increased summertime temperatures and can lead to overheating. It can also be experienced when the indoor temperature is exceeded long enough to make occupants feel unacceptably uncomfortable, linking overheating to one of the major reasons for occupants’ discomfort and dissatisfaction in buildings (Adekunle and Nikolopoulou, 2016).

Indoor temperature ranges of 25°C-28°C during the summer can result in an increasing number of occupants feeling hot and uncomfortable, while most of the occupants will feel increasingly dissatisfied and uncomfortable when the indoor temperatures stay at or above 25°C for long hours in a day. The duration of hours at which the temperatures stay at or above 25°C should not be exceeded for more than 5% of the total occupied hours per year (usually 125 hrs). For bedrooms, lower temperatures are better, as thermal comfort and quality of sleep decrease with temperatures increasing over 24°C or exceed 26°C with ceiling fans (CIBSE, 2006). These static criteria have been used extensively to evaluate the overheating risk in dwellings (Wright et al., 2003; Firth, 2008; Lomas and Kane, 2010; Beizaee et al., 2013; Eppel and Lomas, 1992; Peacock, 2010; Adekunle and Nikolopoulou, 2014; Adekunle and Nikolopoulou, 2016). As people can adapt to changing temperatures, the adaptive comfort model is used for free-running buildings. In the UK, most of the dwellings are considered free-running in the summer, i.e. not mechanically heated or cooled. In that case, comfort temperature is considered to drift with the outdoor temperature, rising at about 0.33 K per K rate as the moving average of the outdoor temperature (T_{rm}) rises within the limit $10 < T_{rm} < 30°C$ (BSEN 15251, 2008). The BSEN 15251 (2008) specifies various categories of comfort, depending on the temperature limits defining thermal comfort.

However, Nicol et al. (2009) raised some concerns about the definition, suggesting that the definition of overheating is flawed for several reasons:

- They noted that although overheating can occur in mechanically cooled buildings, the solution to the problem there is managerial rather than environmental. The greatest danger of overheating is in buildings in the free-running mode whose poor design has meant higher temperatures. For free-running buildings, temperature limits are adaptive, and a single temperature limit will give a poor estimate of the overheating danger.
- An ‘hours over’ criterion can define the frequency of overheating but not the severity: 8 hours over the limit by 1K may be more uncomfortable than 4 hours by 3K. Overheating is a function of time and severity. Excess heat affects the health and wellbeing of occupants, especially if sleep is degraded. In an extremely difficult situation, the heat stress caused can lead to premature mortality, especially amongst more vulnerable members of society (Lomas and Porritt, 2017).
- The ‘hours over’ criterion and any criterion that has a sharp threshold temperature will be sensitive to the nature of the assessment method for the internal temperatures. Systematic errors in calculation methods can lead to changes in the shape of the distribution of indoor temperatures that can significantly affect the extreme ‘tail’, which is the critical part of the distribution for discomfort.
- Even if the likelihood of discomfort is a good measure of overheating, the perception that a building overheats may be subtler and include other factors such as room size, the effectiveness of the ventilation, the number of occupants and so on. Careful and perceptive research is needed from which a definition of overheating can be developed.

Future standards will need to provide a definition of overheating which, while not complete, will at least overcome the shortcomings of the ‘hours over’ model. Nicol and Humphreys, (2007) have shown that the likelihood of discomfort in European free-running buildings is a function of the difference of the actual indoor temperature and the comfort temperature as defined in equation 2.22.

2.11 Thermal comfort studies in tropical regions

There have been many thermal comfort studies carried out in hot humid climates with most results showing a wide range of temperatures at which people feel comfortable (comfort or neutral temperature) measured in air-conditioned (AC) and naturally ventilated (NV) buildings, see table 2.5. The studies also showed that neutral temperatures of naturally ventilated buildings were higher compared to the recorded temperatures in air-conditioned buildings. Buildings in hot humid climates develop thermal discomfort conditions because of their location. Feasibly, air-conditioning is often used to improve indoor comfort and reduce internal temperatures, but then again this is a process that requires energy and money, resources which most people in developing countries cannot afford (Zain et al., 2007) and if this problem is not taken care of it often leads to serious indoor environmental conditions like heat stress, lack of comfort and poor indoor air quality which are highly linked with low-income family units in developed and developing countries (Santamouris et al., 2007).

This is crucial for health and efficiency for the people in the building. Researchers have used indoor thermal measurements such as EN ISO 7730 and the ASHRAE standard 55 to determine indoor thermal comfort and expression of satisfaction with the thermal environment. The results and analyses from these experiments have created thermal comfort templates, definitions and standards which are used in temperate regions; after all it was developed to serve the temperate climate. According to Ealiwa, (1999) he noted that these standards tend to fall short of meeting the extreme climatic conditions of the tropics and are often challenged by researchers. The comfort standards based on climate chambers tend to overlook how vital the interaction is between the occupants and their environments in achieving thermal comfort (Ealiwa, 1999; Djongyang, et al. 2010; Akande and Adebamowo, 2010; Halawa and van Hoof, 2012).

Table 2.5: Neutral temperature results from field experiments conducted in hot-humid climates

Year	**Researcher**	**Building**	**Location**	**Neutral temperature of subjects**	
				AC	**NV**
1990	J.F Busch	Office	Bangkok, Thailand	24.5°C (ET)	28.5°C (ET)
1991	R.J. de Dear, K.G. Leow *et al.*	Residential and office	Singapore	24.2°C	28.5°C
1994	R.J. de Dear, M.E. Fountain	AC Office	Townsville, Australia	24.2°C	24.6°C
1998	T.H. Karyono	Office	Jakarta, Indonesia	26.7°C	-
1998	W.T. Chan *et al.*	Office	Hong Kong	23.5°C	-
1998	A.G. Kwok	Classroom	Hawaii, USA	26.8°C	27.4°C
2003	N.H. Wong *et al.*	Classroom	Singapore	-	28.8°C

E.T. (Effective Temperature), N.V. (Naturally Ventilated), A.C. (Air-conditioned). Source: Hwang et al. (2006) in Akande and Adebamowo, (2010)

2.12 Thermal comfort studies in Nigeria

Studies in Nigeria have reported neutral temperatures above 26.0°C as seen in Ogbonna and Harris (2007), and a study carried out on naturally ventilated buildings in Jos, Nigeria, a neutral temperature of 25.1°C was reported. A study in a naturally ventilated building in Lagos, Nigeria by Adebamowo (2007) reported a neutral temperature of 29.1°C. In Akande and Adebamowo (2010), a study on naturally ventilated residential buildings in Bauchi, Nigeria, reported a neutral temperature of 28.4°C. In Adebamowo and Adeniyi (2013) a survey was conducted in naturally ventilated buildings in three areas in Lagos, namely Festac town, V.G.C. and University of Lagos (four-bedroom terraced housing) showed an effective temperature of 27.1°C, 27.6°C and 26.8°C respectively. In Efeoma and Uduku (2016), they reported a neutral temperature above 28°C in a study carried out in an office building in Enugu Nigeria (Table 2.6).

The neutral temperature range of 28 – 30°C reported in Efeoma and Uduku (2016) is outside the comfort range of the results of Ojosu et al. (1988), which predicted a PMV comfort range of 21–26°C for the climate zone. However, it is more consistent with some more recent studies, such as those of Akande and Adebamowo (2010) in the hot dry region, northern Nigerian city of Bauchi which is 28.4°C. The neutral temperature is also slightly closer to the 29.1°C obtained by Adebamowo (2007) in the southern city of Lagos in the warm humid climate zone. Also, it is not within the 90% comfort range of the study of Ogbonna and Harris (2008), which was carried out in the city of Jos in the temperate dry zone; the reported neutral temperature is slightly higher than the 26.7°C. Taking into consideration the characteristic of the hot humid climate zone where this study was carried out in comparison with the temperate dry zone where Ogbonna and Harris carried out their studies, there is a clear indication that there is little disparity (about 2°C) in the thermal neutralities obtained.

Table 2.6: Summary of thermal comfort research in Nigeria with reported neutral and acceptable comfort range

Year	researcher	Location (Climatic zone)	Building	Period (season)	Key findings
2016	Efeoma and Uduku	Enugu (Hot Humid)	Office (A.C.)		1. Neutral temp. = 28°C
2012	Adunola A. O.	Ibadan (Hot Humid)	Residential (N.V.)	April	1. Regression equation: $Y = 0.483*X - 15.59$(TSENS with respect to TOP*) 2. Neutral temp. = 32.3°C TOP*
2010	Akande & Adebamowo	Bauchi (Hot Dry)	Residential (N.V.)	Rainy and Dry Season	1. Regression equation: $Y = 0.357*X - 10.2$ (Dry Season) 2. Regression equation: $Y = 0.618*X - 15.4$ (Rainy Season) 3. Combined neutral temp. = 28.4°C TOP* 4. Acceptable comfort range = 25.5 – 29.5°C TOP*
2008	Ogbonna & Harris	Jos (Temperate Dry)	Residential	July & August (Rainy Season)	1. Regression equation: $Y = 0.3589*X - 9.4285$

Year	researcher	Location (Climatic zone)	Building	Period (season)	Key findings
			(N.V.)		2. Neutral temp. = 26.270C TOP* 3. Acceptable comfort range = 25.5 – 29.50C TOP* (-0.5 ≤ TSENS ≤ +0.5) 4. PMV neutral temp. = 25.06°C
2007	Adebamowo	Lagos (Warm Humid)	Residential (N.V.)		1. Neutral temp. = 29.09°C
1988	Ojosu et al	Hot Dry Temperate Dry Hot Humid Warm Humid			1. Acceptable comfort zone = 21 – 26°C 2. Acceptable comfort zone = 18 – 24°C 3. Acceptable comfort zone = 21 – 26°C 4. Acceptable comfort zone = 21 – 26°C
1955	Ambler H. R.	Port Harcourt (Warm Humid)	Office (A.C.)		Office 1. Neutral temp. = 23.13°C ET*

Note: ET* (Effective Temperature), TOP* (Operative Temperature), TSENS (Thermal Sensation Vote). N.V. (Naturally Ventilated), A.C. (Air-conditioned)

The neutral temperature range reported in Ojosu et al. (1988), predicted a PMV comfort range of 21–26°C for the hot dry, hot humid and warm humid climates zones in Nigeria. However, it is more consistent with some more recent studies, such as those of Akande and Adebamowo (2010) in the hot dry region, northern Nigerian city of Bauchi that was 28.4°C. The neutral temperature is also slightly closer to the 29.1°C obtained by Adebamowo (2007) in the southern city of Lagos in the warm humid climate zone. In addition, it is not within the 90% comfort range of the study of Ogbonna and Harris (2008), which was carried out in the city of Jos in the temperate dry zone; the reported neutral temperature is slightly higher than the 26.7°C (Ogbonna and Harris, 2008).

Apart from the study locations in different climate zones in Nigeria, other factors that might account for the disparity in thermal neutrality with some of the selected previous works done in Nigeria might be time and duration of study, methodology used or accuracy of reading of equipment used. For example, the result obtained from work carried out in another hot humid climate zone of Ibadan by Adunola (2012), yielded a thermal neutrality of 32.3°C.

These studies show that neutral temperatures can exceed the higher range of comfort temperature of 26.0°C as prescribed by Fountain et al. (1999) and the ISO EN 7730 (1994) standard. Although the studies have proved to be important, their findings have yet to be widely recognized (Adebamowo, 2007). Because of previous research suggestions, the wider range of comfort conditions in reality is where occupants have the sensation of feeling comfortable. Also, their environment is affected by several factors like physiological adaptations (experiences, acclimatisation), psychological adaptations (expectations) and behavioural adjustment (modifications made by a person consciously or unconsciously) which could contribute to occupants adapting to changes (Adebamowo, 2007; Peeters et al., 2009).

Regarding human thermal comfort, there has been much documented material worldwide from physiological and adaptive studies but throughout sub-Saharan Africa especially the tropic regions, there have been few literature reports on the comfort of occupants and the residential thermal environment. The tropical climates may require a different level of comfort standard, besides the current standards are almost all based on experiments and studies across a variety of climatic zones including temperate, hot-humid, and cold regions (Djongyang et al., 2010).

2.13 Passive cooling

Passive cooling as described by Givoni (2011) is a process that does not use energy for operation i.e. indoor cooling and minimizing internal heat gain. Givoni spoke about considering the elements of proper architectural and urban design responsive to climate as a way of treating the building by aiming to improve comfort in hot periods even if the building is not mechanically conditioned or by reducing the equipment size and an air-conditioned building’s energy consumption. In this interpretation, passive cooling enhances heat loss from buildings. The several types of passive cooling and passive cooling research applications will be discussed in this section.

2.13.1 Types of passive cooling

According to (Givoni, 1998, 2011; Sahoo and Sahoo, 2010; Muselli, 2010), several cooling techniques available are:

i. **Natural ventilation:** this technique enhances comfort that lowers indoor temperature when the outdoor temperature is less than the indoor temperature (based on the use of ambient air). This is achieved through free-flowing daytime air ventilation by the movement of outdoor air through a building’s openings, effective cross or single sided ventilation or using a stack.

ii. **Nocturnal ventilative cooling:** this involves reducing the indoor temperature at night, by ventilating outdoor air into building interiors. The thermal mass of the building is cooled when ventilated at night from inside. By the thermal resistance of the building envelope is bypassed and during the day the cooled mass serves as a heat sink.

iii. **Radiant cooling:** heat may be lost from external surfaces (especially roof tops) to the sky, by emitting long wave radiation towards the sky. Radiant heat loss takes place during day and night although the radiant balance is negative only at night. Radiative cooling processes the sky as a heat sink.

iv. **Evaporative cooling:** cooling is achieved by arranging for water to evaporate into ventilation air. Although this process requires energy, the latent heat of vaporisation of air, and this is taken from the water and the air – thus cooling it and the indoor temperature.

v. **Indirect evaporative cooling:** water is evaporated into air not in contact with the internal air and so it does not raise the internal air's absolute humidity. In practice, this can be done using a roof pond, or through using ducting.

vi. **Earth cooling:** the temperature of the ground is used as a heat sink to reduce the indoor temperature of buildings.

2.13.2 Passive cooling research and application

There has been extensive research on passive cooling by applying methods and techniques from traditional buildings (Singh et al., 2009; Singh et al., 2010; Edward and Kurian, 2008; Indraganti, 2010; Dili et al., 2009; Dili et al., 2010). In Dili et al. (2011), research comparing traditional and modern buildings in Kerala, India, showed that the minimum temperature recorded in the bedrooms of the two types of building was the same, but the maximum temperature of the modern-day building was higher by 2.5°C. They also observed that the internal environmental conditions were more stable and comfortable than those of the modern-day building. These residential buildings need cooling and with the power, economic crisis and high-energy cost, the only option remaining is the adoption of low-cost passive cooling techniques. Research in passive cooling techniques is given in Givoni (1991) who presents some of the known techniques for passive cooling, insulated roofs and walls (Asan, 2008; Kumar et al., 1989 and Shariah et al., 1997). In Sodha et al. (1978, 1986), roof ponds were considered as a passive cooling strategy while earth-air tunnel was considered in (Mihalakakou et al., 1995) and ventilation (Hamdy and Firky, 1998).

Several studies have been carried out regarding the cooling potential of the application of reflective coatings on buildings. Bansal et al. (1992) studied the effect of external surface colour on the thermal behaviour of a building. White coloured coatings performed better than aluminium-pigmented coatings. Although several types of coatings may be characterized by a high solar reflectance, aluminium-pigmented coatings are less desirable because they tend to remain hotter due to their low infrared emissivity. The differences in the thermal behaviour even among coatings of the same type and colour, are due mainly to the differences in their spectral reflectance which mainly affects their performance during the day and their emissivity that is the predominant factor affecting the thermal performance of the various coatings during the night. Passive cooling can also be achieved by roof albedo modifications with simple white coatings (Berdahl, 1995; Akbari et al., 1997; Simpson and McPherson, 1997) or with silver colours (McPherson, 1997). This allows air-conditioning energy savings to be made such as in Arizona (Simpson and McPherson, 1997) where white roof coatings (0.9 albedo, 0.98 emissivity) led to a reduction in daily total air-conditioning energy and peak hourly demand for houses by 28 and 18% respectively, compared to a dark brown roofing.

In Florida, Parker and Barkaszi (1997) have examined the impact of whitened reflective roof coatings on air-conditioning energy use in a series of tests on occupied homes. Measured air conditioner electrical savings in the buildings averaged 19%, ranging from a low of 2% to a high of 43%. In California, Akbari et al. (2005) monitored six buildings to determine energy savings using reflective roof coatings. The results show that on three potential sites (Sacramento, San Marcos and Reedley), the estimated savings in average air-conditioning energy use could reach 81 Wh/m^2/day. Thus, according to climate zones, installing a cool roof can save about 4.5–7.4 kWh/m^2/year of conditioned roof area. Other research developed software to simulate the thermal behaviour of buildings using reflective coatings on their fabric under different climates in Iran (Hatamipour et al., 2007), Brazil (Olivera et al., 2009), and Australia (Suehrcke et al., 2008). The authors showed efficient light and heat reflective coating technology allowed a decrease by up to 90% in the air-conditioning cooling energy. It should be noted that the effectiveness of reflective roof coatings will depend on the roof construction and in particular thermal conductance.

Santamouris et al. (2007) have focused on improving passive cooling techniques like cool reflective coatings to enhance outdoor and indoor conditions of low-income households in warm areas of the planet. They also examined ground cooling using earth to air heat exchangers and the potential for new ventilation techniques and systems for improving indoor comfort and air quality. Uemoto et al. (2010) presented the thermal performance of cool coloured (white) paints on surface temperature materials concluding that these new substrates enhance thermal comfort inside buildings.

Research carried out in Athens on 1100 households showed that low-income people tend to live in older buildings. The mean age of the houses of the lower income group was 29 years while for the richest group it was 19 years. In parallel, a very clear connection is found between the income level and the quality of the envelope. Only 28% of people in the low-income group lived in insulated buildings, while the corresponding figure for the high-income group is close to 70%. In parallel, it is found that the higher the income the higher the percentage of buildings with double glazing. For the poorest group, the percentage of double glazed buildings was 24% while for the richest group the corresponding figure was 67%. Finally, insulated buildings with double glazing were quite rare for the lower income groups (8%), but this increased to 60% for the high-income group (Santamouris, 2006b).

A design strategy that is widely accepted for passive cooling is to follow the three main steps: Prevention of heat gains, modulation of heat gains and heat dissipation. Important research has been carried out in the field of passive cooling of buildings and existing experience has shown that passive cooling can provide excellent thermal comfort and indoor air quality, together with low energy consumption. New materials, systems and techniques have been developed, applied and are now commercially available (Michelozzi et al., 2005).

Santamouris et al. (2007) stated that it has become clear that it is appropriate to implement alternative means to conventional air conditioning to improve indoor thermal conditions of low-income households. The intention is not to keep temperatures within the ASHRAE comfort zone of 20°C - 27°C by using systems driven by energy but to create buildings that would not put the lives of occupants in danger under ambient conditions even when there is power outage or if inhabitants cannot afford to pay for it (Santamouris et al., 2007).

From the literature review, most of the passive strategies presented might not work or would be ineffective in sub-Saharan countries like Nigeria because of the hot-humid climate. Moreover, the technicality involved, the non-availability of materials and equipment, the lack of technical manpower and maintenance skills, expense of installation and difficulty of maintenance might be a serious challenge. Nonetheless, by adopting Santamouris (2007) suggestion of applying passive means that are affordable, in areas where there is power outage, where they are easy to install and maintain, passive cooling approaches can work and even create an enable sustainable environment in the location of application.

2.14 Conclusions

The public housing programmes have generally failed to deliver well-constructed and well performing houses and the reasons for this appear to be legion: that lack of financial caution, public justice and accountability, inefficient and ineffective administrative machinery, mass importation of foreign technology, material, personnel and inflation. These housing programmes were initiated with modern construction methods to provide affordable housing and solve the housing deficiencies in the country. Unfortunately, they have all almost invariably failed due to lack of proper planning, implementation and corruption. In addition, there is a lack of a sustainable approach and building environmental performance agenda in these housing programmes and policies. Hence, the traditional architecture of Nigeria has been neglected and pushed aside, and the western architecture, materials, construction style and technology embraced. This has disrupted the natural development of traditional architecture, which was adapted to the Nigerian climate and replaced with incongruous housing forms imported from temperate climates.

Field surveys have been used to develop empirical, statistically based indices of thermal comfort to understand and improve indoor conditions in buildings. Such indices share the objective of the theoretical heat balance indices to estimate the conditions which people find comfortable. However, they suffer the limitation that they apply only to the conditions and context of the field survey on which they were based, and it is difficult to accurately extrapolate those results to fit the conditions that exist in another location and site.

This review revealed that occupants' responses in terms of thermal discomfort are subjective while responses regarding thermal sensation are objective and noted that thermal comfort of occupants is influenced by environmental, subjective and objective factors. It explained that preference for higher air movement is influenced by occupants' feeling of warmth. The chapter also discussed the effect of age, gender and level of control on how occupants perceived and rate satisfaction within the thermal environment. The literature mentioned that the occupants' rating regarding satisfaction declined when they perceive they have low or no level of control to regulate their thermal environments. This suggests that the occupants who are likely to be thermally satisfied perceive they have a high level of control to adjust the thermal environment.

Recent studies that have investigated overheating in buildings, especially in dwellings, were also discussed. From different definitions gathered from various studies, overheating is a condition when most of the occupants feel uncomfortable within the thermal environment. This period was considered in terms of percentage of total hours occupied by occupants. Major thermal comfort indicators that were used to assess overheating risk in dwellings were discussed. The static CIBSE criteria and the EN 15251 dynamic adaptive comfort model have been widely used in the studies reviewed and were used as indicators for assessing the overheating risk at the case studies investigated. This will be discussed in Chapters 5 and 6.

Naturally ventilated buildings, which occupy an overwhelming proportion of the current building stock in Nigeria, require a thermal comfort guide for design. Currently there is none in the Nigerian building code (NBC, 2006) nor any that prescribe the environmental performance of building standards for Nigeria during the dry and rainy seasons for residential buildings. There is a need for a comfort model for naturally ventilated buildings in the various seasons in Nigeria though this model should be extended to Air-conditioned buildings

The next chapter introduces the measurements carried out in Abuja to understand the real conditions experienced by occupants in this hot and humid dry region of Nigeria.

CHAPTER 3

Survey and Monitoring protocol

CHAPTER 3: Survey and Monitoring protocol

This chapter discusses the survey and monitoring protocol used for this study. These sets of goals were pursued through the field studies: first, the study tried to obtain a comprehensive understanding of occupants' thermal comfort sensation within buildings through thermal comfort surveys; secondly, the environmental performance of existing buildings around the selected case studies for monitoring and occupant's energy demand and use in the hot-humid climate of Abuja was acquired through post occupancy survey and environmental monitoring; thirdly, dynamic building simulation was used to predict the effect of design interventions on energy and comfort.

3.1 Data Collection Procedure and Strategy

This section will discuss the ethical clearance, subjective questionnaires' (post-occupancy and comfort survey) development, subjective questionnaires' testing and target population and sampling.

3.1.1 Ethical clearance

A participant's information sheet, consent form, post-occupancy survey, comfort survey and cover letter for questionnaires were approved to be in accordance with the guidelines set by the University of Kent Ethics committee. The approved documents were presented to participants of the study and the survey was explained in detail to them. Each component of the data collection process received appropriate ethical clearance prior to commencement.

3.1.2 Subjective questionnaire test sampling and equipment calibration

A pilot survey, divided into two parts, was carried out. The first part dealt with pilot post-occupancy and comfort survey questionnaire distribution, review and was implemented with two objectives: (1) assessing the understanding level of the surveyed volunteers concerning survey questions, (2) estimating the average duration for each survey. The second part looked at using the environmental monitoring equipment. This was implemented with two objectives: (1) to develop and improve the skills in handling of monitoring equipment, (2) to undertake test recordings and calibration of equipment.

3.1.3 Target population

All the selected buildings for this study, (i.e. for both the comfort and post-occupancy survey) have been defined primarily as all one-storey occupied residential buildings, a representation of the building type in the low-income/ low-middle income neighbourhood areas of Abuja. Although hotels and hospitality places are mostly residential, they were not included as part of the selected buildings for this study because the residents do not take any major decisions about thermal comfort and are mostly in transit.

3.1.4 Sample selection and sampling

A multi-stage area sampling technique was applied in the selection of the households in the survey. The house type census was conducted in two out of the five local government councils in Abuja and in the selected local councils, five neighbourhoods (Lugbe, Mpape, Dutse Alhaji, Kubwa and Bwari) were grouped into five case study locations, based on geographical affinity and socio-economic characteristics. The selection process is further discussed in Chapter 4. The two local government areas were selected because of their easy accessibility compared to the remaining three. These case study locations were selected for the post-occupancy survey and in each selected location, two dwellings were selected for monitoring, making it ten houses for the comfort survey and environmental monitoring in the five locations in Abuja. The selected post-occupancy locations were representative of the low-income/ low-middle income residential distribution in Abuja. Satellite maps from Google earth and Google maps pro, community meetings and site visits were used to identify areas, houses and streets within these locations.

This study was hindered by the limited availability of up to date addresses and street maps and therefore simple random sampling was adopted for this study. A disadvantage of this sampling method is the lack of availability of a current survey of the housing stock reflecting the profiles in the parameters under review.

In effect, a house type quota was set along with quotas for the different neighbourhoods based on the concentration of house types. This was the basis for the selection of the occupants and dwellings for the comfort and post-occupancy survey of the study. The survey methods adopted provide a direct and reliable method for understanding residential thermal comfort, adaptability, and thermal environment of residential buildings in a real-life context. Five basic tools were employed in the study; a comfort survey (daily diary questionnaires), a post-occupancy survey (general questionnaires), environmental monitoring, dynamic building simulation and observation checklists and interviews under an experimental plan discussed further in this chapter.

3.2 Post-occupancy survey

The post-occupancy survey (the general questionnaires) was designed to provide a general profile and representation of dwellings in Abuja. This helped to understand the thermal environment and perceived thermal comfort of occupants in the comfort survey dwellings during the dry and rainy seasons. These surveys were aimed at obtaining a comprehensive understanding of occupants' thermal comfort sensation within the buildings, building environmental performance and occupant's energy demands and use. The survey was conducted in the dwellings for methodological and practical reasons. Post-occupancy surveys also compare the nature and frequency of occupants' complaints that cannot be measured during surveys (Figure 3.2), especially why they feel warm or hot. That is why they are critical in improving the value of the thermal environment. This survey focused on dwellings other than the case study buildings but situated in the same area. They add breadth and support the results from the individual case studies.

3.2.1 Development of Post-occupancy questionnaire

The post-occupancy questionnaire (Appendix 4) had 32 questions, requiring 8-10 minutes to complete. The questions were aimed at probing the issues identified under technical and non-technical factors in domestic energy consumption. The list below indicates the survey issue areas for the post-occupancy questionnaire survey.

House types and neighbourhoods were used as criteria to select the dwellings for the sampling. Tables 3.1, Table 3.2 and Table 3.3 show the sampling strata (i.e., house types and neighbourhoods were identified by their proximity to the selected case studies for indoor monitoring, tenement status and length of stay). To achieve the post-occupancy survey objective, the sampling was spread across the different neighbourhoods in proportion to the recorded number of the different house types within the district around Abuja.

Table 3.1: House type

Single-Family Bungalow	Semi-detached Bungalow	Detached	Semi-detached building

Table 3.2: Rented or owned

Rented (tenancy)	Owner occupier

Table 3.3: Number years in the dwelling

Less than 1 year	1 – 3 years	4 – 5 years	More than 5years

House type: Questions about house type sought to elicit information about the house different house types and validate the census findings.

Household demographics: This included questions about the household size, gender compositions, age of members and characteristics of the householder, as well as household income category.

Space types and quantity: Space types and quantities were identified and associated with house types

Energy sources: Questions were asked about the household energy sources, the energy source choice motivators and alternative energy sources.

These questions in the questionnaire offered the prospect for the association of energy sources, household characteristic, appliance ownership and income with each other and with house types. See Appendix 4 for full description of the post-occupancy questionnaire.

3.2.2 Administration of Post-occupancy Questionnaire

Post-occupancy questionnaires were administered to the residents of the five case study locations (Lugbe, Mpape, Dutse Alhaji, Kubwa and Bwari) were considered for this investigation between March and June 2015 after permission to access their houses has been granted by the relevant head of the household and family members. Distribution of the questionnaires was based on the number of occupants in each household.

Distribution of the questionnaires was based on the number of occupants in each household. The information gathered during the preliminary studies of the case studies provided a good knowledge for distribution. In some cases where the numbers of occupants were not given, the numbers of rooms of the households were considered for distribution. For example, in Adekunle and Nikolopoulou (2014), two questionnaires were allocated to one-bed flat and in some instances; the two questionnaires were completed and returned by the occupants. The survey participants were young, adult and elderly occupants and fairly represented in terms of gender (male and female) and age (between 18 and 65) as they are not vulnerable to the thermal environment. In Limbachiya et al., (2012), the residents for their survey have been residing in the UK for not less than 5 years and have been living at the buildings for not less than 6 months to have acclimatised to the case studies and understand the thermal conditions of the internal spaces. These concepts used in Limbachiya et al., (2012) and Adekunle and Nikolopoulou (2014), were adopted for this survey in Abuja. However, this survey also included residents that have stayed in their building for more than five years in the case study location (Table 3.3).

The issues of concern of the survey as well as the nature of the study tools suggested that data be collected in the respondents' home. This allowed for direct observations of parameters and complemented questionnaire entries. Within the sample, the respective head of house, usually the husband or their spouse, who was directly involved with household energy decisions and expenditure were issued a questionnaire and interviewed. The primary language of the survey was English, although a very good knowledge of Pigeon English (Nigerian broken English), a local language, was necessary. This was to ensure that the head of the house or household members who did not speak English well enough were not denied participation in the survey. The permission of the head of the house was obtained prior to the thermal comfort surveys in which adolescents participated. Very often, the permission to interview adolescents in a household was obtained in the pre-survey visits where the dates and timing of the study were set.

One criterion for the selection of households for the thermal comfort study is that they had to have been selected and accepted to participate in the main thermal comfort survey. This enabled a direct association between the occupants' adaptation, indoor activities, household energy demand and use, thermal comfort and house type. Data was collected mostly through face-to-face meeting using questionnaires. The decision on the method of completion of the questionnaire was a major issue in the study; the options were `self-completion' or `interviewer completion'. The preferred option was interviewer completion to ensure the reliability of the selections. This option was however not always possible due to the varied work schedules of household heads and their requests for time to gather some of the information required. The major concern for the self-completion option was the quality of response expected from the householders with limited literacy. A compromise approach had the interviewer offer to assist the household head to complete the questionnaire at a date of their choice or review the questionnaire entries with them after self-completion.

Questions on overall thermal comfort and thermal satisfaction in different seasons were asked for respondents to evaluate. The questionnaire was divided into three main sections: Section 'A' looked at background information about their location, gender, age, socio-economic status, educational and occupancy status. Section 'B' focused on questions about building attributes and energy consumption including house type, number of rooms in the building and duration of occupancy. Section 'C' considered indoor thermal conditions, how residents made themselves comfortable (control votes) and clothing type (Appendix 4). Overall 273 questionnaires were distributed, 251 (91.9%) were returned and of these 222 (81.3%) were correctly completed. The survey visits were conducted between 6.30am and 18.00pm. The analysis of completed post-occupancy questionnaire will be discussed in Chapter 5. The completed questionnaire was returned and collected on-site. The occupants were asked to drop it at each case study representative's house or flat in sealed envelopes provided when it was distributed.

Figure 3.1: Post-occupancy survey

3.2.3 Collection of Post-occupancy Questionnaire

The completed questionnaire was returned and collected on-site. The occupants were asked to drop it at each case study representative's house or flat in sealed envelopes provided when it was distributed.

3.3 Comfort Surveys

The easiest method of evaluating indoor occupants' comfort is by using a subjective questionnaire along with environmental monitoring by comparing what occupants recorded in terms of their feeling of warmth or cold and measured environmental parameters particularly indoor air temperature (Darby and White, 2005; Adekunle and Nikolopoulou 2014). The comfort survey questionnaires were designed to provide micro-level daily activities data on thermal comfort adaptability of the respondents in the selected case studies for environmental monitoring. A comfort survey was carried out concurrently with the physical measurements to understand various environmental conditions which the indoor occupants find comfortable during the dry and rainy seasons. The comfort survey questionnaire used to collect data from the residents and administration of the questionnaire will be presented in the following sub-sections.

3.3.1 Development of Comfort Surveys' Questionnaire

Ten dwellings were selected for the comfort survey, which were also monitored simultaneously. They comprised five naturally ventilated and five air-conditioned buildings across five locations in Abuja. Thermal comfort questionnaires were issued to the occupants of the dwellings monitored and they were asked to complete the questionnaires three times a day to assess their thermal comfort state (using the seven-point ASHRAE thermal sensation scale and a five-point preference scale). Further information on clothing insulation and activity were also collected. The comfort survey was designed as a daily diary evaluating occupants' response to discomfort and how they achieve comfort at various times of the day (morning, afternoon and evening) for a week during the dry and raining season. These data were used to support the physical data collected at the same time.

Overall, it had 26 short questions requiring between 3 and 4 minutes to complete. The participants were asked to evaluate their feeling of warm or cold (thermal sensation, from 1- cold to 7-1 hot), how comfortable were they (thermal comfort, from 1- very uncomfortable to 7- very comfortable), how they would prefer to be (thermal preference, from 1- much cooler to 5- much warmer) (See Appendix 5). Their thermal acceptability along with several aspects of control used in the last 15-minutes or more to improve the thermal environment was also recorded, i.e. opening and closing windows or doors, using air-conditioning. A checklist of activities involved prior to filling in the questionnaire by the occupant in the last 15-minutes, from sedentary to active lifestyle was also noted. Also, questions included clothing insulation checklist in line with ASHRAE standard, clothing preference, drinks consumed (cold or hot) in the last 10 to 30-minutes, preference for higher air movement, daylighting, air humidity and overheating experience. In addition, basic background information about the age of participant, gender and space occupied were gathered. See Appendix 5 for full comfort questionnaire.

3.3.2 Administration of the Comfort Survey Questionnaire

The residents were asked to fill in the subjective questionnaire three times a day (morning, afternoon and evening) for a week between 05:30 and 23:00. They were encouraged to carry out activities for at least 30-minutes before they filled in the questionnaires at any time of the day. They were also asked not to fill in more than one questionnaires within a period less than 2 hours to allow the participants to adjust to a broader range of indoor environmental conditions. Overall, 196 comfort survey questionnaires were collected during the dry season surveys and 155 during the rainy season survey. Further analysis of the surveys is presented in Chapter 5.

3.3.3 Collection of the Comfort Survey Questionnaire

The completed comfort survey questionnaires were collected during the final day of the surveys when the data loggers were retrieved at the end of the week. The questionnaires were returned by the participants in the envelopes provided at the beginning of the survey. Some returned questionnaires were not completed during the survey and they were separated and not considered for further analysis. To ensure that the date and time were entered correctly during the voting period, all the questionnaires were checked, and codes were allocated using numbers and alphabets for easy identification during analysis and cross-checking with measured data. The statistical programme SPSS (Statistical Package for Social Sciences) was used for further analysis of the entered data from the returned questionnaire.

3.4 Environmental Monitoring

3.4.1 Indoor monitoring

Abuja has two main seasons: the dry (Hot) season and the rainy (cooler) season. The environmental monitoring was conducted during the dry and rainy seasons from 18/03/15 to 07/05/15 and 17/06/15 to 30/07/15 respectively. The ten dwellings selected in the comfort survey had their indoor environment recorded. The sensors were mounted on the internal walls to measure temperature experienced by the occupants. (Figure 3.3).

Figure 3.2: HOBO data loggers used for indoor environmental monitoring

Figure 3.3: Indoor monitoring during survey

3.4.2 Outdoor monitoring

The outdoor environmental conditions measured were air temperature and relative humidity using two Tiny Tag T/RH sensors inside a radiation shield while the total solar radiation on the horizontal was measured using a Kipp and Zonen pyranometer. The outdoor monitoring was conducted during the dry and rainy seasons from 11/03/15 to 07/05/15 and 10/06/15 to 30/07/15 respectively. The mean indoor environmental data on an hourly basis was considered for comparative analysis with the outdoor weather data and will be discussed in Chapter 5.

3.5 Dynamic building modelling and simulation

To investigate the thermal performance of the ten case study buildings and compare the different residential dwellings, the dynamic thermal simulation software tool, DesignBuilder version 4.7.0 was used. This was necessary due to the limited monitoring and was essential to ensure valid comparison and identification of overheating under similar conditions.

3.5.1 The simulation software

The dwelling simulation was carried out by means of the DesignBuilder programme, an application that has a user-friendly graphical interface that controls the underlying simulation engine, EnergyPlus. This programme was used to calculate the thermal performance of the selected case studies and give an understanding of the thermal comfort in the buildings. The software allows the dynamic evaluation of heating and cooling consumption all year-round and includes the complete EnergyPlus HVAC package.

3.5.2 The weather file

Weather files were uploaded to the software to allow the software to evaluate energy flow including solar gain. The Typical Meteorological Year (TMY3) weather data files for Abuja for the 2000s were generated by Weather Analytic for the simulations used in this software. Four out of the ten monitored dwellings selected during the comfort survey were simulated and modified with various passive interventions to determine the effects on the thermal conditions. The selected dwellings for the simulation comprised two naturally ventilated and air-conditioned building from two locations.

3.6 Interview with professionals

To get an insight into why housing is the way it is in Nigeria, an academic, a developer and an architect were interviewed to get their views. The constraints of the study did not allow for further investigation, but valid information was obtained.

3.7 Logging equipment

This section will discuss the logging equipment and installation, and calibration of the equipment in more details.

3.7.1 Installation of loggers and radiation shields

3.7.1.1 Data loggers

Outdoor air temperature and relative humidity were measured every 15 minutes using Tinytag Plus *2* T/RH data loggers (Figure 3.4). Tinytag Plus *2* loggers are designed for measuring temperature and humidity in a variety of harsh outdoor conditions. The loggers are housed in robust, waterproof casings, and deployed for outdoor environmental monitoring. The averages of the quarter hourly readings from each Tinytag logger were then taken to produce hourly data for each day. This hourly data was required for comparison with the simulation model and for comfort model calculations because the timing of temperatures is important in assessing the demand for cooling and overheating analysis. The total solar radiation on the horizontal was measured using a Kipp and Zonen CMP3 pyranometer (Figure 3.5). The instrument does not require any power and is ideal for remote sites with limited power availability or for field studies. It had an individual calibration factor of 20 $\mu V/W/m^2$ with a spectral range of 285 to 2800 nm. It was installed at a height where there was no building or structure to avoid overshadowing (Figure 3.5).

Figure 3.4: Tinytag and HOBO data loggers used for environmental monitoring

Indoor temperature and relative humidity were measured every 15 minutes using Hobo series UX100 003 data logger. The data logger is suitable for monitoring occupant comfort and logging temperatures in residential buildings. Loggers were placed at a height of 1.1m, not exposed to direct sunlight, heat or cooling sources and not placed close to any windows or doors. Two loggers were placed on the walls in the living room and bedroom in each dwelling and the data was logged every 15 minutes.

Figure 3.5: Installed Kipp and Zonen pyranometer for solar radiation measurement

3.7.1.2 **Radiation shield**

The long hours of sunny conditions can lead to outdoor temperatures reaching as high as 45°C (NiMet Abuja 2014) in Abuja during the dry season. There was therefore a need to minimise the effect of solar radiation on the air temperature and relative humidity measurements. The logger was enclosed in a radiation shield which also protected it from exposure to harsh weather elements like rain, wind and hail stones. The radiation shield and logger were positioned at a height of 1.5m above the ground. It was attached to specially manufactured wall brackets in Abuja, placed 500mm, from the outdoor wall. The radiation shield was welded to a spacing arm, wall bracket and plate for attachment to the wall (Figure 3.6 and 3.7).

Figure 3.6: Tinytag data logger's outdoor installation with radiation shield.

Figure 3.7: Installed Tiny Tag T/RH outdoor logger in radiation shield

3.7.2 Calibration of internal data loggers

The Hobo T/RH UX100-003 data loggers have a quoted accuracy of ±0.2°C with a resolution of 0.024°C. As it was considered that small temperature differences (less than half a degree) might be important, all the loggers were tested together to determine their individual differences. The loggers were placed in a closed filing cabinet, in cardboard box (see Figure 3.8) and left for 24 hours (From 12:00 on Friday 27.02.15 until 12:00 on Saturday 28.02.15). The data were then analysed. 'Hobo data logger 4' was selected as the reference logger as it was closest to the mean of all four loggers. The data showed that the mean values of the individual Hobo data loggers were within 0.1 to 0.2°C the mean for all data loggers. This was within the quoted accuracy of ±0.2°C. Both the minimum and maximum temperatures recorded across all the loggers were within 0.4°C of each other respectively (Table 3.4). Therefore, all the internal temperature data was then normalised to the selected reference Hobo logger.

Table 3.4: Summary of results from HOBO data loggers for calibration

	HOBO DATA LOGGER 1	**HOBO DATA LOGGER 2**	**HOBO DATA LOGGER 3**	**HOBO DATA LOGGER 4**
Max	21.0	20.7	21.1	20.9
Min	20.0	19.9	19.7	19.9
Mean	20.2	20.0	19.9	20.1

Figure 3.8: HOBO and Tinytag data loggers in a box for initial recording and calibration

3.8 Experimental plan

The following experimental plan was developed and adopted for this survey.

1. A participant's information sheet, consent form and cover letter for questionnaires were approved in accordance with the guidelines set by the University of Kent Ethics committee. The approved documents were presented to participants of the study and the survey was explained in detail to them.
2. Post-occupancy questionnaires were distributed among residents in the selected study location to understand their thermal conditions during the dry and rainy season. Each questionnaire had 31 questions divided into three groups.
3. Each participant of the ten case study houses was asked to fill in a comfort survey (daily dairy) questionnaire in the morning, afternoon and night, (but depending on when they were available at home) while carrying out their normal activities like cooking, watching TV, reading, eating or working on their computers/ laptops.
4. A Hobo temperature and relative humidity data logger was placed in the living room and bedroom of each of the case study houses after obtaining their consent.
5. The ten participants were asked to report on their activities and how they adapt and respond to discomfort. Their various ways of adapting to comfort and daily activities were recorded by the participants using the scales below:
    a) The thermal comfort scale of 1 (Cold) to 7 (Hot) with 4 being neutral
    b) Their environment was rated on a 1 (Uncomfortable) to 7 (Comfortable) scale
    c) Their thermal preference was rated on a 1 (much cooler) to 7 (Much warmer) scale
    d) Their judgment on thermal acceptability was rated on a two-point scale, 1 for acceptable and 2 for not acceptable scale
    e) They also recorded when they came into the house, how long they had been in the house and how they had spent the last hour in the house.
    f) The clothes they wore to keep themselves comfortable was also recorded by the participants.
6. In each case study house, two installed loggers recorded the air temperature and relative humidity at 15-minute intervals throughout each day for one week.
   Overall the survey lasted for about a week in each house for the dry and for the rainy seasons. Two houses were monitored each week before moving on to the next pair of houses.
7. Two outdoor loggers recorded the external air temperature and relative humidity, while the total solar radiation on the horizontal was measured using a Kipp and Zonen CMP3

pyranometer at 15-minute intervals throughout the monitoring period from 18/03/2015 – 06/05/2015.

8. Interviews were conducted with an academic, a developer and an architect to get an insight into why housing is the way it is, a context of housing in Nigeria. The constraints of the study did not allow for further investigation, but valid information was obtained.

3.9 Conclusion

This study adopted five methodologies to understand the real and ideal indoor conditions of residential buildings and occupants' perception of their environment in Abuja. The first was a post-occupancy survey which focused on dwellings around the case study buildings situated in the same areas. They added breadth and supported the results from the individual case studies.

The second, environmental monitoring comprised outdoor monitoring of, air temperature, relative humidity and solar radiation throughout the dry and rainy season and indoor monitoring of air temperature and relative humidity of the ten dwellings selected for the comfort survey.

The third selected methodology was a thermal comfort survey where occupants were asked to complete questionnaires three times per day to assess their thermal comfort state, (using the seven-point ASHRAE thermal sensation scale and a five-point preference scale). These data were used to support the physical data collected at the same time.

The fourth approach used the dynamic thermal simulation tool, DesignBuilder, which was used to model four out of the ten houses monitored during the survey to understand fully the thermal conditions when they were modified to improve the indoor conditions. The selected buildings for the simulation work comprised one naturally ventilated and one air-conditioned building from each of two case study locations. These selected case studies best represented the conditions in the study area.

Finally, observations and interviews were used to understand and get an insight into the context of housing in Nigeria together with the interviewees views on thermal comfort and residential buildings in Nigeria and possible solutions and advice on how to improve residential comfort.

CHAPTER 4

Case Study: Abuja (F.C.T.)

CHAPTER 4: Case Study, Abuja (F.C.T.)

4.1 Introduction

Abuja, the Federal Capital Territory, (F.C.T.) officially became Nigeria's (Figure 4.1) capital on 12 December 1991. The FCT boundary covers an area of about 7,315km^2 divided into six Area Councils namely; Abuja Municipal Area Council ((AMAC) (Phases I, II, III, & IV)), Gwagwalada, Abaji, Kuje, Bwari and Kwali (Figure 4.2). and major settlements planned and unplanned like, Nyanyan/Karu, Orozo, Karshi, Kubwa, Idu/Karmo/Gwagwa, Zuba, Mpape, Dutse Alhaji, Dakwa and many other squatters and shanty settlement that today is the housing stock available and affordable for substantial percentage of the low-income within Abuja. The city is the headquarters of the Economic Community of West African States (ECOWAS) as well as its Military arm (ECOMOG). It also has the regional headquarters of OPEC.

Figure 4.1: A map of Nigeria showing, FCT, Abuja in the middle. Source: Google maps

Presently, a large population of low-income and some middle-income earners live in squatters/semi planned settlements mentioned above, they commute four hours daily, back and forth the city centre daily with associated stress on top of environmental hazards when they return home-mostly a night. Utilities, facilities and basic amenities are very limited in these settlements while the rent they pay is relatively excessive, besides many security and social challenges are also associated with these settlements.

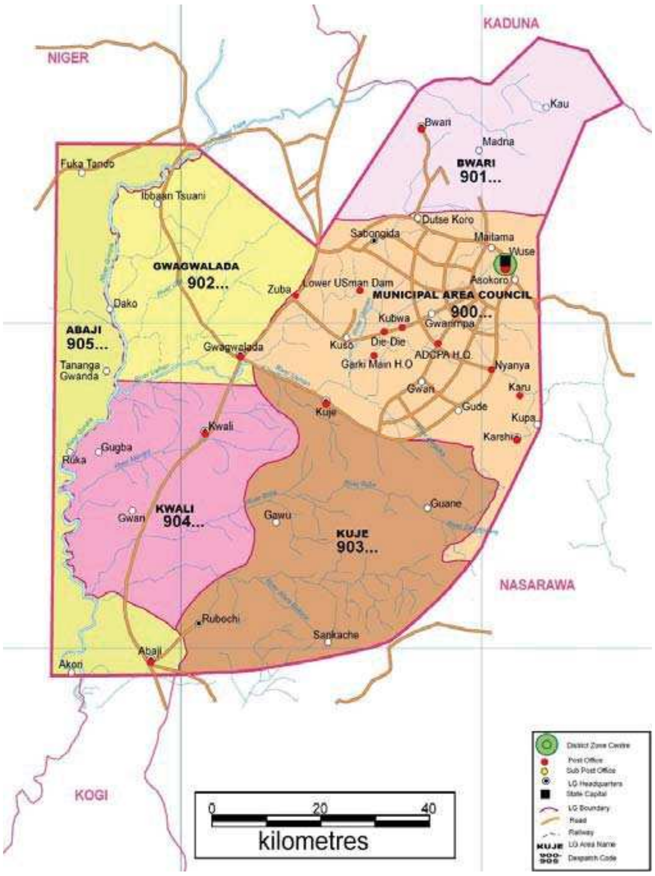


Figure 4.2: A map of Abuja showing the six area councils. Source: Ezike *et al*., 2016

Like many major cities in developing countries, Abuja is experiencing a high rate of population growth. Certainly, its urbanization rate of 8.32% per annum makes it the fastest growing city in Africa (Myers, 2011). While the current population of the city is estimated at over 3 million people, its day-time population often reaches up to 7 million (Iro, 2007 in Abubakar, 2014). This makes Abuja the fourth largest urban area in Nigeria after Lagos, Kano and Ibadan. Moreover, the city's rapid rate of urban growth is unprecedented in its satellite settlements, which are growing at about 20% per annum (Abubakar and Doan, 2010). Even though natural population increase is part of this growth, the major force underlying this overwhelming growth is in-migration due to perceived better economic opportunities in Abuja, rural people's quests for urban life, lack of investment in Nigeria's smaller towns and villages, and the belief that the city is much safer than other parts of the country (Abubakar 2014). The results of this explosive growth are the acute shortage of housing (Abdullahi 2010; Umoh 2012), the proliferation of informal settlements (Amba 2010; Jibril, 2006), occupation of uncompleted buildings (Abubakar and Doan, 2010; Abubakar 2014).

4.2 Location, climate and geography (Study area and case study description)

The study area Abuja lies at latitude 9° 04’ N and longitude 7° 29’ E, at an elevation of 840 m (2760 ft.) above sea-level. The area now designated the Federal Capital Territory (F.C.T.), Abuja, Nigeria’s capital, falls within the Savannah Zone vegetation of the West African sub region with Patches of rain forest. As it is in the tropics, Abuja experiences two weather conditions annually; the rainy season ranging from 305 to 762 mm (12 – 30 in.) which begins in April and ends in October and the dry season (the equivalent of summer in a temperate climate) which begins in November and ends in March. However, within this period, there is a brief interlude of Harmattan. A period when the North-East Trade Wind moves in with the main feature of dust haze intensified coolness and dryness. Fortunately, the high altitudes and undulating terrain of the FCT act as a moderating influence on the weather of the territory. Temperatures can rise to 40°C during the dry season with dry winds lowering the temperature to as low as 12°C (Abubakar, 2014).

Her abundant rainfall, rich soil and the location within the Guinea-Savanna vegetation zone makes the region agriculturally productive, with maize and tubers as the dominant crops. Abuja’s location at the geographical centre of Nigeria and its strategic position at the intersection of two highways linking the northern and southern parts of the country make it more accessible than Lagos. This centrality and accessibility is one of the reasons why the new capital city was created.

4.3 Criteria for income status, comfort and post-occupancy dwelling selection

This section will discuss the criteria for selecting the types of income status, post-occupancy survey area in Abuja and comfort survey dwelling location.

4.3.1 Criteria for income status selection for case studies

The current level of income earners in Nigeria is also a representation of the lower (working class) and middle (middle class) income earners in Abuja, Nigeria, which is classified into the following:

- A (Upper Middle Class - Higher managerial, administrative or professional)
- B (Middle Class - Intermediate managerial, administrative or professional)
- C1 (Lower Middle Class - Supervisory or clerical and junior managerial, administrative or professional)
- D (Working Class - Semi and unskilled manual workers)
- E (Those at the lowest levels of subsistence - Entirely dependent on state, family and friends for long-term income) (Kazeem, 2008).

4.3.2 Criteria adopted for comfort survey dwelling selection

The following criteria were adopted for the selection of the ten dwellings for the environmental monitoring and comfort survey:

1. The buildings must be in Abuja

2. The buildings that are related to low income and low-middle income earners i.e. in relation to class C1, D and E representation above)

3. Houses built with conventional materials like sandcrete blocks for the walls, sharp sand, Portland cement. They should either be roofed with either galvanized corrugated iron roofing sheets or aluminium roofing sheets and seasoned wood.

4. The houses should be, 1, 2 or 3 prototypes bedroom bungalows, detached or semi-detached, from low density to high density neighbourhoods in Abuja.

5. Housing development built within the last 10 years.

6. Social housing developed by the government (public), government and private development (public-private-partnership) and private developers.

7. A case study that has not been investigated

8. A house that has a complete building fabric i.e. wall, roof, doors and windows

9. Houses that are naturally ventilated or air-conditioned houses, (hybrid houses)

10. Households selected for the post-occupancy study must accept to participate in the main thermal comfort survey and environmental survey.

11. The dwellings must be accessible as much as possible to check on the equipment for the environmental monitoring and be available for any questions regarding the survey.

12. The security threat in the area must be low.

4.3.3 Criteria for post-occupancy survey area selection for this study

To get an idea of what type of dwellings and targeted end users to adopt for this study, the following parameters were looked at to select five neighbourhoods from the list of potential case studies above (Section 4.4).

i. Type of housing

- Single storey flat
- Bungalow
- Semi-detached bungalow

ii. Facilities provided
   - Number of rooms provided, 1,2 ,3 or 4-bedroom units
   - Electricity from mains and generators
   - Water supply from public mains, bore holes and wells

iii. Building construction parameters
   - External walling material: Sandcrete cement block.
   - Roofing material: Aluminium or zinc iron.
   - External rendering or finish: Painted, not painted or cement sand/plaster finish

iv. Location
   - Low – middle income settlements
   - Quiet, semi quiet or noisy environment
   - Distance from the central business district, the seat of power (location of the central government) and central Abuja
   - Low, medium or high density
   - Security- the crime rate in a location should be low - medium

v. Targeted end users
   - Bankers, teachers, administrators, lecturers etc. These class of people (lower – middle-class) would not want to live in a place with high crime rate either but won't mind an area that the facilities are not up to high standards but is considerably alright to use. Most of them would like to live in buildings with a generous size, a study and a dining room.
   - The working class like the self-employed, the market women, teachers, provision shop owners, handy workers and low-income earners mostly do not have a choice but to stay in areas with poor quality in facilities, mostly with high crime rate but low house rents, a high density and a noisy and unhealthy environment. Although some would tend to move to where mostly the middle class or low-middle class are located if money or a decent job comes their way.

4.4 Proposed case study areas for the post-occupancy and comfort survey in Abuja

A total of nine settlements and residential developments in Abuja were selected initially as possible post-occupancy survey locations for this study based on their designation as low and low-middle income residential areas and the criteria laid out in section 4.3.3. This section will discuss the nine initially proposed case study dwellings.

1. **Federal Housing Authority estate, Lugbe: (Lugbe in AMAC)**

The Lugbe estate, which was developed to cater for the low and low-middle-income groups of the city, this housing estate contains bungalows only and they range from two-bedroom semi-detached flats, two-bedroom flats and three-bedroom semi-detached, flats.

2. **Private residential development Kubwa: (Kubwa in Bwari area council)**

The buildings here are either privately owned or developed by the government. They are mostly single storey detached and semi-detached bungalows or semi-detached duplexes buildings ranging from one, two and three-bedrooms in a low – high density area of Kubwa, Abuja.

3. **Trade Moore estate Lugbe: (Lugbe in AMAC)**

This housing is developed by private developers, originally designed for low income earners but is now occupied mostly by the low middle/ middle-income earners. It contains a range of two-bedroom and three-bedroom bungalows.

4. **Apo (Abuja City) re-settlement scheme: (AMAC)**

The re-settlement scheme, which was developed as an idea to move original inhabitants of the area to alternative housing environments to replace their former habitat with new developments contains a range of two-bedroom and three-bedroom bungalows built with sancrete blocks.

5. **Peyi re-settlement scheme: (Bwari in Bwari area council)**

As in Apo (above), this is also a re-settlement scheme, developed as an idea to move original inhabitants of the area to alternative housing environments to replace their former habitat with new developments ranging from one, two and three-bedroom semi-detached and detached bungalows built with sancrete blocks or red earth bricks.

6. **Sokale, Dutse Alhaji: (Dutse Alhaji in Bwari area council)**

A low-income area scattered with several types of housing ranging from studio to three-bedroom bungalows. The area is synonymous with its irregular pattern of housing arrangements with only the major road giving it a clear distinction. A privately developed detached and semi-detached house ranging from one, two and three-bedroom located in a low-density area of Mpape, Abuja.

7. **Mpape residential settlement: (Mpape in Bwari area council)**

A low-income area scattered with unplanned housing developments, with several types of housing ranging from studio to three-bedroom bungalows, detached or semi-detached buildings. The area is synonymous with its irregular pattern of housing arrangements with only the major road giving it a clear distinction. The residential buildings are mostly privately developed and owned by individuals.

8. **Private residential development: (Gwagwalada in Gwagwalada area council)**

Is a low-income area scattered with several types of housing ranging from studio to three-bedroom bungalows with high presence of student because of its proximity to the University of Abuja and the Federal Medical Center Gwagwalada. The area is synonymous with its irregular pattern of housing arrangements with only the major road giving it a clear distinction.

9. **Kuje residential settlement: (Kuje in Kuje area council)**

This is a low-income residential area housing with several types of housing ranging from studio to four-bedroom bungalows, detached or semi-detached buildings. The area is synonymous with its irregular and regular pattern of housing arrangements with two major roads giving it a clear distinction. The residential buildings are mostly privately developed and owned by individuals.

Houses built with a different walling material (i.e. red earth bricks) contrary to the commonly used conservative sandcrete blocks would also be monitored. These case studies include:

I. **The Army quarters in Kubwa: (Kubwa)**
   A two to four-bedroom unit ranging from bungalow to duplexes, built with plastic fabric as its external walling system supported with concrete columns mostly at the edges.

II. **The red brick estate, Kubwa: (Kubwa)**
   A housing estate ranging from one to four-bedroom units in bungalow, semi-detached bungalows, duplexes and one-storey building, built mostly with red earth bricks.

III. **The Shehu Musa Yaradua Barracks, Abuja: (Abuja City)**
   Is a one to four-bedroom unit of blocks of flats for junior officers of the Nigerian army. They are built with red earth bricks as its external walling system supported with concrete columns mostly at the edges.

4.5 Selected Case study locations and dwellings in Abuja

Five low/ low-middle income case study locations for the post-occupancy survey were finally identified and selected for this study (Figure 4.3). Based on the criteria laid out in section 4.3.1 and 4.3.2. They are:

i. Lugbe
ii. Mpape
iii. Dutse Alhaji
iv. Kubwa
v. Bwari

Furthermore, one to one contact and interaction with house owners and tenants was used to identify and gain access to the dwellings used in this survey. This section will discuss the selected case study areas for the post-occupancy survey and the dwellings selected for the comfort survey for this study.

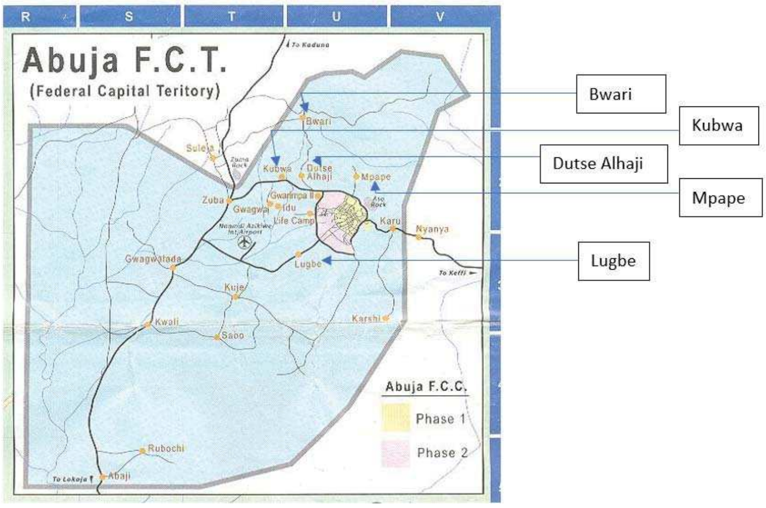


Figure 4.3: A map of Abuja showing the selected five neighbourhoods. Source: Google images/Abuja

4.5.1 Case study areas selected for the post-occupancy survey

I. Lugbe

Lugbe is one of the popular suburban settlements in Abuja. It is in the Abuja Municipal Area Council (AMAC). It is largely residential and densely populated (Figure 4.4). Lugbe is about 17 minutes' drive from the Central Business District of Abuja and 13 minutes' drive to the Abuja Airport. It is along the airport road. Lugbe is divided into five districts namely Lugbe south, Lugbe north, Lugbe central, Lugbe west, Lugbe east. Lugbe is a low/ low-middle income neighbourhood located 14.3km from Abuja city centre.

Though Lugbe is not in the Federal Capital City (FCC), its proximity to the city centre and to the Abuja airport has brought it into lime light and attracted significant development to the area. The area is developing very fast and is viable area to invest in real estate. The Airport road has heavy traffic (around Lugbe area) in the early hours of the morning between 6.00am to 10.00am and 4.00pm to 8.30pm on the lanes from Lugbe to city centre and city centre to Lugbe respectively. During these periods of heavy traffic, the journey to or from Lugbe to city centre could take up to 30 minutes. The Express way was recently expanded from four lanes to ten lanes. Lugbe is mainly a residential area and has several housing estates, some already completed and occupied and others still under construction.

Figure 4.4: Lugbe district. Source: Google maps

II. Mpape

Swarming with people, a noisy atmosphere mixed with stench and smoke, Mpape is a slum perched atop one of the undulating hills in the Federal Capital Territory (FCT) (Figure 4.5). Densely populated, the hilltop urban slum is a few minutes' drive on a snaky, slopping road from Maitama, Abuja's most luxurious district. It is a low-income neighbourhood located 10.9km from Abuja city centre

Residents of the town live in the shadow of demolition scare. Perhaps, because of its prime location in the capital city, residents live in perpetual fear of waking up one day and seeing bulldozers pulling down their shanty homes. Popularly called Maitama extension, the slum is rather a sharp contrast to the highbrow district, at least in terms of its alarming population and lack of social amenities. Most of the rooms observed were poorly ventilated, typically with a 0.6m x 0.6m window per room. Most houses were built with mud materials with floor area below 50 m^2. The houses were overcrowded and closely built together reducing possible natural air and light flow through the buildings (Figure 4.6a and 4.6b). There is presence of dust on the roof tops and in the atmosphere due to the untarred roads through the area (Figure 4.7a and 4.7b).

Most of the houses within Mpape were built with mud or plastered with cement while few were built with sandcrete concrete blocks. This indicates a relative urban slum quality with wood/iron sheet or others. This however represents only the living houses. The quality of the materials for the walls did not appeared to be in good order. Thus, a larger proportion of the buildings was not in good condition. In addition to the poor condition of the wall, they stood on weak foundation that endangers the life of occupants. Despite the daunting environmental challenges of living in the community, the residents of Mpape, coined from the rocky terrain, take pride in the community's peaceful atmosphere (researcher's field survey. 2015).

Figure 4.5: Mpape district. Source: Google maps

Figure 4.6: Overview of Mpape settlement on the mountain (a), Presence of dusty road and roof tops (b)

Figure 4.7: Presence of dusty roads (a) and roof tops (b).

III. Dutse Alhaji

Dutse Alhaji is one of such small Gbagyi (indigenous people in the area) settlements, which came into existence recently out of present traditional Bwari town in Bwari Area Council of FCT, Abuja. It is a low-medium and low-income area with government workers and privately employed. It serves as a satellite town and squatter settlements for those seeking accommodation close to the Federal Capital City (Figure 4.8). It is a low-income neighbourhood located 14.7km from Abuja city centre.

The available house types were assessed through the effort of the respondents. Bungalows were predominantly building types found in the area. Most of these buildings had no access roads. The only available means of reaching most of these houses were through footpaths only available by chance or circumstances. The sizes of the houses were generally substandard (Nigeria Reviewed Building Code, 2010) with crowded rooms that were below architectural standards. The rooms were poorly ventilated as only one substance window per room was generally recorded. Most houses were built with mud materials with floor area below 50 m^2. In other words, the houses were overcrowded, and congestion set in. Most of the houses within the Dutse Alhaji were either built with mud or plastered with cement while few were built with concrete blocks. This indicates a relative urban slum quality with wood/iron sheet or others. This however represents only the living houses. Though the quality of the materials for the walls appeared in good order, larger proportion of the buildings was not in good condition. In addition to the poor condition of the wall, they stood in weak foundation that endangers the life of occupants (researcher's field survey. 2015).

Figure 4.8: Dutse Alhaji district. Source: Google maps

IV. Kubwa

Kubwa is one of the major suburban districts in Abuja. It is mainly a residential area and is densely populated (Figure 4.9). It is about 25 minutes from the Central Business District of Abuja. It is on the right side of the Murtala Mohammed Express Way (from the city centre to Suleja). It is a low/ low-income neighbourhood located 15.5km from Abuja city centre.

The Murtala Mohammed Express Way has heavy traffic in the early hours of the morning between 6.00am to 10.00am and 4.00pm to 8.30pm on the lanes from Kubwa to city centre and city centre to Kubwa respectively. During these periods of heavy traffic, the journey to or from Kubwa to city centre could take well over one hour. The Express way is presently being expanded.

Kubwa has different parts including Kubwa FHA, Phase 2 (Phase 2 site and Phase 2 site 2), Phase 3, Army Quarters and Kubwa village. Kubwa village is where the indigenes were resettled. There is one major road that runs through Kubwa that is Gado Nasco road. Most commercial buildings in the area are located along Gado Nasco road.

Figure 4.9: Kubwa district. Source: Google maps

V. Bwari

Bwari Area Council (BAC) is located at the North East of the Federal capital territory (FCT), Abuja. It can be accessed from the Abuja – Kubwa expressway (Figure 4.10). The road to Bwari headquarters in on the right just before Kubwa when coming from the city centre. It is the furthest of the other four locations, 26.9km from Abuja city centre. It is a low / low-middle income neighbourhood.

The area council hosts some federal institutions, these include, the Nigerian Law School Headquarters, Nigeria Defence College, Joint Admission and Matriculation Board (JAMB) and Usuma Dam. Bwari is made up of several and diverse ethnic groups such as Gbagyi, Koro, Fulani and other minority migrants in the area. Because people of Bwari are predominantly farmers, the people of Bwari mostly live in sparsely populated settlements.

Figure 4.10: Bwari district. Source: Google maps

4.5.2 Case study dwellings locations selected for the comfort and environmental survey

For the comfort survey and environmental monitoring, two dwellings were selected in Lugbe, Mpape, Dutse Alhaji, Kubwa and Bwari based on the criteria laid out in Chapter 4.3.2. Some initial proposed locations were not selected because they became dangerous as the survey was scheduled to start in March, during the 2015 Nigeria presidential election. Some of the residents contacted earlier for the survey in Abuja, i.e. Gwagwalada and Kuje area councils fled the area for fear of potential post-election violence. Therefore, an area that has a high level of security and was easily accessible became two of the major criteria for the selection of the dwellings for the survey in line with the criteria laid out in 4.3.2.

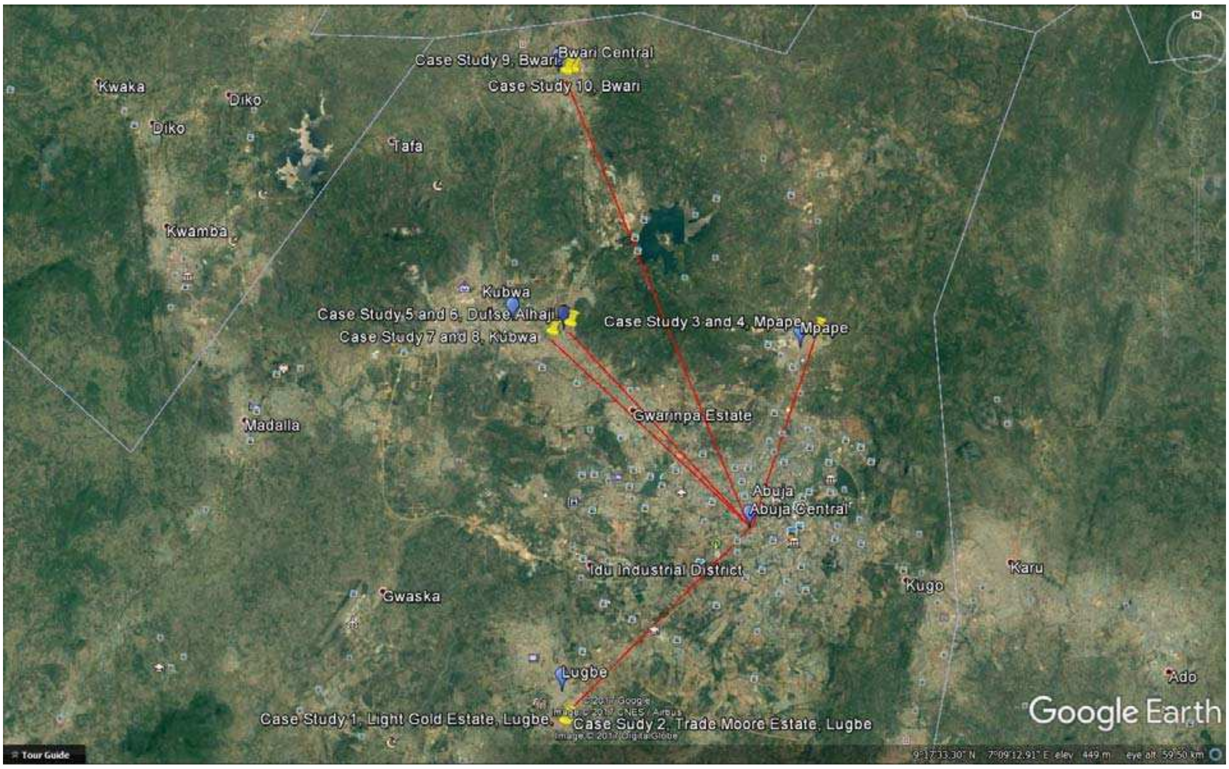


Figure 4.11: Case study dwelling location and their visual distance from Central Abuja city. Source: google earth

1. **Lugbe House 1, Case study 1 (LGH1NV)** is in a low-middle income area called Light Gold Estate just off the express way linking the international airport in Abuja to the city centre. It is in a moderately populated area and the buildings are well-spaced (around 6m apart on the sides) and planned for good air flow (Figure 4.12). The building is a North facing 3-bedroom detached bungalow, built with sandcrete blocks and has aluminium roofing. It is naturally ventilated, and the access road is not good but considered acceptable (Figure 4.13 to 4.15). It has a floor area of 115m^2.

Figure 4.12: Neighbourhood layout showing the location of LGH1NV at Lugbe

Figure 4.13: LGH1NV in Lugbe, Abuja, showing the main building.

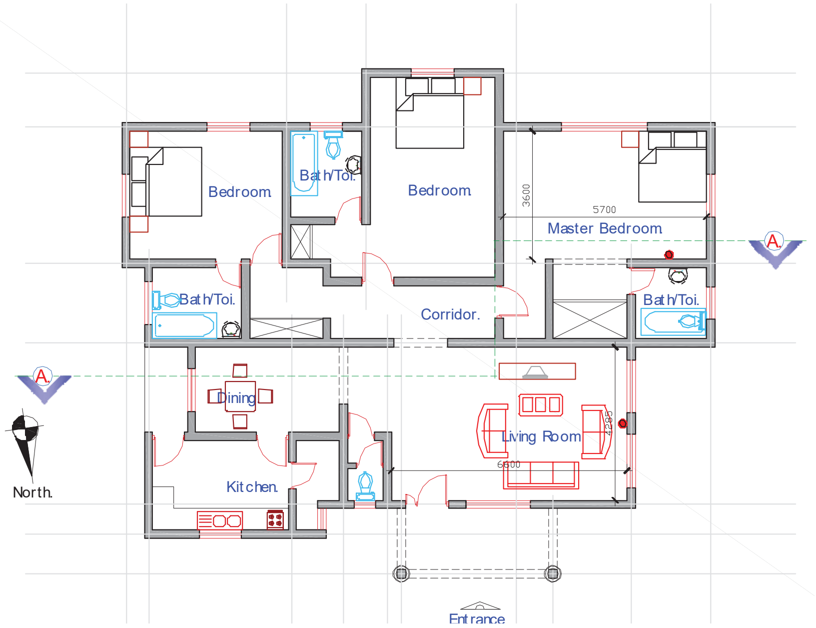


Figure 4.14: Floor Plan of LGH1NV at Lugbe highlighting the location of the sensor placed on the internal wall of the spaces monitored in the house during the surveys.

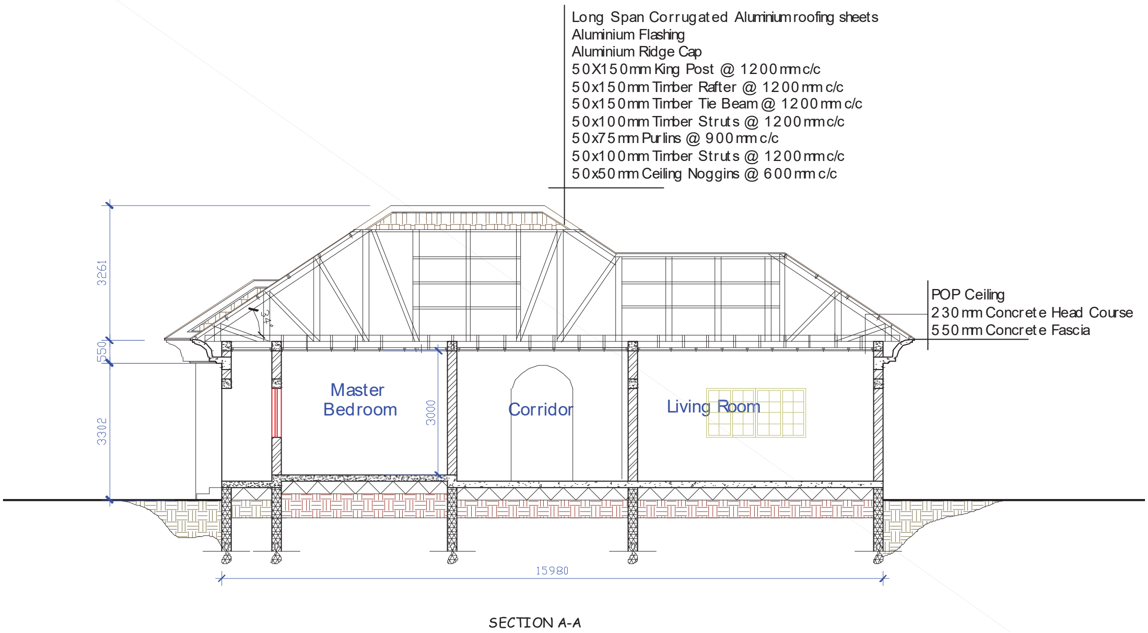


Figure 4.15: LGH1NV at Lugbe, Abuja, showing section A-A.

2. **Lugbe House 2, Case study 2 (LGH2AC)** is also located in a low-middle income area in Lugbe and it is in the same location as the first house but not in the same estate as the first case study, called Trade Moore Estate. It is in a moderately populated area and the buildings are well-spaced (around 6m apart on the sides) and planned for good air flow (Figure 4.16). The building is a North facing two-bedroom semi-detached bungalow, built with sandcrete blocks and has aluminium roofing. It is air conditioned and the access road is not good but considered acceptable (Figure 4.17 to 4.19). It has a floor area of 102m^2.

Figure 4.16: Neighbourhood layout showing the location LGH2AC at Lugbe

Figure 4.17: LGH2AC in Lugbe, Abuja, showing the main building.

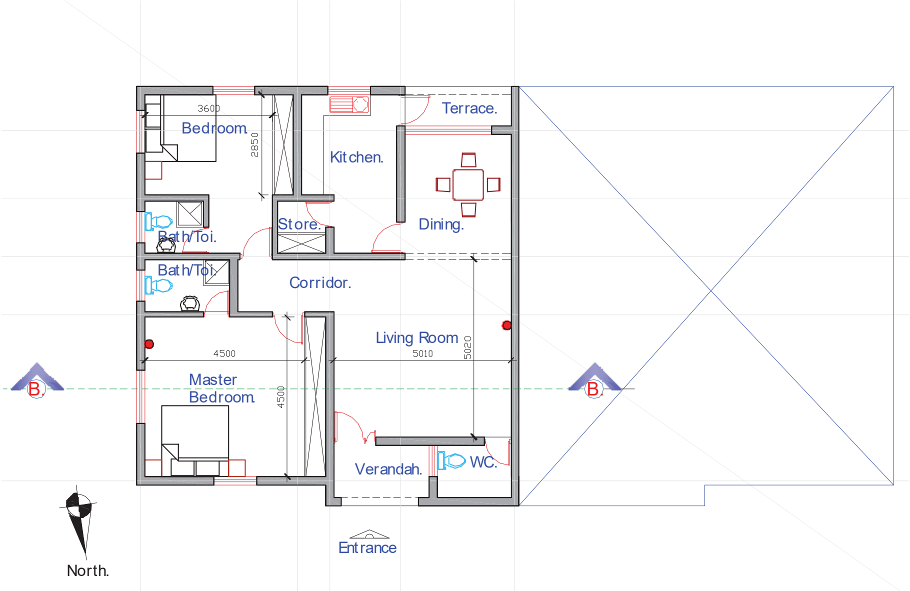


Figure 4.18: Floor Plan of LGH2AC at Lugbe with red circles highlighting the location of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

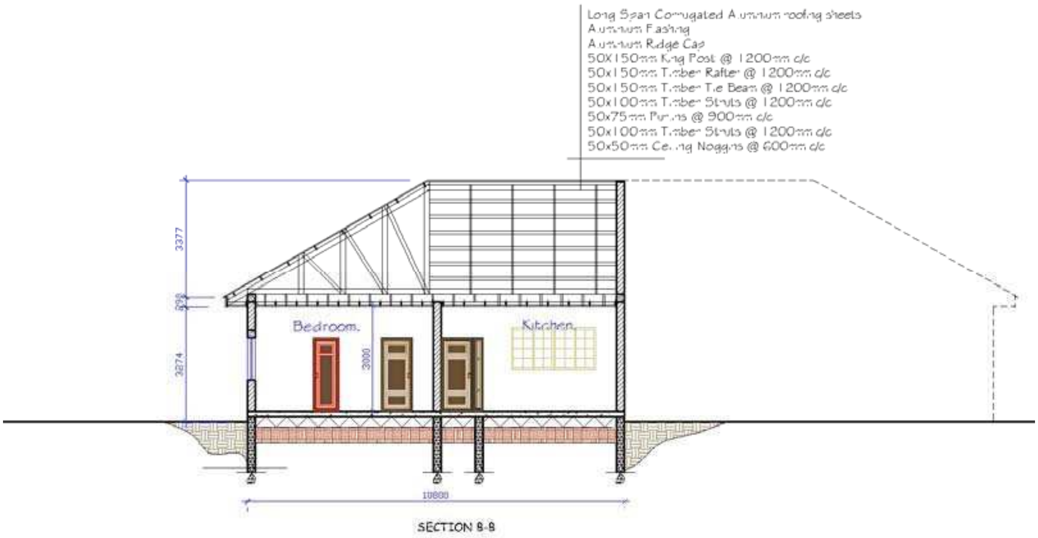


Figure 4.19: LGH2AC at Lugbe, Abuja, showing the section B-B.

3. **Mpape House 1, Case study 3 (MPH1NV)** is in a low income, high density populated area on a street called Mashafa road right in the middle of Mpape. There is no evidence of urban planning of the buildings in this area as buildings are clustered together (around 1.5-3m apart on all sides) and not arranged in any form of order, which also restricts sensible air flow in the area (Figure 4.20). The area is known for its high level of business activities and manual unskilled labour. The house is a naturally

ventilated South-West facing one-bedroom semi-detached bungalow, built with sandcrete blocks and has iron roofing. The exterior is not painted, and the building is in a poor condition and needs major repairs. (Figure 4.21 to 4.23). The dwelling has a floor area of 45m^2.

Figure 4.20: Neighbourhood layout showing the location MPH1NV and MPH2NV at Mpape

Figure 4.21: MPH1NV at Mpape, Abuja, showing the main building.

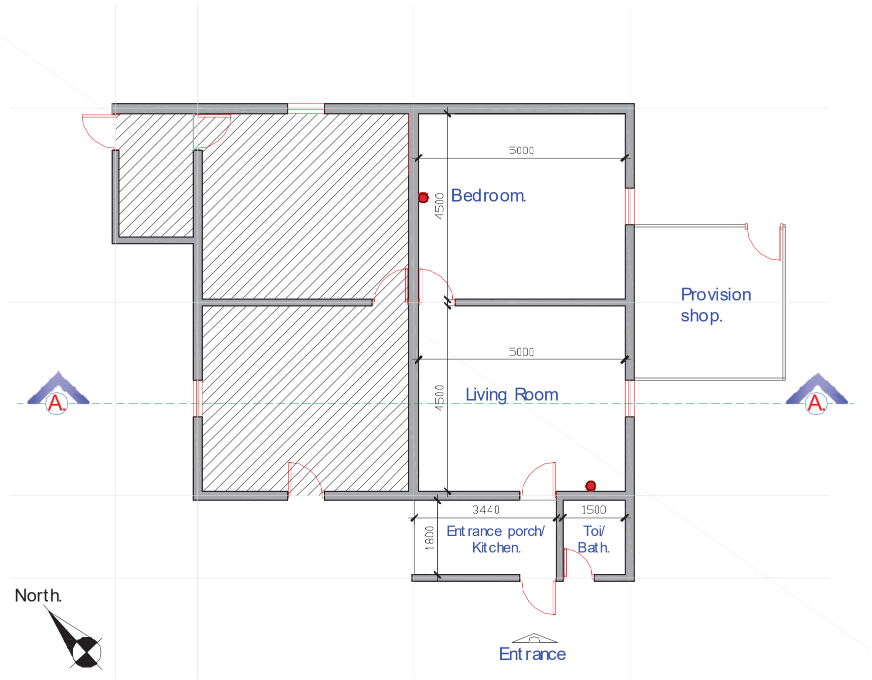


Figure 4.22: Floor Plan of MPH1NV at Mpape with red circles highlighting the location of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

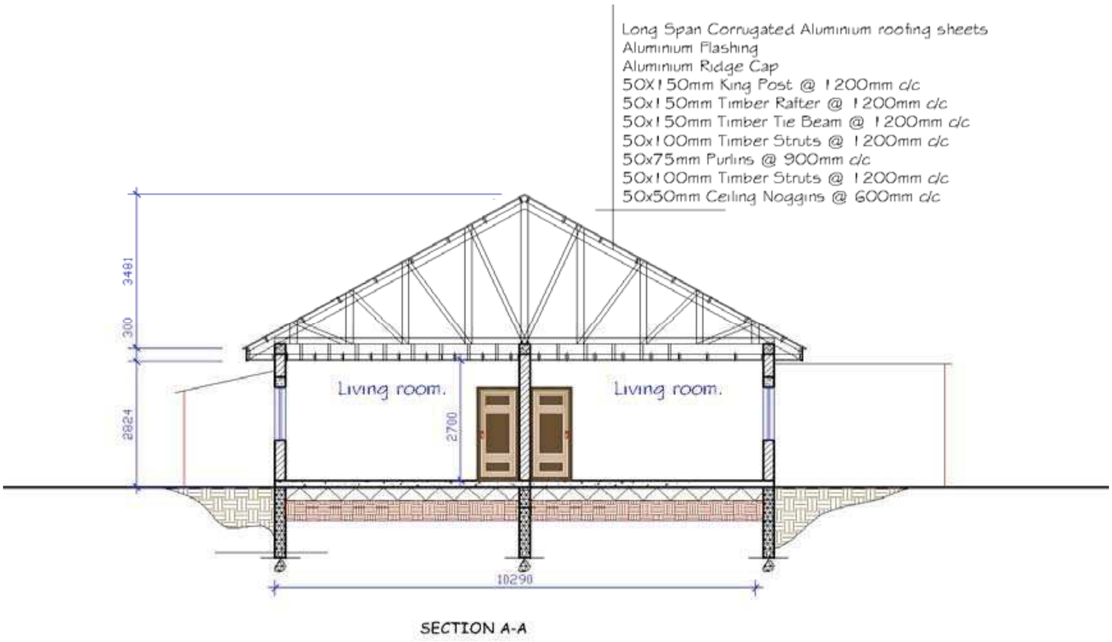


Figure 4.23: MPH1NV and MPH2NV at Mpape, Abuja, showing the Section A-A.

4. **Mpape House 2, Case study 4 (MPH2NV)** is also a South-East facing dwelling attached to MPH1, this house is also naturally ventilated and is built with sandcrete blocks. The exterior is not painted and the building it is a poor state and needs major repairs (Figure 4.24 and 4.26). It has a floor area of 45m^2.

Figure 4.24: MPH2NV at Mpape, Abuja, showing the main building.

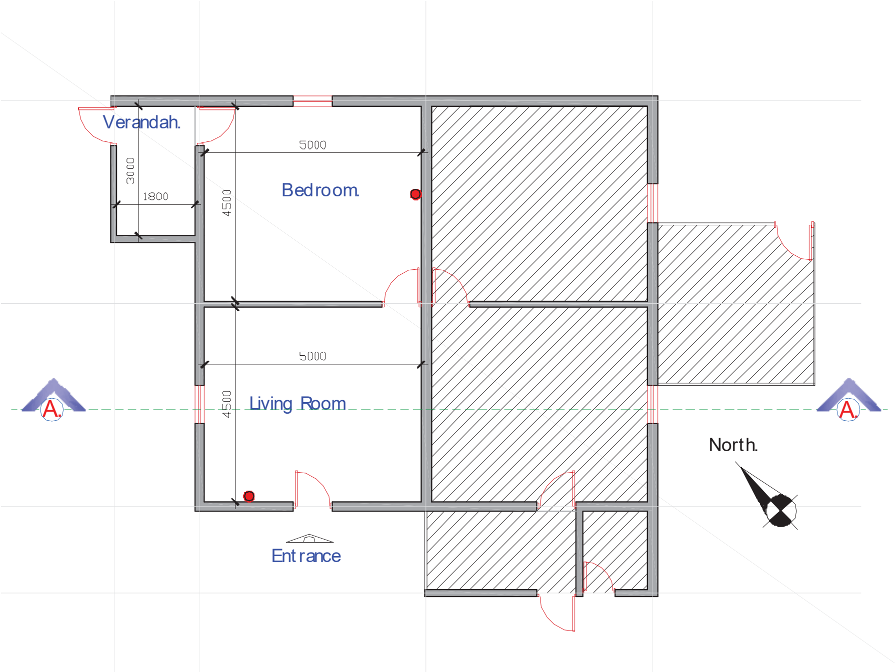


Figure 4.25: Floor Plan of MPH2 at Mpape with red circles highlighting the location of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

5. **Dutse Alhaji House 1, Case study 5 (DAH1NV)** is in a low-income, high density clustered area. The buildings are clustered around 1.5-4m apart on all sides, unplanned and restrict reasonable air flow in the area (Figure 4.26). The one-bedroom terrace dwelling is an East facing naturally ventilated building, with a painted exterior. It is roofed with iron sheets and it is in a sound state, although it needs some minor repairs (Figure 4.27 to 4.29). The building has a floor area of 44m^2.

Figure 4.26: Neighbourhood layout showing the location of DAH1NV and DAH2AC at Dutse Alhaji

Figure 4.27: DAH1NV at Dutse Alhaji, Abuja, showing a naturally ventilated building.

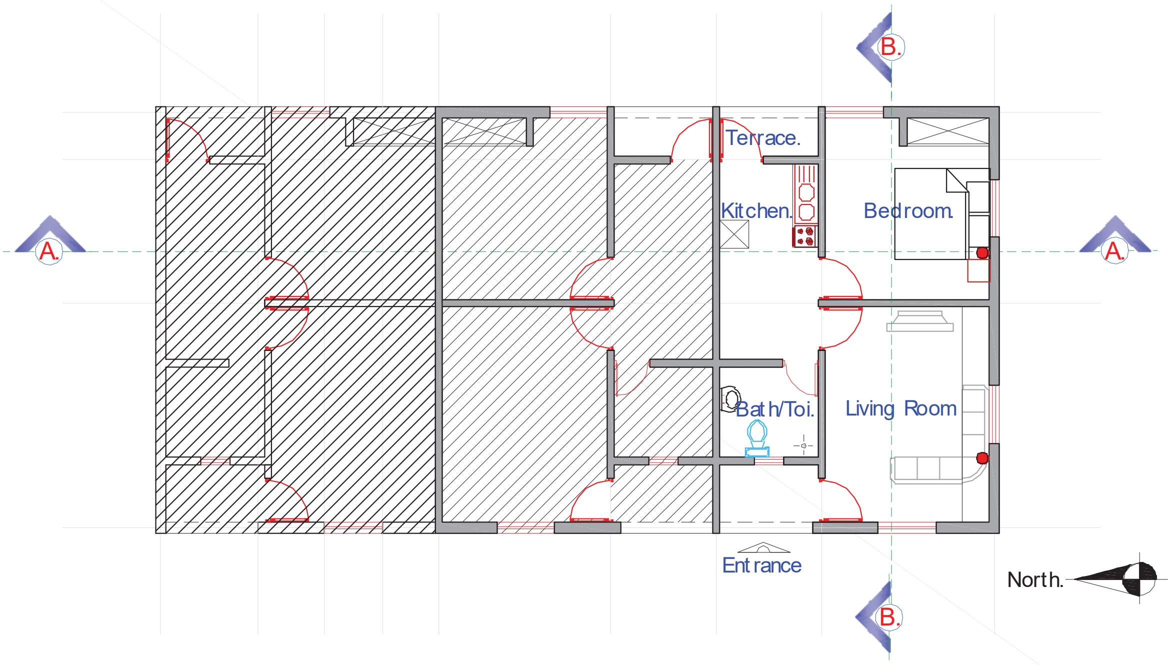


Figure 4.28: Floor Plan of DAH1NV at Dutse Alhaji with red circles highlighting the location of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

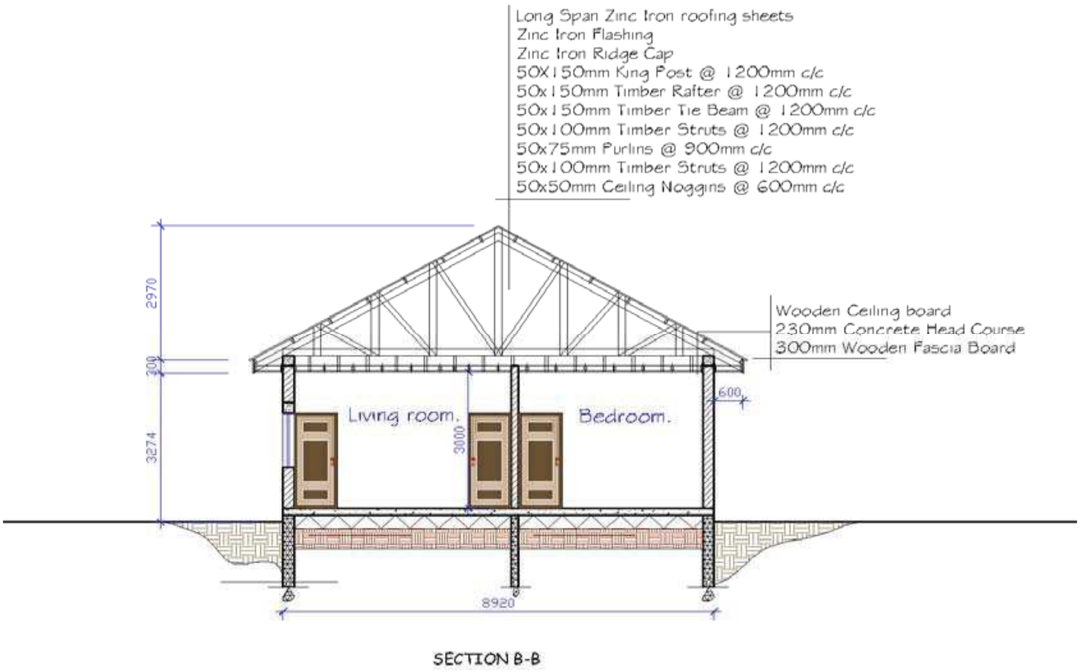


Figure 4.29: DAH1NV at Dutse Alhaji, Abuja, showing the section B-B.

6. **Dutse Alhaji House 2, Case study 6 (DAH2AC)** is also an East facing one-bedroom terrace flat attached to DAH1. It is air conditioned and in a sound state but needs minor repairs too (Figure 4.26 and 4.27). It has a floor area of 44m^2.

Figure 4.30: DAH2 at Dutse Alhaji, Abuja, showing the main building.

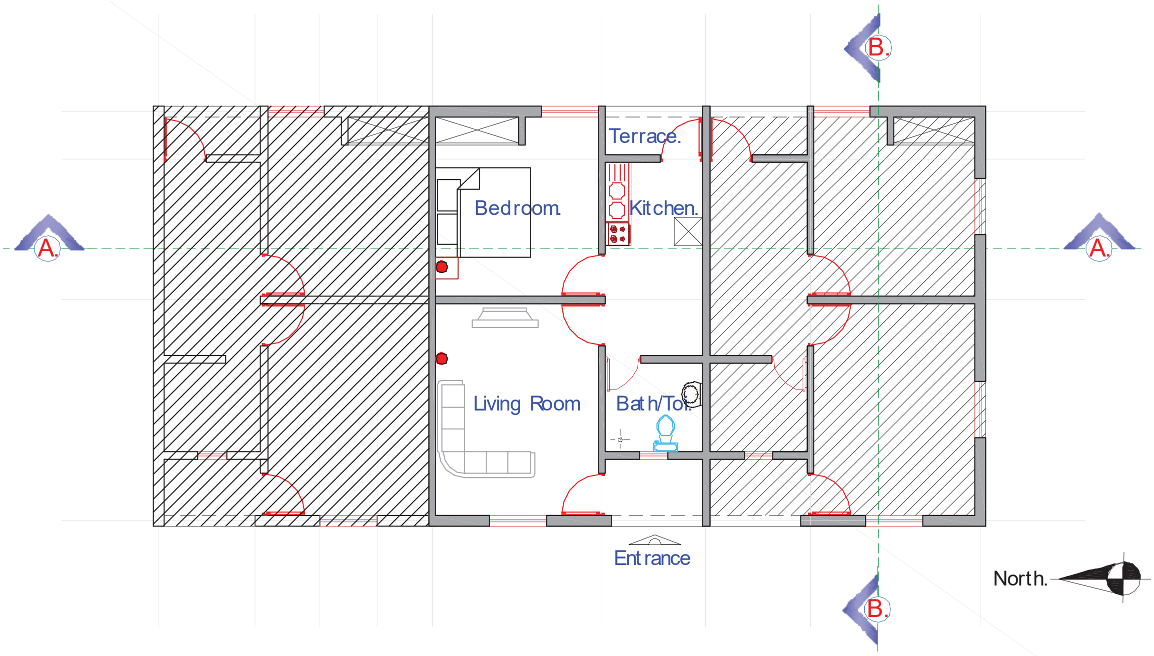


Figure 4.31: Floor Plan of DAH2AC at Dutse Alhaji with red circles highlighting the location of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

7. **Kubwa House 1, Case study 7 (KBH1AC)** is in a medium density area of Kubwa, just close to the Kubwa police barracks (Figure 4.32). It is a North-West facing one-bedroom flat that has air-conditioning, roofed with aluminium corrugated sheets. They are built with sandcrete blocks and have a painted exterior. The building is in a good state and does not need any repairs (Figure 4.33 to 4.35). It has a floor area of 37m^2.

Figure 4.32: Neighbourhood layout showing the location of KBH1AC and KBH2AC at Kubwa

Figure 4.33: KBH1AC at Kubwa, Abuja, showing the main building.

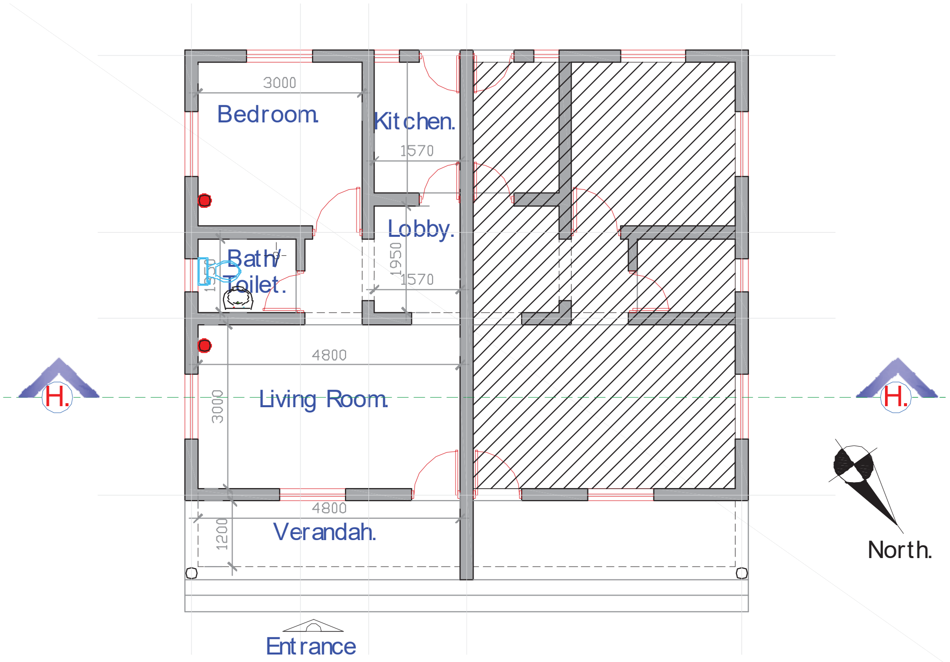


Figure 4.34: Floor Plan of KBH1AC at Kubwa with red circles highlighting the location of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

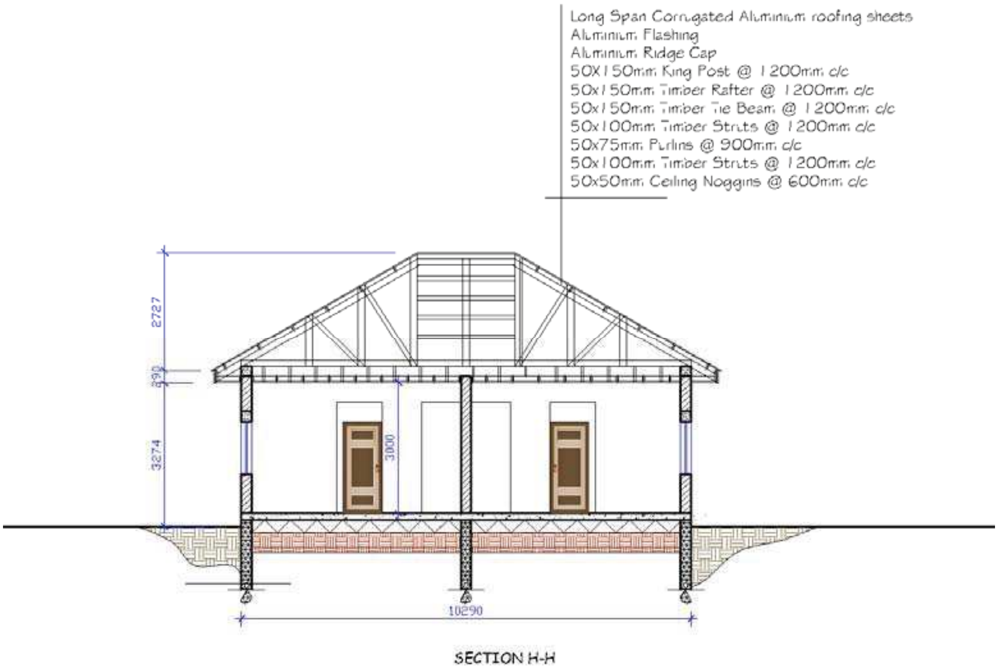


Figure 4.35: KBH1AC at Kubwa, Abuja, showing the section H-H.

8. **Kubwa House 2 Case study 8 (KBH2AC)** is also located in the same compound as KBH1AC (Figure 4.36a), it is a South-East facing air-conditioned one-bedroom terrace flat, roofed with aluminium corrugated sheets. It is in a good state and needs minor repairs (Figure 4.36b). It has a floor area of 38m^2.

Figure 4.36: The main compound and parking (a). Front entrance of KBH2AC at Kubwa (b),

9. **Bwari House1, Case study 9 (BWH1NV)** is a naturally ventilated one-bedroom flat located in a high density low income area. The buildings in this area are clustered and unplanned (Figure 4.37). The case study building is South-West facing, roofed with zinc iron sheets. The building is built with sandcrete block and does not have a painted exterior finish but it is in a good state, although the building needs minor repairs (Figure 4.38 to 4.40). It has a floor area of 40m^2.

Figure 4.37: Neighbourhood layout showing the location of BWH1NV at Bwari

Figure 4.38: BWH1NV at Bwari, Abuja, showing the main building.

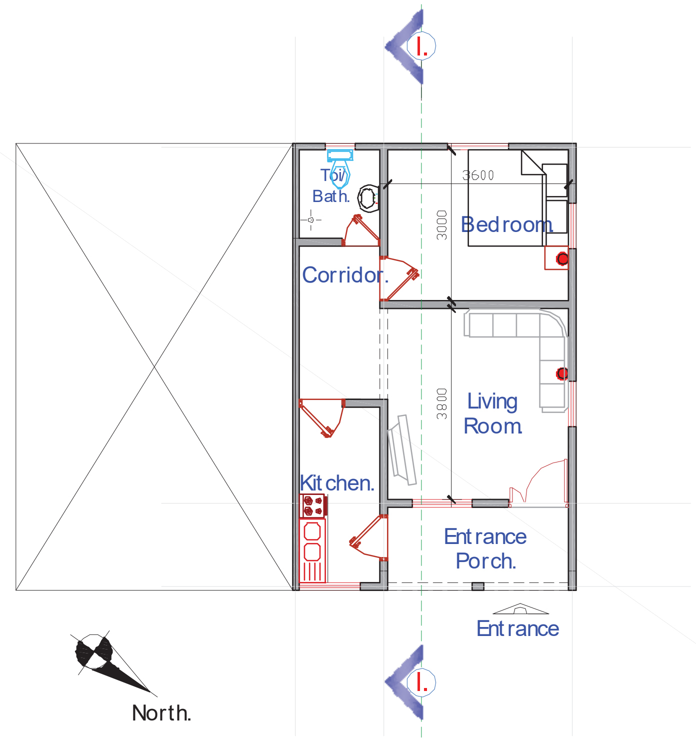


Figure 4.39: Floor Plan of BWH1NV at Bwari with red circles highlighting the location of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

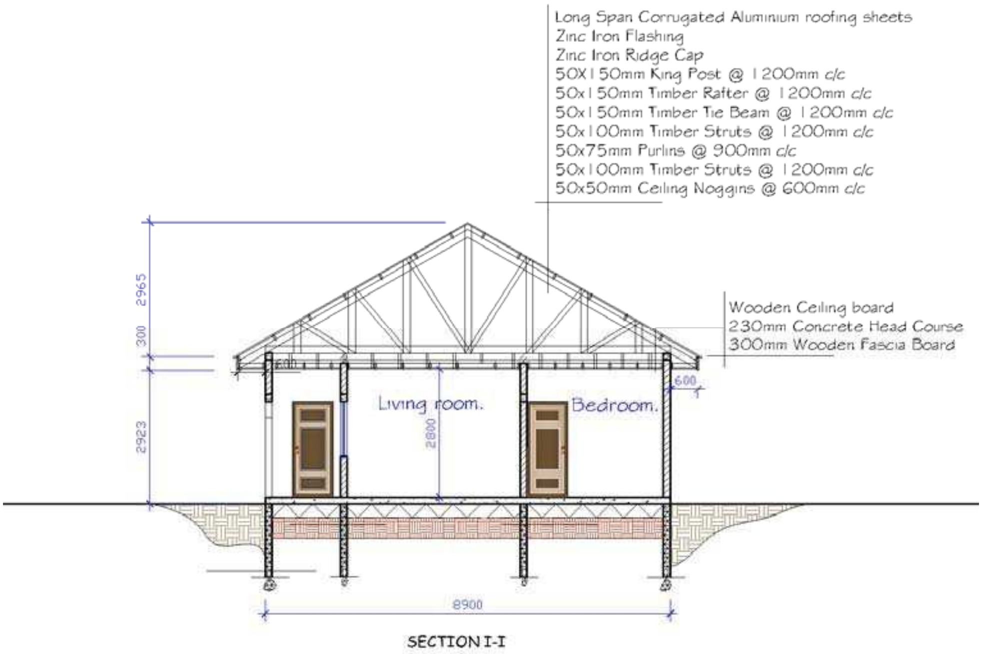


Figure 4.40: BWH1NV at Bwari, Abuja, showing the section I-I.

10. **Bwari House 2, Case study 10 (BWH2AC)** is a North-North-West facing two-bedroom bungalow located in high density, low income area of Bwari, although better planned, less clustered and spacious compared to case study 9 (BWH9), (Figure 4.41). It has air conditioning and it is roofed with aluminium corrugated sheets. The building has a painted exterior finish and it is in a good state (Figure 4.42 to 4.44). It has a floor area of 101m^2.

Figure 4.41: Neighbourhood layout showing the location of BWH2 at Bwari

Figure 4.42: BWH2AC at Bwari, Abuja, showing the main building. Source: researcher’s survey, 2015

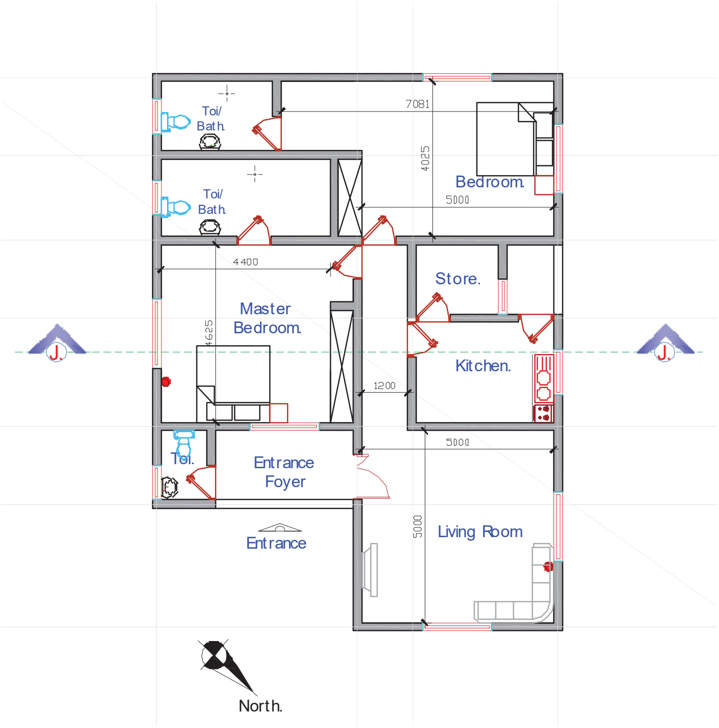


Figure 4.43: Floor Plan of BWH2AC at Bwari with red circles highlighting the location of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

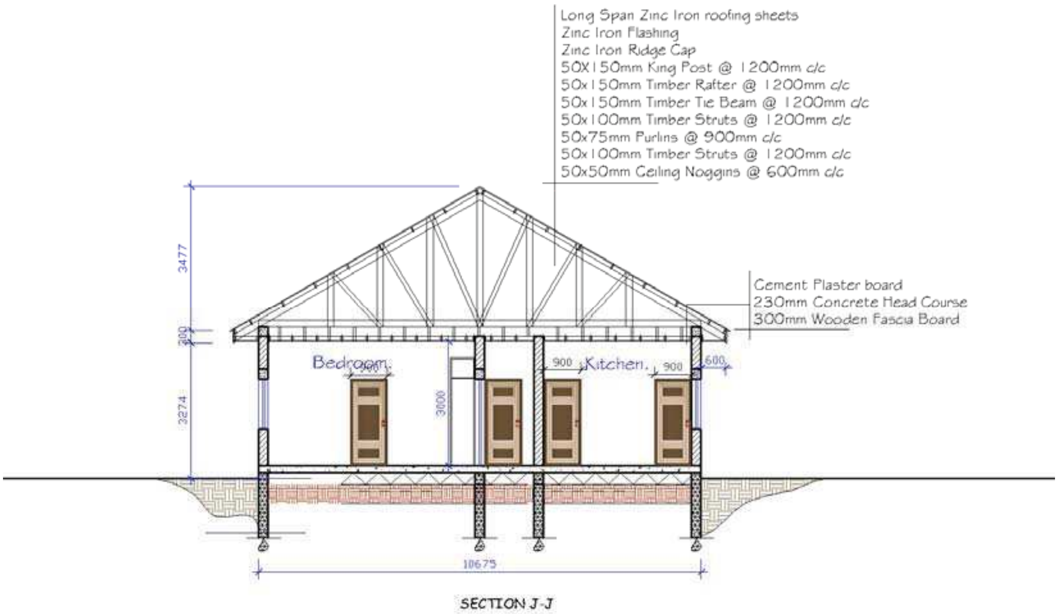


Figure 4.44: BWH2AC at Bwari, Abuja, showing section J-J. Source: researcher’s survey, 2015

4.6 Conclusion

This chapter gave an overview of Abuja, its climate, geography and location. It also discussed the post-occupancy location selection criteria and how five locations were identified and selected for this study. The residents in these locations helped give an insight and understanding of what was perceived as their indoor thermal environment, their energy consumption and comfort measure behaviours during the dry and rainy seasons. In addition, ten dwellings selected for this study met the guidelines discussed in this chapter to evaluate their thermal performance as part of the methodology for this study.

The field survey was conducted in the month of March to May for the dry season because this is when the temperature is highest and June to August for the rainy season, when humidity is high, and temperatures are lower than the dry season temperatures. The next chapter discusses the data analysis of this survey.

CHAPTER 5

Data analysis and Results

CHAPTER 5: Data analysis and Results

The research methodology and survey and monitoring protocol used for this study is discussed in chapter 1 and 3, these included post-occupancy surveys, environmental monitoring of the indoor environment and comfort surveys. In analysing the quantitative data for this research, the SPSS-16.0 statistical package and Microsoft excel were used. Explorative factor analysis is used in the development of the scale, and in assisting in the extraction and classification of the principal factors. Descriptive statistics were used in the analysis of frequencies related to satisfaction within the sub-scales. An Analysis of Variance (ANOVA) test was carried out on samples from ten building types and the 'f' statistic was used to test the statistical hypotheses. To analyse the post-occupancy and thermal comfort survey, themes that were repeatedly expressed were extracted. These were put together with what was surveyed to give interpretation to the findings.

5.1 Analysis of Post-Occupancy Survey

To help understand and compare the perceived nature and frequency of occupants' responses and complaints that cannot be obtained during surveys like feeling warm, hot, uncomfortable or unsatisfied, post-occupancy surveys were critical to appreciating the thermal environment for human occupancy in buildings. The respondents were asked to evaluate their overall thermal sensation, thermal comfort, thermal preference and thermal sensation during the daytime and night-time in the dry and rainy seasons along with their different thermal environment control features.

Overall, 222 valid questionnaires from the five case study areas were collected and analysed (Table 5.1), from respondents with air-conditioned and naturally ventilated buildings. Most of the respondents were males between 60% - 75% (156) across all case studies, representing 70% (156) of the votes while the female votes were 66, representing up to 30% of the total votes. The 31-45 age range had the highest number of votes 132 representing up to 60% and the 18-30 range with 70 votes representing almost 32% of the total survey, (see Table A1.1). The study also showed that more than 62% of the respondents were in either a 1-bedroom or 2-bedroom apartment with more than 42% staying in their apartment for 1-3 years while 31% lived in their apartment for 4-5 years, (see Table A1.2).

Table 5.1: Overall post-occupancy survey questionnaire distribution

Location in Abuja	Number of issued questionnaires	Number of valid questionnaires	Percentage of valid questionnaire (%)
Lugbe	55	43	78
Mpape	55	44	80
Dutse Alhaji	54	43	80
Kubwa	57	51	75

Location in Abuja	Number of issued questionnaires	Number of valid questionnaires	Percentage of valid questionnaire (%)
Bwari	52	41	79
Combined	273	222	81

Majority of the respondents were in employment as more than 90% were either public servants, in the private sector or self-employed. The respondents in Mpape had the largest number of self-employed respondents representing almost 55% of the votes with the same area showing respondents are 100% in the low-income range (Table 5.2). Further breakdown of respondents' socio-economic and employment status (Table 5.2), showed the respondents in Lugbe and Kubwa almost have an even split between low and low-middle income groups, while 72% of the respondents in Dutse were in the low-income range, around 66% were also in the same category in Bwari.

In all, 64% of the total votes were in the low-income range with 142 votes, while 71 votes were low-middle income, representing 32% of the respondents' vote. This shows that most of the residents if not all the residents in Mpape are low-income earners who are mostly self-employed compared to most of those in the remaining case studies where either public servants or privately employed therefore having better economic status.

Table 5.2: Summary of respondents' background information during post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Employ-ment status	**Public servant**	19	44.2	8	18.2	12	27.9	18	35.3	9	22.0	66	29.7
	Private employee	11	25.6	7	16.0	18	41.9	23	45.1	7	17.0	66	29.7
	Self-employed	12	27.9	24	54.5	10	23.3	5	9.8	18	43.9	69	31.1
	student	0	0.0	3	6.8	1	2.3	4	7.8	4	9.8	12	5.4
	unemployed	1	2.3	2	4.5	2	4.6	1	2.0	3	7.3	9	4.1
Socio-economic status	**Low-income**	18	41.9	44	100	31	72.1	22	43.1	27	65.8	142	64.0
	Low-medium	22	51.1	0	0.0	11	35.6	28	54.9	10	24.4	71	32.0
	Medium	3	7.0	0	0.0	1	2.3	1	2.0	4	9.8	9	4.0
Level of education	**No formal education**	0	0.0	0	0.0	3	7.0	1	2.0	2	4.9	6	2.7
	Completed primary	0	0.0	2	4.5	1	2.3	0	0.0	2	4.9	5	2.3
	Secondary	4	9.3	9	20.5	4	9.3	0	0.0	4	9.8	21	9.5
	Post-secondary	22	51.2	33	75.0	21	48.8	20	39.2	24	58.5	120	54.0
	Post-graduate	17	39.5	0	0.0	14	32.6	30	58.8	9	22.0	70	31.5
tenancy	**Rented (tenancy)**	39	90.7	41	93.2	34	79.1	41	80.4	32	78.0	187	84.2
	Owner occupier	4	9.3	3	6.8	9	20.9	10	19.6	9	22.0	35	15.8

S.S. = Sample Size

The energy consumption data (Table 5.3) shows that 60% - 90% of the residents pay more than £7 to per month for electricity bills, though 60% - 80% of the residents paid more than £7 per month for alternative electricity from personal generators except for the residents in Mpape, where about 30% of the residents pay for alternative electricity and around 31% pay above £7, (Table 5.3). This can be connected to the socio-economic data for Mpape where it suggests that the area is majorly a low-income area therefore, most of them cannot afford to buy and maintain generators or pay for extra for alternative source of electricity. Therefore, being a low-income earner has a serious effect on the ability to look for other alternative source of electricity, so they typically rely on electricity from the national grid.

Table 5.3: Summary of respondents' energy consumption, post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Electricity bill/ month	**<£3.64**	1	2.3	0	0.0	3	7.0	1	2.0	1	2.4	6	27.1
	£3.64 - £7.27	0	0.0	10	22.7	2	4.7	1	2.0	5	12.2	18	8.1
	£7.27 - £10.91	21	48.8	14	31.8	19	44.1	12	23.5	23	56.1	89	40.1
	£10.91- £14.54	12	27.9	19	43.2	15	34.9	18	35.2	10	24.4	74	33.3
	>£14.54	9	20.9	1	2.3	4	9.3	19	37.3	2	4.9	35	15.8
Alternative electricity source	**Personal Generator**	33	76.7	14	31.8	27	62.8	43	87.3	30	73.2	147	66.2
	Generating Plant estate	1	2.3	0	0	3	7.0	3	5.9	3	7.3	10	4.5
	Solar Panels (photovoltaic)	0	0.0	0	0	0	0.0	0	0.0	1	2.4	1	0.5
	Other	4	9.3	0	0	2	4.6	0	0.0	0	0.0	6	2.7
	None	5	11.6	30	68.2	11	25.6	5	9.8	7	17.1	58	26.1
Alternative electricity bill /month	**<£3.64**	1	2.3	0	0.0	0	0.0	1	2.0	1	2.4	2	0.9
	£3.64 - £7.27	0	0.0	2	4.5	1	2.3	4	7.8	0	0.0	8	3.6
	£7.27 - £10.91	8	18.1	2	4.5	2	4.7	1	2.0	11	26.8	24	10.8
	£10.91- £14.54	12	27.9	7	16.0	6	14.0	10	19.6	9	22.0	44	19.8
	>£14.54	16	37.2	5	11.4	21	48.8	30	58.8	13	31.7	85	38.3
	N/A	6	14.0	28	63.6	13	30.2	5	9.8	7	17.1	59	26.6

S.S. = Sample Size

Low-income earners/ areas were also seen to use less air conditioning for cooling compared to low-middle and middle-income earners as over 80% of the houses in Mpape do not have air conditioning compared to over 50% - 80% in the remaining case studies that have air conditioning (Table 5.4). This shows a strong relationship between low-income areas and the availability of air-conditioning.

Table 5.4: Summary of respondents' use of air conditioning, post-occupancy survey

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S.	%	S.S.	%	S.S.	%	S.S.	%	S.S.	%	S.S.	%
Living room	**Yes**	28	65.1	4	9.1	16	37.2	35	68.6	17	41.5	100	45.0
	No	15	34.9	40	90.9	27	62.8	16	31.4	24	58.5	122	55.0
Bedroom	**Yes**	25	58.1	2	4.5	13	30.2	20	39.2	10	24.4	70	31.5
	No	18	41.9	42	95.5	30	69.8	31	60.8	31	75.6	152	68.5
Houses with AC	**Yes**	35	81.4	7	15.9	22	51.2	35	68.6	19	46.3	118	53.2
	No	8	18.6	37	84.1	21	48.8	16	31.4	22	53.7	104	46.8

S.S. = Sample Size

Table 5.5: Summary of respondents' use of windows, post-occupancy survey

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S.	%	S.S.	%	S.S.	%	S.S.	%	S.S.	%	S.S.	%
Living room	**Yes**	19	44.2	36	81.8	35	81.4	21	41.2	23	56.1	134	60.4
	No	24	55.8	8	18.2	8	18.6	30	58.8	18	43.9	88	39.6
Bedroom	**Yes**	17	39.5	17	38.6	20	46.5	11	21.6	29	24.4	94	42.3
	No	26	60.5	27	61.4	23	53.5	40	78.4	12	75.6	152	57.7

S.S. = Sample Size

The response for use of indoor controls like open widows, electric fans and air conditioning for indoor comfort control ranged from 'slightly much' to 'very much' (Table 5.5). The votes were skewed to the 'slightly much' response (Figure 5.1) and with a mean of 5.9, the results showed that more than 50% - 80% of the residents either used open widows, electric fans or air conditioning at some point to change their indoor environment from an uncomfortable to a more comfortable state. The 'use of window' votes across all case studies showed that more than 60% of the respondents open their windows to achieve indoor comfort in the living room compared to 42% that opened their windows in the bedroom (Table 5.5). Also, most of those that voted to open window do not have air-conditioning in the living room or bedroom space (Figure 5.4 and 5.5).

The votes for the level of satisfaction for the use of these controls (Figure 5.2) was spread across 'dissatisfied' to 'satisfied', with more than 95% of respondents indicating to be in this range, (Table 5.6). With the satisfaction votes skewing towards slightly dissatisfied and neutral responses, with a mean of 3.9 (Figure 5.2). Overall, it suggest that most people were neutral or satisfied with their use of controls through the dry and rainy season regardless of their socio-economic status, though those that use of alternative energy sources to support cooling and the lack of constant power supply might be a contributing factor.

Table 5.6: Summary of respondents' use of indoor controls during the dry season, post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Use of indoor controls	**Very little**	0	0.0	0	0.0	1	2.3	0	0.0	0	0.0	1	0.5
	Little	4	9.3	2	4.5	1	2.3	2	3.9	1	2.4	10	4.5
	Slightly little	1	2.3	0	0.0	4	9.3	2	3.9	1	2.4	8	3.6
	Neutral	10	23.3	6	13.6	2	4.7	9	17.6	0	0.0	27	12.2
	Slightly much	4	9.3	5	11.4	9	20.9	14	27.5	15	36.6	47	21.1
	Much	20	46.5	23	52.3	20	46.5	13	25.5	20	48.8	96	43.2
	Very much	4	9.3	8	18.2	6	14.0	11	21.6	4	9.8	33	14.9
Satisfac-tion with indoor controls	**Very dissatisfied**	0	0.0	0	0.0	0	0.0	1	2.0	3	7.3	4	1.8
	Dissatisfied	8	18.6	5	11.4	11	25.6	4	7.8	6	14.6	34	15.3
	Slightly dissatisfied	3	7.0	15	34.1	13	30.2	12	23.5	9	22.0	52	23.4
	Neutral	15	34.9	16	36.4	8	18.6	12	23.5	7	17.1	58	26.2
	Slightly satisfied	13	30.2	6	13.6	8	18.6	11	21.6	12	29.2	50	22.5
	Satisfied	3	7.0	2	4.5	3	7.0	9	17.6	4	9.8	21	9.5
	Very satisfied	1	2.3	0	0.0	0	0.0	2	4.0	0	0.0	3	1.4

S.S. = Sample Size

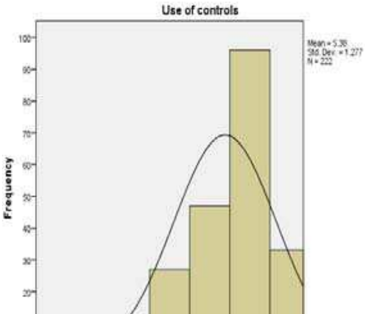


Figure 5.1: Distribution of overall use of control votes during post-occupancy survey, all case studies (Scale: 1 = very little to 7 = very much)

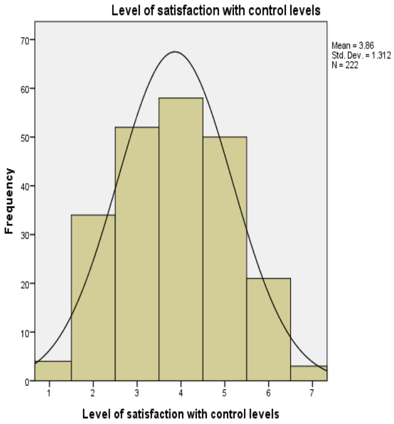
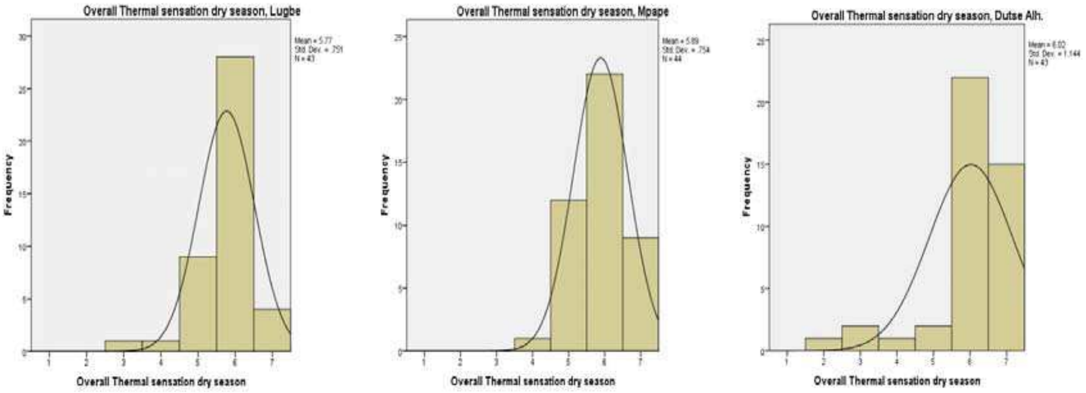


Figure 5.2: Distribution of level of satisfaction with control votes during post-occupancy survey, all case studies (Scale: 1 = very dissatisfied to 7 = very satisfied)

5.1.1 Thermal sensation analysis of post-occupancy survey

5.1.1.1 Post-occupancy thermal sensation – Dry season

The post-occupancy survey for the indoor thermal conditions of the five case studies showed an overwhelming response for the warm/hot part of the scale in the dry season across the buildings where more than 75% of the occupants were feeling 'warm' and 'hot' (Table 5.7) and with the warm response receiving most of the votes of 55% (Figure 5.3). The occupants in Dutse Alhaji had the highest levels of warm/hot thermal sensation response with over 86% (Figure 5.3) and a recorded highest mean thermal sensation response of 6.0 (Table 5.7) amongst all the other case study areas.



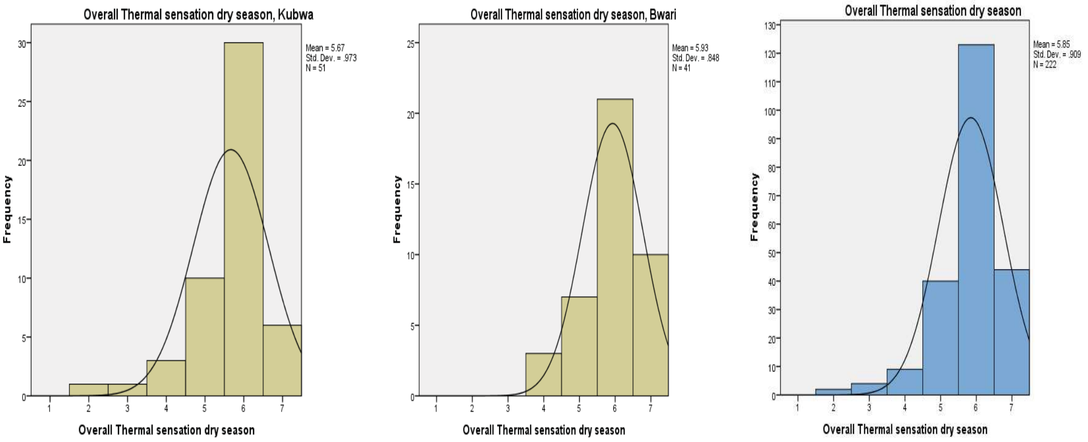


Figure 5.3: Distribution of overall thermal sensation votes during the dry season across all case studies and the overall combined data (bottom right) (Scale: 1 = cold to 7 = hot)

Table 5.7: Summary of respondents' indoor thermal sensation during the dry season, post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Thermal sensation	**Cold**	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
	Cool	0	0.0	0	0.0	1	2.3	1	2.0	0	0.0	2	0.9
	Slightly cool	1	2.3	0	0.0	2	4.7	1	2.0	0	0.0	4	1.8
	Neutral	1	2.3	1	2.3	1	2.3	3	5.9	3	7.3	9	4.1
	Slightly warm	9	20.9	12	27.3	2	4.7	10	19.6	7	17.1	40	18.0
	Warm	28	65.1	22	50.0	22	51.2	30	58.8	21	51.2	123	55.4
	Hot	4	9.3	9	20.5	15	34.9	6	11.8	10	24.4	44	19.8

5.1.1.2 **Post-occupancy thermal sensation – Rainy season**

In the rainy season, there was a noticeable shift of thermal sensation (Table 5.8), with more than 60% of the responses from all the case studies at either 'slightly cool', 'neutral' or 'slightly warm' part of the scale (Figure 5.4), with the mean thermal sensation focusing around thermal sensation neutrality (Table 5.8). Dutse Alhaji had the highest response for the warm/hot part of the scale with over 46% of the occupants feeling 'warm' or 'hot' followed by the response from Mpape with 36% feeling same. Residents in Lugbe had the lowest response for the warm part of the scale with only 11.6% feeling 'slightly warm'. However, Lugbe had the highest response for the cool/slightly cool part of the scale with 65% feeling 'cool' or 'slightly cool'. In addition, at least 45% of the residents in Kubwa and Bwari were also feeling the same with lowest response of 20% at Mpape.

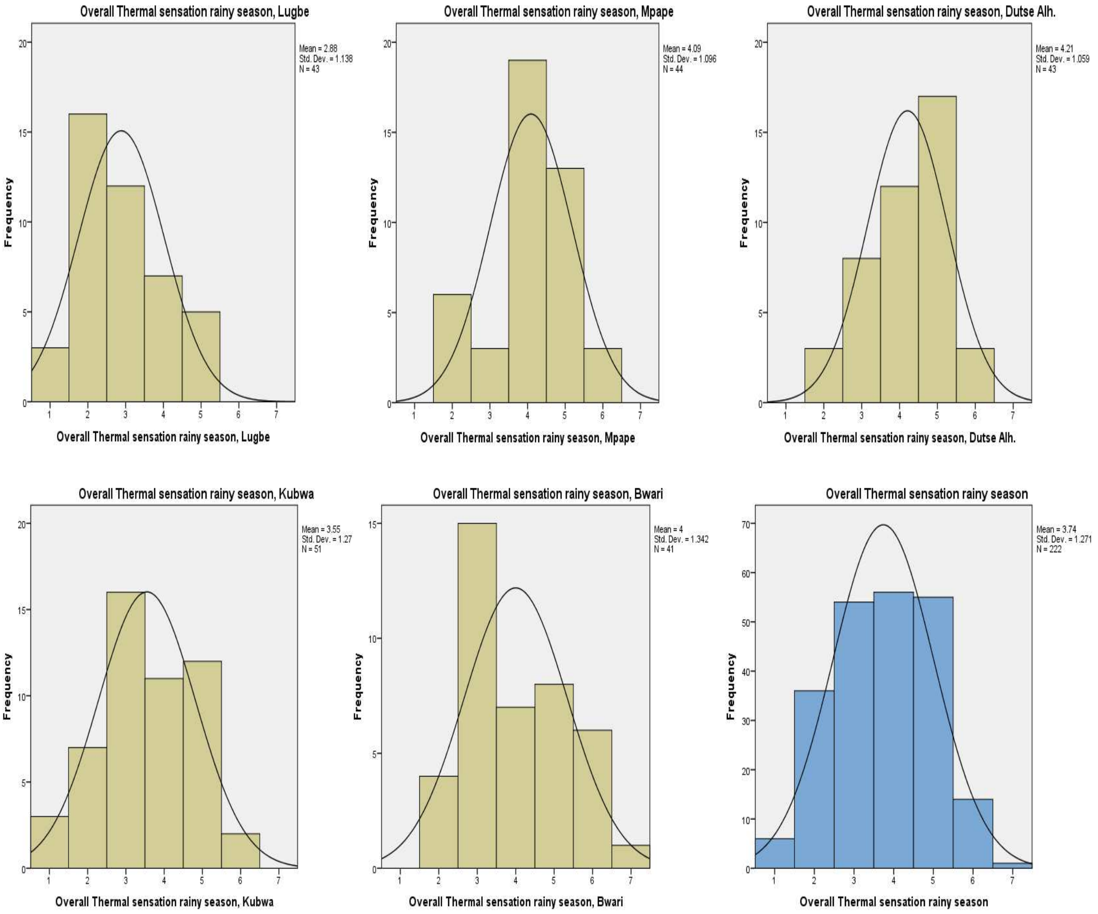


Figure 5 4: Distribution of overall thermal sensation votes during the rainy season across all case studies and the overall combined data (bottom right) (Scale: 1 = cold to 7 = hot)

Table 5.8: Summary of respondents' indoor thermal conditions during the rainy season, post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Thermal sensation	**Cold**	3	7.0	0	0.0	0	0.0	3	5.9	0	0.0	6	2.7
	Cool	16	37.2	6	13.6	3	7.0	7	13.7	4	9.8	36	16.2
	Slightly cool	12	27.9	3	6.8	8	18.6	16	31.4	15	36.6	54	24.3
	Neutral	7	16.3	19	43.2	12	27.9	11	21.6	7	17.1	56	25.2
	Slightly warm	5	11.6	13	29.5	17	39.5	12	23.5	8	19.5	55	24.8
	Warm	0	0.0	3	6.8	3	7.0	2	3.9	6	14.6	14	6.3
	Hot	0	0.0	0	0.0	0	0.0	0	0.0	1	2.4	1	0.5

5.1.2 Thermal comfort analysis of post-occupancy survey

5.1.2.1 Post-occupancy thermal comfort – Dry season

A 7-point scale (from 1 for very uncomfortable to 7 for very comfortable) was used to measure the thermal comfort responses. Overall, more than 50% (Table 5.9) of the total votes from the respondents indicated to be ‘very uncomfortable’ or ‘uncomfortable’ (Figure 5.5). However, Bwari recorded the lowest mean thermal comfort response of 2.3 (Table 5.17) and the highest number of votes with 71% of the respondents (Table 5.9) indicating they were uncomfortable with their thermal environment. They commented that although some had air conditioners, there was poor supply of electricity in the area to power their air conditioners. The lowest votes for discomfort was recorded at Lugbe, where there was an almost even distribution between discomfort/comfort votes with 46.5% experiencing discomfort i.e. only slightly skewed towards discomfort response (Figure 5.5) with a mean response thermal comfort of 3.6 (Table 5.17). The area also recorded the highest number of responses in the comfort range with 25.6% recording a vote of ‘slightly comfortable’ and ‘comfortable’ and a high ‘neutral’ vote of 27.9%.

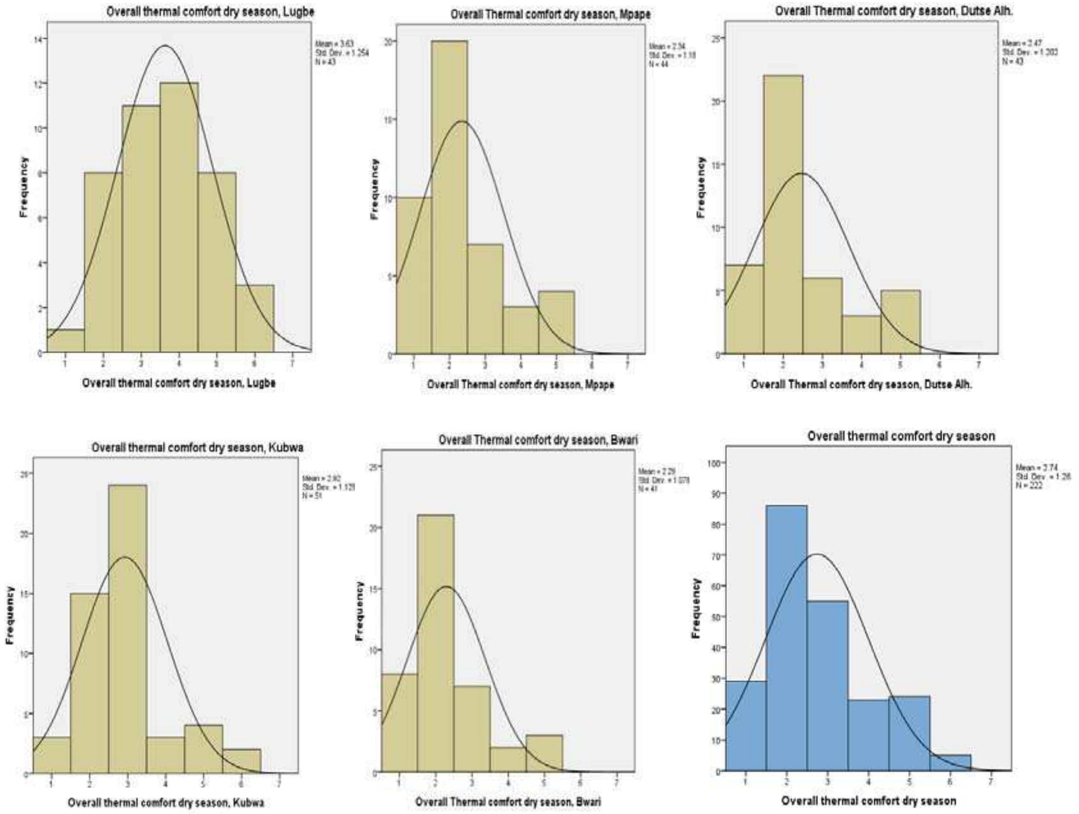


Figure 5.5: Distribution of overall thermal comfort votes during the dry season across all case studies and the overall combined data (Scale: 1 = very uncomfortable to 7 = very comfortable)

Table 5.9: Summary of respondents' indoor thermal comfort during the dry season, post-occupancy survey

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Indoor Thermal comfort	**Very uncomfort.**	1	2.3	10	22.7	7	16.3	3	5.9	8	19.5	29	13.1
	Uncomfort.	8	18.6	20	45.5	22	51.2	15	29.4	21	51.2	86	38.7
	Slightly uncomfort.	11	25.6	7	15.9	6	14.0	24	47.1	7	17.1	55	24.8
	Neutral	12	27.9	3	6.8	3	7.0	3	5.9	2	4.9	23	10.4
	Slightly comfortable	8	18.6	4	9.1	5	11.6	4	7.8	3	7.3	24	10.8
	Comfortable	3	7.0	0	0.0	0	0.0	2	3.9	0	0.0	5	2.3
	Very comfortable	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0

The relative humidity experienced by respondent was measured on a 7-point scale with 1 for very dry to 7 for very humid with 73% of the total votes in all the case studies indicated they were 'very dry', 'dry' and 'slightly dry'. Dutse Alhaji recorded the highest number of votes skewed to the dry part of the scale, with 87.8% occupants feeling 'very dry', 'dry' and 'slightly dry' and residents in Kubwa recorded the lowest number of votes of 56.8 % (Table 5.10).

Table 5.10: Summary of respondents' indoor relative humidity during the dry season, post-occupancy survey

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Humidity	**Very dry**	0	0.0	0	0.0	3	7.0	4	7.8	2	4.9	9	4.1
	dry	18	41.9	15	34.1	24	55.8	12	23.5	19	46.3	88	39.6
	Slightly dry	10	23.3	21	47.7	10	23.3	13	25.5	11	26.8	65	29.3
	Neutral	9	20.9	8	18.2	6	14.0	10	19.6	9	22.0	42	18.9
	Slightly humid	4	9.3	0	0.0	0	0.0	7	13.7	0	0.0	11	5.0
	humid	2	4.7	0	0.0	0	0.0	3	5.9	0	0.0	5	2.3
	Very humid	0	0.0	0	0.0	0	0.0	2	3.9	0	0.0	2	0.9

S.S. = Sample size

5.1.2.2 **Post-occupancy thermal comfort – Rainy season**

The thermal comfort responses for the rainy season showed 45.5% (Table 5.11) of the total votes from the respondents of all the case studies were either 'very comfortable', 'comfortable' and 'slightly comfortable' compared to 26% who felt 'very uncomfortable', 'uncomfortable' and 'slightly uncomfortable', indicating a shift towards the slightly comfortable/comfortable part of the scale (Figure 5.6), compared to the dry season where most of the respondents experienced discomfort. Respondents in Lugbe had the highest response of on the comfortable part of the scale with over 83% feeling either 'very comfortable', 'comfortable' or 'slightly comfortable' with 18% of the respondents in Dutse Alhaji showing the least comfortable votes.

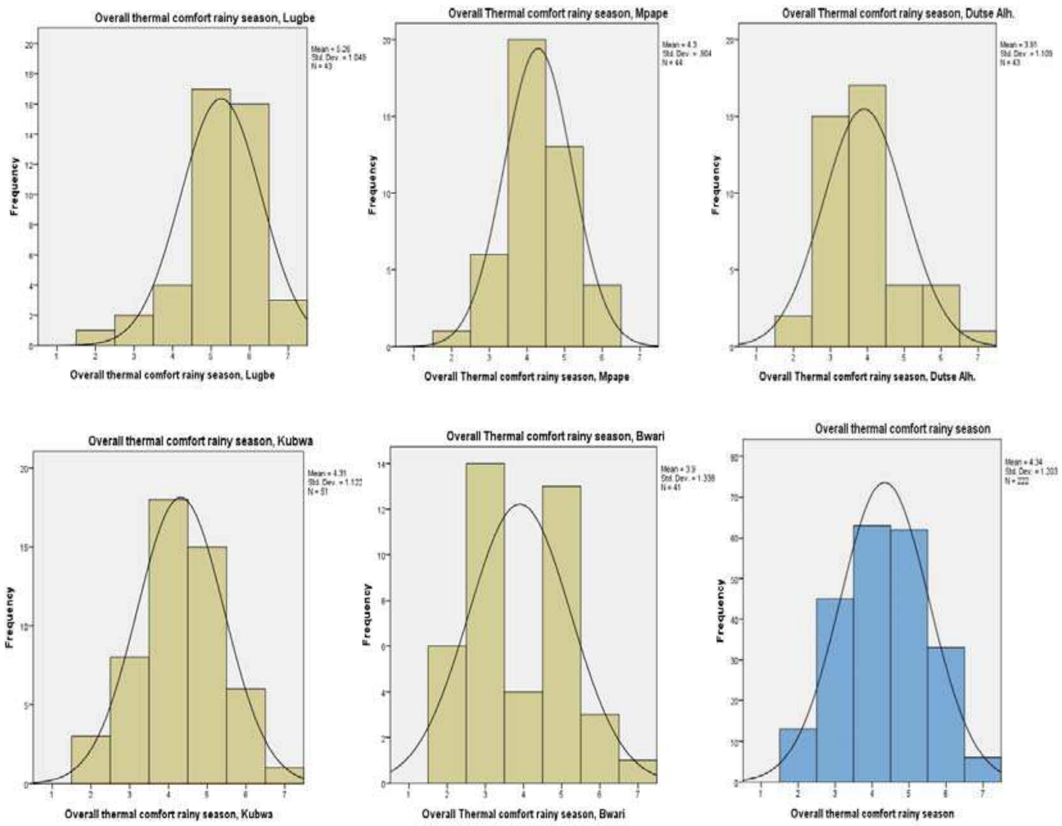


Figure 5.6: Distribution of overall thermal comfort votes during the rainy season across all case studies and the overall combined data (Scale: 1 = very uncomfortable to 7 = very comfortable)

Table 5.11: Summary of respondents' indoor thermal comfort during the rainy season, post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Indoor Thermal comfort	**Very uncomfort.**	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
	Uncomfort.	1	2.3	1	2.3	2	4.7	3	5.9	6	14.6	13	5.9
	Slightly uncomfort.	2	4.7	6	13.6	15	34.9	8	15.7	14	34.1	45	20.3
	Neutral	4	9.3	20	45.5	17	39.5	18	35.3	4	9.8	63	28.4
	Slightly comfortable	17	39.5	13	29.5	4	9.3	15	29.4	13	31.7	62	27.9
	Comfortable	16	37.2	4	9.1	4	9.3	6	11.8	3	7.3	33	14.9
	Very comfortable	3	7.0	0	0.0	1	2.3	1	2.0	1	2.4	6	2.7

S.S. = Sample size

The relative humidity experienced by respondent was skewed towards ‘slightly humid’ and ‘humid’ part of the scale (Table 5.12), with over 60% of the responses at either ‘slightly humid’, ‘humid’ or ‘very humid’. There was a low response for the dry part of the scale with less than 10% feeling either ‘very dry’ or ‘slightly dry’. This can be attributed to the rainy season where the humidity levels are high compared to the dry season.

Table 5.12: Summary of respondents’ indoor relative humidity during the rainy season, post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Humidity	**Very dry**	0	0.0	0	0.0	1	2.3	1	2.0	0	0.0	2	0.9
	dry	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
	Slightly dry	1	2.3	3	6.8	1	2.3	3	5.9	2	4.9	10	4.5
	Neutral	4	9.3	19	43.2	9	20.9	17	33.3	11	26.8	60	27.0
	Slightly humid	11	25.6	20	45.5	12	27.9	16	31.4	19	46.3	78	35.1
	humid	20	46.5	2	4.5	19	44.2	10	19.6	6	14.6	57	25.7
	Very humid	7	16.3	0	0.0	1	2.3	4	7.8	3	7.3	15	6.8

S.S. = Sample size

5.1.3 Thermal preference analysis of post-occupancy survey

5.1.3.1 Post-occupancy thermal preference – Dry season

The thermal preference was recorded on a 5-point scale of ‘1’ for much cooler and ‘5’ for much warmer. The results showed an overwhelming response for the much cooler/ cooler part of the scale during the dry season across all the dwellings (Table 5.13), with more than 80% of the occupants preferring to be ‘much cooler’ and ‘cooler’ and a mean response of 1.7 (Table 5.17) in all the case studies during the dry season (Figure 5.7).

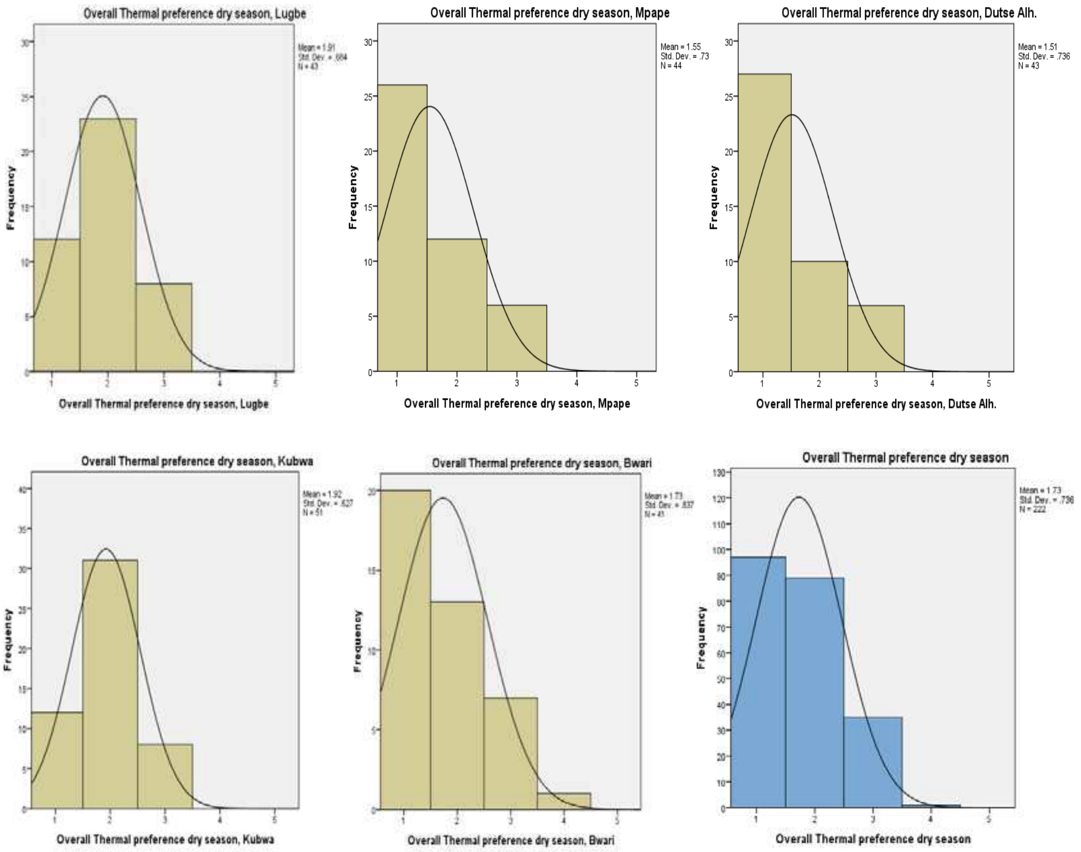


Figure 5.7: Distribution of overall thermal preference votes during the dry season across all case studies and the overall combined data (Scale: 1 = much cooler to 5 = much warmer)

Table 5.13: Summary of respondents' indoor thermal preference during the dry season, post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Thermal preference	**Much cooler**	12	27.9	26	59.1	27	62.8	12	23.5	20	48.8	97	43.7
	Cooler	23	53.5	12	27.3	10	23.3	31	60.8	13	31.7	89	40.1
	No change	8	18.6	6	13.6	6	14.0	8	15.7	7	17.1	35	15.8
	Warmer	0	0.0	0	0.0	0	0.0	0	0.0	1	2.4	1	0.5
	Much warmer	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0

S.S. = Sample size

5.1.3.2 Post-occupancy thermal preference – Rainy season

The thermal preference showed an overwhelming response for the cooler part of the scale during the rainy season across all the dwellings (Table 5.14), with at least 48% of the occupants preferring to be 'cooler' and a mean response of 2.3 (Figure 5.8) indicating high temperatures during the rainy season where occupants want to be cooler. However, there was a high neutrality response of 46%, for occupants in Lugbe who preferred ‘no change’ at all to their indoor thermal conditions.

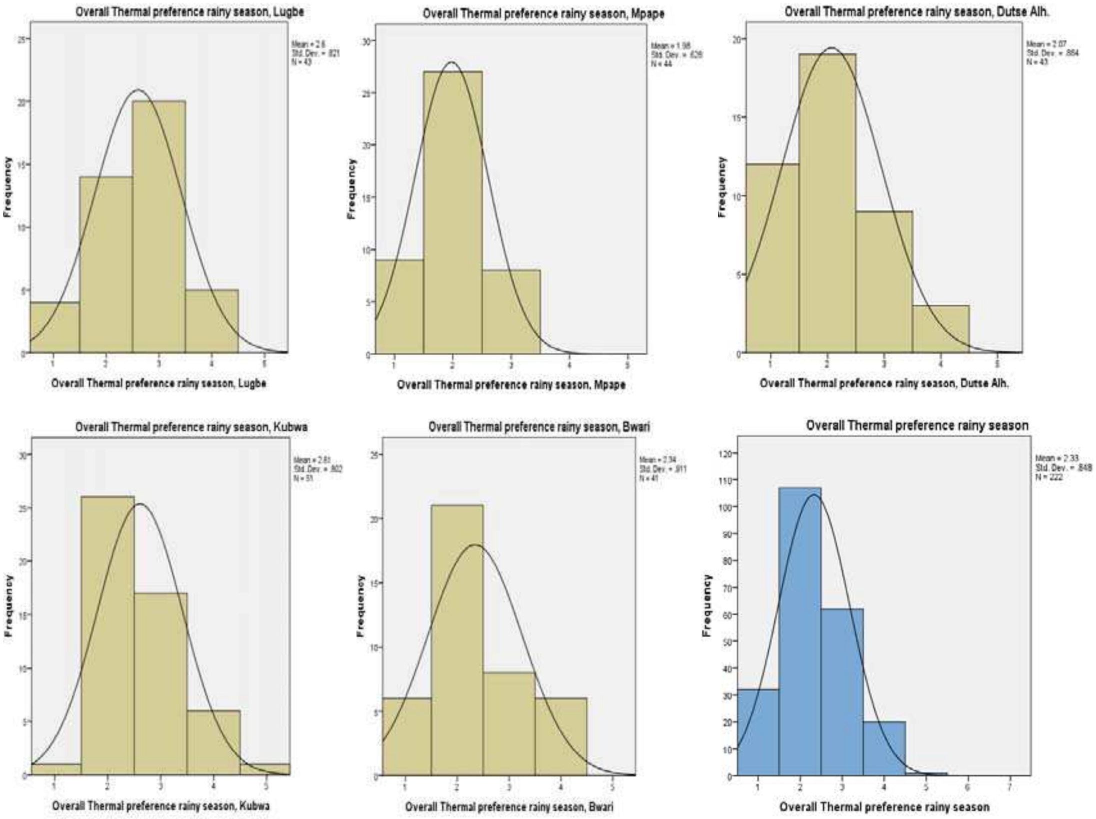


Figure 5.8: Distribution of overall thermal preference votes during the rainy season in across all case studies and the overall combined data (Scale: 1 = much cooler to 5 = much warmer)

Table 5.14: Summary of respondents’ indoor thermal preference during the rainy season, post-occupancy survey

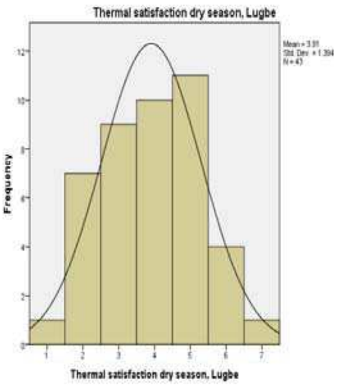
		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Thermal preference	**Much cooler**	4	9.3	9	20.5	12	27.9	1	2.0	6	14.6	32	14.4
	cooler	14	32.6	27	61.4	19	44.2	26	51.0	21	51.2	107	48.2
	No change	20	46.5	8	18.2	9	20.9	17	33.3	8	19.5	62	27.9
	warmer	5	11.6	0	0.0	3	7.0	6	11.8	6	14.6	20	9.0
	Much warmer	0	0.0	0	0.0	0	0.0	1	2.0	0	0.0	1	0.5

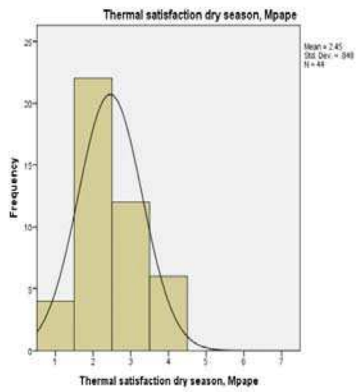
5.1.4 Thermal satisfaction analysis of post-occupancy survey

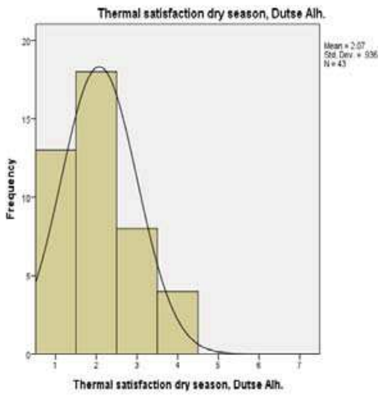
5.1.4.1 Post-occupancy thermal satisfaction – Dry season

Practitioners and researchers refer to standards to determine appropriate thermal conditions. The standards outline temperature ranges that should result in thermal satisfaction for at least 80% of occupants in a space (Charles, 2003; Djongyang et al., 2010). The thermal satisfaction votes were measured on a 7-point scale with '1' for very dissatisfied to '7' for very satisfied. More than 40% of the occupants were either 'very dissatisfied satisfied' or 'dissatisfied' with their thermal environment (Table 5.15 and Figure 5.9). A further breakdown of the thermal satisfaction responses within all the case studies shows that the occupants' in Dutse Alhaji had the highest dissatisfied response with 90.7% of the occupants' indicating they were either 'very dissatisfied', 'dissatisfied' or slightly dissatisfied' followed by Mpape 86.4%, Bwari 66.6%, then Kubwa 65.9% compared to the lowest of 39.5% recorded in Lugbe. Lugbe also had the highest neutral and satisfaction response of 23.3% and 37.2% respectively, (Table 5.15).

These results suggest that the thermal environment has been influenced mostly by the air-conditioning in these buildings and the socio-economic status of the occupants as seen in Table 5.2, Table 5.3 and Table 5.4. Lugbe had the highest number of households with air conditioning with more than 81% of the respondents using air conditioning. However, the level of only air conditioning usage could not be established during this survey.







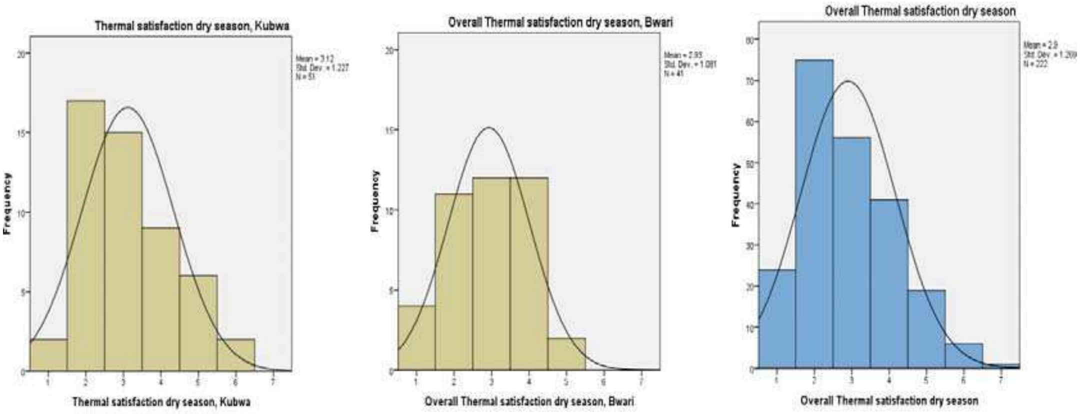


Figure 5.9: Distribution of overall thermal satisfaction votes during the dry season across all case studies and the overall combined data (bottom right) (Scale: 1= very dissatisfied to 7= very satisfied)

The socio-economic status of the occupants in this area also made it possible for them to buy air conditioning systems and pay for alternative source of electricity like generators, when there was no electricity supply from the power grid to power their air conditioners as they could afford it compared to the remaining areas. This impact is also reflected amongst the residents in Kubwa as 68% of residents have air conditioning and were next to the thermal comfort and satisfaction responses when compared to the responses in Lugbe.

Table 5.15: Summary of respondents' indoor thermal conditions during the dry season, post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**
Thermal Satisfaction	**Very dissatisfied**	1	2.3	4	9.1	13	30.2	2	3.9	4	9.8	24	10.8
	Dissatisfied	7	16.3	22	50.0	18	41.9	17	33.3	11	26.8	75	33.8
	Slightly dissatisfied	9	20.9	12	27.3	8	18.6	15	29.4	12	29.3	56	25.2
	Neutral	10	23.3	6	13.6	4	9.3	9	17.6	12	29.3	41	18.5
	Slightly satisfied	11	25.6	0	0.0	0	0.0	6	11.8	2	4.9	19	8.6
	Satisfied	4	9.3	0	0.0	0	0.0	2	3.9	0	0.0	6	2.7
	Very satisfied	1	2.3	0	0.0	0	0.0	0	0.0	0	0.0	1	0.5

5.1.4.2 **Post-occupancy thermal satisfaction – Rainy season**

The thermal satisfaction showed a noticeable shift to the 'neutral' part of the scale with at least 15% of the occupants feeling 'very satisfied' or 'satisfied' and more than 8% felt 'very satisfied' or 'satisfied' with their thermal environment (Table 5.16). This indicates an improved drift from the vastly dissatisfied response recorded in the dry season that can be attributed to the temperature drop during the rainy season.

Linking the results with the post occupancy surveys suggest that 81% of the occupants at Lugbe are mostly satisfied with how they feel in the rainy season compared to less than 50% recorded responses all the other case study locations who feel satisfied (Figure 5.7).

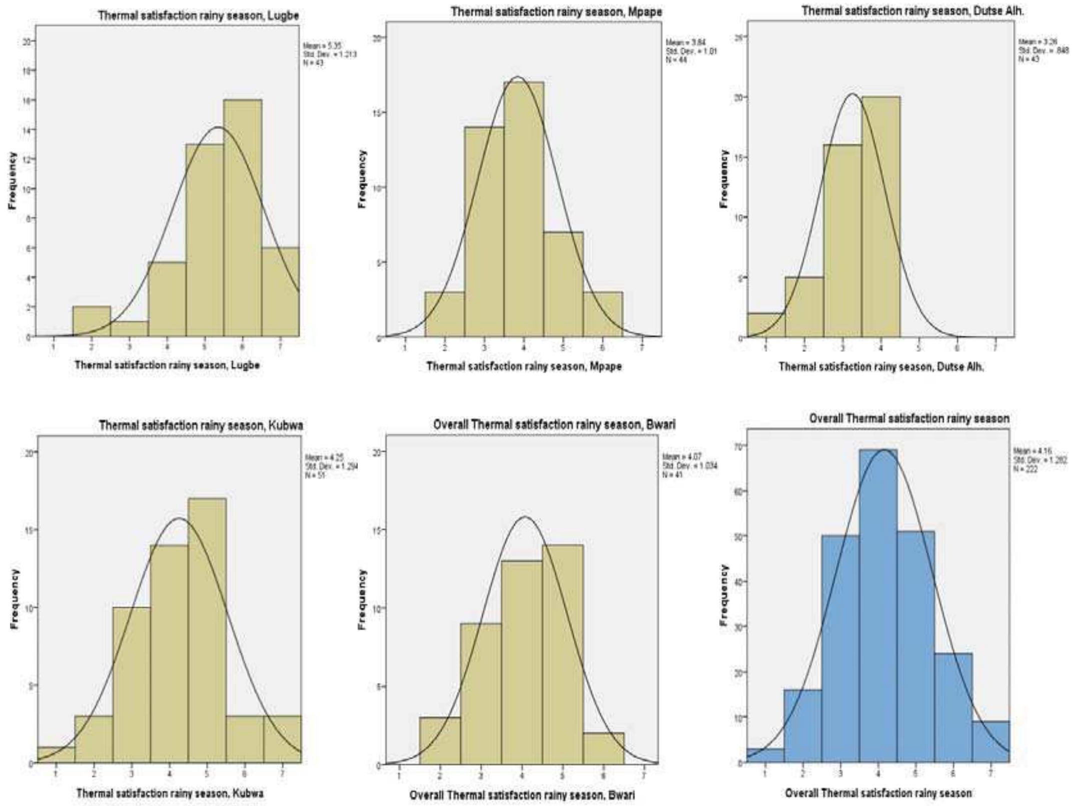


Figure 5.10: Distribution of overall thermal sensation votes during the rainy season across all case studies and the overall combined data (bottom right) (Scale: 1= very dissatisfied to 7= very satisfied)

Table 5.16: Summary of respondents' indoor thermal conditions during the rainy season, post-occupancy survey

		Lugbe (n=43)		**Mpape (n=44)**		**Dutse Alh. (n=43)**		**Kubwa (n=51)**		**Bwari (n=41)**		**Combined (n=222)**	
		S.S.	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S.S.**	**%**	**S. S.**	**%**
Thermal Satisfaction	**Very dissatisfied**	0	0.0	0	0.0	2	4.7	1	2.0	0	0.0	3	1.4
	Dissatisfied	2	4.7	3	6.8	5	11.6	3	5.9	3	7.3	16	7.2
	Slightly dissatisfied	1	2.3	14	31.8	16	37.2	10	19.6	9	22.0	50	22.5
	Neutral	5	11.6	17	38.6	20	46.5	14	27.5	13	31.7	69	31.1
	Slightly satisfied	13	30.2	7	15.9	0	0.0	17	33.3	14	34.1	51	23.0
	Satisfied	16	37.2	3	6.8	0	0.0	3	5.9	2	4.9	24	10.8
	Very satisfied	6	14.0	0	0.0	0	0.0	3	5.9	0	0.0	9	4.1

Table 5.17: Mean responses for thermal sensations (from 1 = cold to 7 = hot), thermal comfort (from 1 = very uncomfortable to 7 = very comfortable) and thermal satisfaction (from 1 = very dissatisfied to 7 = very satisfied) in the dry and rainy season from the post-occupancy survey

		Thermal sensation				**Overall Thermal comfort**				**Thermal satisfaction**			
		Dry Season		**Rainy Season**		**Dry Season**		**Rainy Season**		**Dry Season**		**Rainy Season**	
Location	**N(%)**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Lugbe	43 (78)	5.8	0.751	2.9	1.138	3.6	1.254	5.3	1.049	3.9	1.394	5.4	1.213
Mpape	44 (80)	5.9	0.754	4.1	1.096	2.3	1.18	4.3	0.904	2.5	0.848	3.8	1.01
Dutse A.	43 (80)	6.0	1.144	4.2	1.059	2.5	1.202	3.9	1.109	2.1	0.936	3.3	0.848
Kubwa	51 (75)	5.7	0.973	3.6	1.27	2.9	1.129	4.3	1.122	3.1	1.227	4.3	1.294
Bwari	41 (79)	5.9	0.848	4.0	1.342	2.3	1.078	3.9	1.338	2.9	1.081	4.1	1.034
Combined	222(81)	5.9	0.909	3.7	1.271	2.7	1.26	4.3	1.203	2.9	1.269	4.2	1.282

Daytime post occupancy survey (Dry season)

During the daytime in the dry season, the mean thermal sensation and thermal comfort votes showed an overwhelming response for the warm/hot and very uncomfortable/ uncomfortable/slightly uncomfortable part of the scale (Table 5.18). At least 2% felt comfortable and at least 70 - 89% of the occupants felt warm or hot except for Lugbe that had at least 30% of the respondents feeling warm. It also recorded the highest response of cool/slightly cool range with over 15%, with a mean thermal sensation response of 5.7 (see Table A1.3). This can be attributed to the data in Table 5.4 where Lugbe had the highest households with air conditioning.

Night-time post occupancy survey (Dry season)

During the night-time in the dry season, the thermal sensation votes showed a slight shift in response compared to the daytime responses (Table 5.18), with less than 60% feeling warm/hot across all case studies and more responses in the very cool/cool/slightly cool part of the scale. Overall, only 38% across all case studies felt uncomfortable and very uncomfortable, more than a 10% shift towards the comfort part of the scale compared to the daytime comfort response (see Table A1.4).

Table 5.18: Mean responses for thermal sensation and thermal comfort in the daytime and night-time during the dry season from the post-occupancy survey

		Thermal sensation				**Overall Thermal comfort**			
		Daytime		**Night time**		**Daytime**		**Night time**	
Location	**N(%)**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Lugbe	43 (78)	5.7	1.423	4.5	1.517	2.7	1.347	3.3	1.432
Mpape	44 (80)	6.1	0.668	5.2	0.803	2.0	0.876	2.7	0.708
Dutse A.	43 (80)	6.3	0.934	5.3	1.260	2.5	1.202	2.9	0.990
Kubwa	51 (75)	6.2	1.159	5.2	1.461	3.0	1.140	3.2	1.332
Bwari	41 (79)	5.9	1.020	5.4	1.220	2.3	0.923	3.0	0.880
Combined	222 (81)	6.1	1.085	5.1	1.311	2.5	1.160	3.0	1.134

Daytime post occupancy survey (Rainy season)

During the day time in the rainy season, the mean thermal sensation votes showed a shift in votes from the warm/hot part of the scale to slightly warm/neutral/slightly cool. This shift suggests the rain during the day has contributed to lower temperatures compared to the dry season when temperatures where high. More respondents also felt more comfortable across all case studies, though 62% preferred to be slightly cooler (see Table A1.5).

Night-time post occupancy survey (Rainy season)

During the night time in the rainy season, the thermal sensation votes showed an overwhelming shift in response for the slightly cool/cool/cold part of the scale with at least 41% feeling ‘cool’ or ‘cold’ across all case studies. Overall, only 3.2% across all case studies felt uncomfortable, at least a 16% shift towards the comfort part of the scale compared to the daytime comfort response. The comments from the survey showed that occupants acknowledged that this is the period where they least use their controls like air conditioners and opening of windows due to a shift in indoor thermal sensation from the warm part of the scale experienced in the dry season to the cool part of the scale during the rainy season (see Appendix 1.6). The mean thermal sensation votes show a massive shift towards the neutral part of the scale (Table 5.19).

Table 5.19: Mean responses for thermal sensations and thermal comfort in the daytime and night time during the rainy season from the post-occupancy survey

		Thermal sensation				**Overall Thermal comfort**			
		Daytime		**Night time**		**Daytime**		**Night time**	
Location	**N(%)**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Lugbe	43 (78)	4.2	1.525	3.2	1.385	3.9	1.366	4.3	1.161
Mpape	44 (80)	3.6	0.754	2.7	0.983	3.3	1.073	3.8	1.091
Dutse A.	43 (80)	4.5	1.241	3.3	1.241	3.4	1.220	3.8	1.146
Kubwa	51 (75)	3.7	1.372	2.9	1.475	4.1	1.200	4.8	1.233
Bwari	41 (79)	4.2	1.364	3.2	1.476	3.5	1.247	4.2	1.263
Combined	222(81)	4.0	1.313	3.0	1.333	3.7	1.254	4.2	1.233

5.1.5 Statistical analysis of Post-Occupancy Survey

Statistical tests were carried out to further understand how thermal comfort and adaptation parameters affect occupants comfort. There is a need to look whether there are significant relationships between these parameters to know the most effective.

5.1.5.1 **Data banding**

By choosing possible explanatory parameters (thermal sensation, thermal comfort, thermal preference, etc) and their banding values, it is possible to check for the significant difference in the mean for each parameter. A series of one-way analysis of variance tests (ANOVAs) were ran on the following factors (see Table 5.20) to find out their level of significance.

Table 5.20: Banding of data for ANOVA and Independent T – Tests

Factor	Banding
Thermal sensation	Cold ::= 1 Cool ::= 2 Slightly cool ::= 3 Neutral ::= 4 Slightly warm ::= 5 Warm ::= 6 Hot ::= 7
Indoor Thermal comfort	Very uncomfortable ::= 1 Uncomfortable ::= 2 Slightly uncomfortable ::= 3 Neutral ::= 4 Slightly comfortable ::= 5 Comfortable ::= 6 Very comfortable ::= 7
Thermal preference	Much cooler ::= 1 Slightly cooler ::= 2 No change ::= 3 Slightly warmer ::= 4 Much warmer ::= 5
Thermal Satisfaction	Very dissatisfied ::= 1 Dissatisfied ::= 2 Slightly dissatisfied ::= 3 Neutral ::= 4 Slightly satisfied ::= 5 Satisfied ::= 6 Very satisfied ::= 7
Socio-economic status	Low-income ::= 1 Low-medium ::= 2 Medium ::= 3
Houses with AC	Yes ::= 1 No ::= 2
Use of indoor controls	Very little ::= 1 Little ::=2 Slightly little ::= 3 Neutral ::= 4 Slightly much ::= 5 Much ::= 6 Very much ::= 7

Statistical tests were conducted based on the correlation between the parameters in table 5.20 and details of the results are discussed below:

i. **Socio-economic status and thermal satisfaction*:*** In terms of the relationship between socio-economic status and thermal satisfaction, the low-income, low-middle and upper income earners across the case study locations are not thermally satisfied with their thermal environment during the dry season (Table 5.21). On the contrary, there was significance (Table 5.21 and 5.22) at Lugbe where it showed the lowest level of dissatisfaction was recorded by the middle earners with the low-middle earners indicating neutrality ($r = 0.045$, $p < 0.05$). The $F_{criterion} = 3.23$, where $F_{criterion} = F_{.95}(\upsilon_1\upsilon_2)$ at $\alpha = 0.05$, which is less than the F value in table 5.22 (i.e. 3.23 < 7.21). Therefore, there is a significant difference between the means in Lugbe.

Table 5.21: ANOVA test description between socio-economic status and thermal satisfaction

Thermal satisfaction dry season, Lugbe			
	N	Mean	Std. Deviation
Low-income	18	3.50	1.383
Lower medium-income	22	4.50	1.102
Upper medium-income	3	2.00	1.000
Total	43	3.91	1.394

Table 5.22: ANOVA test results between employed status and thermal satisfaction

Thermal satisfaction dry season, Lugbe						
	Sum of Squares	df	Mean Square	Sig.	R	F
Between Groups	21.628	2	10.814	.002	.045	7.21
Within Groups	60.000	40	1.500			
Total	81.628	42				

ii. ***Socio-economic status and thermal comfort:*** The findings show that the low-income earners and the low-middle income earners are less comfortable compared to the middle-income earners (Table 5.23). A correlation is formed between socio-economic status and thermal comfort in Dutse Alhaji during the dry season. Significance was noted as $r = 0.384$, $p < 0.05$ and in Bwari, $r = 0.577$, $p < 0.05$ (Table 5.24).

Table 5.23: ANOVA test description between socio-economic status and thermal comfort

Thermal comfort dry season						
	Dutse Alhaji			**Bwari**		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
Low-income	31	2.23	1.117	27	1.93	0.675
Lower medium-income	11	2.91	1.136	10	2.60	1.174
Upper medium-income	1	5.00	.	4	4.00	1.414
Total	43	2.47	1.202	41	2.29	1.078

Table 5.24: ANOVA test results between employment status and thermal comfort

Thermal comfort dry season												
	Dutse Alhaji						Bwari					
	Sum of Squares	df	Mean Square	Sig.	R	F	Sum of Squares	df	Mean Square	Sig.	R	F
Between Groups	10.369	2	5.185	.024	.384	4.12	16.236	2	8.118	0.000	.577	10.20
Within Groups	50.328	40	1.258				30.252	38	0.796			
Total	60.698	42					46.488	40				

In terms of thermal comfort, there is a higher satisfaction rate in the middle income. In Dutse Alhaji and Bwari, income level is directly proportional to comfortability. However, the mean values in Lugbe were focused on neutrality across the different categories of income earners when it came to overall thermal comfort though there was no significant difference, $r = 0.199$, $p > 0.05$ while $r = 0.111$, $p > 0.05$ in Kubwa. It was noted in the comments by the respondents that the residents here spend longer hours outdoors compared to residents in Dutse Alhaji. As income increases, people tend to be more comfortable in their spaces and can afford alternative source of power and cater for maintenance i.e. generators and provision of fuel for generators. For the level of satisfaction for the use of control for Dutse Alhaji, the $F_{criterion} = 3.23$, is less than the F value of 4.12 in table 5.24 (i.e. $3.23 < 4.12$). While in Bwari, the $F_{criterion} = 3.23$, less than the F value of 10.197 (i.e. $3.23 < 10.20$). Therefore, there is a significant difference between the means in Dutse Alhaji and Bwari.

iii. **Thermal satisfaction and the use of controls:** Across all case studies, Dutse Alhaji and Lugbe had a correlation between thermal satisfaction and the use of controls, however there was no significant difference between the variables where $r = 0.473$, $p > 0.05$ was noted in Dutse Alhaji and $r = 0.363$, $p > 0.05$ in Lugbe (Table 5.25). The occupants' in both case study areas perceived little level of control and are not thermally satisfied (Table 5.26). There is a potential that there is limited period to use the control, there might be limited time to use controls like air conditioners, fans due to power cuts and poor power supply to the area. Also, residents noted that they cannot keep their windows and doors open for longer periods due to security concerns and mosquitoes especially at night. Significance was not reported in other case studies though there was high response of thermal dissatisfaction. There was also significance recorded between the level of satisfaction of the use of control and thermal satisfaction in Lugbe where $r = 0.764$, $p < 0.05$. However, the P – values in all the other case studies where higher than 0.05, therefore there is no evidence of significance. This shows that the residents that are thermally dissatisfied have a low level of control while people that thermally satisfied have high level of control.

Table 5.25: ANOVA test description between level of satisfaction of the use of control and thermal satisfaction

Use of controls dry season, Lugbe			
	N	Mean	Std. Deviation
Dissatisfied	8	2.13	0.641
Slightly dissatisfied	3	3.33	1.528
Neutral	15	4.00	0.845
Slightly satisfied	13	4.31	1.032
Satisfied	3	6.00	0.000
Very satisfied	1	7.00	-
Total	43	3.91	1.394

Table 5.26: ANOVA test results between level of satisfaction of the use of control and thermal satisfaction

Use of controls dry season, Lugbe						
	Sum of Squares	df	Mean Square	Sig.	R	F
Between Groups	51.317	5	10.263	0.000	.764	12.53
Within Groups	30.311	37	0.819			
Total	81.628	42				

For the level of satisfaction for Dutse Alhaji, the $F_{criterion}$ = 3.23, is less than the F value of 12.53 in table 5.26 (i.e. 2.45 < 12.53). Therefore, there is a significant difference between the means in Lugbe.

iv. ***Dwellings with air conditioning and the level of satisfaction of use of controls:*** The study shows there was correlation between the dwellings with air conditioning with the level of satisfaction of use of controls in Lugbe and Dutse Alhaji. There was a significance between people that use air conditioning and people that do not use air conditioning where Lugbe had a significant level of $r = 0.357$, $p < 0.05$ and $r = 0.439$, $p < 0.05$ in Dutse Alhaji (Table 5.27 and 5.28). All the remaining case studies reported no correlation or significant difference. It was expected that occupants living in houses with air conditioning would have high level of control. However, the study shows that people living in building with air conditioning do not have high level of control as the mean value of the subject votes focuses on neutrality. The occupants living in the buildings with no air conditioning do have high level of control. The irregular supply of power also affects performance of air conditioning due to damages caused when high voltage electricity was supplied into the buildings. For the level of satisfaction for the use of control for Dutse Alhaji, the $F_{criterion}$ = 3.23, is less than the F value of 5.99 in table 5.28 (i.e. 3.23 < 5.99). While in Bwari, the $F_{criterion}$ = 3.23, less than the F value of 9.76 (i.e. 3.23 < 9.76). Therefore, there is a significant difference between the means in Dutse Alhaji and Bwari.

Table 5.27: ANOVA test description between level of satisfaction of the use of control and dwellings with Air Conditioning

level of satisfaction of the use of control						
	Lugbe			**Dutse Alhaji**		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
Yes	35	4.29	1.226	22	4.05	1.253
No	8	3.13	1.126	21	2.95	1.024
Total	43	4.07	1.280	43	3.51	1.261

Table 5.28: ANOVA test results between level of satisfaction of the use of control and dwellings with Air Conditioning

level of satisfaction of the use of control												
	Dutse Alhaji						**Bwari**					
	Sum of Squares	df	Mean Square	Sig.	R	F	Sum of Squares	df	Mean Square	Sig.	R	F
Between Groups	8.773	1	8.773	.019	.357	5.99	12.837	1	12.837	.003	.439	9.76
Within Groups	60.018	41	1.464				53.907	41	1.315			
Total	68.791	42					66.744	42				

For the level of satisfaction of the use of control for Lugbe, the $F_{criterion}$ = 4.08, which is less than the F value in table 5.28 (i.e. 5.9 > 4.08). Therefore, there is a significant difference between the means.

v. ***Thermal comfort and thermal satisfaction:*** Applying Pearson correlation shows that thermal satisfaction and thermal comfort are correlated only in Mpape, where $r = 0.562$, $p < 0.05$ (Table 5.29). The respondents that are thermally dissatisfied where also thermally uncomfortable. Further analysis shows that more than 80% of the buildings surveyed do no use air conditioning during the dry season (Table 5.4) for adjusting the thermal environment of the indoor spaces. Linking the findings to overall design of Mpape, it shows the buildings were clustered (i.e. around 1.5-3m apart) and this may be a contributing factor, as fresh air is not properly circulated within the buildings. Thermal comfort and thermal satisfaction statistical analysis for Mpape showed $F_{criterion}$ = 2.84, less than the F value in table 5.30 (i.e. 2.84 < 15.85). Therefore, there is a significant difference between the means.

Table 5.29: ANOVA test description between thermal comfort and thermal satisfaction

Overall Thermal comfort dry season, Mpape			
	N	Mean	Std. Deviation
Very dissatisfied	4	2.00	0.816
Dissatisfied	22	1.95	0.999
Slightly dissatisfied	12	2.08	0.289
Neutral	6	4.50	0.837
Total	44	2.34	1.180

Table 5.30: ANOVA test results between thermal comfort and thermal satisfaction

Overall Thermal comfort dry season, Mpape						
	Sum of Squares	df	Mean Square	Sig.	R	F
Between Groups	32.515	3	10.838	.000	.562	15.85
Within Groups	27.371	40	.684			
Total	59.886	43				

vi. ***Thermal comfort and thermal preference:*** People that prefer to be much cooler are not comfortable with their thermal environment, however people that prefer no change indicated neutrality in Mpape ($r = 0.643$, $p < 0.05$). In Kubwa, people that prefer no change and prefer to be cooler are not comfortable with their thermal environment ($r = 0.338$, $p < 0.05$), (Table 5.31 and 5.32). It was observed that kubwa had longer hours of electricity supply, this may likely can possibly contribute to higher satisfaction rate reported at the case study location. For the level of satisfaction of the use of control for Dutse Alhaji, the $F_{criterion} = 3.23$, is less than the F value in table 5.32 (i.e. 3.23 < 24.942). While in Bwari, the $F_{criterion} = 3.23$, less than the F value of 3.68 (i.e. 3.23 < 3.68). Therefore, there is a significant difference between the means (Table 5.32).

Table 5.31: ANOVA test description between thermal comfort and thermal preference

level of satisfaction of the use of control						
	Mpape			Kubwa		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
Much cooler	26	1.92	0.628	12	2.25	0.965
Slightly cooler	12	2.17	1.193	31	3.03	0.948
No change	6	4.50	0.548	8	3.50	1.604
Total	44	2.34	1.180	51	2.92	1.129

Table 5.32: ANOVA test results between thermal comfort and thermal preference

level of satisfaction of the use of control												
	Dutse Alhaji						**Bwari**					
	Sum of Squares	df	Mean Square	Sig.	R	F	Sum of Squares	df	Mean Square	Sig.	R	F
Between Groups	32.874	2	16.437	0.000	.643	24.94	8.469	2	4.234	0.033	.338	3.68
Within Groups	27.013	41	0.659				55.218	48	1.150			
Total	59.886	43					63.686	50				

vii. ***Thermal satisfaction and thermal preference***: There was a correlation between occupants in Mpape and Dutse Alhaji between the thermal satisfaction and thermal preference. Further test indicated a significant difference with $r = 0.417$, $p < 0.05$ in Mpape and $r = 0.569$, $p < 0.05$ in Dutse Alhaji (Table 5.33 and 5.34), though there was no correlation and significance recorded in the remaining case studies. The significance recorded in Mpape shows that the urban cluster characteristics of the building in the area can be a contributing factor to the thermal dissatisfaction among the residents in the area. Also, the high temperatures recorded and cluster design in Dutse Alhaji can be contributing factors to the recorded dissatisfaction and the preference to feel much cooler. Thus, further investigation will be required to establish if cluster design would be a significant impact on thermal satisfaction and thermal preference at the case study location in Mpape and Dutse Alhaji. For thermal preference for Dutse Alhaji, the $F_{criterion} = 2.84$, is less than the F value in table 5.34 (i.e. $2.84 < 8.81$). While in Bwari, the $F_{criterion} = 2.84$, less than the F value of 8.19 (i.e. $2.84 < 8.19$). Therefore, there is a significant difference between the means.

Table 5.33: ANOVA test description between thermal comfort and thermal preference

Thermal preference dry season						
	Mpape			Dutse Alhaji		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
Very dissatisfied	4	1.25	0.500	13	1.00	0.000
Dissatisfied	22	1.45	0.671	18	1.44	0.511
Slightly dissatisfied	12	1.25	0.452	8	2.25	0.886
Neutral	6	2.67	0.516	4	2.00	1.155
Total	44	1.55	0.730	43	1.51	0.736

Table 5.34: ANOVA test results between thermal comfort and thermal preference

Thermal preference dry season												
	Dutse Alhaji						**Bwari**					
	Sum of Squares	df	Mean Square	Sig.	R	F	Sum of Squares	df	Mean Square	Sig.	R	F
Between Groups	9.121	3	3.040	0.000	.417	8.81	8.800	3	2.933	0.000	.569	8.19
Within Groups	13.788	40	0.345				13.944	39	0.358			
Total	22.909	43					22.744	42				

5.2 Analysis of Environmental Survey

The outdoor monitoring during the dry season surveys was carried out in Abuja from 11/03/2015 to 06/05/2015. The indoor monitoring started at Lugbe on 18/03/2015 and ended on 06/03/2015 at Bwari. The outdoor monitoring during the rainy season was carried out from 10/06/2015 to 16/07/2015, while the indoor monitoring started at Lugbe on 17/06/2015 and ended on 23/07/2015 at Bwari.

5.2.1 Outdoor dry season conditions

The external temperatures for Lugbe throughout the monitoring period in the dry season varied from the minimum of 23.5°C on 21/3/2015 to a maximum of 41.1°C on 19/03/2015, which was the highest during the entire monitoring period. The survey reported an average temperature of 31°C (Table 5.35), while the relative humidity varied from 18.7% on 19/03/2015 to a maximum of 91.2% on 21/03/2015 (Figure 5.11a), and an average of 56%. The outdoor temperature for Mpape varied from 21.5°C on 31/03/2015 to a maximum of 37.5°C on 06/04/2015. The survey in Mpape reported an average outdoor temperature of 29.4°C (Table 5.36), while the relative humidity varied from 14% on 02/03/2015 to a maximum of 99.3% on 31/04/2015 (Figure 5.11b), and an average of 56%. The outdoor temperature in Dutse Alhaji varied from 23.0°C on 15/04/2015 to a maximum of 38.4^{o} on 14/04/2015 (Figure 5.12a) and an average of 35.4% throughout the monitoring period (Table 5.36). The area also recorded a relative humidity varying from 9.9% on 11/04/2015 to a maximum of 92.7% on 17/04/2015 and an average of 36.6%.

The outdoor temperature in Kubwa varied from 30.9°C on 21/04/2015 to a maximum of 38.9^{o} on 27/04/2015 and an average of 30.3% throughout the monitoring period (Table 5.35). The area also recorded a relative humidity varying from 21.5% on 21/04/2015 to a maximum of 85.5% on 26/04/2015 (Figure 5.12b) and an average of 54.7%. Lastly, the temperature in Bwari varied from 30°C on 15/04/2015 to a maximum of 38.6^{o} on 14/04/2015 and an average of 30.9°C throughout the monitoring period (Table 5.36). The area also recorded a relative humidity varying from 31.4% on 30/04/2015 to a maximum of 97% on 07/05/2015 (Figure 5.13) and the highest average of 68.7% during the entire monitoring period in the dry season.

Table 5.35: Summary of maximum, minimum, average and range of external temperature and relative humidity during the environmental monitored period in the dry season in Abuja.

	Temperature (°C) data				**Relative humidity (%) data**				**Max (°C)**	**Min (°C)**
	Max Temp.	**Min Temp**	**Avg. Temp**	**Temp Range**	**Max R.H**	**Min R.H.**	**Avg. R.H.**	**R.H. Range**	**Date/ time**	**Date/ time**
Lugbe	41.1	23.5	31.1	22.4	91.2	18.7	56.1	67.7	19/03/2015 16:00	21/03/2015 18:00
Mpape	37.5	21.5	29.4	16.0	99.3	14.1	50.1	85.2	06/04/2015 16:00	31/03/2015 03:00
Dutse Alh.	38.4	23.0	30.3	15.4	92.7	9.9	36.6	82.8	14/04/2015 16:00	15/04/2015 06:00

	Temperature (°C) data				Relative humidity (%) data				Max (°C)	Min (°C)
	Max Temp.	Min Temp	Avg. Temp	Temp Range	Max R.H	Min R.H.	Avg. R.H.	R.H. Range	Date/ time	Date/ time
Kubwa	38.9	24.9	30.9	14.0	85.5	21.5	54.7	64.0	21/04/2015 16:00	27/04/2015 07:00
Bwari	38.6	22.2	30.1	16.4	97.0	31.4	68.7	65.6	04/05/2015 16:00	07/05/2015 00:00

Measured weighted running mean temperatures

The measured outdoor temperature had a running mean temperature, $T_{rm,}$ for the dry season (Figures 5.11-5.13) as defined by BSENI 15251 (BSI, 2008) varying from 32°C on 23/03/2015 to a maximum of 33.3°C on 21/03/2015 in Lugbe. In Mpape it varied from 29.3°C on 01/04/2015 to a maximum of 31°C on 06/04/2015; it varied from 30.8°C 11/04/2015 to a maximum of 31.4°C on 17/04/2015. In Dutse Alhaji; in Kubwa it varied from 31.8°C on 27/04/2015 to a maximum of 32.6°C on 24/04/2015 and lastly it varied in Bwari from 31°C on 04/05/2015 to a maximum of 32°C on 01/05/2015 during the dry season monitoring. During the rainy season (Figures 5.14-5.16), the T_{rm} varied from 26.7°C on 19/06/2015 to a maximum of 26.9°C on 20/06/2015 in Lugbe. In Mpape it varied from 26.9°C on 28/06/2015 to a maximum of 27.2°C on 02/06/2015; it varied from 26.7°C on 05/07/2015 to a maximum of 28.4°C on 10/06/2015 in Dutse Alhaji. In Kubwa it varied from 27°C on 18/07/2015 to a maximum of 28°C on 13/07/2015 and lastly it varied in Bwari from 25.3°C on 29/07/2015 to a maximum of 26°C on 23/07/2015 during the dry season monitoring.

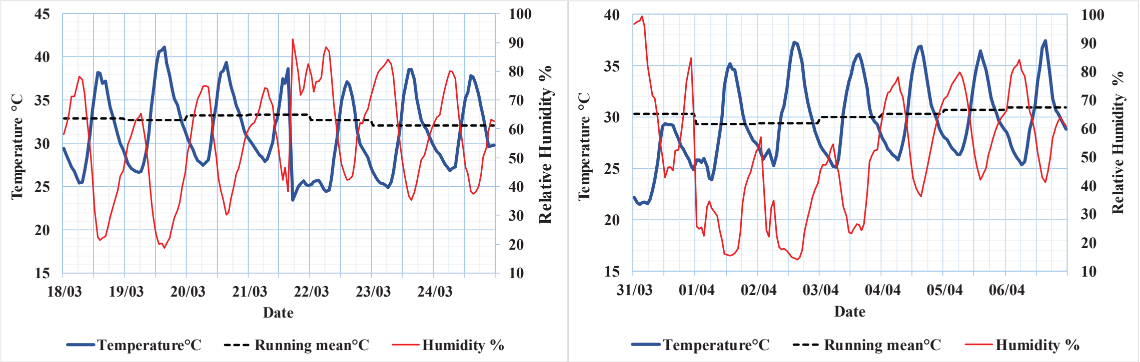


Figure 5.11: Outdoor temperature, relative humidity, and running mean of daily average temperature during the dry season monitoring in Lugbe (left) and Mpape (right)

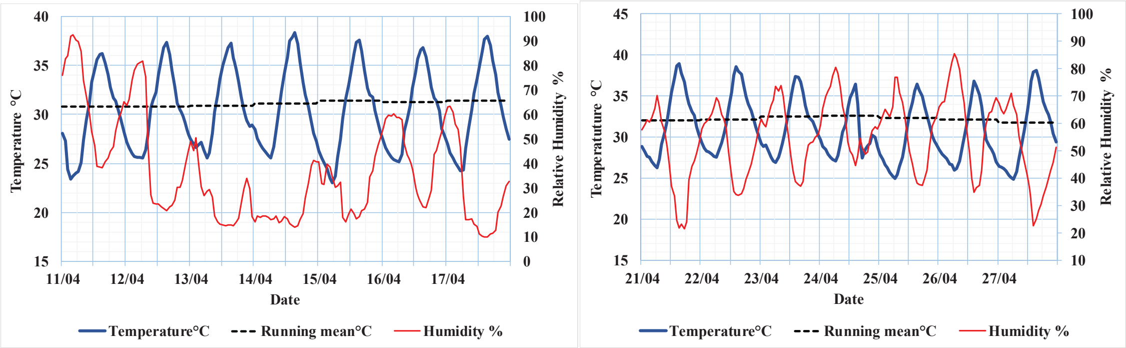


Figure 5.12: Outdoor temperature, relative humidity and running mean of daily average temperature during the dry season monitoring in Dutse Alhaji (left) and Kubwa (right)

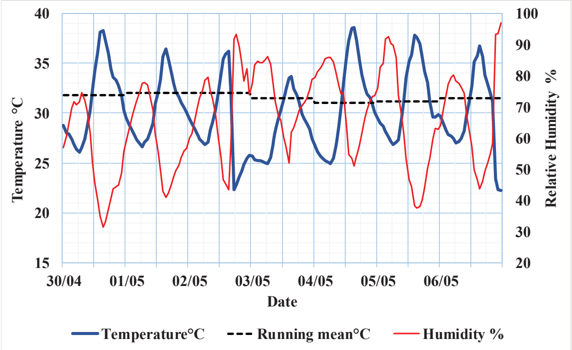


Figure 5.13: Outdoor temperature, relative humidity and running mean of daily average temperature during the dry season monitoring in Bwari

In March, Lugbe recorded the hottest outdoor temperature during the monitored period, with an average monthly temperature of 31.1°C and a maximum outdoor temperature of 41.7°C on 19/03/2015. In addition, all the recorded high temperatures in the case studies during the dry season occurred at 16:00pm (Table 6.36). Low temperature was recorded in the early hours of the morning between 06:00 and 07:00, except for Lugbe where there was a drastic drop in temperature from 30.4°C at 17:00 to 23.5°C at 18:00 under an hour due to sudden rain and windy conditions. Therefore, recording the lowest temperature during the daytime throughout the dry season environmental monitoring. Throughout the monitoring period, the T_{rm} rose above 30°C for 100% of the time across all case studies (Figure 5.11 – 5.13).

5.2.1.1 Daytime external temperatures during the dry season

According to the Nigerian metrological Agency, Abuja, the sun rises at 6.30am for most of the time especially during the dry season and sets at 18.30. The highest recorded temperature during the day was reported in Lugbe with a maximum temperature of 41.7°C from 08:00 – 22:00 and 37.8°C from 18:00 – 22:00 (Table 5.35). Mpape recorded the lowest daytime temperatures with a maximum of 37.5°C, a minimum of 22.8C and a mean of 31.7°C from 08:00 – 22:00 and a maximum of 37.8°C from 18:00 – 22:00, though Bwari recorded the lowest minimum temperature of 22.4°C from 08:00 – 22:00.

Table 5.36: Summary of monitored external day & evening time temperatures at 08.00 – 22.00 and evening time temperatures at 18.00 – 22.00 during the dry season

	Max. day-evening Temp°C (8.00 - 22.00)	Min. day-evening Temp°C (8.00 - 22.00.	Mean day-evening Temp°C (8.00 - 22.00	Max. evening Temp°C (18.00 - 22.00)	Min. evening Temp°C (18.00 - 22.00.	Mean evening Temp°C (18.00 - 22.00	Max. Temp °C	Min. Temp °C	Mean Temp °C
Lugbe	41.1	23.5	33.1	37.8	23.5	32.1	41.1	23.5	31.1
Mpape	37.5	22.8	31.7	35.3	25.9	30.6	37.5	21.5	29.4
Dutse A.	38.4	25.1	32.7	35.5	29.3	32.1	38.4	23.0	30.3
Kubwa	38.9	25.4	32.7	36.8	27.5	32.5	38.9	24.9	30.9
Bwari	38.6	22.4	31.8	36.0	22.4	31.0	38.6	22.2	30.1

5.2.1.2 Night time external temperatures during the dry season

The highest temperature night time of 32.3°C was recorded in Lugbe, making the case study location with the highest daytime and night time recorded temperatures in all case studies. Mpape recorded the lowest temperature overall with a minimum and average temperature of 21.5°C and 26.2°C respectively (Table 5.37).

Table 5.37: Summary of monitored external night time temperatures at 23.00 – 07.00 during the dry season

	Max. night-time Temp °C (23.00 - 07:00)	Min. night-time Temp °C (23:00 -07:00.	Mean night-time Temp °C (23.00 - 07:00	Max. Temp °C	Min. Temp °C	Mean Temp °C
Lugbe	32.3	24.4	27.8	41.1	23.5	31.1
Mpape	29.4	21.5	26.2	37.5	21.5	29.4
Dutse A.	29.4	23.0	26.3	38.4	23.0	30.3
Kubwa	31.3	24.9	27.9	38.9	24.9	30.9
Bwari	31.8	22.2	27.4	38.6	22.2	30.1

5.2.2 Outdoor rainy season conditions

The rainy season recorded an outdoor temperature that varied from 21°C on 20/06/2015 to a maximum of 31°C on 23/06/2015 and an average of 26°C in Lugbe (Table 5.38), with a relative humidity varying from 57% on 23/06/2015 to a maximum of 99.5% on 20/06/2015 (Figure 5.14a), and an average of 81.7%. For the outdoor temperature in Mpape, it varied from 22°C on 27/06/2015 to a maximum of 32.6°C on 01/07/2015 and an average of 27.3°C, with a relative humidity varying from 62.3% on 01/07/2015 to a maximum of 98.5% on 27/07/2015 (Figure 5.14b) and an average of 81.7%.

Table 5.38: Summary of maximum, minimum, average and range of external temperature and relative humidity during the environmental monitored period in the rainy season in Abuja.

	Temperature (°C) data				**Relative humidity (%) data**				**Max (°C)**	**Min (°C)**
	Max Temp.	**Min. Temp**	**Avg. Temp**	**Temp Range**	**Max R.H**	**Min R.H.**	**Avg. R.H.**	**R.H. Range**	**Date/ time**	**Date/ time**
Lugbe	30.7	21.0	26.0	9.7	99.5	57.1	81.7	42.4	23/06/2015 16:00	20/06/2015 07:00
Mpape	30.4	21.9	25.9	8.5	98.5	62.3	81.7	36.2	01/07/2015 15:00	27/06/2015 05:00
Dutse Alh.	32.6	20.6	27.3	12.0	97.6	46.6	74.7	82.8	07/07/2015 15:00	05/07/2015 07:00
Kubwa	31.7	21.0	26.2	10.7	100	55.1	80.4	44.9	18/07/2015 17:00	19/07/2015 07:00
Bwari	29.7	20.6	24.2	9.1	100	64.8	88.8	35.2	26/07/2015 15:00	23/07/2015 07:00

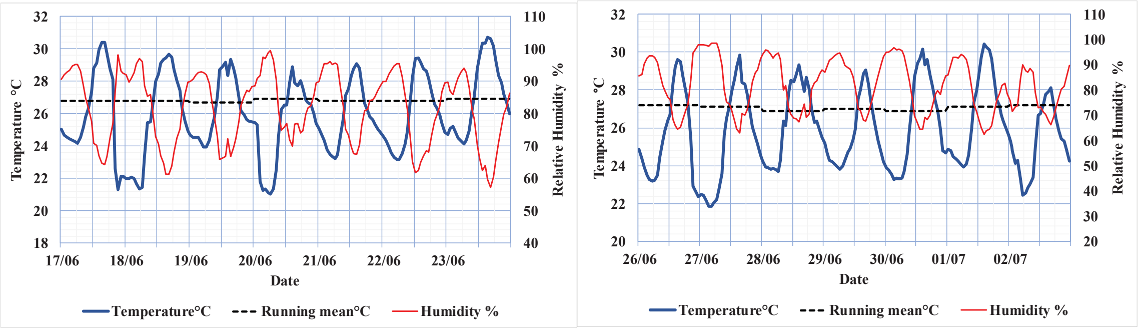


Figure 5.14: Outdoor temperature, relative humidity, and running mean of daily average temperature during the rainy season monitoring in Lugbe (left) and Mpape (right)

The highest outdoor temperature recorded during the monitoring period in the rainy season was for Dutse Alhaji, it varied from 20.6°C on 05/07/2015 to a maximum of 32.6°C on 07/07/2015 and an average of 27.3°C, with a relative humidity varying from 46.6% on 11/07/2015 to a maximum of 97.6% on 05/07/2015 (Figure 5.15a) and an average of 74.7% throughout the monitoring period. The outdoor temperature in Kubwa varied from 21°C on 19/07/2015 to a maximum of 31.7°C on 18/07/2015 and an average of 26°C, with a relative humidity varying from 55% on 13/07/2015 to a maximum of 100% on 19/07/2015 (Figure 5.15b) and an average of 80.4%.

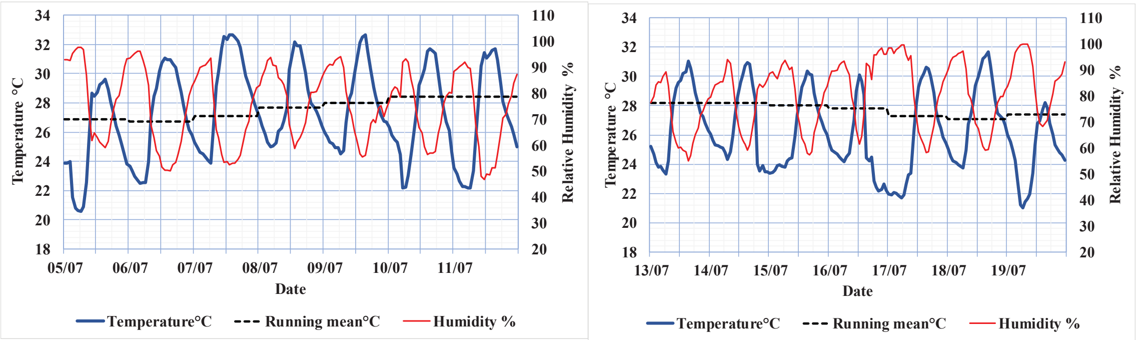


Figure 5.15: Outdoor temperature, relative humidity and running mean of daily average temperature during the rainy season monitoring in Dutse Alhaji (left) and Kubwa (right)

Lastly, the lowest outdoor temperatures were recorded for Bwari, which varied from 20.6°C on 23/07/2015 to a maximum of 29.7°C on 26/07/2015 and an average of 24.2°C, with a relative humidity varying from 55% on 26/07/2015 to a maximum of 100% on 23/07/2015 (Figure 5.16) and an average of 88.8% which is the lowest throughout the whole rainy season monitoring period.

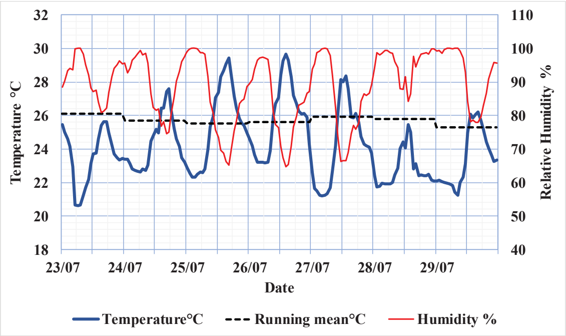


Figure 5.16: Outdoor temperature, relative humidity and running mean of daily average temperature during the rainy season monitoring in Bwari

5.1.1 Indoor temperatures during the dry season

During the indoor monitoring at the naturally ventilated building in Lugbe H1 (LGH1), a maximum temperature of 36.2°C was reported compared to 32.7°C recorded in the air conditioned building of Lugbe H2 (LGH2). Making Lugbe H1 the warmest monitored building in Lugbe with a mean temperature of 32°C (Table 5.40). The average indoor temperature between 08:00 and 22:00 in the monitored living areas in Lubge was 32.1°C for the living rooms and 31.2°C was recorded in the bedrooms between 23:00 – 07:00 (Table 5.41). The living rooms space recorded the hottest temperature in the building with a mean of 32.5°C and a maximum temperature of 36.2°C. The average temperature between 23:00 and 07:00 was 31.2°C for the bedrooms. The living rooms were also the hottest space in the building with a mean temperature of 31.1°C and a maximum temperature of 34.6°C (Figure 5.17).

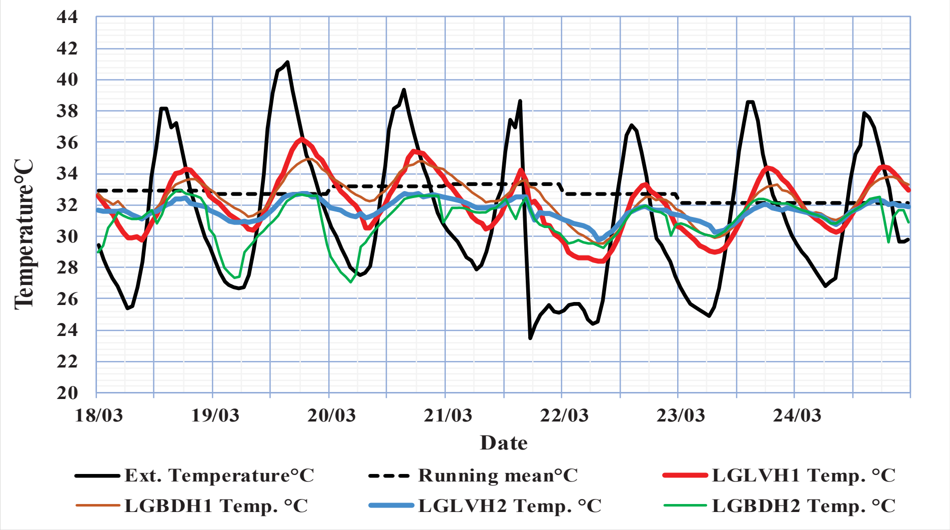


Figure 5.17: Living rooms and bedrooms monitored in two different buildings in Lugbe during the dry season

A maximum daytime temperature of 33.5°C was recorded in both the naturally ventilated monitored buildings in Mpape H1 (MPH1) and Mpape H2 (MPH2) at Mpape (Table 5.40), where Mpape H2 was the warmest with a mean temperature of 30.1°C, though it was just 0.4°C more than Mpape H1. The average temperature between 08:00 and 22:00 in the monitored living areas in was 30.2°C for the living rooms and 30.8°C between 18:00 – 22:00. The living room space recorded the hottest temperature in the building with a mean of 34.5°C and a maximum temperature of 36.8°C. The average temperature between 23:00 and 07:00 was and 29.7°C for the bedrooms. The living rooms also were the hottest space in the building with a mean temperature of 32.9°C and a maximum temperature of 34.8°C (Table 41 and Figures 5.18).

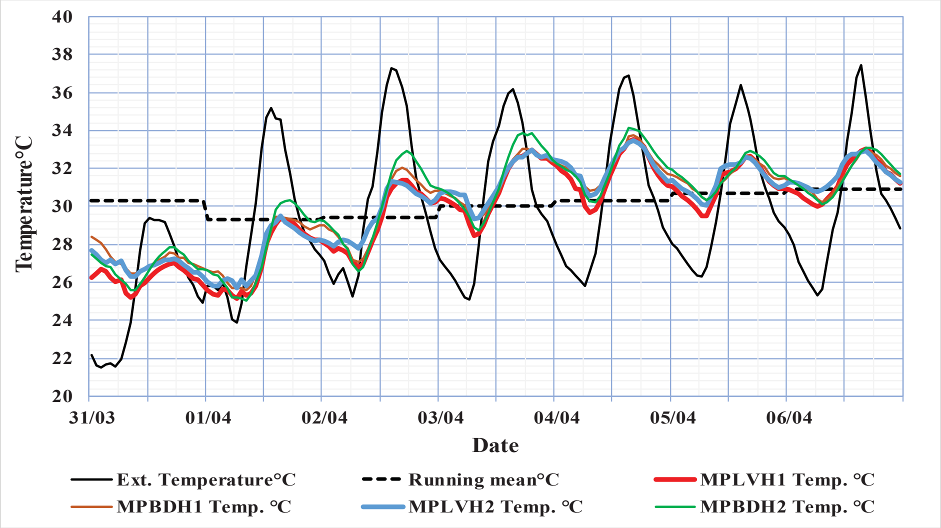


Figure 5.18: Living rooms and bedrooms monitored in two different buildings in Mpape during the dry season

The warmest temperature of 37.2°C was recorded in the air conditioned building in Dutse H2 (DAH1) compared to the maximum of 36.2°C recorded in the naturally ventilated building of Dutse H1 (DAH1). This was a contradiction from the theory that air conditioned buildings should be cooler not warmer than the naturally ventilated buildings. The average indoor temperature between 08.00 and 22.00 in the monitored living areas in Dutse Alhaji was 33.8°C for the living rooms and 34.8°C for between 18:00 – 22:00 (Table 40). The living room space recorded the hottest temperature in the building with a mean of 34.5°C and a maximum temperature of 36.8°C. The average temperature between 23.00 and 07.00 was 32.7°C for the living rooms and 31.3°C for the bedrooms. The living rooms also were the hottest space in the building with a mean temperature of 32.9°C and a maximum temperature of 34.8°C (Table 41 and Figures 5.19).

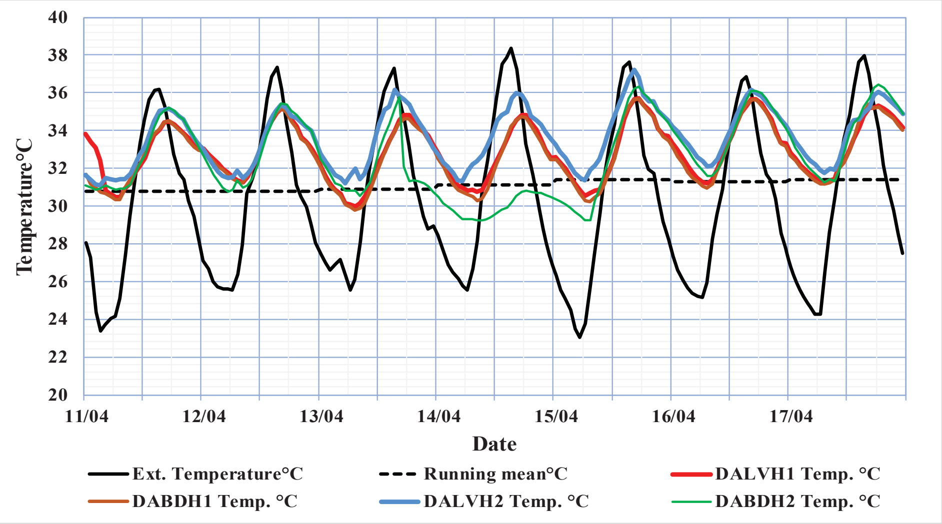


Figure 5.19: Living rooms and bedrooms monitored in two different buildings in Dutse Alhaji during the dry season

Further investigations was carried out to understand why the air conditioned building recorded the warmest temperature compared to the naturally ventilated building in Dutse Alhaji. The investigations from the comments and interview of the occupants' revealed less use the air conditioning for the first four days of the survey and a complete breakdown of the air conditioning system during the last three days of the survey when visitors where hosted in the house over the weekend of the survey. The occupant also commented that there was poor electricity supply and electricity bills have been high in the area leading to a protest to the local electricity office for better supply and a fair billing system for all the residents in the area.

The indoor monitoring of the two air conditioned buildings in Kubwa; Kubwa H1 (KBH1) and Kubwa (KBH2), recorded a maximum temperature of 36.2°C and 32.7°C respectively (Table 5.41 and Figure 5.20). The results suggest KBH1 to be the warmest with a higher average temperature of 34C compared to 31C recorded in KBH2. The average indoor temperature between 08:00 and 22:00 in the monitored living areas in Kubwa was 32.1°C for the living rooms (Table 5.40). and 31.2°C was recorded in the bedrooms between 23:00 – 07:00 (Table 5.41). The living rooms space recorded the hottest temperature in the building with a mean of 32.5°C and a maximum temperature of 36.2°C. The average temperature between 23:00 and 07:00 was 31.2°C for the bedrooms. The living rooms were also the hottest space in the building with a mean temperature of 31.1°C and a maximum temperature of 34.6°C (Figure 5.20).

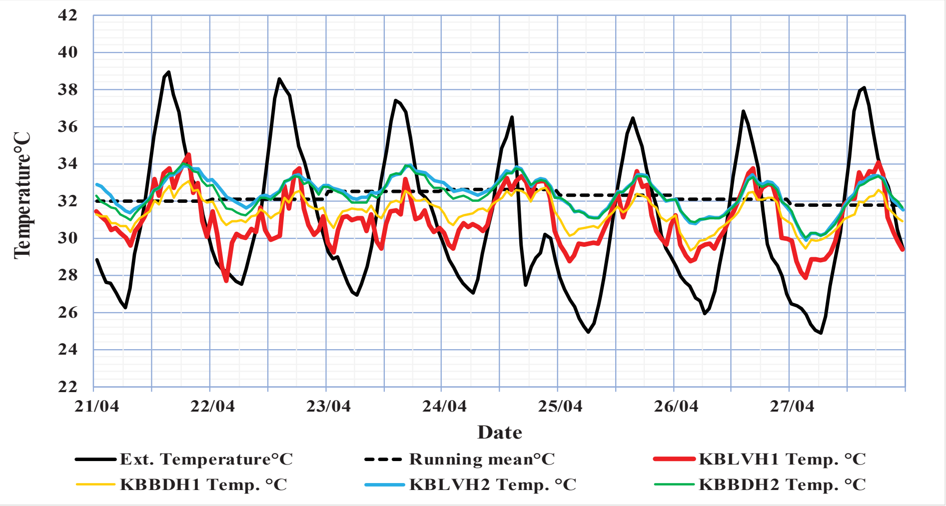


Figure 5.20: Living rooms and bedrooms monitored in two different buildings in Kubwa during the dry season

In Bwari, a maximum temperature of 34.8°C was recorded in the naturally ventilated monitored buildings in Bwari H1 (BWH1) while the air conditioned building, Bwari H1 (BWH1) recorded a maximum temperature of 31.5°C (Figure 5.21). BWH1 was the warmest building with a mean temperature of 30.9°C, though it was just 1.7°C more than BWH2. The average temperature between 08:00 and 22:00 in the monitored living room space in BWH1 was 32.3°C and 29.7°C in BWH2. An average temperature of 32.9°C was also reported in BWH1 between 18:00 – 22:00 and 29.2°C in BWH2 (Table 5.39). The living room spaces recorded the hottest temperature in the buildings with a mean of 30°C and a maximum temperature of 32.8°C. The average temperature between 23:00 and 07:00 was and 30.7°C for the bedrooms with a maximum of 33.6°C (Table 5.40 and Figure 5.21).

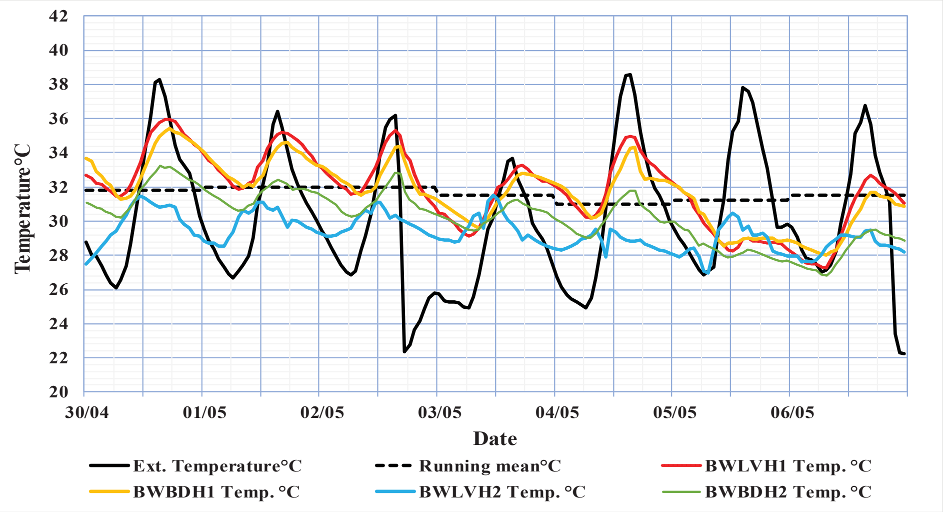


Figure 5.21: Living rooms and bedrooms monitored in two different buildings in Bwari during the dry season

Table 5.39: Summary of monitored indoor daytime and evening period temperatures in the living rooms at 08.00 – 22.00 and 18.00 – 22.00 during the dry season

Name of space-living rooms	**Max. daytime Temp°C (8.00 - 22.00)**	**Min. daytime Temp°C (8.00 - 22.00**	**Mean daytime Temp°C (8.00 - 22.00**	**Max. daytime Temp°C (18.00 - 22.00)**	**Min. daytime Temp°C (18.00 - 22.00**	**Mean daytime Temp°C (18.00 - 22.00**	**Max. Temp °C**	**Min. Temp °C**	**Mean Temp °C**
LGH1	36.2	28.4	32.4	36.2	30.7	33.9	36.2	28.4	32.0
LGH2	32.7	29.8	31.7	32.7	31.1	32.1	32.7	29.8	31.6
MPH1	33.5	25.2	30.1	33.4	26.2	30.8	33.5	25.2	29.7
MPH2	33.5	25.8	30.4	33.3	26.5	30.8	33.5	25.7	30.1
DAH1	35.7	30.0	33.3	35.7	33.4	34.6	35.7	30.0	32.9
DAH2	37.2	31.4	34.2	36.8	34.0	35.2	37.2	31.1	33.6
KBH1	34.5	28.8	31.7	34.5	30.0	32.3	34.5	27.7	31.1
KBH2	33.9	30.2	32.6	33.9	32.0	33.2	33.9	29.9	32.4
BWH1	36.0	27.3	32.3	36.0	28.7	32.9	36.0	27.3	31.9
BWH2	31.5	26.9	29.7	30.9	28.1	29.2	31.5	26.9	29.3
Lugbe (Average living rooms)	34.4	29.1	32.1	34.4	31.1	33.0	34.1	29.1	31.7
Mpape (Average living rooms)	33.5	25.4	30.2	33.4	26.4	30.8	33.5	28.9	31.4
Dutse A (Average living rooms)	36.4	30.7	33.8	36.3	33.8	34.8	36.4	31.0	33.6
Kubwa (Average living rooms)	34.2	29.5	32.2	34.2	31.2	32.7	33.7	28.9	31.7
Bwari (Average living rooms)	33.5	27.9	31.0	33.5	28.4	31.0	32.8	27.6	30.0

LG - Lugbe, MP - Mpape, DA - Dutse Alhaji, KB - Kubwa, BW - Bwari, H1 - House 1, H2 - House 2.

Table 5.40: Summary of monitored daytime indoor temperatures in the bedrooms at 23.00 – 07.00 during the dry season

Name of space-Bedrooms	Max. night-time Temp °C (23.00 - 07:00)	Min. night-time Temp °C (23:00 - 07:00.	Mean night-time Temp °C (23.00 - 07:00	Max. Temp °C	Min. Temp °C	Mean Temp °C
LGH1	34.4	29.6	32.2	34.9	29.5	32.4
LGH2	32.6	27.0	30.2	32.9	27.0	31.0
MPH1	32.5	25.7	29.7	33.8	25.6	30.1
MPH2	32.9	25.2	29.6	34.2	25.03	30.2
DAH1	34.3	30.0	31.9	35.7	29.8	32.8
DAH2	35.2	29.3	31.7	36.5	29.2	32.6
KBH1	32.3	29.4	30.9	33.1	29.4	31.4
KBH2	33.1	30.0	31.8	34.0	30.0	32.3
BWH1	34.6	28.1	31.6	35.4	28.0	31.7
BWH2	32.3	26.9	29.9	33.2	26.8	30.2
Lugbe (Average Bedrooms)	33.5	29.5	31.2	33.7	29.4	31.7
Mpape (Average Bedrooms)	32.7	25.5	29.7	33.9	29.0	31.7
Dutse A (Average Bedrooms)	34.8	29.8	31.8	36.0	29.7	32.9
Kubwa(Average Bedrooms)	32.6	29.7	31.3	33.2	29.7	31.7
Bwari(Average Bedrooms)	33.4	27.5	30.7	33.6	27.4	30.2

LG - Lugbe, MP - Mpape, DA - Dutse Alhaji, KB - Kubwa, BW - Bwari, H1 - House 1, H2 - House 2.

The results indicate the living room is the hottest monitored space in the building and occupants in Dutse Alhaji experienced a higher temperature compared to the occupants across the remaining case studies. A plausible reason for these reported high indoor temperatures might be the lack of heated air circulation. Since hot air rises, it is possible that the indoor heated air that was supposed to move from inside the space to the outdoor environment is often blocked by curtains on windows or the opening of windows during hot days allowing warm air to flow into the living room and bedroom spaces therefore increasing the indoor temperature.

5.2.3 Measured indoor and outdoor conditions across all case studies during the dry season

It was found out that the indoor and outdoor temperatures in the living rooms and bedrooms in all case studies were higher in the afternoon and lower in the early morning and late night (Figure 5.22- 5.24). The internal temperature is related to the external temperature, and the living spaces are much warmer than the bedroom spaces. The monitored living room space in Lugbe H1 (LGLVH1) recorded warmer temperatures than the the bedroom space (LGBDH1) when compared to the external temperatures. However, there was a wide distribution from low temperatures at 29.5°C to the living room where r^2 was 0.437 for the living room and $r^2 = 0.268$ for the bedroom), (Figure 5.22a). The monitored living room space in Lugbe H2 (LGLVH2) also reported warmer temperatures than the bedroom space in Lugbe H2

(LGBDH2) when compared to the external temperatures. However, there was a wide distribution from low temperatures at 27°C to the bedroom where r^2 was 0.41 for the living room and $r^2 = 0.32$ for the bedroom), (Figure 5.22b).

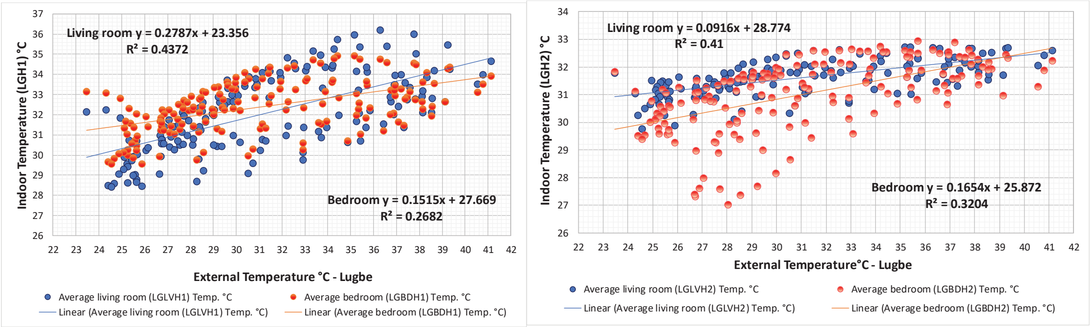


Figure 5.22 Relationship between the mean internal temperature of the living rooms and bedrooms monitored in two different buildings at Lugbe and the external temperature during the dry season.

The monitored bedroom space in Mpape H1 (MPBDH1) recorded warmer temperatures than the the living room space (MPLVH1) when compared to the external temperatures. However, there was a wide distribution from low temperatures at 29.5°C to the bedroom where r^2 was 0.4 for the living room and $r^2 = 0.34$ for the bedroom), (Figure 6.23a). The monitored bedroom space in Lugbe H2 (MPBDH2) also reported warmer temperatures than the living room space in Lugbe H2 (MPLVH2) when compared to the external temperatures where r^2 was 0.35 for the living room and $r^2 = 0.39$ for the bedroom), (Figure 6.23b).

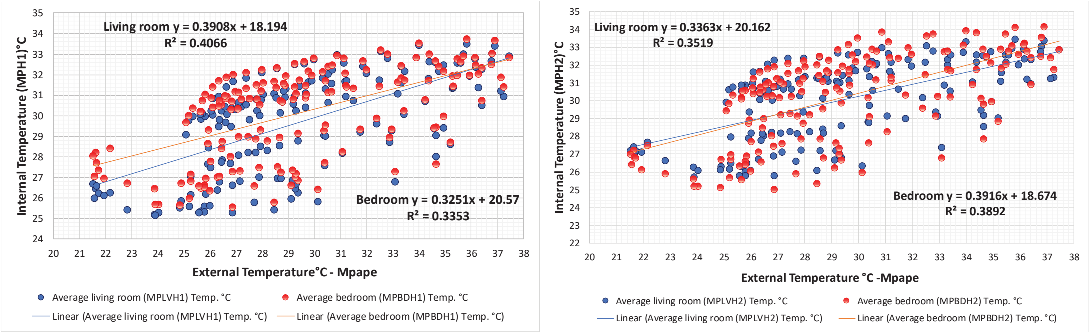


Figure 5.23: Relationship between the mean internal temperature of the living rooms and bedrooms monitored in two different buildings at Mpape and the external temperature during the dry season.

The monitored living room space in Dutse Alhaji H1 (DALVH1) recorded warmer temperatures than the the bedroom space (DABDH1) when compared to the external temperatures where r^2 was 0.45 for the living room and $r^2 = 0.51$ for the bedroom (Figure 5.24a). The monitored living room space in Lugbe H2 (DALVH2) also reported warmer temperatures than the bedroom space in Lugbe H2 (DABDH2) when compared to the external temperatures. However, there was a wide distribution from low temperatures at 29°C to the bedroom where r^2 was 0.59 for the living room and $r^2 = 0.27$ for the bedroom (Figure 5.24b).

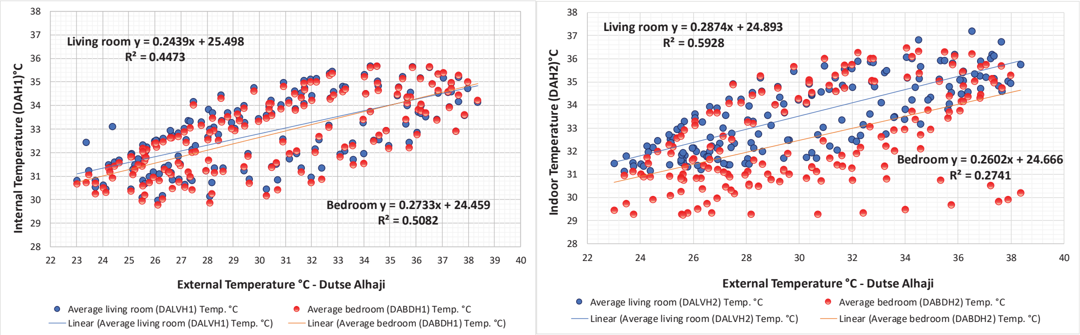


Figure 5.24: Relationship between the mean internal temperature of the living rooms and bedrooms monitored in two different buildings at Dutse Alhaji and the external temperature during the dry season.

The monitored living room space in Kubwa H1 (KBLVH1) recorded warmer temperatures than the the bedroom space (KBBDH1) when compared to the external temperatures where r^2 was 0.48 for the living room and $r^2 = 0.48$ for the bedroom (Figure 5.25a). The monitored living room space in Kubwa H2 (KBLVH2) also reported warmer temperatures than the bedroom space in KBBDH2 when compared to the external temperatures. However, there was a wide distribution from low temperatures at 27.5°C to the living room where r^2 was 0.46 for the living room and $r^2 = 0.53$ for the bedroom (Figure 5.25b).

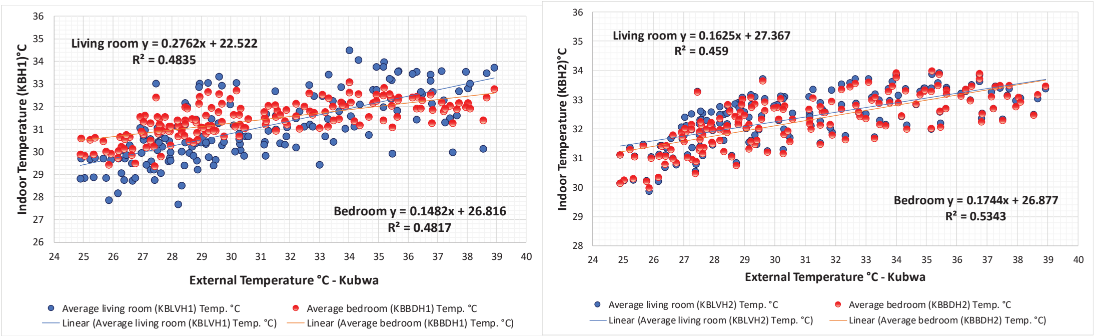


Figure 5.25: Relationship between the mean internal temperature of the living rooms and bedrooms monitored in two different buildings at Kubwa and the external temperature during the dry season.

The monitored living room space in Bwari H1 (BWLVH1) recorded warmer temperatures than the the bedroom space (BWBDH1) when compared to the external temperatures where r^2 was 0.17 for the living room and $r^2 = 0.09$ for the bedroom (Figure 5.26a). The monitored bedroom space in Bwari H2 (BWBDH2) also reported warmer temperatures than the living room space in BWLVH2 when compared to the external temperatures where r^2 was 0.13 for the living room and $r^2 = 0.09$ for the bedroom (Figure 5.26b).

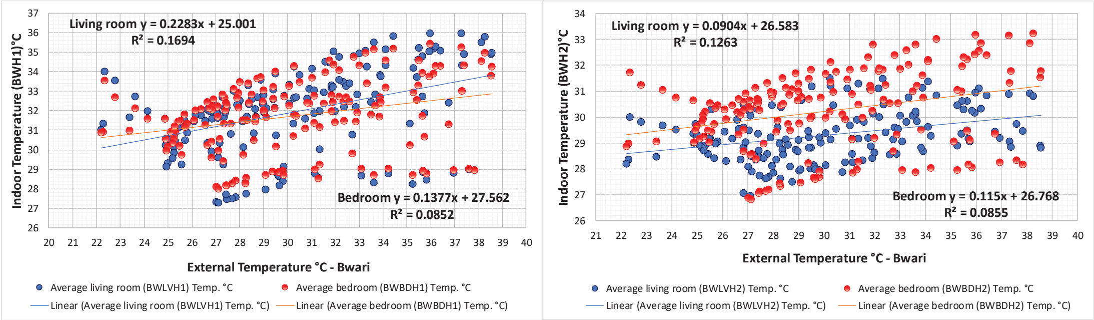


Figure 5.26: Relationship between the mean internal temperature of the living rooms and bedrooms monitored in two different buildings at Bwari and the external temperature during the dry season

5.3 Analysis of Comfort Survey

The thermal comfort questionnaires received from the case studies, were analysed and the results show a total of 273 questionnaires were administered during the dry season and 187 were received representing a 68.5% response, while 252 were administered during the rainy season and 155 were received, representing a 61.5% response. The survey showed that the thermal comfort survey analysing the thermal sensation, thermal comfort and thermal preference are discussed in this section.

5.3.1 Thermal sensation analysis of comfort survey

Comfort survey, thermal sensation – Dry season

The comfort surveys (Figures 5.27-5.31 and Table 5.42) show most of the occupants were felt warm for more than 50% of the time with most of the distribution of votes varying from 'slightly warm', 'warm' to 'hot' except for KBH2 and BWH2 (Figures 5.30b and 5.31b) were they were slightly skewed to the neural part of the scale. The results suggest that 50% of the time the occupant in Lugbe LGH1 felt 'warm' or 'hot' while 25% of the time occupants in Lugbe LGH2 felt 'warm' or 'hot' (Figure 5.27).

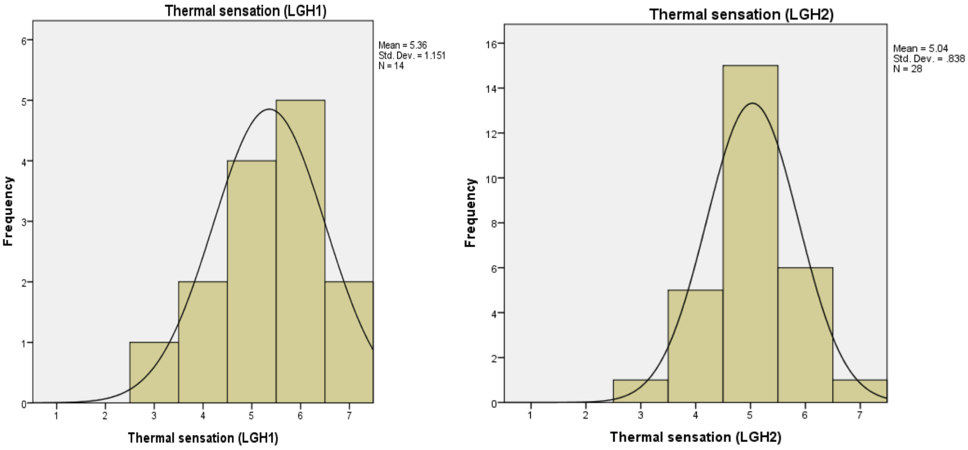


Figure 5.27: Distribution of overall thermal sensation votes during the dry season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

The occupant in MPH1 felt ‘warm’ or ‘hot’ 50% of the time compared to 70% of the time the occupant in MPH2 felt ‘warm’ or ‘hot’ (Figure 5.28).

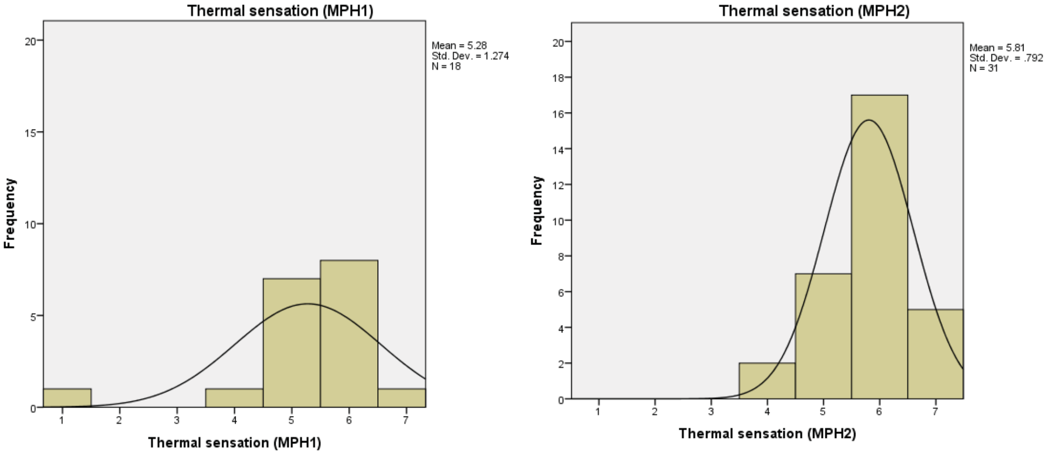


Figure 5.28: Distribution of overall thermal sensation votes during the dry season in Mpape with naturally ventilated building (left) and (right) (Scale: 1= cold to 7= hot)

Around 77% of the time, the occupants in Dutse Alhaji DAH1 felt ‘warm’ or ‘hot’ compared to 25% of the time in Dutse Alhaji DAH2 that felt warm (Figure 5.29).

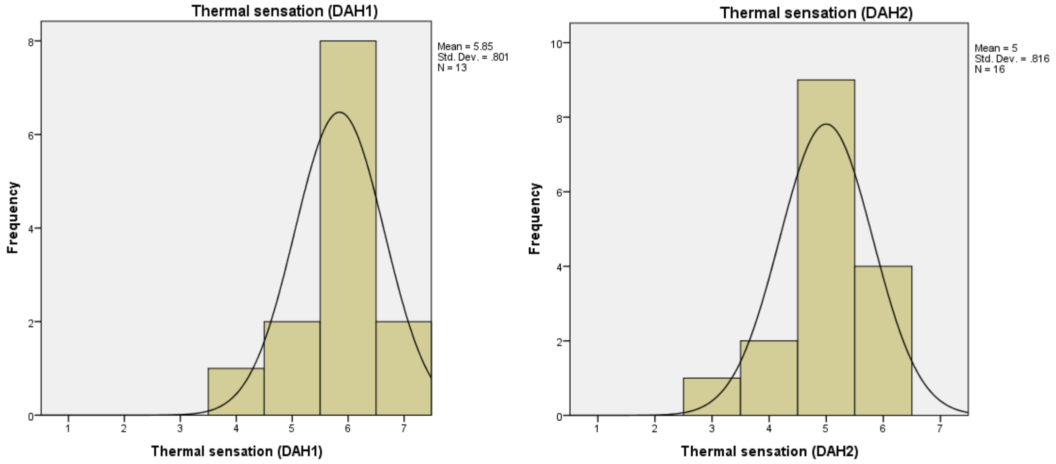


Figure 5.29: Distribution of overall thermal sensation votes during the dry season in Dutse Alhaji with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

The occupant in KBH1 voted for ‘warm’ or ‘hot’ 14% of the time compared to 23% of the time the occupant in KBH2 felt ‘warm’ or ‘hot’ with the overall votes tilting to the neutral part of the scale (Figure 5.30).

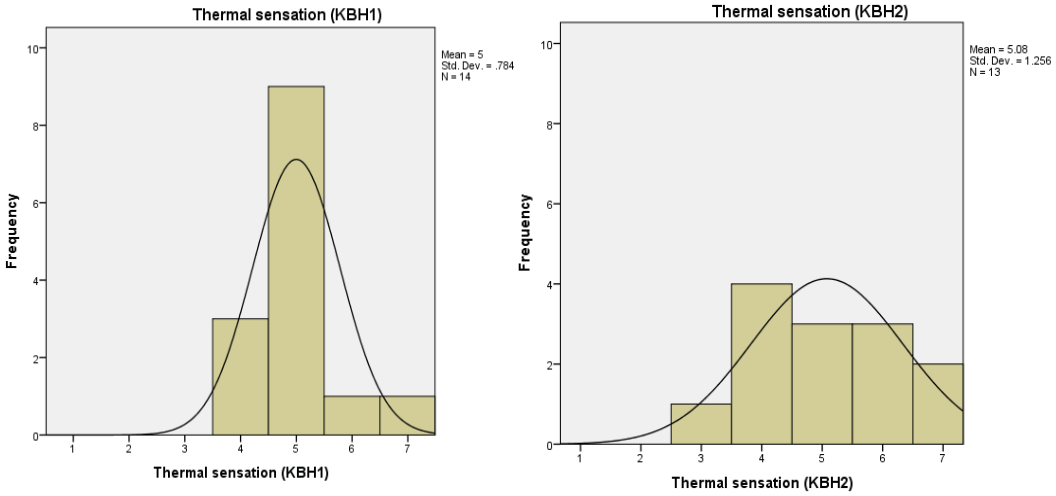


Figure 5.30: Distribution of overall thermal sensation votes during the dry season in Kubwa with air-conditioned building (left) and (right) (Scale: 1= cold to 7= hot)

More than 14% of the time, the occupant in BWH1 felt warm and hot though the votes were skewed to the ‘slightly warm’ and ‘warm’ part of the scale compared to 15% of the time the occupant in BWH2 felt ‘warm’ or ‘hot’ and the votes tilting towards neutrality (Figure 5.31).

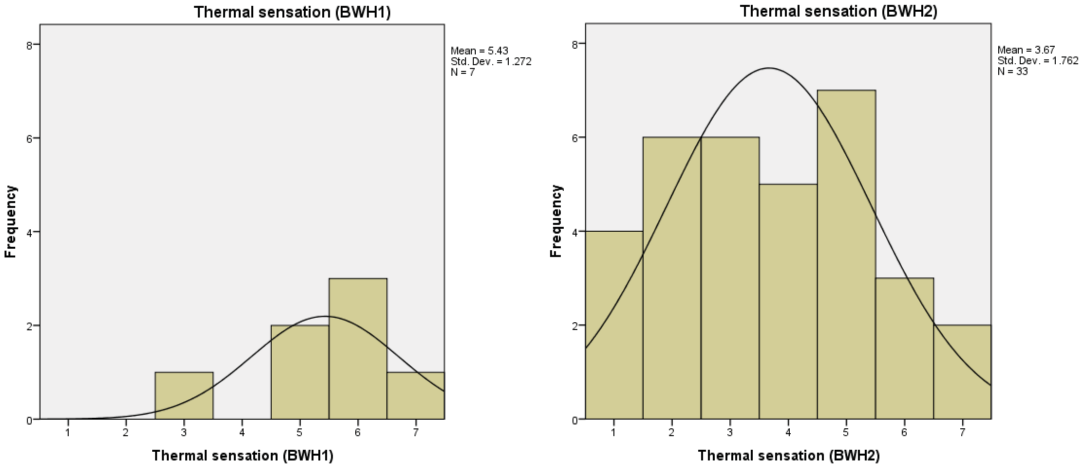


Figure 5.31: Distribution of overall thermal sensation votes during the dry season in Bwari with naturally ventilated (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

The high thermal sensation neutrality votes recorded in KBH2 and BWH2 can be attributed to the use constant use of air-conditioning in these dwellings indicated by the comments in the survey compared to the less use of air conditioners in LGH2 and DAH2 as the residents indicated. Most of the residents spent 12 hours inside the house per day and most of the participants from the survey have lived in the case study buildings for over 36 months. The residents in Lugbe owned the properties they live in while the occupants in Dutse Alhaji lived in rented buildings. More than 70% of the spaces monitored in all case studies recorded temperatures above the comfort range showed in Section 5.3.5. Overall, most resident felt warm within their indoor environment (Table 5.41).

Table 5.41: Summary of respondents' percentage of indoor thermal sensation during the dry season, comfort survey.

		Lugbe		**Mpape**		**Dutse Alhaji**		**Kubwa**		**Bwari**	
		LGH1 %	LGH2 %	MPH1 %	MPH2 %	DAH1 %	DAH2 %	KBH1 %	KBH2 %	BWH1 %	BWH2 %
		N=14	N=28	N=18	N=31	N=13	N=16	N=14	N=13	N=7	N=33
Thermal sensation	**Cold**	0	0	5.6	0	0	0	0	0	0	12.1
	Cool	0	0	0	0	0	0	0	0	0	18.2
	Slightly cool	7.1	3.6	0	0	0	6.3	0	7.7	14.3	18.2
	Neutral	14.3	17.9	5.6	6.5	7.7	12.5	21.4	30.8	28.6	15.2
	Slightly warm	28.6	53.6	38.9	22.6	15.4	56.3	64.3	23.1	42.9	21.2
	Warm	35.7	21.4	44.4	54.8	61.5	25.0	7.1	23.1	14.3	9.1
	Hot	14.3	3.6	5.6	16.1	15.4	0	7.1	15.4	0	6.1

Rainy season (Thermal sensation)

There was a shift in the thermal sensation mean votes during the rainy season to the cool and neutral part of the scale (Figures 5.32 – 5.36). More than 67% of the time the residents in Lugbe felt either ‘slightly cool’ or ‘neutral’ or ‘slightly warm’ compared to more than 88% of the time in Dutse Alhaji that either felt ‘neutral’ or ‘slightly cool’. The results further suggest that most of the time the residents in the case studies in Dutse Alhaji felt warmer in the rainy season compared to residents in Lugbe (Table 5.42).

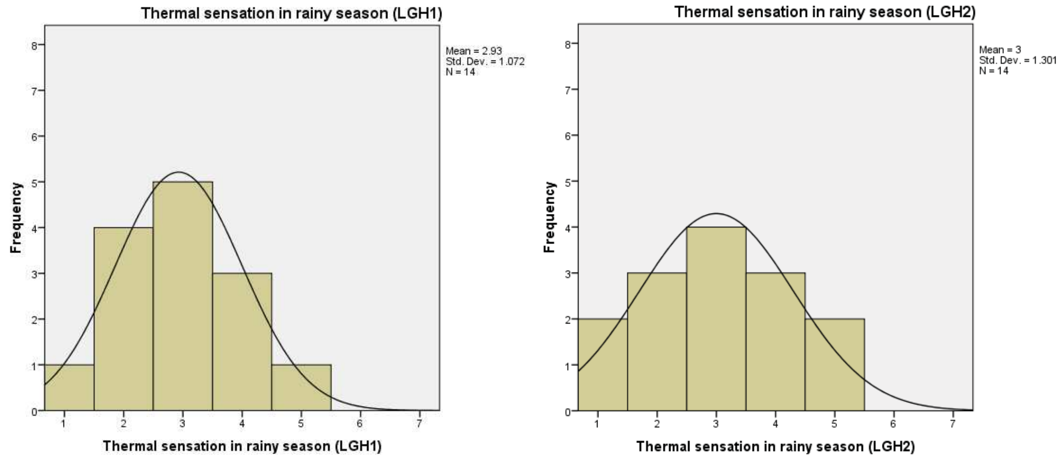


Figure 5.32: Distribution of overall thermal sensation votes during the rainy season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

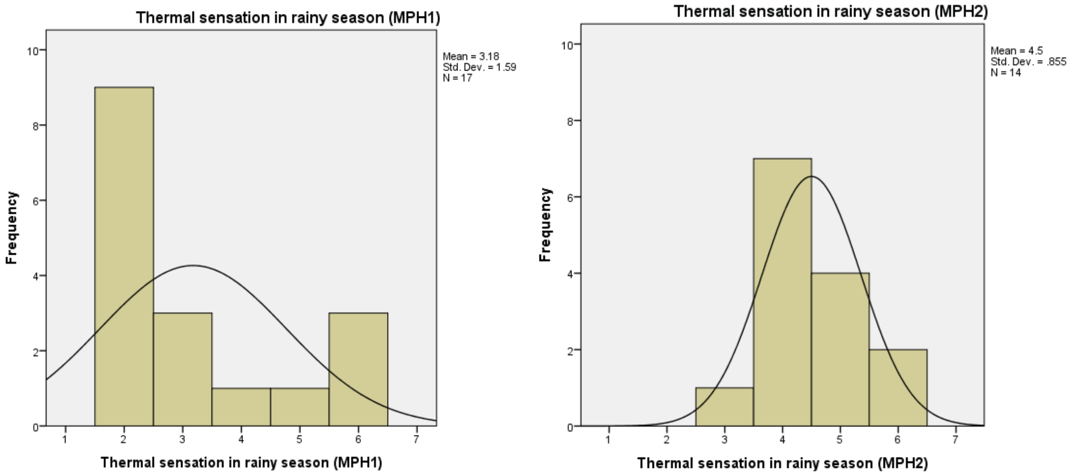


Figure 5.33: Distribution of overall thermal sensation votes during the rainy season in Lugbe with naturally ventilated building (left) and (right) (Scale: 1= cold to 7= hot)

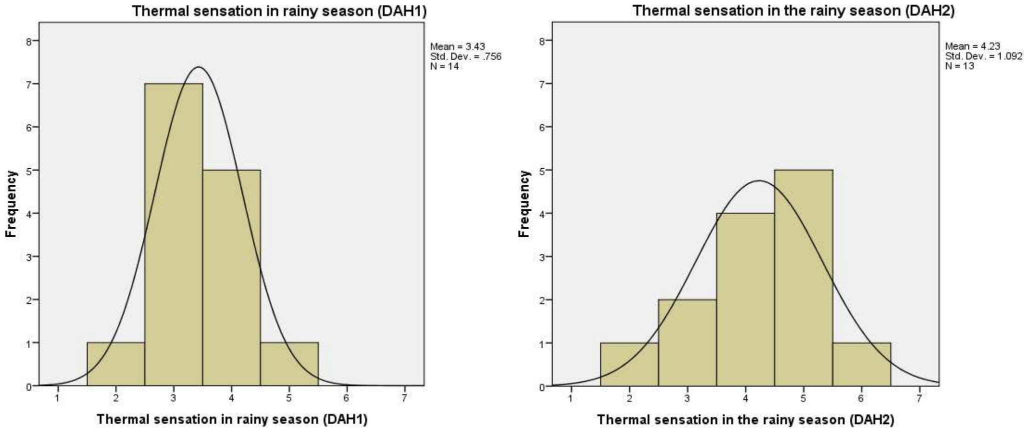


Figure 5.34: Distribution of overall thermal sensation votes during the rainy season in Dutse Alhaji with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

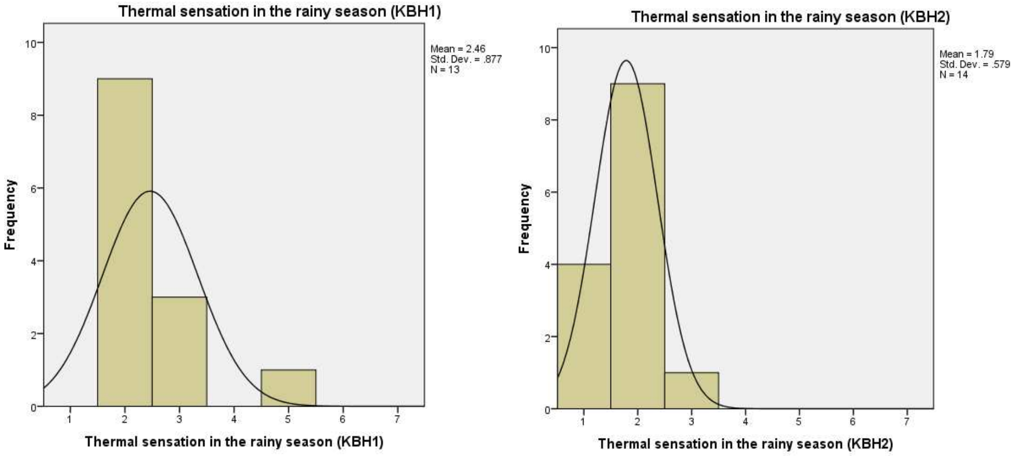


Figure 5.35: Distribution of overall thermal sensation votes during the rainy season in Kubwa with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

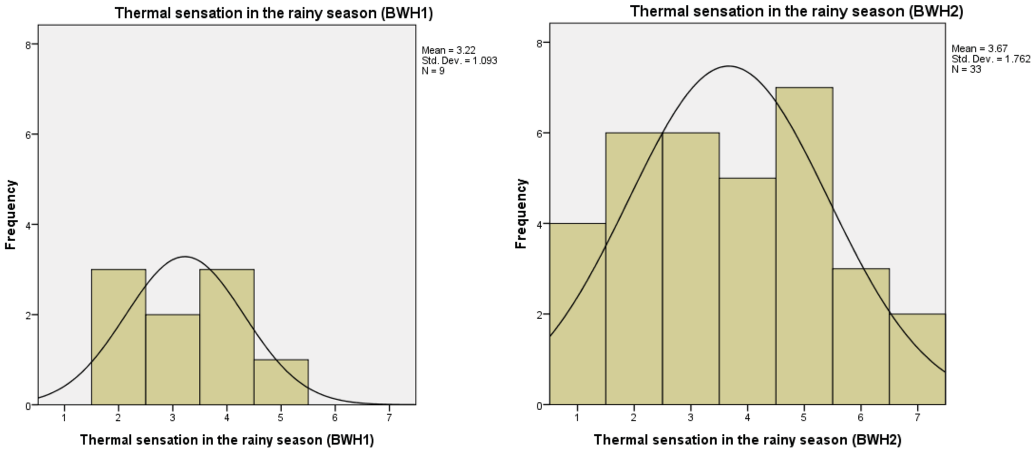


Figure 5.36: Distribution of overall thermal sensation votes during the rainy season in Bwari with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

Table 5.42: Summary of respondents' percentage of indoor thermal sensation during the rainy season, comfort survey

		Lugbe		Mpape		Dutse Alhaji		Kubwa		Bwari	
		LGH1 %	LGH2 %	MPH1 %	MPH2 %	DAH1 %	DAH2 %	KBH1 %	KBH2 %	BWH1 %	BWH2 %
		N=14	N=14	N=17	N=14	N=14	N=13	N=13	N=14	N=9	N=33
Thermal sensation	**Cold**	7.1	14.3	0	0	0	0	0	28.6	0	12.1
	Cool	28.6	21.4	52.9	0	7.1	7.7	69.2	64.3	33.3	18.2
	Slightly cool	35.7	28.6	17.6	7.1	50.0	15.4	23.1	7.1	22.2	18.2
	Neutral	21.4	21.4	5.9	50.0	35.7	30.8	0	0	33.3	15.2
	Slightly warm	7.1	14.3	5.9	28.6	7.1	38.5	7.7	0	11.1	21.2
	Warm	0	0	17.6	14.3	0	7.7	0	0	0	9.1
	Hot	0	0	0	0	0	0	0	0	0	6.1

5.3.2 Thermal comfort analysis of the comfort survey

Dry season (Thermal comfort)

The thermal comfort votes (Table 5.43 and Figures 5.37 – 5.41) show most of the occupants were feeling uncomfortable across all dwellings except for KBH1, KBH2 and BWH2 whose votes were skewed to 'neutral', 'slightly comfortable' or 'comfortable' part of the scale (Figures 5.37 and 5.39b). The results suggest that 35.7% of the time the occupant in Lugbe LGH1 felt 'uncomfortable' and 35.7% of the time the occupant also felt 'slightly uncomfortable' while around 43% of the time, the occupant in Lugbe LGH2 felt 'slightly comfortable' (Figure 5.37).

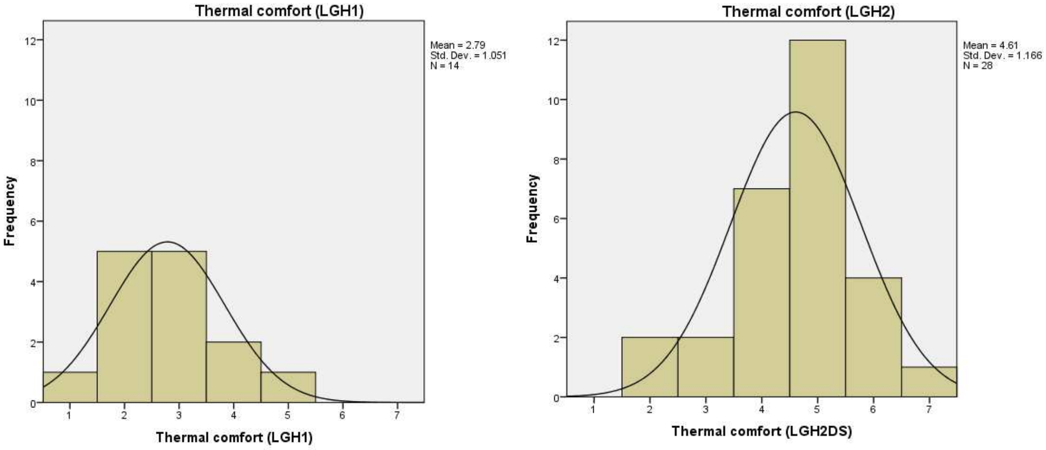


Figure 5.37: Distribution of overall thermal comfort votes during the dry season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1 = very uncomfortable to 7 = very comfortable)

More than 77% of the time, the occupant in MPH1 felt ‘uncomfortable’ or ‘slightly uncomfortable’ compared to 74% of the time the occupants’ in MPH2 felt ‘uncomfortable’ or ‘slightly uncomfortable’, though the occupant in MPH2 also felt ‘very uncomfortable,’ 19% of the time (Figures 5.38). About, 62% of the time the occupant in Dutse Alhaji DAH1 felt ‘very uncomfortable’ or ‘uncomfortable’ compared to 50% of the time in Dutse Alhaji DAH2 that felt ‘very uncomfortable’ or ‘uncomfortable’ (Figures 5.39).

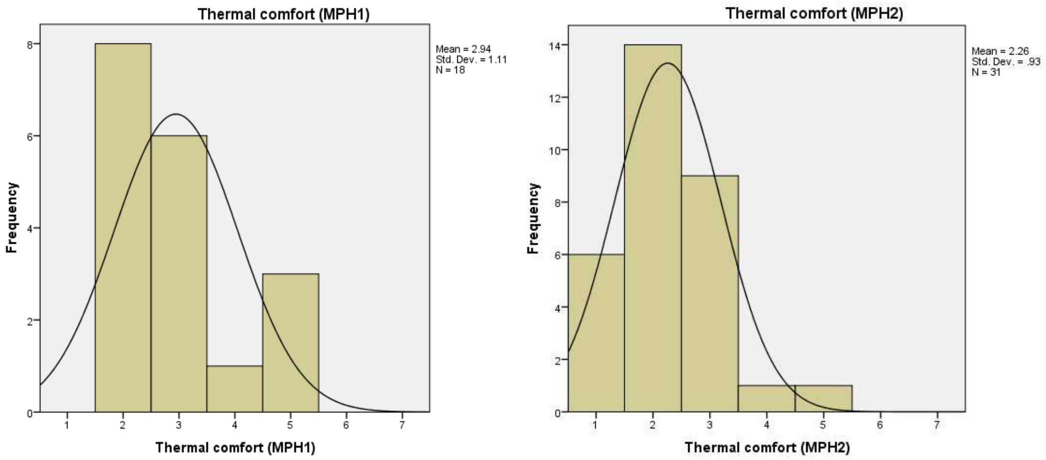


Figure 5.38: Distribution of overall thermal sensation votes during the dry season in Mpape with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= very uncomfortable to 7= very comfortable)

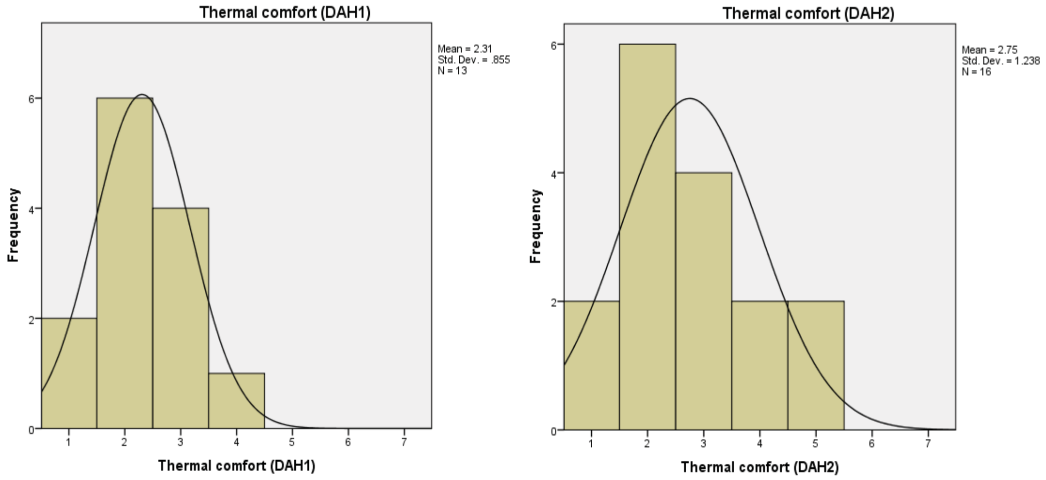


Figure 5.39: Distribution of overall thermal sensation votes during the dry season in Dutse Alhaji with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= very uncomfortable to 7= very comfortable)

The occupant in KBH1 voted for ‘uncomfortable’ or ‘slightly uncomfortable’ 14% of the time compared to 23% of the time the occupant in KBH2 felt ‘uncomfortable’ or ‘slightly uncomfortable’. The overall votes for KBH1 and KBH2 tilted towards the comfortable part of the scale with the occupant KBH1 feeling ‘comfortable’ for more than 28% of the time compared to the occupant in KBH2 who felt ‘very comfortable’ or ‘comfortable’, for over 45% of the time (Figures 5.40).

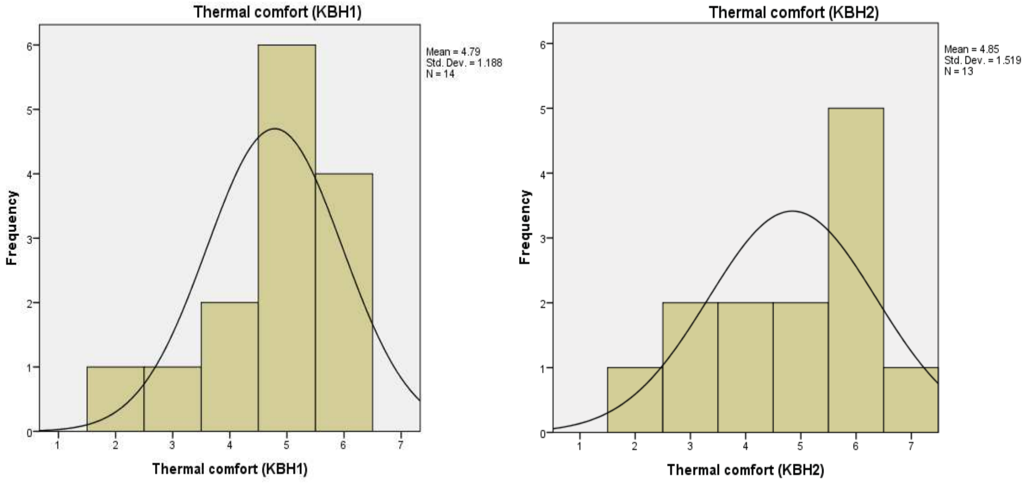


Figure 5.40: Distribution of overall thermal comfort votes during the dry season in Kubwa with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= very uncomfortable to 7= very comfortable)

More than 43% of the time, the occupant in BWH1 felt ‘uncomfortable’ and 28% of the time felt ‘slightly uncomfortable’ compared to 6% the occupants’ in BWH2 felt ‘slightly uncomfortable’. A further look at the results from showed that the occupant in BWH1 felt ‘slightly comfortable’ for 14% of the time compared to more than 78% reported in BWH2, indicating the occupants are comfortable most of the time (Figures 5.41).

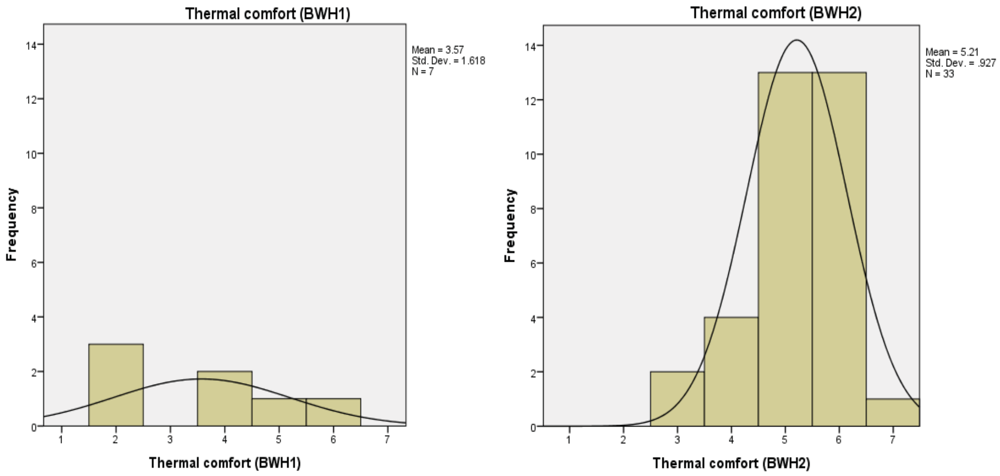


Figure 5.41: Distribution of overall thermal comfort votes during the dry season in Bwari with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= very uncomfortable to 7= very comfortable)

Table 5.43: Summary of respondents' percentage of indoor thermal comfort during the dry season, comfort survey

		Lugbe		**Mpape**		**Dutse Alhaji**		**Kubwa**		**Bwari**	
		LGH1 %	LGH2 %	MPH1 %	MPH2 %	DAH1 %	DAH2 %	KBH1 %	KBH2 %	BWH1 %	BWH2 %
		N=14	N=28	N=18	N=31	N=13	N=16	N=14	N=13	N=7	N=33
Indoor Thermal comfort	**Very uncomfortable**	7.1	0	0	19.4	15.4	12.5	0	0	0	0
	Uncomfortable	35.7	7.1	44.4	45.2	46.2	37.5	7.1	7.7	42.9	0
	Slightly uncomfortable	35.7	7.1	33.3	29.0	30.8	25.0	7.1	15.4	28.6	6.1
	Neutral	14.3	25.0	5.6	3.2	7.7	12.5	14.3	15.4	14.3	12.1
	Slightly comfortable	7.1	42.9	16.7	3.2	0	12.5	42.9	15.4	14.3	39.4
	Comfortable	0	14.3	0	0	0	0	28.6	38.5	0	39.4
	Very comfortable	0	3.6	0	0	0	0	0	7.7	0	3.0

Rainy season (Thermal comfort)

There was a drift in the thermal comfort mean votes during the rainy season from the uncomfortable part of the scale to the slightly comfortable and comfortable part of the scale, (Table 5.44 and Figures 6.42-6.46). Across all case studies, only 7% in KBH2 and 11% in BWH2 felt very uncomfortable and uncomfortable. In LGH1, 50% of the time the occupant felt comfortable or very comfortable and the occupant in LGH2 felt the same, 64% of the time. More than 76% of the time the resident in MPH1 felt either 'slightly comfortable' or 'comfortable' compared to more than 14% of the time the occupant felt 'slightly comfortable', though the occupant in MPH2 felt 'slightly uncomfortable', 50% of the time (Table 5.42).

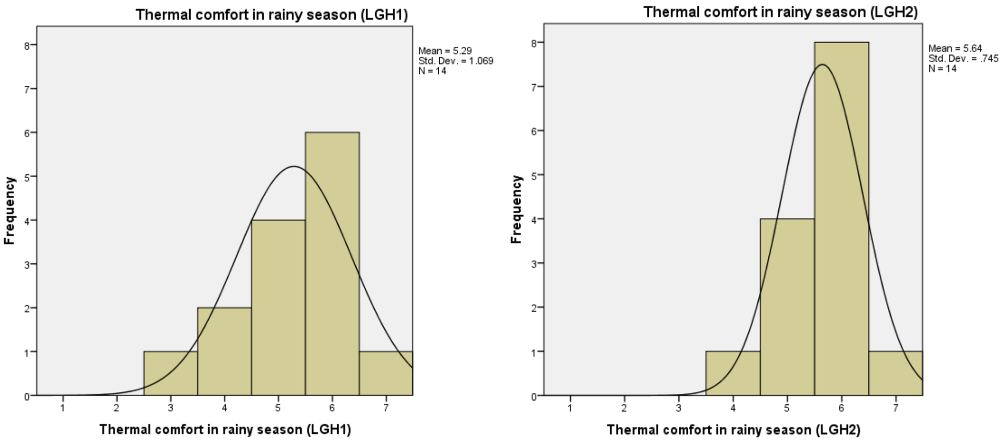


Figure 5.42: Distribution of overall thermal sensation votes during the d season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= very uncomfortable to 7= very comfortable)

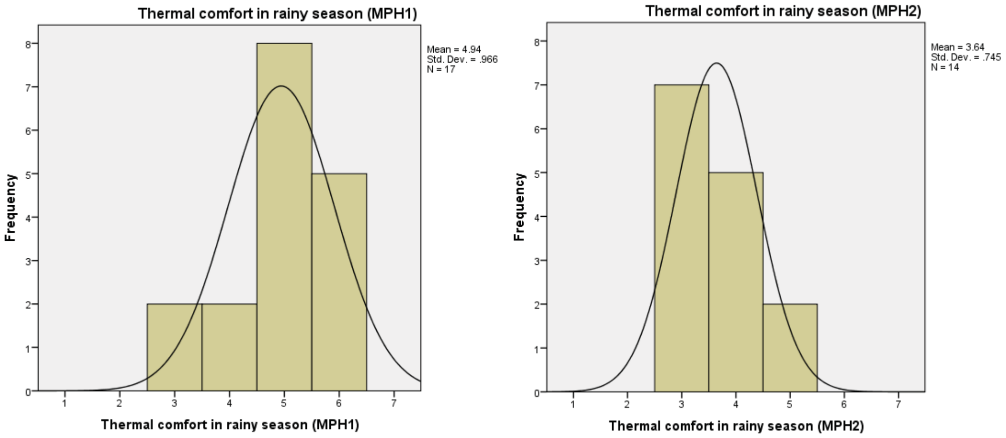


Figure 5.43:Distribution of overall thermal comfort votes during the rainy season in Mpape with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= very uncomfortable to 7= very comfortable)

In DAH1, the occupant felt ‘slightly comfortable’ over 85% of the time, indicating a big drift from the uncomfortable part of the scale recorded in the dry season. The occupant in DAH2 on the other hand, felt ‘slightly comfortable’ for 31% of the time. The occupant also felt ‘neutral for more than 53% of the time (Table 5.45).

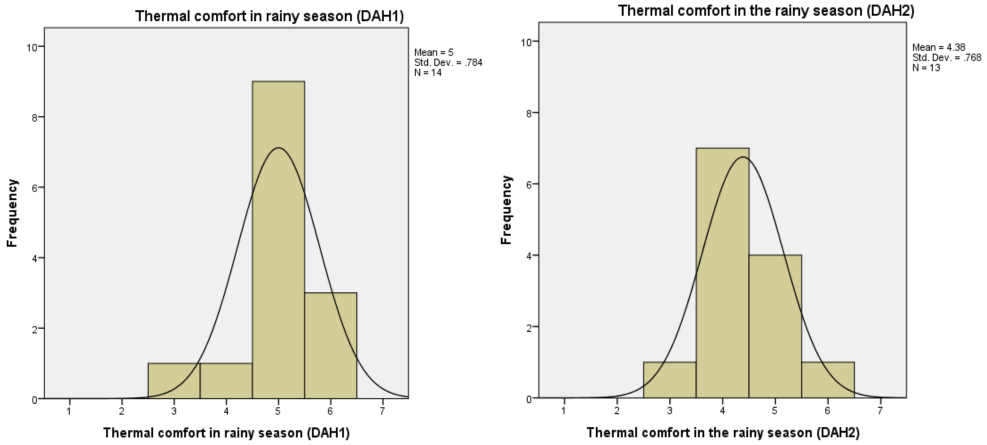


Figure 5.44: Distribution of overall thermal comfort votes during the rainy season in Dutse Alhaji with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= very uncomfortable to 7= very comfortable)

Over 92% of the time, the occupant in KBH1 felt ‘slightly comfortable’ or ‘comfortable’ compared to the occupant in KBH2 who felt ‘slightly comfortable’ or ‘comfortable’, 85% of the time (Figure 5.45). The occupant in BWH1 felt ‘slightly comfortable’ or ‘comfortable’ 66% of the time compared to more than 81% the occupant in BWH2 felt ‘slightly comfortable’ or ‘comfortable’ (Figure 5.46).

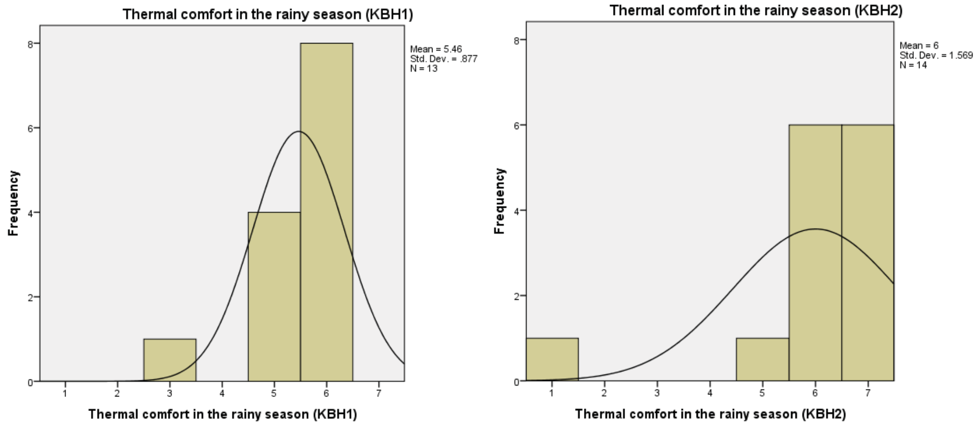


Figure 5.45: Distribution of overall thermal comfort votes during the rainy season in Kubwa with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= very uncomfortable to 7= very comfortable)

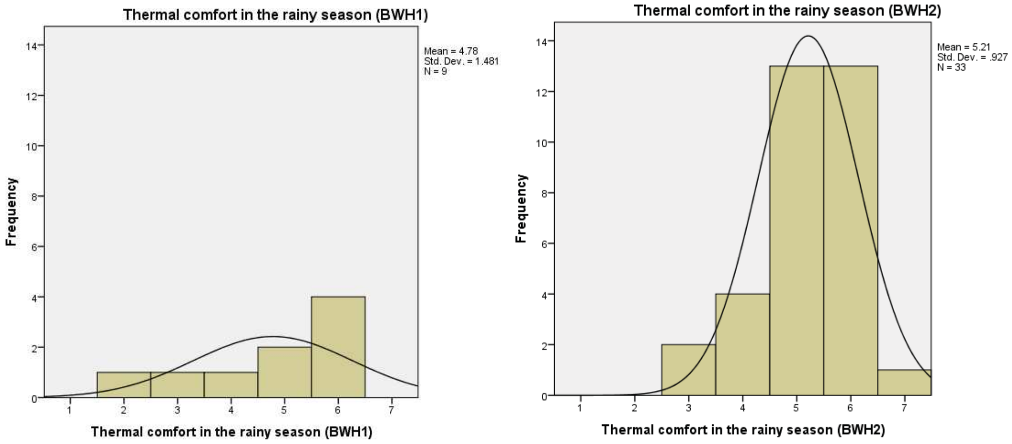


Figure 5.46: Distribution of overall thermal comfort votes during the rainy season in Bwari with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= very uncomfortable to 7= very comfortable)

Table 5.44: Summary of respondents' percentage of indoor thermal comfort during the rainy season, comfort survey

		Lugbe		**Mpape**		**Dutse Alhaji**		**Kubwa**		**Bwari**	
		LGH1 %	LGH2 %	MPH1 %	MPH2 %	DAH1 %	DAH2 %	KBH1 %	KBH2 %	BWH1 %	BWH2 %
		N=14	N=14	N=17	N=14	N=14	N=13	N=13	N=14	N=9	N=33
Indoor Thermal comfort	**Very uncomfortable**	0	0	0	0	0	0	0	7.1	0	0
	Uncomfortable	0	0	0	0	0	0	0	0	11.1	0
	Slightly uncomfortable	7.1	0	11.8	50.0	7.1	7.7	7.7	0	11.1	6.1
	Neutral	14.3	7.1	11.8	35.7	7.1	53.8	0	7.1	11.1	12.1
	Slightly comfortable	28.6	28.6	47.1	14.3	64.3	30.8	30.8	42.9	22.2	39.4
	Comfortable	42.9	57.1	29.4	0	21.4	7.7	61.5	42.9	44.4	39.4
	Very comfortable	7.1	7.1	0	0	0	0	0	0	0	3.0

5.3.3 Thermal preference analysis of comfort survey

Dry season (Thermal preference)

The mean distribution of occupants' responses across all case studies from the dry season surveys shows they prefer to be 'much cooler' or 'cooler' (Table 5.45 and Figure 5.47 – 5.51). Over 70% of the time, the occupants' in LGH1 and LGH2 prefer to be 'much cooler' or 'cooler' (Figure 5.47).

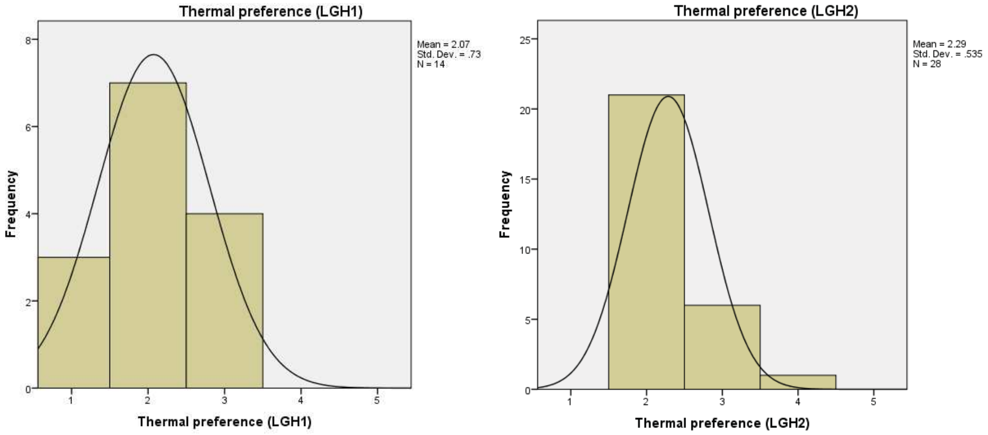


Figure 5.47: Distribution of overall thermal preference votes during the dry season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

About 89% of the time, the occupant' in MPH1 prefer to be 'much cooler' or 'cooler' compared to more than 93% of the time the occupant in MPH2 preferred the same (Figure 5.48). The occupant in DAH1 prefers to be 'much cooler' or 'cooler', 84% of the time compare to the occupant in DAH2 who prefers to be 'cooler', 75% of the time (Figure 5.49).

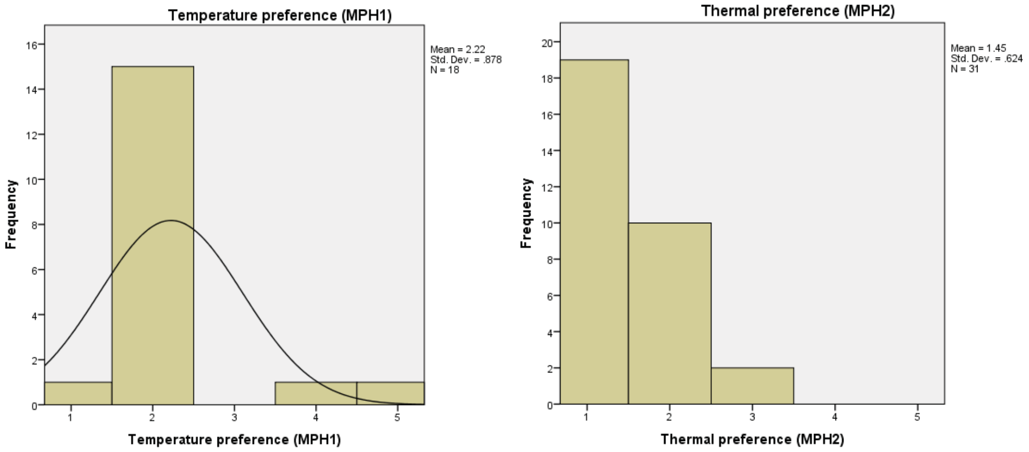


Figure 5.48: Distribution of overall thermal preference votes during the dry season in Mpape with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

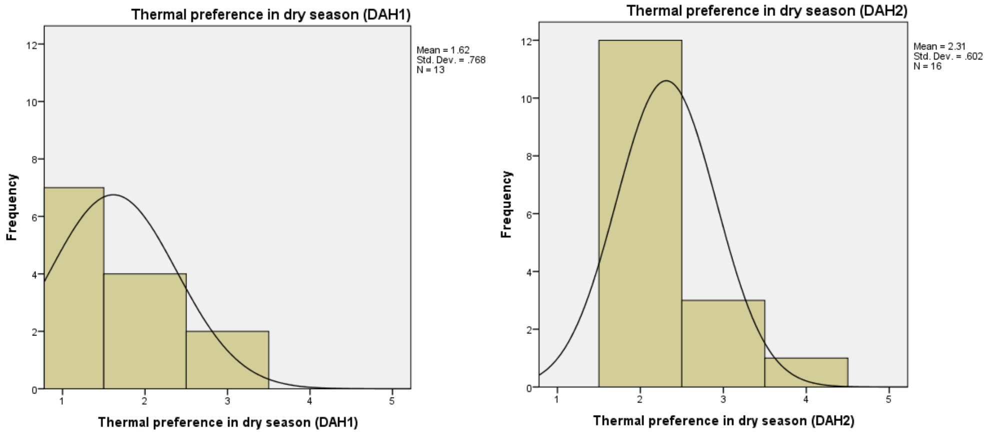


Figure 5.49: Distribution of overall thermal preference votes during the dry season in Dutse Alhaji with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

Nearly 79% of the time, the occupant' in KBH1 prefer to be 'much cooler' or 'cooler' compared to more than 62% of the time the occupant in KBH2 prefer to be 'much cooler' or 'cooler', though the occupant also prefer to be 'neutral' for 38% of the time (Figure 5.50).

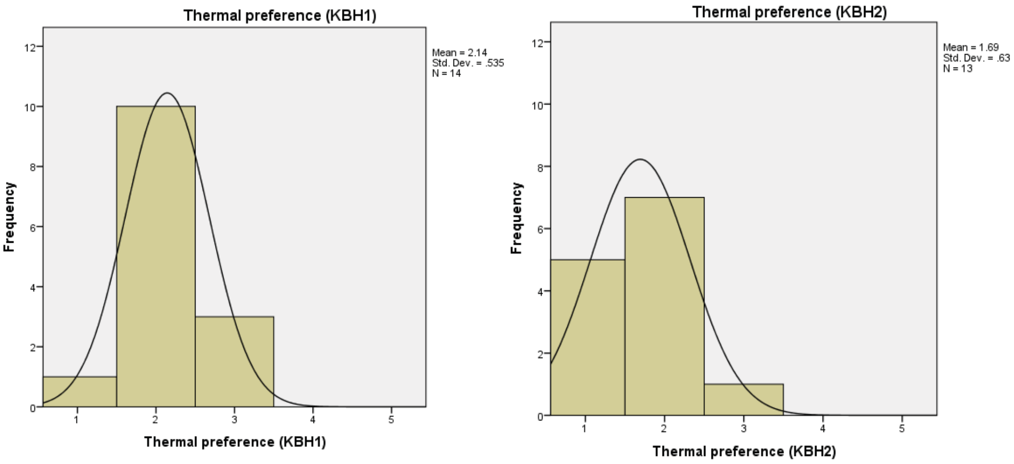


Figure 5.50: Distribution of overall thermal preference votes during the dry season in Kubwa with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

The occupant in BWH1 prefer to be ‘neutral, for more than 85% of the time compared to the occupant in BWH2 who prefers to be ‘neutral’ or ‘warmer’, over 85% of the time (Figure 5.51).

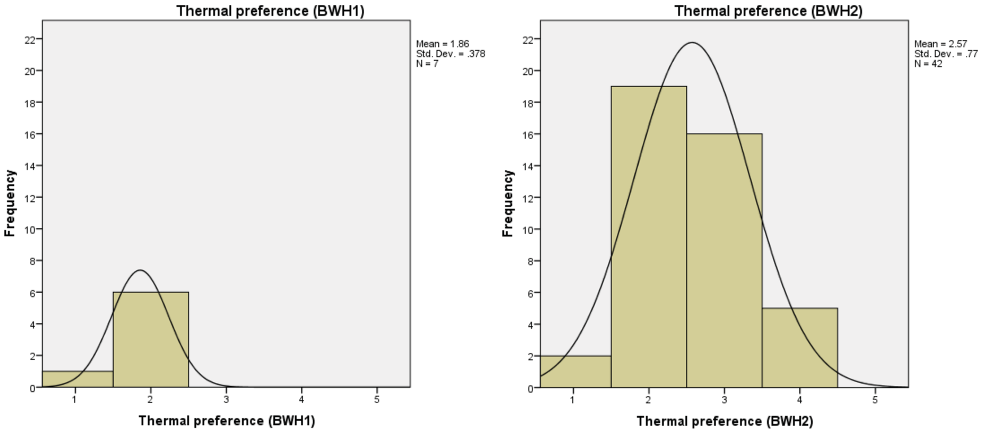


Figure 5.51: Distribution of overall thermal preference votes during the dry season in Bwari with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

Table 5.45: Summary of respondents’ percentage of indoor thermal preference during the dry season, comfort survey

		Lugbe		Mpape		Dutse Alhaji		Kubwa		Bwari	
		LGH1 %	LGH2 %	MPH1 %	MPH2 %	DAH1 %	DAH2 %	KBH1 %	KBH2 %	BWH1 %	BWH2 %
		N=14	N=28	N=18	N=31	N=13	N=16	N=14	N=13	N=7	N=33
Thermal preference	**Much cooler**	21.4	0	5.6	61.3	53.8	0	7.1	23.1	0	0
	Cooler	50.0	75.0	83.3	32.3	30.8	75.0	71.4	38.5	14.3	18.2
	No change	28.6	21.4	5.6	6.5	15.4	18.8	21.4	38.5	85.7	30.3
	Warmer	0	3.6	5.6	0	0	6.3	0	0	0	45.5
	Much warmer	0	0	0	0	0	0	0	0	0	6.1

Rainy season (Thermal preference)

There was a drift from the ‘much cooler’ or ‘cooler’ vote to the ‘no change’ vote during the rainy season (Table 5.46 and Figure 5.52 – 5.56). The survey indicates that most occupants prefer their thermal environment the way it is during the rainy season. Over 51% of the time in LGH1 and LGH2 prefer to be neutral though more than 28% of the time the occupant in LGH1 prefer to be warmer compared to 36% of the occupant in LGH2 prefer to be warmer (Figure 5.52). More than 52% of the time in MPH1 and MPH2 prefer to be cooler or neutral though the occupant in MPH1 prefers to be much cooler 29% of the time and the occupant in MPH1 prefers ‘no change’ more than 35% of the time (Figure 5.53).

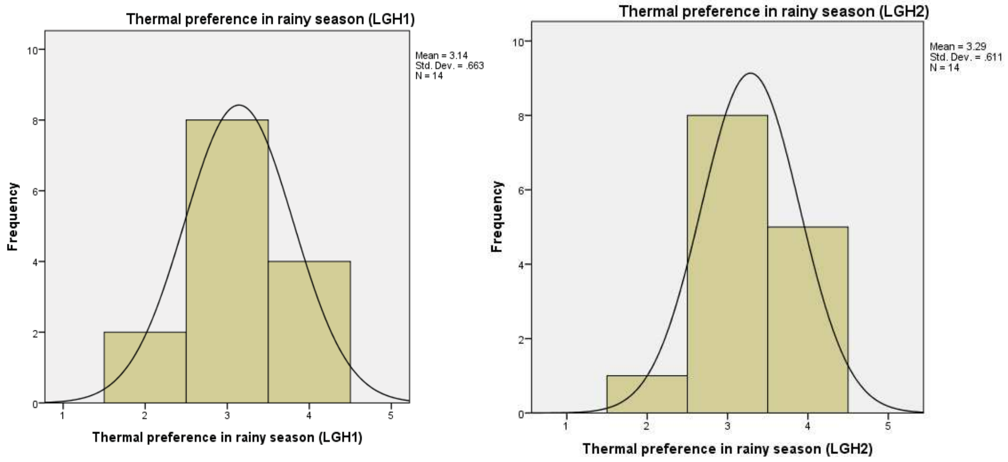


Figure 5.52: Distribution of overall thermal preference votes during the dry season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

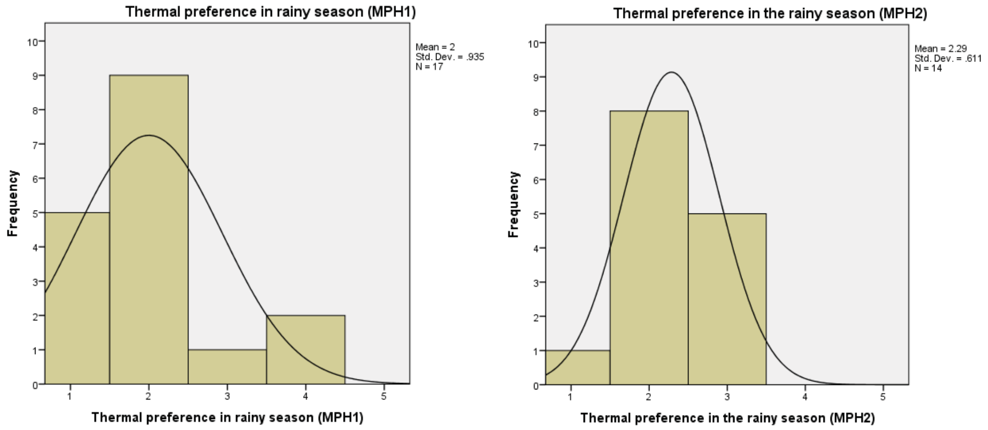


Figure 5.53: Distribution of overall thermal preference votes during the dry season in Mpape with naturally ventilated building (left) and (right) (Scale: 1= much cooler to 5= much warmer)

In DAH1, the occupant prefers to be cooler 57% of the time and neutral more than 35% of the time compared to 85% of the time the occupant in DAH2 prefers ‘no change’ (Figure 5.54). The occupant in KBH1 prefer ‘no change’ or ‘warmer’ 85% of the time compared to almost 93% of the time the occupant in KBH2 prefer ‘no change’ or ‘warmer’. The occupants’ in KBH1 and KBH2 prefer to be ‘slightly cooler’ or ‘no change’ 61% of the time, though 31% of the time the occupant in KBH1 prefer to be ‘much cooler’ and about 15% of the time, the occupant in KBH2 prefer ‘no change’ (Table 5.55).

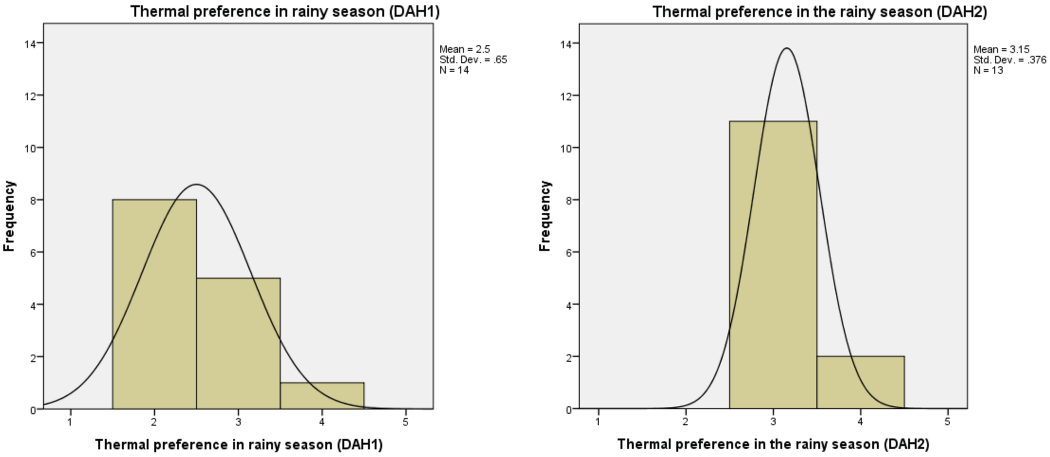


Figure 5.54: Distribution of overall thermal preference votes during the rainy season in Dutse Alhaji with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

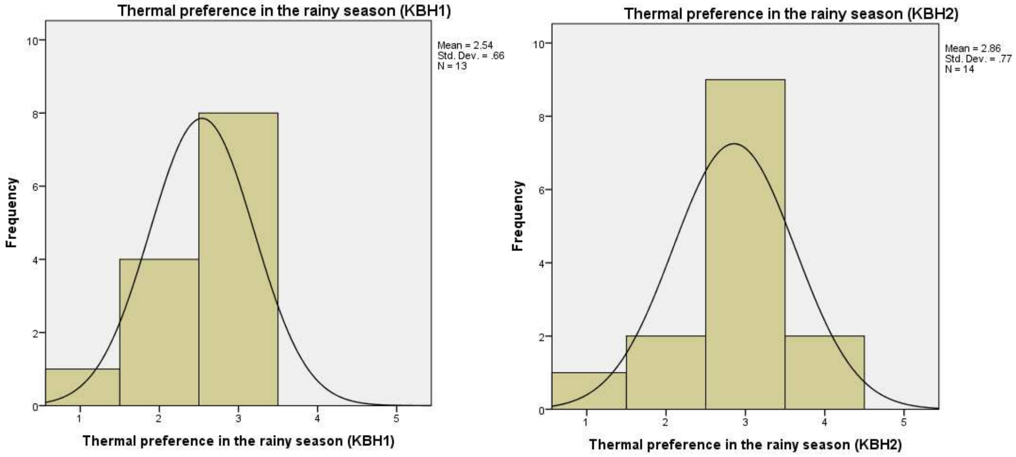


Figure 5.55: Distribution of overall thermal preference votes during the rainy season in Kubwa with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

In BWH1, the occupant prefers ‘no change’ to their thermal environment compared 30% of the time the occupant in BWH2 prefer to be no change, though more than 45% of the time, the occupant prefer to be warmer (Table 5.56).

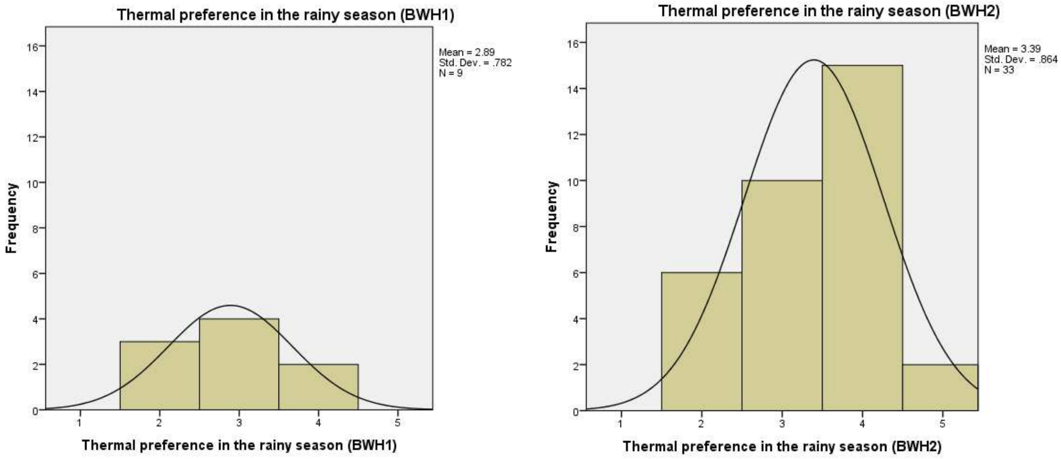


Figure 5.56: Distribution of overall thermal preference votes during the rainy season in Bwari with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

Table 5.46: Summary of respondents’ percentage of indoor thermal preference during the rainy season, comfort survey

		Lugbe		Mpape		Dutse Alhaji		Kubwa		Bwari	
		LGH1 %	LGH2 %	MPH1 %	MPH2 %	DAH1 %	DAH2 %	KBH1 %	KBH2 %	BWH1 %	BWH2 %
		N=14	N=14	N=17	N=14	N=14	N=13	N=13	N=14	N=9	N=33
Thermal preference	**Much cooler**	0	0	29.4	7.1	0	0	7.7	7.1	0	0
	Cooler	14.3	7.1	52.9	57.1	57.1	0	30.8	14.3	33.3	18.2
	No change	57.1	57.1	5.9	35.7	35.7	84.6	61.5	64.3	44.4	30.3
	Warmer	28.6	35.7	11.8	0	7.1	15.4	0	14.3	22.2	45.5
	Much warmer	0	0	0	0	0	0	0	0	0	6.1

5.3.4 Thermal acceptability analysis of comfort survey

Occupants were thermally dissatisfied with their thermal environment in both seasons though more than 80% acceptability rate were reported in the rainy season

Dry season (Thermal acceptability)

Overall, 60% of the votes revealed unacceptability of their thermal environment in the dry season. The result on thermal acceptability in the dry season does not agree with ASHRAE's recommendation that at least 80% of the occupants must find the thermal environment acceptable (Table 5.47).

Table 5.47: Summary of respondents' percentage of indoor thermal acceptability during the dry season, comfort survey

		Lugbe		Mpape		Dutse Alhaji		Kubwa		Bwari	
		LGH1 %	LGH2 %	MPH1 %	MPH2 %	DAH1 %	DAH2 %	KBH1 %	KBH2 %	BWH1 %	BWH2 %
		N=14	N=28	N=18	N=31	N=13	N=16	N=14	N=13	N=7	N=33
Thermal acceptability	**Yes**	21.4	35.7	22.2	12.9	15.4	43.8	85.7	76.9	14.3	72.7
	No	78.6	64.3	77.8	87.1	84.6	56.3	14.3	23.1	85.7	27.3

Rainy season (Thermal acceptability)

More than 80% of the votes reported acceptability of their thermal environment in the rainy season compared to the low votes recorded in the dry season. The result on thermal acceptability in the rainy season agrees with ASHRAE's recommendation that at least 80% of the occupants must find the thermal environment acceptable (Table 5.48).

Table 5.48: Summary of respondents' percentage of indoor thermal acceptability during the rainy season, comfort survey

		Lugbe		Mpape		Dutse Alhaji		Kubwa		Bwari	
		LGH1 %	LGH2 %	MPH1 %	MPH2 %	DAH1 %	DAH2 %	KBH1 %	KBH2 %	BWH1 %	BWH2 %
		N=14	N=14	N=17	N=14	N=14	N=13	N=13	N=14	N=9	N=33
Thermal acceptability	**Yes**	92.9	85.7	82.4	85.7	78.6	100	92.3	100	77.8	72.7
	No	7.1	14.3	17.6	14.3	21.4	0	7.7	0	22.2	27.3

Table 5.49: Comfort survey mean responses for the thermal sensation and thermal satisfactions in the dry and rainy season

	Thermal sensation				**Thermal comfort**				**Thermal preference**			
	Dry season		**Rainy season**		**Dry season**		**Rainy season**		**Dry season**		**Rainy season**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
LGH1 (NV)	5.4	1.15	2.9	1.07	2.8	1.05	5.2	1.07	2.0	0.73	3.1	0.66
LGH2 (AC)	5.0	0.84	3.0	1.30	4.6	1.17	5.6	0.75	2.3	0.54	3.3	0.61
MPH1 (NV)	5.3	1.27	3.2	1.59	2.9	1.11	4.9	0.97	2.2	0.85	2.0	0.94
MPH2 (NV)	5.8	0.79	4.5	0.86	2.3	0.93	3.6	0.75	1.5	0.62	2.3	0.61
DAH1 (NV)	5.9	0.80	3.4	0.76	2.3	0.86	5.0	0.78	1.6	2.31	2.5	0.65
DAH2 (AC)	5.0	0.82	4.2	1.09	2.8	1.24	4.4	0.77	2.3	0.60	3.2	0.38
KBH1 (AC)	5.0	0.78	2.5	1.79	4.8	1.19	5.5	0.88	2.1	0.54	2.5	0.66
KBH2 (AC)	5.1	1.26	1.8	0.58	4.9	1.52	6.0	1.57	2.3	0.60	2.9	0.77
BWH1 (NV)	5.4	1.27	3.2	1.09	3.6	1.62	4.8	1.48	1.7	0.63	2.9	0.78
BWH2 (AC)	3.7	1.76	3.7	1.76	5.2	0.93	5.2	0.93	2.8	0.77	3.4	0.86

NV: naturally ventilated building, AC: air-conditioned building

The mean values of the post-occupancy thermal sensation during the dry season survey reported more than 5 across all case studies apart from BWH2 (Table 5.49). The comfort survey also showed BWH2 had the highest value of 5.2 and tilting towards the neutral part of the scale in the thermal preference vote. This suggest that the occupant in BWH2 is the most comfortable and is satisfies with their thermal environment during the dry season which might imply a high use of air-conditioning and its larger floor area came into consideration.

5.3.5 Preferred and Neutral temperatures from the Comfort Survey

Linear regression analysis was used to calculate neutral and preferred temperatures (See Figure 5.57 – 5.62). This showed that occupants in this region of Abuja have a potential to adapt to high temperatures. The results suggest occupants showed that more adaptation potential, with higher neutral temperatures more than 30°C (28-30.4°C) and preferred temperature between 27°C – 28.5°C. This section will discuss the preferred and neutral temperature reported across all case studies in this study.

Neutral and preferred temperatures, Lugbe

The results suggest occupants in LGH1 showed more adaptation potential, with a higher neutral temperature of 29.5°C and preferred temperature of 28.3°C, compared to a recorded neutral temperature of 28.8°C and a lower preferred temperature of 28.1°C in LGH2 (Figure 5.57 and 5.58).

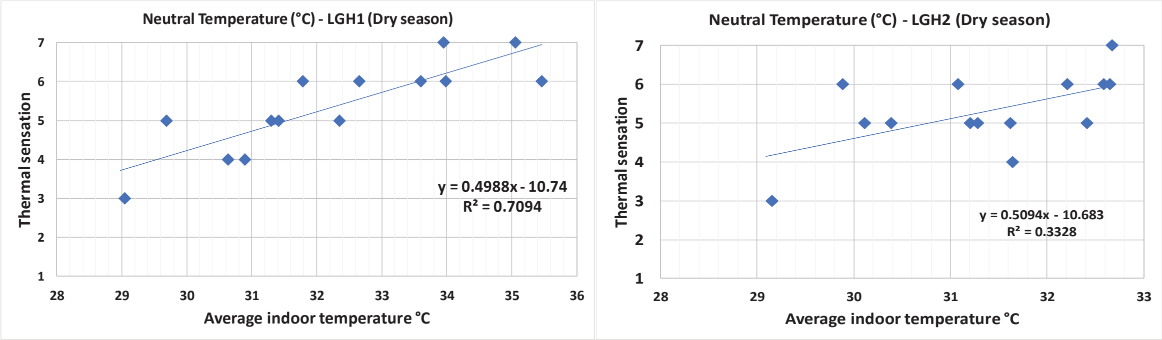


Figure 5.57: Relationship between thermal sensation and the average indoor temperature at LGH1 (left) and LGH2 (right)

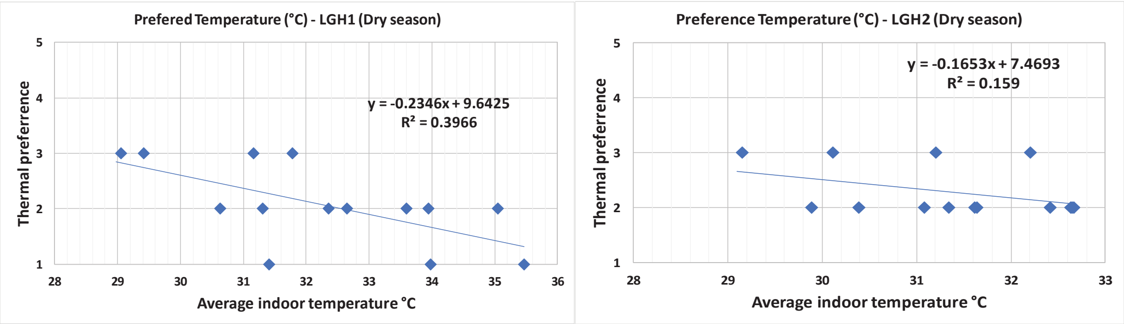


Figure 5.58: Relationship between thermal preference and the average indoor temperature at LGH1 (left) and LGH2 (right)

Neutral and preferred temperatures, Mpape

The results suggest occupants in MPH1 showed more adaptation potential, with a higher neutral temperature of 28.4°C and preferred temperature of 27.3°C, compared to a recorded neutral temperature of 28.2°C and a lower preferred temperature of 27.2°C in MPH2 (Figure 6.59 and 6.60).

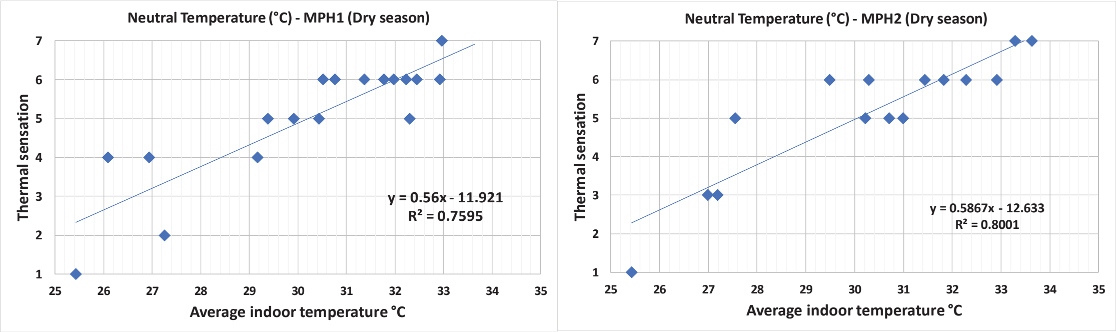


Figure 5.59: Relationship between thermal sensation and the average indoor temperature at MPH1 (left) and MPH2 (right)

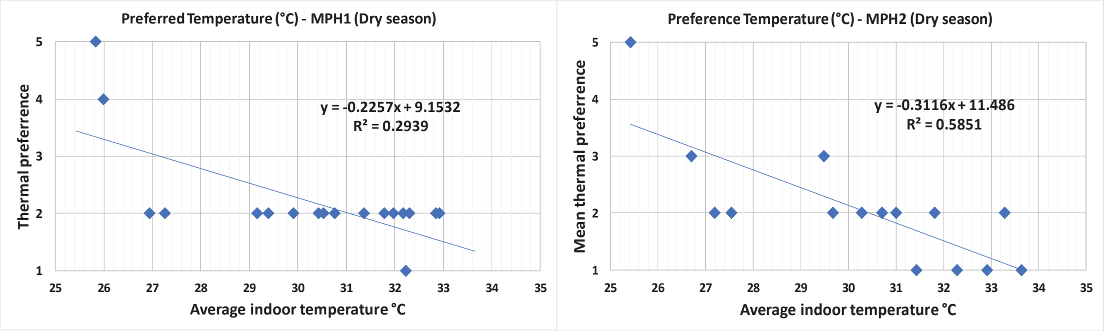


Figure 5.60: Relationship between thermal preference and the average indoor temperature at MPH1 (left) and MPH2 (right).

Neutral and preferred temperatures, Dutse Alhaji

The results suggest occupants in DAH2 showed more adaptation potential, with a higher neutral temperature of 30.1°C and preferred temperature of 28.5°C, compared to a recorded neutral temperature of 28°C and a lower preferred temperature of 26.1°C in DAH1 (Figure 6.61 and 6.62).

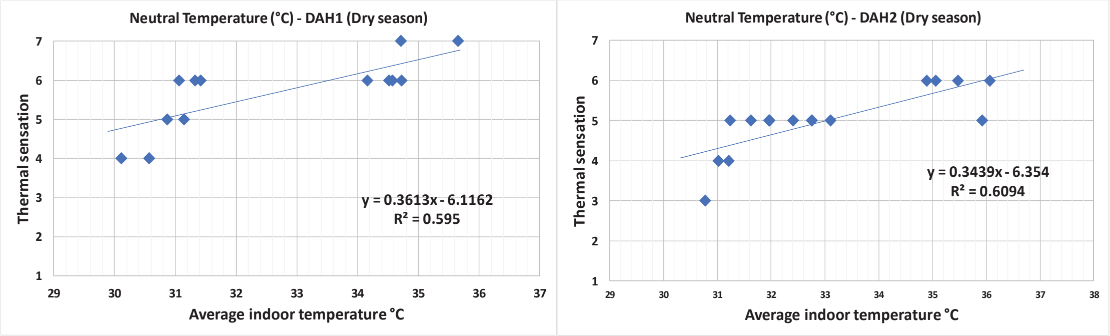


Figure 5.61: Relationship between thermal sensation and the average indoor temperature at DAH1 (left) and DAH2 (right)

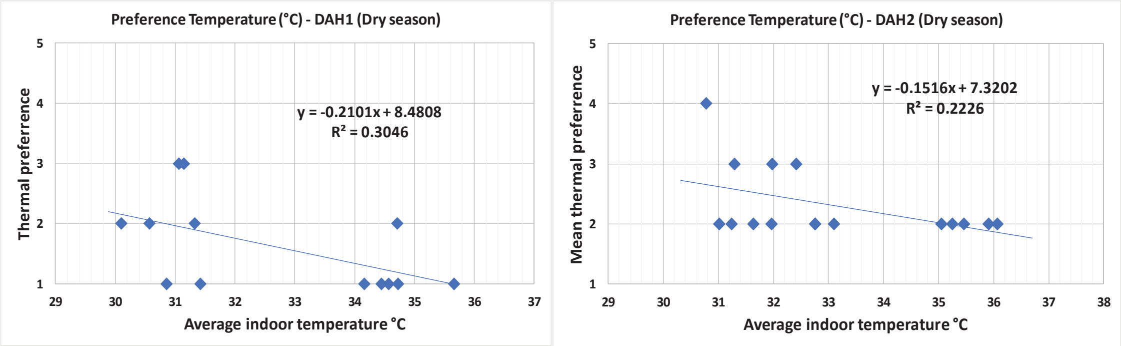


Figure 5.62: Relationship between thermal preference and the average indoor temperature at DAH1 (left) and DAH2 (right)

Neutral and preferred temperatures, Kubwa

The results suggest occupants in KBH1 showed a high adaptation potential, with a neutral temperature of 29.1°C and preferred temperature of 27.3°C, compared to a recorded neutral temperature of 29.2°C and a preferred temperature of 27.3°C in KBH2 (Figure 5.63 and 5.64).

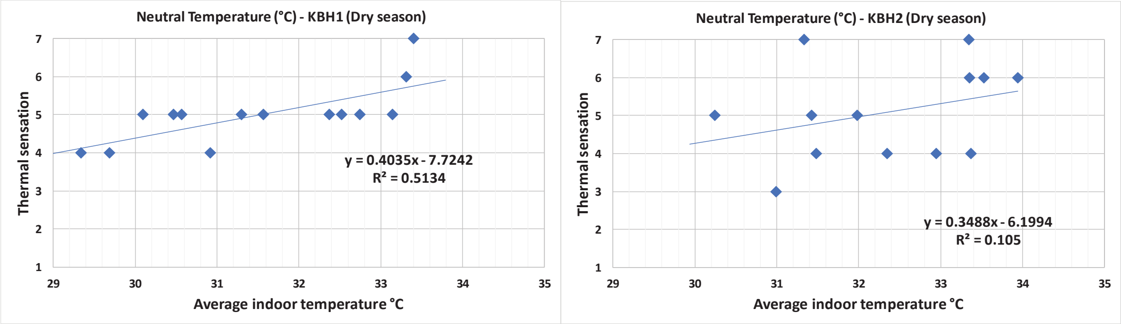


Figure 5.63: Relationship between thermal sensation and the average indoor temperature at KBH1 (left) and KBH2 (right)

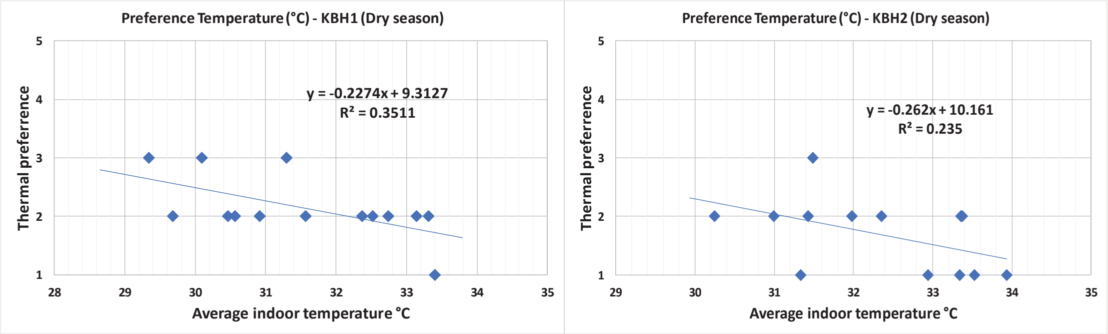


Figure 5.64: Relationship between thermal preference and the average indoor temperature at KBH1 (left) and KBH2 (right)

Neutral and preferred temperatures, Bwari

The results suggest occupants in BWH1 showed more adaptation potential, with a higher neutral temperature of 30.4°C and preferred temperature of 28.2°C, compared to a recorded neutral temperature of 29.4°C and a lower preferred temperature of 27.5°C in BWH2 (Figure 5.65 and 5.66).

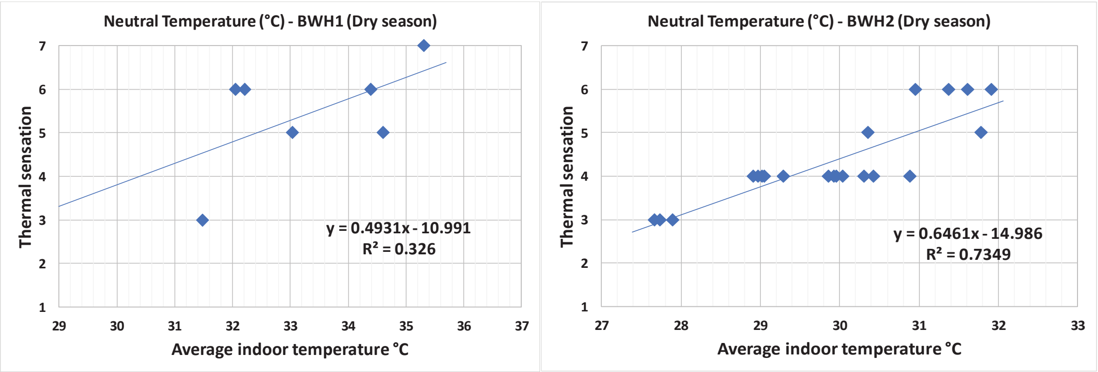


Figure 5.65: Relationship between thermal sensation and the average indoor temperature at BWH1 (left) and BWH2 (right)

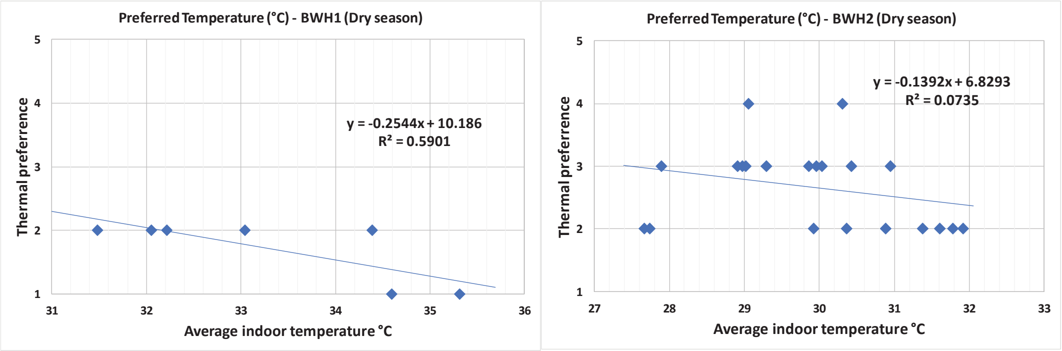


Figure 5.66: Relationship between thermal preference and the average indoor temperature at BWH1 (left) and BWH2 (right)

The higher neutral temperatures recorded showed the adaptation to high temperatures across all case studies.

5.4 Overheating analysis for the measured dwellings

A research in India by Mishra, A.K. and Ramgopal, M. (2015) showed that the adaptive comfort model from EN15251 in particularly was well suited for comfort analysis when compared to ASHRAE Standard-55 and may be used for hot-humid regions of India until more field studies are done to develop a model specifically for India. The results also confirmed that Adaptive Comfort Equation (ACE) of EN15251 was significantly better at predicting comfort temperatures of Indian surveys than the ASHRAE ACE.

Highest energy savings were also predicted using EN15251, followed by Nguyen et al.'s model, and ASHRAE Standard 55. Models by Nguyen et al. (2012) and from EN15251 gave good approximations for the actual field study data and at the same time, are likely to give significant energy savings if implemented compared to ASHRAE Standard 55. Due to the hot climate, comfort temperatures from the field studies analysed are on the higher side. Studies in Uganda by Hashemi, (2016) and Hashemi, et al. (2015) also used EN15251 adaptive comfort model rather than ASHRAE Standard 55 for hot-humid climates. Hence, based on these studies and their conclusions, the overheating analysis was carried out using two models, the static CIBSE comfort model and EN15251 adaptive comfort model. The results from this analysis were discussed in this section.

5.4.1 The static CIBSE comfort model for the measured dwellings

This section discusses the static CIBSE analysis for overheating across all the monitored spaces in Abuja. The model uses the number of occupied hours, 5% of hours above 25°C (5%>25°C) and 1% of hours above 28°C (1%>28°C) as indicators of moderately warm and extremely hot overheating risk for living room spaces, with 5% of hours above 24°C (5%>24°C) and 1% of hours above 26°C (%>26°C), used for bedroom spaces. However, average temperatures reported across all case studies were between 29°C to 33°C, indicating high percentage of hours were above 25°C and 28°C for the living room and 24°C and 26°C as suggested by CIBSE. Therefore, this study adopted 1% of hour above 28°C indicator for extremely hot and 1% hours above 26°C threshold for the bedrooms spaces for extremely hot conditions. Below, Figures 5.65-5.79 and Tables Table A1.8-A1.10 summarises the overheating risks for all the monitored case studies in Abuja.

Lugbe

Overheating analysis risk using the CIBSE comfort model showed the temperature rose above 1% of hours above 28°C indicator for the 100% of the living rooms and 100% of the bedrooms rose above the 1% of hours above 26°C indicator. (Figure 5.67). Considering the day & evening time monitored from 08:00 – 22:00, 100% of living rooms in Lugbe recorded temperatures exceeded the 1% > 28°C threshold of extremely hot overheating in the dry season (summertime) for 100% of the time (Figure 5.68). Looking at the evening period from 18:00 – 22:00, temperatures were above the 1% > 28°C indicator in 100% of the living areas (Figure 5.68). At night-time, 23:00 – 07:00, temperatures recorded were above the 1% > 26°C mark in 100% of the bedrooms monitored at the buildings and even exceeded the 50% > 32°C indicator in 100% of the bedrooms (Figure 5.69).

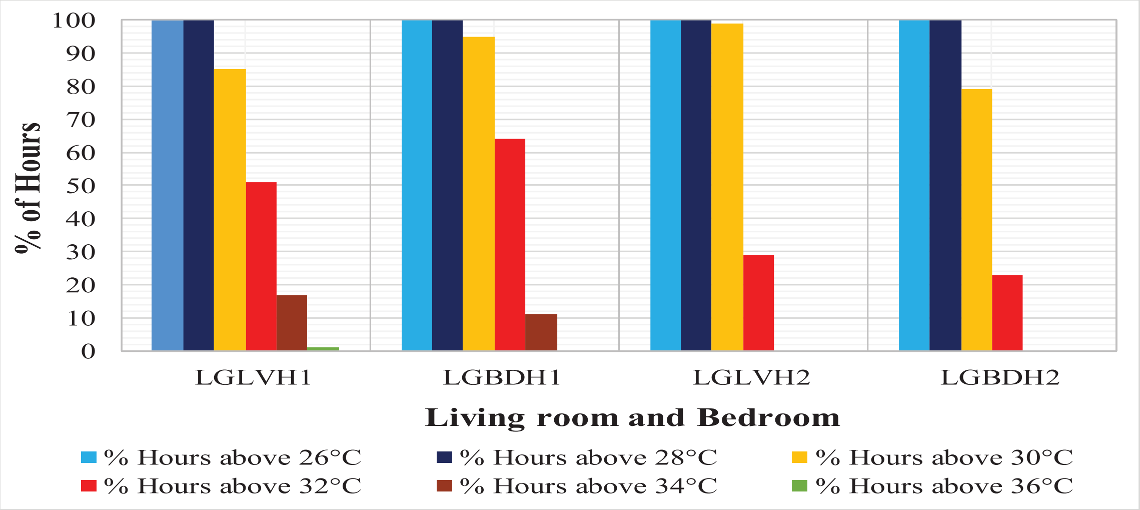


Figure 5.67: Monitored temperatures and overheating risks criteria for the living rooms and bedrooms at Lugbe during the dry season

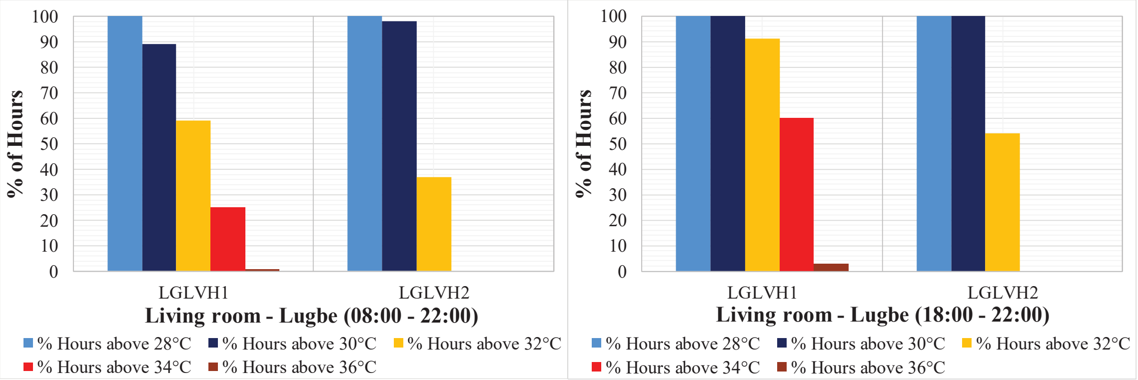


Figure 5.68: Monitored temperatures and overheating risks criteria for living rooms at Lugbe (08:00 – 22:00, left and 18:00 – 22:00, right).

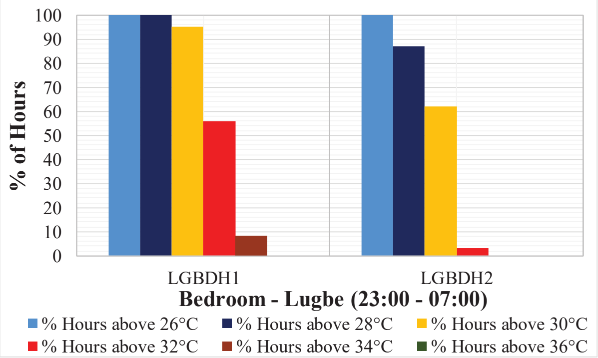


Figure 5.69: Monitored temperatures and overheating risks criteria, bedrooms (23:00 – 07:00) at Lugbe.

Mpape

At the case study location in Mpape, the living room temperatures rose above the 1% > 28°C indicator for the 100% of the spaces and 100% of the bedrooms exceeded the 1% of hours above 26°C indicator.

(Figure 5.70). 100% of living rooms monitored from 08:00 – 22:00 in Mpape, temperatures exceeded the 1% > 28°C indicator of extremely hot in the dry season for 100% of the time (Figure 5.71). The evening period temperatures from 18:00 – 22:00, were above the 1% > 28°C threshold in 100% of the living areas (Figure 5.71). At night-time, 23:00 – 07:00, temperatures recorded rose above the 1% > 26°C mark in 100% of the bedrooms monitored at the buildings (Figure 5.72).

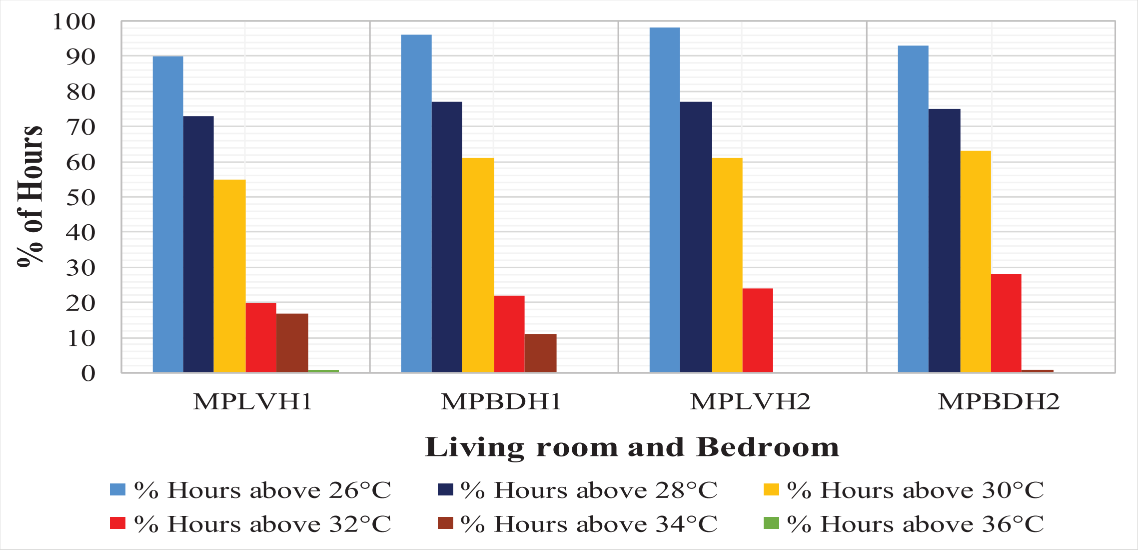


Figure 5.70: Monitored temperatures and overheating risks criteria for the living rooms and bedrooms at Mpape during the dry season

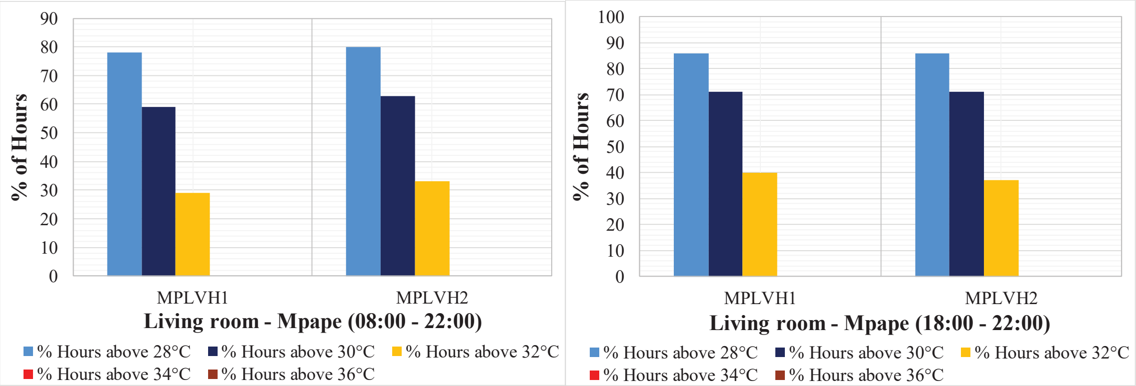


Figure 5.71: Monitored temperatures and overheating risks criteria for living rooms at Mpape (08:00 – 22:00, left and 18:00 – 22:00, right).

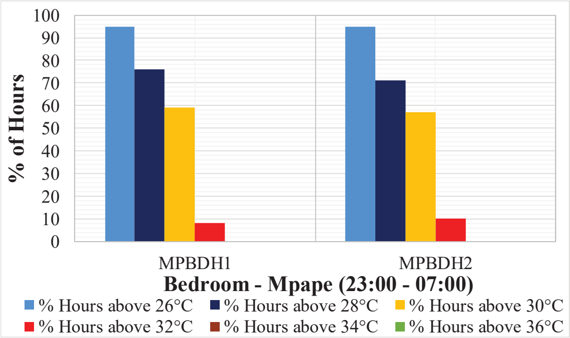


Figure 5.72: Monitored temperatures and overheating risks criteria, bedrooms (23:00 – 07:00) at Mpape

Dutse Alhaji

At Dutse Alhaji, 100% of living rooms reported indoor conditions exceeded the 1%>28°C indicator for 100% of the time and exceeded the 1% > 26°C threshold for 100% of the time in 100% of the bedrooms (Figure 5.73). Considering the monitored living room spaces from 08:00 – 22:00 in Dutse Alhaji, temperatures rose above the 1% > 28°C indicator of extremely hot in the dry season for 100% of the living rooms (Figure 5.74). The evening period temperatures from 18:00 – 22:00, rose above the 1% > 28°C threshold in 100% of the living areas (Figure 5.74). The night-time period recorded temperatures above the 1% > 26°C threshold in 100% of the bedrooms monitored at the buildings (Figure 5.75).

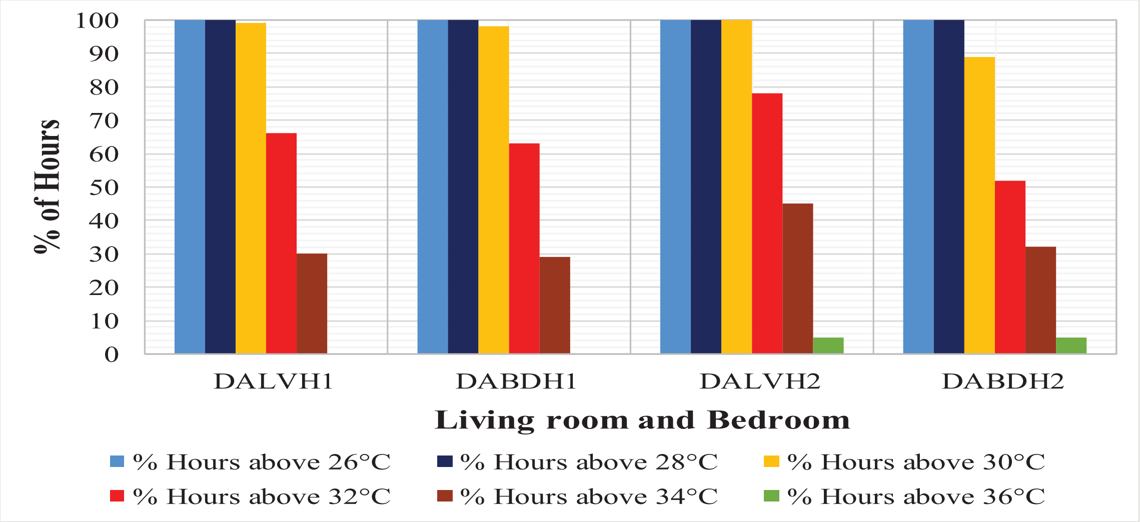


Figure 5. 73: Monitored temperatures and overheating risks criteria for the living rooms and bedrooms at Dutse Alhaji during the dry season.

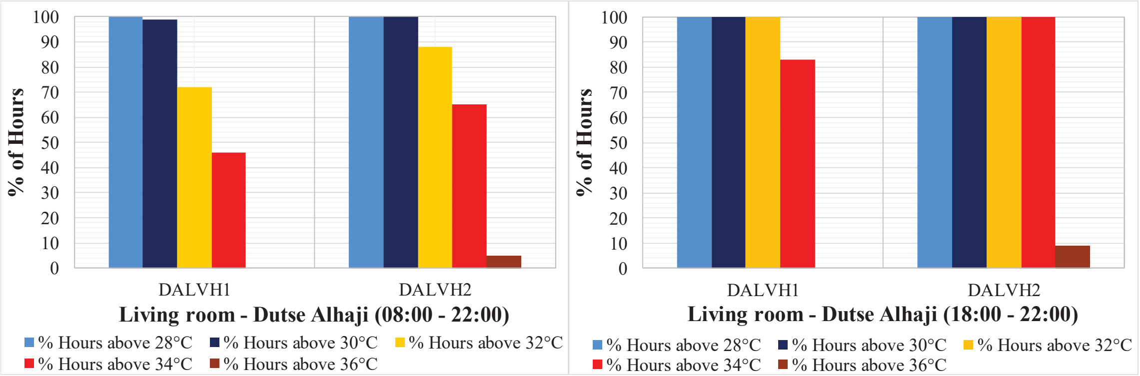


Figure 5.74: Monitored temperatures and overheating risks criteria for living rooms at Dutse Alhaji (08:00 –22:00, left and 18:00 – 22:00, right).

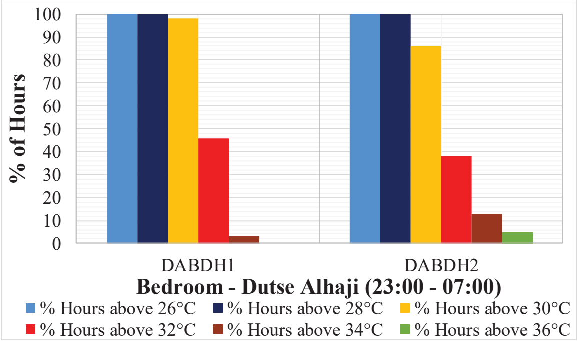


Figure 5.75: Monitored temperatures and overheating risks criteria, bedrooms (23:00 – 07:00) at Dutse Alhaji

Kubwa

The temperature exceeded the 1% > 28°C threshold in 100% the living room spaces and exceeded 26°C in 100% of the bedroom spaces at Kubwa (Figure 5.76). Considering all the two living rooms monitored from 08:00 – 22:00 in Lugbe, temperatures rose above the 1% > 28°C threshold for 100% of the living room spaces indicating extremely hot conditions in the dry season (Figure 5.77). Looking at the evening period from 18:00 – 22:00, temperatures were above the 1% > 28°C indicator in 100% of the living areas (Figure 5.77). The night-time period recorded temperatures above the 1% > 26°C threshold all the two bedrooms monitored at the buildings (Figure 5.78).

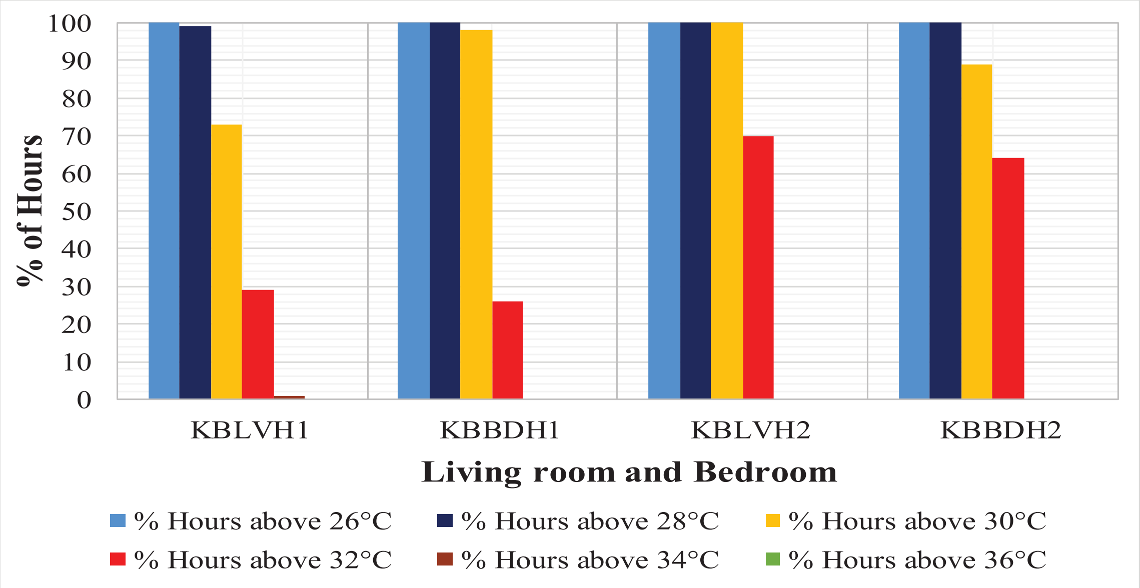


Figure 5.76: Monitored temperatures and overheating risks criteria for the living rooms and bedrooms at Kubwa during the dry season.

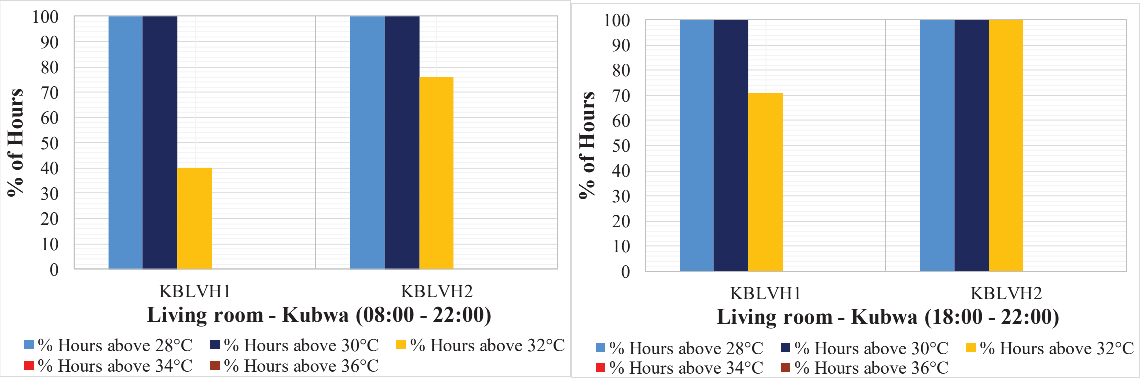


Figure 5.77: Monitored temperatures and overheating risks criteria for living rooms at Kubwa (08:00–22 :00, left and 18:00 – 22:00, right).

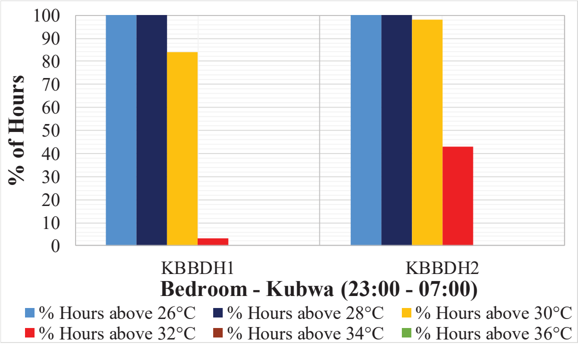


Figure 5.78: Monitored temperatures and overheating risks criteria, bedrooms (23:00 – 07:00) at Kubwa

Bwari

Overheating analysis risk in Bwari showed indoor temperatures rose above 1% > 28°C marker for 100% of the living rooms during the daytime and evening periods (Figure 5.79-5.80). The night-time temperatures exceeded the 1% > 26°C indicator for 100% of the bedrooms (Figure 5.81).

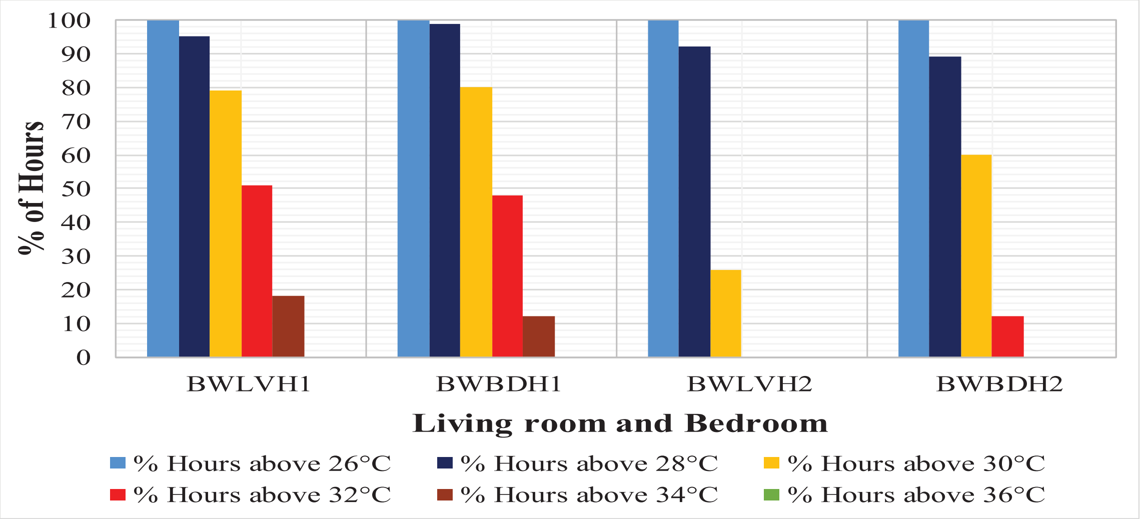


Figure 5.79: Monitored temperatures and overheating risks criteria for the living rooms and bedrooms at Bwari during the dry season.

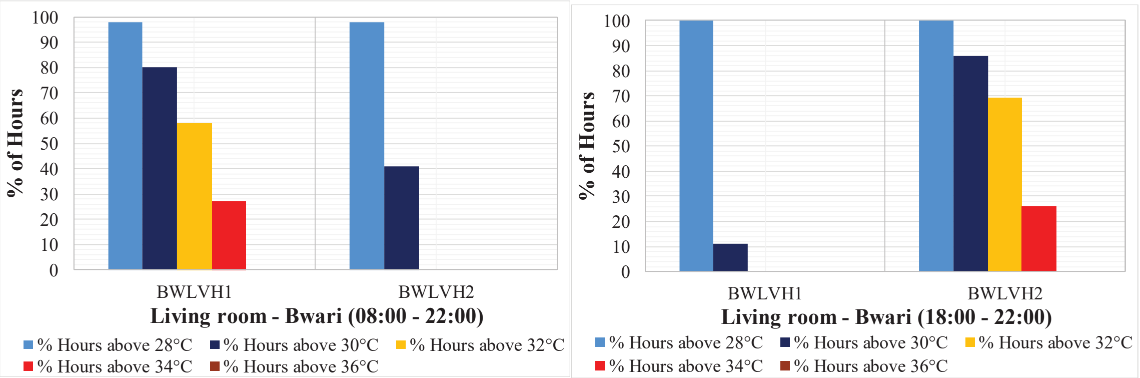


Figure 5.80: Monitored temperatures and overheating risks criteria for living rooms at Bwari (08:00–22 :00, left and 18:00 – 22:00, right).

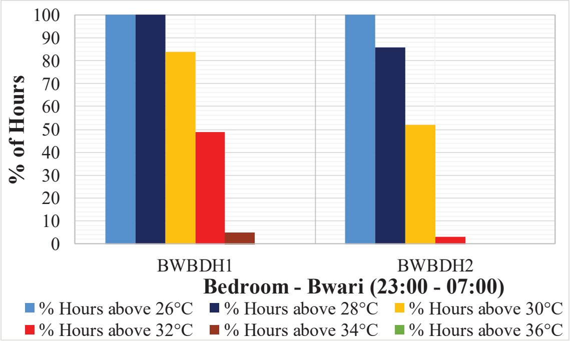


Figure 5.81: Monitored temperatures and overheating risks criteria, bedrooms (23:00 – 07:00) at Bwari

The CIBSE overheating analysis during the daytime and evening period shows that 100% of the living rooms across all the case studies recorded temperatures above 1% > 28°C indicator for extremely hot conditions. The night-time (23:00 – 07:00) overheating analysis results show that 100% of the bedrooms across all the case studies reported temperatures rose above the 1% > 26°C marker for most of the time. This shows that at night, the occupants are experiencing extreme hot conditions during the sleeping hours.

5.4.2 The EN 15251 dynamic adaptive comfort model for the measured dwellings

Overheating was also examined in the naturally ventilated dwellings using the adaptive comfort model, category II (Cat. II) 'normal level of expectation'. Linking monitored hourly temperatures with the running mean of the daily mean outdoor temperature (T_{rm}) established a drift towards much warmer indoor temperatures as T_{rm} increased (Figure 5.82-5.90). Most of the difference in indoor temperatures for certain T_{rm} value (30°C – 33°C) did not really differ from one dwelling to another. For the BSEN15251 adaptive model, Cat. II is employed for evaluating thermal comfort in buildings where rigorous tasks are not expected to be carried out and people can open or close windows and likely to adjust clothing insulation to meet the thermal conditions of their environment. Category II provides a temperature range of 6 K. The EN15251 provides no restriction on the acceptable limits of the category markers and 5% of hours over (warm discomfort) or lower (cold discomfort) the category limit will be considered as an indicator in this study. However, considering the high temperatures recorded and high adaptation to these high temperatures, Category III (Cat. III) was also considered to understand the extent of occupants' experience to these extreme indoor conditions during the dry season across all case studies. This section will discuss the overheating analysis across all the spaces in the ten monitored dwellings in Abuja.

The dynamic adaptive comfort model in Lugbe

In the living room spaces, LGLVH1 recorded temperatures exceeded 5% Cat. II threshold for more than 10% of the time and rose above the Cat. III upper threshold for more than 30% of the time during the day & evening period (08:00-22:00). During the evening period (18:00-22:00), LGLVH1 recorded temperatures rose above Cat. II upper threshold for more than 10% of the time and it rose above Cat. III upper threshold for more than 65% of the time (Figure 5.82). This shows extreme indoor condition during the daytime and evening period. The bedroom in LGBDH1 recorded temperatures exceeded Cat. II upper threshold for more than 20% of the time and rose above Cat. III upper marker for 10% of the time (Figure 5.83).

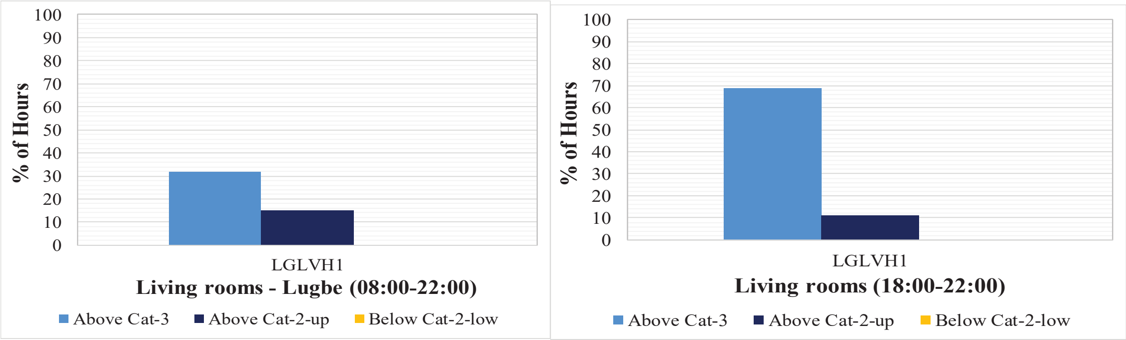


Figure 5.82: Percentage of hours of the living room temperature in EN15251 Cat. II and Cat. III thermal comfort category at Lugbe (08:00–22 :00, left and 18:00 – 22:00, right).

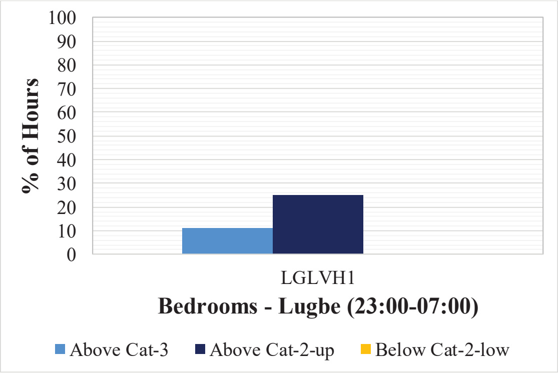


Figure 5.83: Percentage of hours of the bedroom temperature in EN15251 Cat. II and Cat. III thermal comfort category at Lugbe (23:00 – 07:00).

The dynamic adaptive comfort model in Mpape

In MPLVH1 and MPLVH2, the living room spaces reported temperatures exceeded Cat. II upper threshold for more than 10% of the time and exceeded Cat. III upper threshold for more than 5% of the time during the daytime & evening period (08:00-22:00). The evening period recorded temperatures exceeded Cat. II upper threshold for more than 20% of the time and above the Cat. III upper threshold for 10% of the time (Figure 5.84). The bedroom temperatures in MPBDH1 recorded temperatures exceeded Cat. II upper marker for 10% of the time while MPBDH2 also recorded temperatures exceeded Cat. II upper marker for more than 10% of the time. In addition, less than 5% of the time, the recorded temperature was below Cat. II lower marker in MPBDH2 (Figure 5.85).

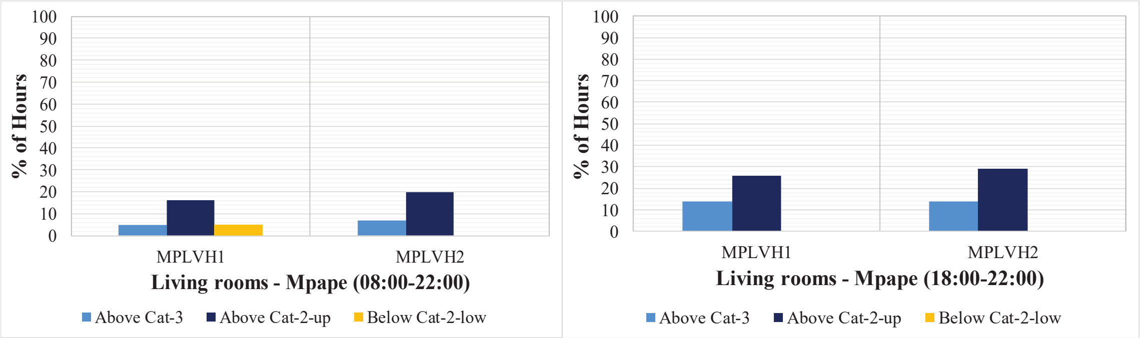


Figure 5.84: Percentage of hours of the living room temperature in BSEN 15251 Cat. II and Cat. III thermal comfort category at Mpape (08:00–22:00, left and 18:00 – 22:00, right).

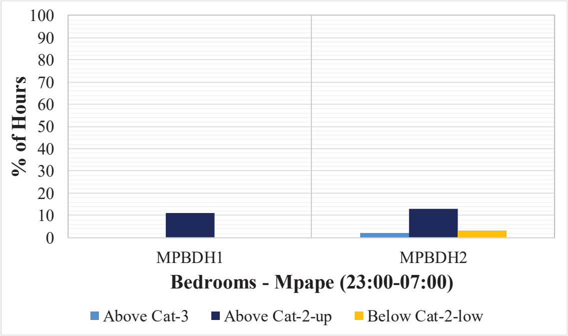


Figure 5.85: Percentage of hours of the bedroom temperature in BSEN 15251 Cat. II and Cat. III thermal comfort category at Mpape (23:00 – 07:00).

The dynamic adaptive comfort model in Dutse Alhaji

In the living room spaces during the daytime and evening period (08:00-22:00), DALVH1 recorded temperatures exceeded Cat. II upper marker for more than 10% of the time and above the Cat. III upper threshold for more than 60% of the time (Figure 5.86). In the evening period (18:00-22:00), DALVH1 showed temperature above the Cat. III upper threshold for 100% of the time, suggesting that for six hours, temperatures were above Cat. III threshold and the occupants had experience extremely high levels of indoor temperatures (Figure 5.86). The bedroom temperatures in DABDH1 recorded temperatures exceeded Cat. II upper threshold for more than 20% of the time and above Cat. III for more than 10% of the time (Figure 5.87).

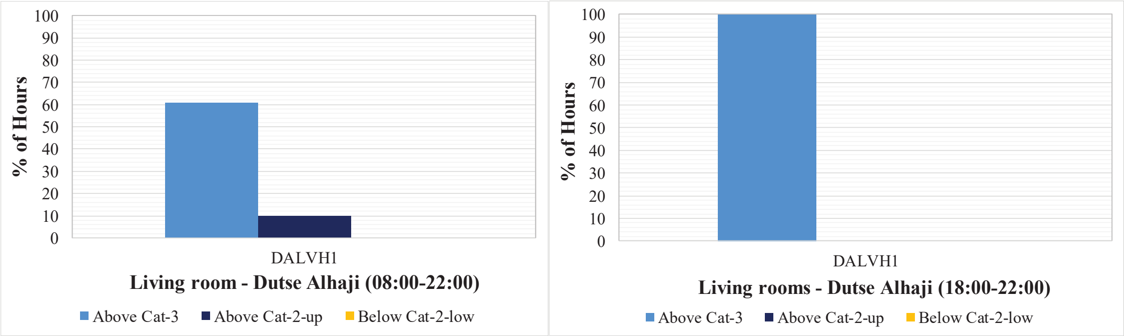


Figure 5.86: Percentage of hours of the living room temperature in BSEN 15251 Cat. II and Cat. III thermal comfort category at Dutse Alhaji (08:00–22:00, left and 18:00 – 22:00, right).

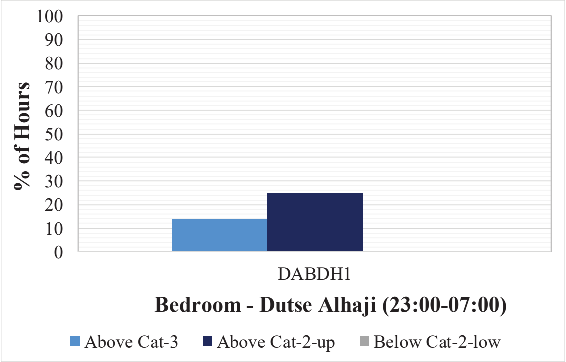


Figure 5.87: Percentage of hours of the bedroom temperature in BSEN 15251 Cat. II and Cat. III thermal comfort category at Dutse Alhaji (23:00 – 07:00).

The dynamic adaptive comfort model in Bwari

In BWLVH1, the living room spaces recorded temperatures exceeded Cat. II upper marker for more than 10% of the time and above the Cat. III upper threshold for more than 30% of the time in the daytime and evening period while the evening time in BWLVH1 reported temperatures exceeded Cat. II upper threshold for more than 20% of the time and exceeded Cat. III for more than 40% of the time. BWBDH1 reported temperatures exceeded Cat. II upper threshold for more than 30% of the time and exceeded Cat. III upper threshold for more than 10% of the time (Figure 5.89).

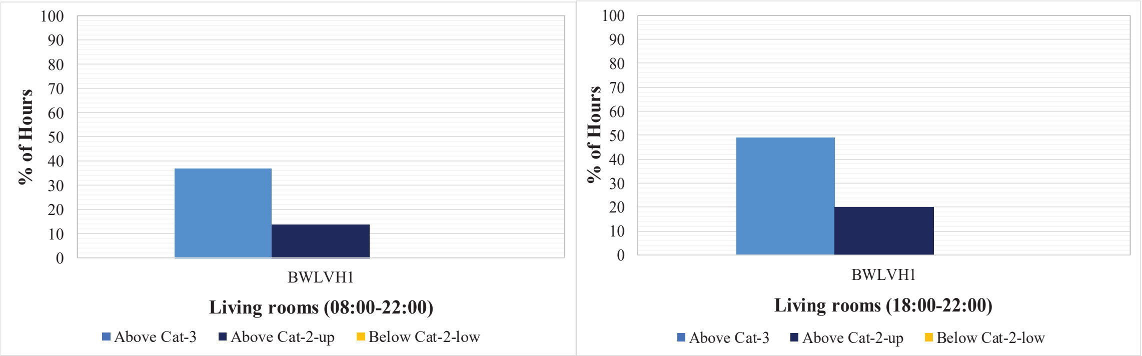


Figure 5.88: Percentage of hours of the living room temperature in BSEN 15251 Cat. II and Cat. III thermal comfort category at Bwari (08:00–22 :00, left and 18:00 – 22:00, right).

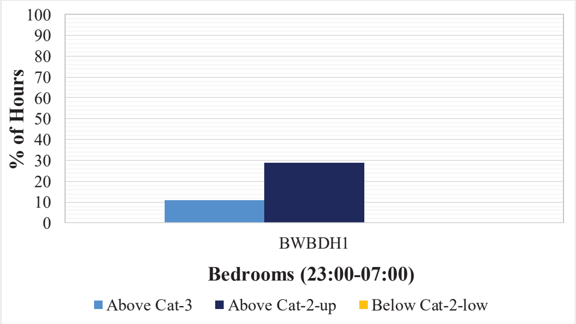


Figure 5.89: Percentage of hours of the bedroom temperature in BSEN 15251 Cat. II and Cat. III thermal comfort category at Bwari (23:00 – 07:00)

The results suggest the occupants exceeded the moderate level of expectation for most of the time warm discomfort across all the spaces in the case studies indicating warm discomfort during the daytime, evening time and night-time. They occupants of all the monitored naturally ventilated spaces exceeded the moderate level of expectation.

5.4.2.1 Measured temperatures between different BSEN15251 thermal comfort thresholds

The EN15251 thermal comfort standard was used to classify and compare the internal temperatures in all indoor spaces. The bar charts (Figure 5.90 – 5.93) showing percentage of hours that fall between various categories were developed. The percentage of hours above the Cat. II upper and below the Cat. II margins for all the spaces monitored across all case studies (Figure. 5.90 – 5.93). Looking at 5% of hours above the Cat. II upper thresholds, the analysis suggest 100% of overheating occur in the bedrooms and 50% of overheating occurred in the living room, but across all case studies, 75% of overheating is recorded. Below is the analysis for overheating using adaptive model in bar charts for all the spaces across the ten monitored dwellings.

Lugbe

The results show the living room and the bedroom spaces in Lugbe H1 were warm, as they reported high number of hours above Cat. II and Cat. III upper threshold (Figure 5.90). The results also show that warm discomfort occurred in those spaces. In addition, cold discomfort was not reported in any of the spaces in Lugbe, which shows that extreme dry season overheating is occurring during the dry season at the case study location.

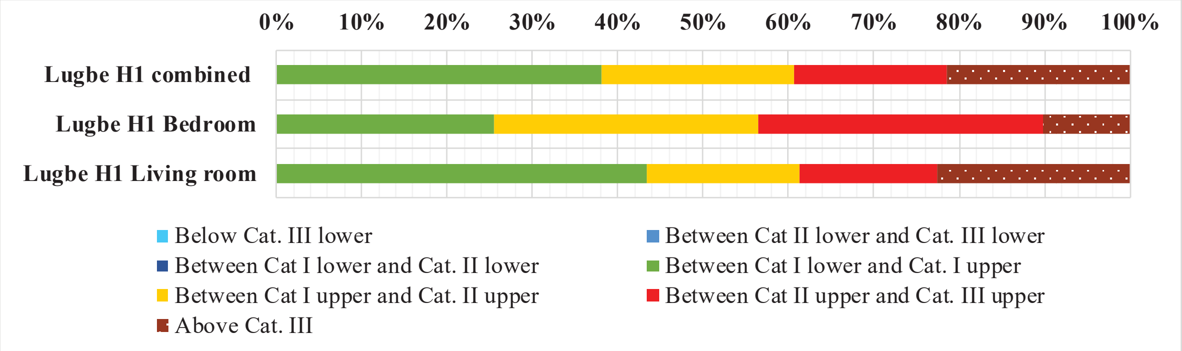


Figure 5.90: Percentage of hours of temperatures recorded in the dwellings monitored at Lugbe that fall between different EN15251 thermal comfort thresholds.

Mpape

The overheating analysis suggest in Mpape shows 100% of overheating occur in the bedrooms and 100% of overheating occurred in the living rooms, thus across all case studies, 100% of overheating is recorded (Figure 5.91). The results indicate the living room and the bedroom spaces in Mpape are the above Cat. II and III comfort thresholds. The analysis indicates living room spaces (Mpape LV H1H2) are the most heated spaces in the building compared to the bedroom spaces (Mpape BD H1H2). The results at the case study location show that warm discomfort has occurred in all the spaces with no report of cold discomfort.

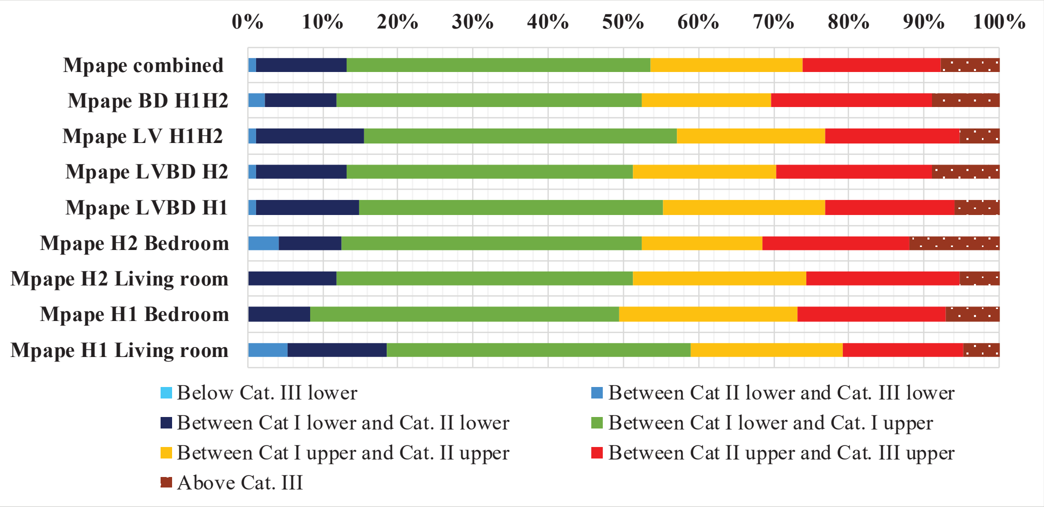


Figure 5. 91: Percentage of hours of temperatures recorded in the dwellings monitored at Mpape that fall between different EN15251 thermal comfort thresholds.

Dutse Alhaji

The naturally ventilated living room and bedroom spaces in Dutse Alhaji recorded temperatures above 5% of hours over the Cat. II upper limit indicating 100% of overheating occurred in all monitored spaces. In addition, more than 35% of the time of the time, all the spaces in the Dutse Alhaji where above the Cat. III upper threshold indicating extreme overheating at the case study location. None of the spaces recorded temperatures below Cat. I lower threshold (Fig. 5.92). The results also show that warm discomfort occurred in all the spaces and cold discomfort is not reported in any of the spaces which shows that extreme dry season overheating is occurring during the dry season at the case study location.

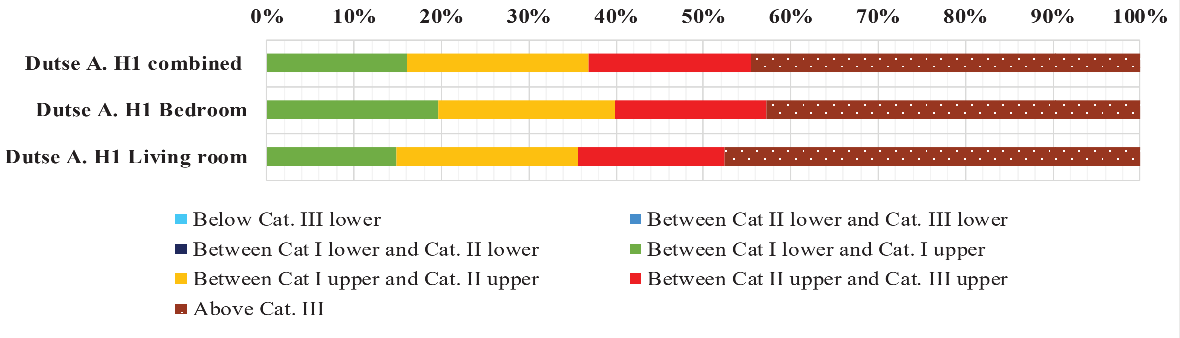


Figure 5.92: Percentage of hours of temperatures recorded in the dwellings monitored at Dutse Alhaji that fall between different EN15251 thermal comfort thresholds.

Bwari

The EN15251 threshold analysis for temperatures above Cat. II upper thresholds for the naturally ventilated building in Bwari suggest 100% of overheating occur in the bedrooms and 100% of overheating occurred in the living room (Figure 5.93). The results indicate the living room and the bedroom spaces in Bwari H1 were the most heated where 20% of the time, temperature where recorded above category III. The results suggest that warm discomfort occurred in all the spaces in Bwari. Cold discomfort was not reported in any of the spaces in Bwari.

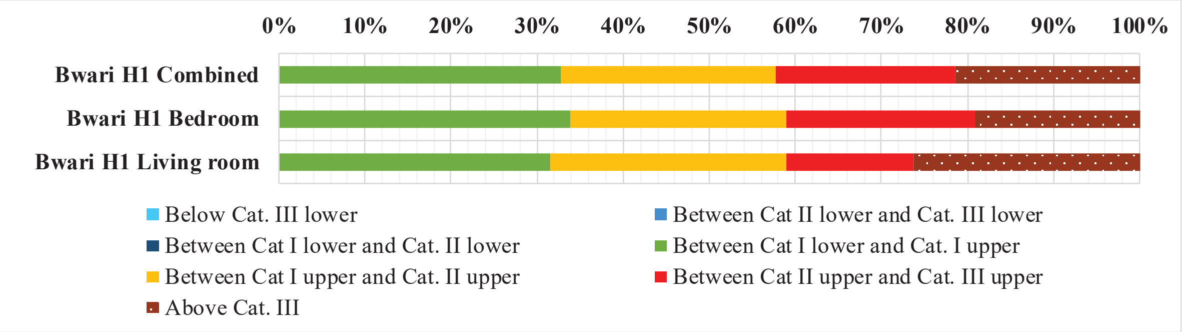


Figure 5.93: Percentage of hours of temperatures recorded in the dwellings monitored at Bwari that fall between different EN15251 thermal comfort thresholds.

Overall, all the naturally ventilated case studies recorded warm discomfort indicating overheating in all the monitored spaces.

5.5 Comparison between static and adaptive models

Using the CIBSE 'static' and the EN15251 adaptive comfort models to evaluate the risk of dry season temperatures in the living area and the bedrooms, the results showed dry season overheating occurs. The measured temperature rose above 28°C threshold for over 82 hours (78%) during daytime and evening period (08:00 – 22:00) out of 168 hours of monitoring and it rose above the BSEN15251 Cat. II upper indicator for more than 5% of the time in the living area (Table 5.51). The measured indoor temperature also rose above the 28°C indicator for over 30 hours (86%) during evening time (18:00 – 22:00) out of 168 hours of monitoring and it rose above the BSEN15251 Cat. II upper indicator for more than 5% of the time in the living area (Table 5.52). The temperature rose above 30°C for 25 hours (71%) except for BWH1 that reported only 4 hours above 30°C (Table 5.53).

In the bedroom, the measured temperature rose above the 26°C indicator for over 100% of the time during the same period across all case studies except for BWH2 that reported temperature above 26°C for 60 hours (95%) of the time during the night-time (23:00 – 07:00). The recorded temperature rose above the BSEN15251 Cat. II upper threshold for over 10% of the time (Figure 5.55) except for

LGBDH1, that did not record temperatures above Cat. II. The results showed the both the living room and bedroom are prone to extreme dry season overheating and occupants are likely subject to warm discomfort in for more than 80% of the time in the dry season in Abuja.

Table 5.50: Summary of comparison between measured maximum, minimum and mean indoor daytime and evening period (08:00-22:00) temperatures and CIBSE static model and the adaptive comfort threshold during the dry season

Year	**Indoor monitored living spaces 08:00 – 22:00 (March – May 2015)**					
Name of space-Living room	**CIBSE: total % above 28°C**	**Above CIBSE % thresh-old 30°C**	**Above CIBSE % thresh-old 32°C**	**Above CIBSE % thresh-old 34°C**	**% of Hours above EN15251 Cat. II upper threshold**	**% of Hours above EN15251 Cat. III**
LGLVH1	100	89	59	25	15	32
LGLVH2	100	98	37	0	-	-
MPLVH1	78	59	29	0	16	5
MPLVH2	80	63	33	0	20	7
DALVH1	100	99	72	46	10	61
DALVH2	100	100	88	65	-	-
KBLVH1	100	100	40	0	-	-
KBLVH2	100	100	76	0	-	-
BWLVH1	98	80	58	27	14	37
BWLVH2	98	41	0	0	-	-

Table 5.55 Summary of comparison between measured maximum, minimum and mean indoor evening time (18:00-22:00) living room temperatures and CIBSE adaptive comfort threshold during the dry season

Year	**Indoor monitored living spaces 18:00 – 22:00 (March – May 2015)**					
Name of space-Bedroom	**CIBSE: total % above 26°C**	**Above CIBSE % threshold 28°C**	**Above CIBSE % threshold 30°C**	**Above CIBSE % threshold 32°C**	**% of Hours above EN15251 Cat. II upper threshold**	**% of Hours above EN15251 Cat. III threshold**
LGBDH1	100	100	91	60	11	69
LGBDH2	100	100	54	0	-	-
MPBDH1	86	71	40	0	26	14
MPBDH2	86	71	37	0	29	14
DABDH1	100	100	100	83	0	100
DABDH2	100	100	100	100	-	-
KBBDH1	100	100	71	0	-	-
KBBDH2	100	100	100	0	-	-
BWBDH1	100	11	0	0	20	49
BWBDH2	100	86	69	26	-	-

Table 5.56. Summary of comparison between measured maximum, minimum and mean indoor night-time (23:00-07:00) bedroom temperatures and CIBSE adaptive comfort threshold during the dry season

Year	Indoor monitored living spaces 23:00 – 07:00 (March – May 2015)					
Name of space-Bedroom	CIBSE: total % above 26°C	Above CIBSE % threshold 28°C	Above CIBSE % threshold 30°C	Above CIBSE % threshold 32°C	% of Hours above EN15251 Cat. II upper threshold	% of Hours above EN15251 Cat. III
LGBDH1	100	100	95	56	25	11
LGBDH2	100	87	62	3	-	-
MPBDH1	95	76	59	8	11	0
MPBDH2	95	71	57	10	13	2
DABDH1	100	100	98	46	25	14
DABDH2	100	100	86	38	-	-
KBBDH1	100	100	84	3	-	-
KBBDH2	100	100	98	43	-	-
BWBDH1	100	100	84	49	29	11
BWBDH2	100	86	52	3	-	-

5.6 Conclusion

This chapter discussed the results from the post-occupancy survey, environmental monitoring and comfort surveys carried out at the in five case study locations to evaluate thermal performance of residential houses in Abuja, Nigeria. The study showed that the social-economic factor of residents in Abuja played a major role in the level of indoor comfort experienced. The residents with higher income or those above the low-income groups tend to be more comfortable. This is possible because they can afford air-conditioning and are able to put them on for longer hours compared to those in the low-income areas, where most of the residents cannot afford air-conditioning, generators for backup power or even put air-conditioning on for longer hours during the day.

The post-occupancy results on the respondents' feeling of hot and cold in the dry season and the rainy season were discussed. The results indicated overwhelming responses on the warm part of the scale suggesting the occupants feel much warmer in the dry season. The responses suggested the residents were not satisfied with the thermal environment of the case studies with lowest levels of evaluation for thermal satisfaction at Dutse. The post-occupancy results also indicated a noticeable shift in the occupants' responses for 'very uncomfortable' and "uncomfortable" part of the scale during the dry season to 'neutral' and 'comfortable' part of the scale during the rainy season with lowest levels of evaluation for overall thermal comfort in the dry season at Mpape. The occupants' responses during the post-occupancy surveys indicated moderate level of control at the case studies with more than half of the occupants indicating dissatisfaction with the control at the case studies. The participants also indicated the living room as the warmest space at case studies but the results from environmental monitoring suggested otherwise at Mpape and Bwari as the average internal temperature of the bedroom were much higher than the living rooms. Further investigations showed that the two bedrooms had more furniture and clothes and the windows were mostly closed during the day. The responses during the surveys showed that the occupants were generally not satisfied with their experience at the case studies.

The results from environmental monitoring showed the monitoring periods at the five case studies did suggest extreme dry season external temperatures, which could contribute to frequent occurrence of high internal temperatures in the spaces monitored. The mean external temperatures at the case studies were considerably within the range of the mean internal temperatures across all the case studies. The mean internal temperatures in all the spaces monitored were within the comfort range. However, high temperatures were recorded for long hours within the internal spaces at Lugbe, Mpape, Dutse and Kubwa. The outcomes from the survey suggested high temperatures were noticed in all the spaces monitored.

The comfort surveys in the dry season show most of the occupants were felt warm for more than 50% of the time with most of the distribution of votes varying from ‘slightly warm’, ‘warm’ to ‘hot’ There was a shift in the thermal sensation mean votes during the rainy season to the cool and neutral part of the scale. The thermal comfort votes show most of the occupants were feeling uncomfortable across all dwellings. There was a drift in the thermal comfort mean votes during the rainy season from the uncomfortable part of the scale to the slightly comfortable and comfortable part of the scale. The mean distribution of occupants’ responses across all case studies from the dry season surveys shows they prefer to be ‘much cooler’ or ‘cooler’. The survey indicates that most occupants prefer their thermal environment the way it is during the rainy season. Thermal sensation was found to be correlated to voting time of the day in the dry season which suggests occupants’ feeling of hot tend to increase as the external temperature for the day increases.

Evaluation of the risk of overheating at the case study buildings using the CIBSE ‘static’ criteria and the dynamic adaptive comfort (BSEN15251) model was carried out. The findings from the analysis for the static comfort model showed 100% of the living areas monitored across all case studies exceeded Cat. II and Cat. III threshold during the daytime and evening period (08:00-22:00). The results suggested overheating occurred in all the living rooms monitored in Abuja. Considering the bedrooms monitored during the dry season, 100% exceeded Cat. II threshold and 80% exceeded Cat. III threshold for most of the time. The results also indicated extreme summertime overheating in the bedrooms using the static

‘CIBSE’ model. The results from the approved BSEN15251 standard indicated warm discomfort in 100% of the naturally ventilated spaces at Lugbe, Dutse, Mpape and Bwari in the dry season. Comparing the findings from the surveys suggest higher thermal dissatisfaction of the occupants at Mpape than Lugbe despite higher internal temperatures observed at Lugbe. This chapter concluded that overheating occurs in all the houses and the occupants are thermally dissatisfied with their thermal environment. This is enhanced by the higher internal temperatures observed in the buildings during the dry season. The respondents indicated preference to be much cooler in the dry season when the temperature rises. The results also showed that the occupants at Lugbe and Kubwa have a better understanding for control than those in Dutse, Bwari and Mpape. The next chapter will discuss the results from dynamic thermal simulations.

CHAPTER 6

Dynamic Modelling and Simulation

CHAPTER 6 Dynamic Modelling and Simulation

As previously explained in Chapter 5, results from the field surveys (post-occupancy and comfort surveys) and environmental monitoring show a potential of dry season high indoor temperatures; this chapter considers dynamic thermal modelling and simulation using DesignBuilder software (4.7.0 version) to further examine the potential of dry season overheating at two case studies in Lugbe and Bwari.

This chapter discusses the model development for simulation, the predicted results and the relationship between the predicted and measured data. Dynamic thermal simulation was essential to investigate the thermal performance of the four case study buildings and compare the different dwellings on an equal basis, essential to ensure valid comparison and identification of overheating under similar conditions. This was carried out using the DesignBuilder software. This was vital as it gave an insight into the most realistic outcomes of passive cooling interventions in the selected dwellings representing residential buildings in Abuja, Nigeria.

6.1 Pilot modelling

A pilot model was conducted with the DesignBuilder commercially based software (version 4.7.0), which provides a user-friendly graphical interface for the widely used thermal balance engine, EnergyPlus. This programme was used to calculate the thermal performance of the selected case studies. The software allows the dynamic evaluation of heating and cooling energy use all year-round, and included the complete EnergyPlus HVAC package.

6.1.1 The Weather File

Weather file for Abuja was uploaded manually into DesignBuilder (Figure 6.3) as it was not preinstalled, and this posed some challenges since such data was not readily available from sources in Nigeria as the Nigerian Meteorological Agency (NiMet) could only provide daily data not hourly data. The Nigerian Aerospace Management Agency (NAMA) and the Federal Airports Authority of Nigeria (FAAN) could not give the requested data, nor could the Universities or research centres at the time. Other external sources were also contacted i.e. the BBC weather centre, the Met Office U.K., the Department of Energy U.S. and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), but none could provide a comprehensive weather file for Abuja. Eventually, a commercial based weather company, Weather Analytic provided a comprehensive TMY3 weather file for Abuja which was a compiled from real months data for a year was used for this simulation work.

6.1.2 Pilot model development

A pilot model was first developed to gain familiarity with DesignBuilder works (Figure 6.1 and 6.2). The model was run for a one-week period from 30th May – 6th April for the TMY3 file for Abuja during the dry season (summer period) for simulation. The pilot model was considered free-running. Hence, during the set-up for the simulations, there was no mechanical cooling. Assumptions were made on general lighting, task and display lighting, and the outside air change rate was set to 3 ac/h (Table 6.1). The pilot model was made up of 230mm concrete hollow walls on all sides, a 1.2 x 1.2m window and roofed with aluminium, with a 600mm roof overhang. The ceiling was made up of 20mm thick plaster board. Table 6.1 summarizes the major parameters used for the simulation. The modelled building had a headroom height of 3m and a breadth and length of 3m each.

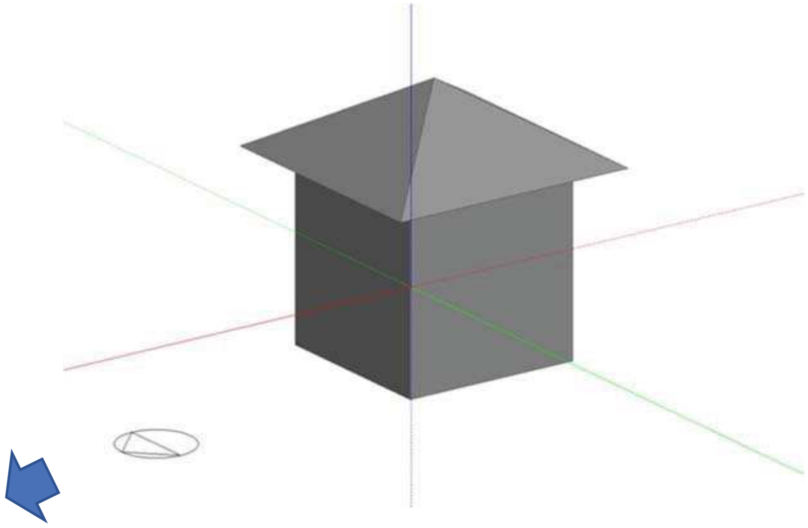


Figure 6.1: A pilot model with roof and no window

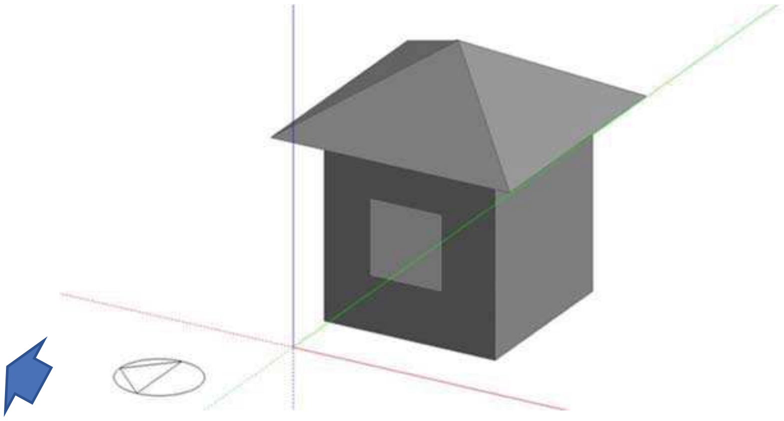


Figure 6. 2: Pilot model with roof and west facing window

6.1.3 Pilot model simulation

To further have a good understanding of DesignBuilder model simulation, two pilot model types were simulated with different model fixed infiltration rates, ranging from 0 – 5 ac/h. These model types were:

i. Naturally ventilated pilot model with a roof ceiling and no window
ii. Naturally ventilated pilot model with roof, ceiling and a window facing east, west, south and north.

Table 6.1: Summary of parameters input for the test modelling

	Input parameters	Value for Naturally Ventilated Pilot model
1	Cooling	No cooling required (free-running)
2	Cooling set point/ setback temperature	No set point/ setback temperature required
3	Heating	No heating required (free-running in dry and rainy seasons)
4	Heating set point/ setback temperature	No set point/ setback temperature required
5	Ventilation	Natural ventilation – No cooling
6	Density (people/m^2)	0.22
7	Total floor area	9m^2
8	Daytime period	08:00 – 22:00
9	Evening period (Living room occupancy period)	18:00 – 22:00
10	Night time-period (Bedroom occupancy period)	23:00 – 07:00
11	General lighting	3.3W/m^2
12	Task and display	0.1W/m^2
13	Metabolic rate (Activity)	0.9
14	Metabolic rate (Clothing)	0.5clo
15	Infiltration rate (ac/h)	0 – 5
16	Outside air change rate (ac/h)	3.0
17	Equipment such as computers	3.9w/m^2
18	Window to floor ratio	16%
19	Window height	1.2m
20	Window width	1.2m
21	Floor to ceiling height	3.0m
22	External wall no bridging (U-Value)	2.03 W/m^{2}K
23	Ceiling, no bridging (U-Value)	2.53 W/m^{2}K
24	Aluminium Roof, no bridging (U-Value)	7.14 W/m^{2}K

6.1.4 Deductions from pilot modelling

The results generated from the pilot models showed the models with west facing windows developed higher temperatures compared to the models with north facing windows. The naturally ventilated model with the west facing window reached the highest temperature of 33.8°C while the north facing window model reached the, 26°C at 5 ac/h (Table 6.2). The results showed that simulating different model infiltration rates led to a rise of around 1.5°C in the maximum indoor temperature at the maximum of 5 ac/h.

Table 6.2: Naturally ventilated (NV) pilot model: Effect of window orientation and air change rate on internal temperature

Window orientation and Air change rate from 0.25 – 5.0										
	NV Pilot model	**Ext Temp.**	**0.0 ac/h**	**0.25 ac/h**	**0.5 ac/h**	**1.0 ac/h**	**2.0 ac/h**	**3.0 ac/h**	**4.0 ac/h**	**5.0 ac/h**
			OT°C	OT°C	OT°C	OT°C	OT°C	OT°C	OT°C	OT°C
No window	**Max**	38.0	29.9	30.1	30.3	30.5	30.9	30.9	30.8	31.0
	Min	22.4	25.6	25.8	25.9	26.0	26.0	26.1	26.2	26.2
	Avg.	29.6	27.7	27.9	28.0	28.1	28.2	28.3	28.5	28.5
North Window	**Max**	38.0	31.6	31.8	31.9	32.0	32.0	32.4	32.9	33.1
	Min	22.4	26.6	26.6	26.5	26.5	26.4	26.3	26.2	26.1
	Avg.	29.6	29.1	29.1	29.1	29.1	29.1	29.1	29.1	29.1
South Window	**Max**	38.0	31.9	32.0	32.2	32.5	32.7	32.7	32.9	33.1
	Min	22.4	27.1	27.1	27.0	26.9	26.7	26.6	26.4	26.3
	Avg.	29.6	29.6	29.7	29.7	29.6	29.5	29.4	29.4	29.4
East Window	**Max**	38.0	32.8	32.9	32.9	33.0	33.1	33.6	33.9	34.1
	Min	22.4	27.4	27.3	27.2	27.1	26.8	26.7	26.5	26.3
	Avg.	29.6	30.1	30.1	30.1	30.1	30.0	30.1	30.1	30.1
West Window	**Max**	38.0	33.8	34.0	34.3	34.5	34.8	34.8	34.9	35.2
	Min	22.4	27.4	27.3	27.2	27.1	27.0	26.8	26.7	26.6
	Avg.	29.6	30.9	31.0	31.0	31.0	30.9	30.8	30.8	30.8

OT = Operative Temperature

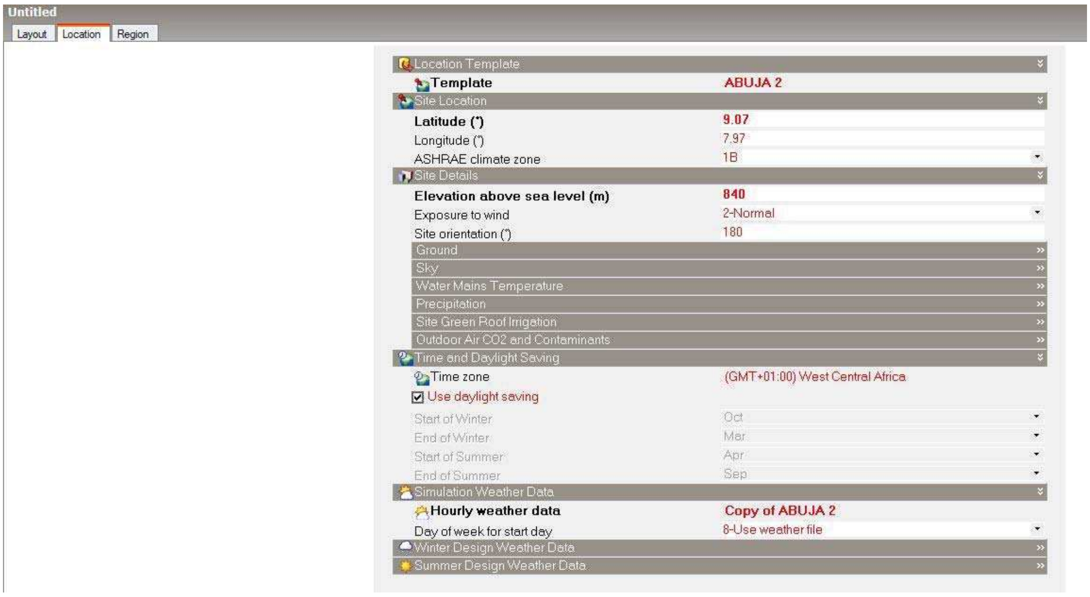
6.2 Main base model development

After the pilot model simulations, the parameters were adjusted where necessary for a detailed base model which was developed to depict selected case study dwellings, i.e. modelled dwellings in Lugbe and Bwari.

Airtightness in DesignBuilder is expressed in terms of a constant rate air changes per hour (ach) schedule. A typical value for modern construction might be 0.5 ac/h, this would not be appropriate for the simulation for this study as the building are not tightly constructed and occupants tend to prefer windows open. The window and door openings are not often sealed properly or checked to counter draught or air leakages in comparison to the buildings in developed countries like United Kingdom and U.S.A. Owing to the average number of occupants in the building, the lack of well-fitting sealed windows and doors, the air change rate for infiltration has been taken as 1.0 ac/h for this study.

From the results in table 6.2, placing larger windows on the north facing sides would be suitable and advantageous for buildings in the hot-humid climate of Abuja. This would allow more daylight and less solar gain into the building as the windows here are not facing the sun directly. Smaller windows on the east-west walls and window shading devices should also be encouraged.

The main base models were developed using six inputs: layout, activity, construction, openings, lighting and HVAC. Most of the parameters had to be adapted and developed from default templates in the software as it does not have building structures or elements appropriate to those in the Nigerian building environment, e.g. in Nigeria, sandcrete hollow blocks are the main construction walling material used but are not found in DesignBuilder. Details of the base model inputs are in Figure A2.1.



Location Template	
Template	ABUJA 2
Site Location	
Latitude (°)	9.07
Longitude (°)	7.97
ASHRAE climate zone	1B
Site Details	
Elevation above sea level (m)	840
Exposure to wind	2-Normal
Site orientation (°)	180
Ground	
Sky	
Water Mains Temperature	
Precipitation	
Site Green Roof Irrigation	
Outdoor Air CO2 and Contaminants	
Time and Daylight Saving	
Time zone	(GMT+01:00) West Central Africa
☑ Use daylight saving	
Start of Winter	Oct
End of Winter	Mar
Start of Summer	Apr
End of Summer	Sep
Simulation Weather Data	
Hourly weather data	Copy of ABUJA 2
Day of week for start day	8-Use weather file
Winter Design Weather Data	
Summer Design Weather Data	

Figure 6.3: Uploaded weather file and site location details

6.2.1 Layout

Four case study dwellings were selected and modelled in DesignBuilder based on imported architect's drawings from AutoCAD 2016 software from two case study areas. The selected study areas were Lugbe and Bwari which had both an air-conditioned and naturally ventilated building, which suited the purpose of this simulation that involved considering the two types of ventilated buildings in different locations in Abuja. The four models were coded LGPDTH1 (Lugbe-H1) and LGPDT-H2 (Lugbe-H2) from Lugbe (Figure 6.4 and 6.5) and BWPDTH1 (Bwari-H1) and BWPDTH2 (Bwari-H2) from Bwari (Figure 6.6 and 6.7). LGPDTH1 and BWPDTH1 were modelled and simulated as naturally ventilated buildings while LGPDTH2 and BWPDTH2 were modelled and simulated as being air-conditioned. Details of the layout for the case study models are described below.

Base model for case study 1: Lugbe LGPDTH1 (Naturally ventilated)

This case study was modelled as a three-bedroom North facing naturally ventilated building with a kitchen and dining room. The living room and master bedroom were selected for simulation since these were the spaces monitored during the field study as the most occupied spaces in the house. This model had a room height of 3 m with 1.2 x 1.2 m windows. There is a 2.1 x1.2 m external steel door serving as the main entrance in the living room and a second 2.1 x 0.9 m external door in the kitchen. All the other rooms have a 2.1 x 0.9 m and 2.1 x 0.75 m wooden doors for all the toilets (Figure 6.4). The building has nine zones with the living room and the master bedroom representing the largest spaces and the most occupied throughout the day (Figure 6.5).

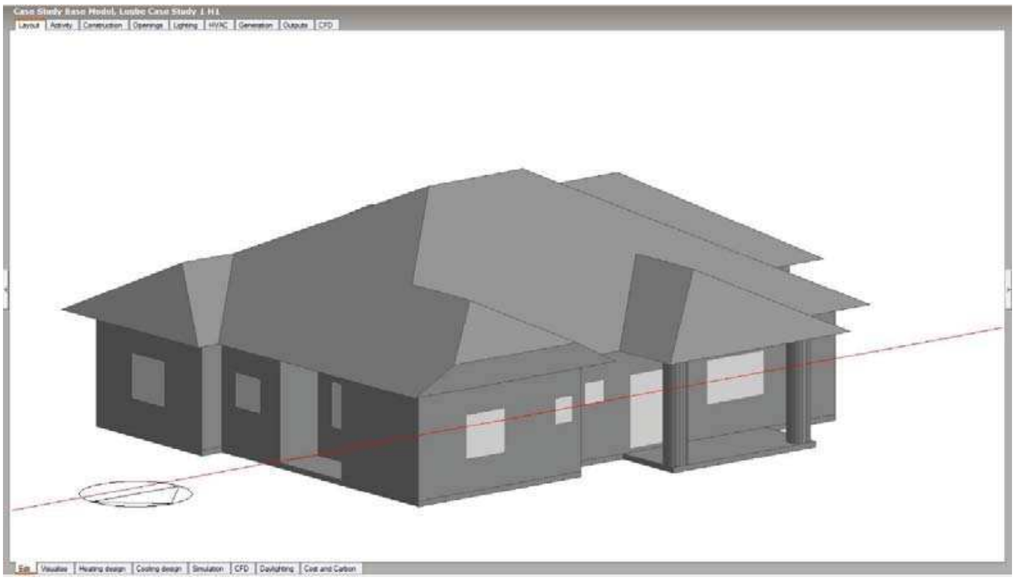


Figure 6. 4: Generated Model for LGPDTH1

Figure 6.5: Generated inner layout and zones for Model LGPDTH1

Base model for case study 2: Lugbe LGPDTH2

This model was a two-bedroom North facing air-conditioned dwelling with a kitchen and dining room. The living room and master bedroom were selected for simulation (Figure 6.6). The building has seven zones with the living room and the master bedroom representing the air-conditioned spaces in the building (Figure 6.7). It has a main external 2.1 x 1.2 steel door in the living room and another 2.1 x 0.9 steel door in the kitchen and 1.2 x 1.2 external window.

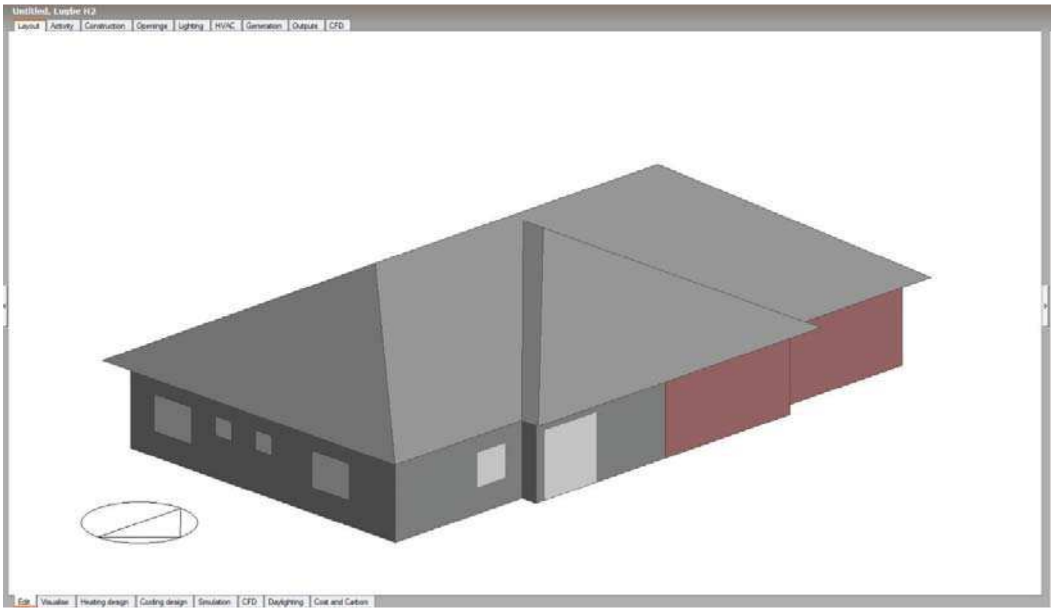


Figure 6.6: Generated Model for LGPDTH2

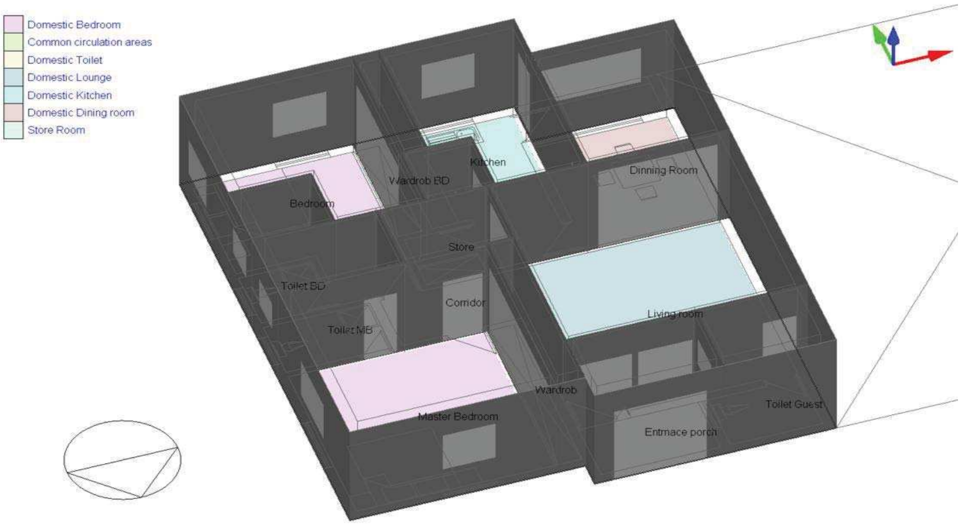


Figure 6.7: Generated inner layout and zones for Model LGPDTH2

Base model for case study 9: Bwari BWPDTH1

This semi-detached model case study is a South-West facing, one-bedroom naturally ventilated building with a kitchen. There is only one external door measuring 2.1 x 1.2 m, and all the remaining are 2.1 x 0.9 wooden doors. The floor to ceiling height is 2.8m (Figure 6.8). The building has six zones with the living room and the master bedroom representing the largest spaces and it is typically occupied during the day (Figure 6.9).

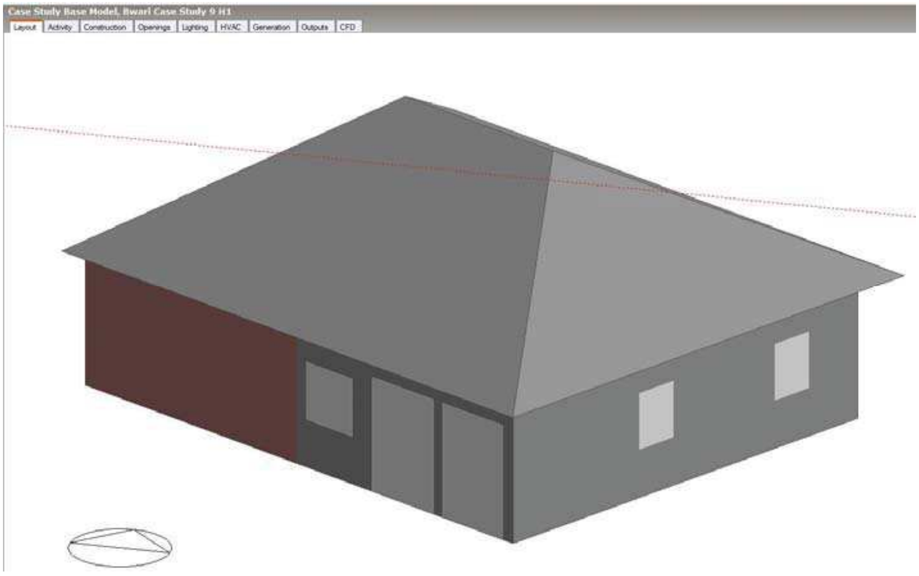


Figure 6.8: Generated Model for BWPDTH1

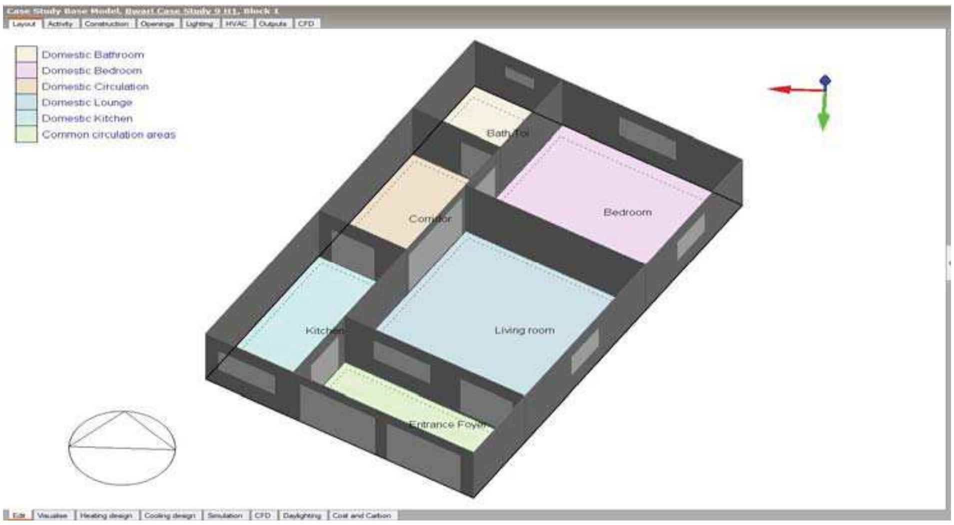


Figure 6.9: Generated inner layout and zones for Model BWPDTH1

Base model for case study 10: Bwari BWPDTH2

This North-North-West (NNW) facing detached model is a two-bedroom house with a kitchen. The floor to ceiling height is 3.0m (Figure 6.10). The building has seven zones with the living room and the master bedroom representing the air-conditioned spaces in the building (Figure 6.11).

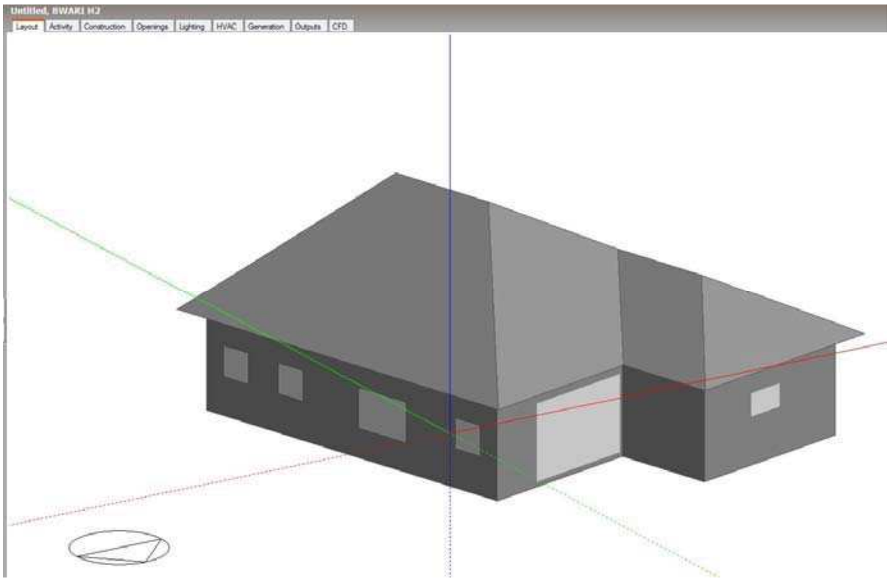


Figure 6.10: Generated Model for BWPDTH2

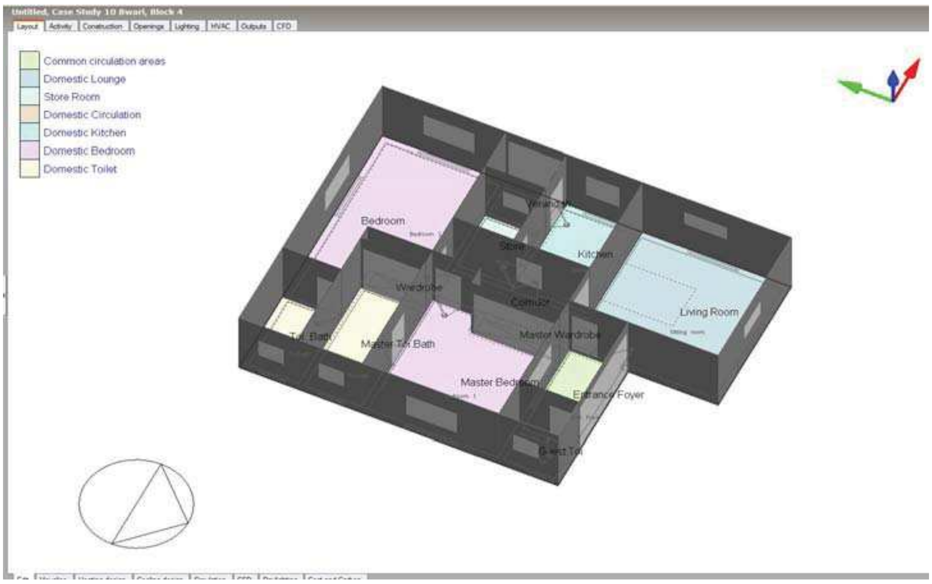


Figure 6.11: Generated inner layout and zones for Model BWPDTH2

6.2.2 Remaining Parameters used for the case study development

The infiltration rate was assumed to be 1 ach while the outside air change (ac/h) rate for cross ventilated indoor spaces was assumed to be 3ac/h and 2 ac/h for single side ventilated spaces (Figure A2.1). The external walls were modelled to represent the Nigerian sandcrete blocks which comprised three layers of 20 mm cement plaster on the outer and inner surfaces with the block comprising the middle component (Further details of sandcrete walls are in Figure A2.2). The modelled cement plaster ceiling board which is a representation of ceiling types across all case studies used for this study. Details of the ceiling are given in Figure A2.2. The external windows were modelled as a single glazed window glass with a 25% - 30% window to wall ratio across the modelled case studies. The window height and length were 1.2 x 1.2m for all the windows (Figure A2.3) except for the toilet windows that were modelled as 0.6 x 0.6m. The simulation prediction concerning window opening actions of occupants during day and night are important but could not be easily determined. The window opening was modelled in accordance with the outcomes obtained from the state loggers used to monitor when windows were opened and closed. The indoor lighting used 60W incandescent bulbs scheduled to turn on and off from 19:00 – 22:00 for indoor lighting and 19:00 – 06:00 for external lighting, (Figure A2.4).

The occupancy schedule for HVAC settings for the naturally ventilated models used a 08:00 – 22:00 schedule for opening and closing of windows during the day for the living room spaces (Figure A2.5) and 23:00 – 07:00 for bedrooms (Figure A2.5) to represent the way occupants use their windows in real life scenarios. The HVAC settings for the air-conditioned models used a system with air supply. A cooling schedule of 08:00 – 22:00 was used to represent dwellings that are occupied throughout the day and 18:00 – 22:00 where the occupants leave for work in the morning and come back around 18:00 (Figure A2.5). Table 6.3 summarize the parameters input for the naturally ventilated and air-conditioned base models.

Table 6.3: Summary of parameters input for the base modelling, for case studies 1, 2, 9 and 10

	Input parameters	**Lugbe**		**Bwari**	
		Value for model LGPDTH1	**Value for model LGPDTH2**	**Value for model BWPDTH1**	**Value model BWPDTH2**
1	Heating set point/ setback temperature	No set point/ setback temperature required	No set point/ setback temperature required	No set point/ setback temperature required	No set point/ setback temperature required
2	Cooling set point/ setback temperature	No set point/ setback temperature required	28°C/ 30°C	No set point/ setback temperature required	28°C/ 30°C
3	Ventilation	Natural ventilation- no heating/ cooling	Natural ventilation/ supplemented with air conditioning	Natural ventilation- no heating/ cooling	Natural ventilation/ supplemented with air conditioning

	Input parameters	**Lugbe**		**Bwari**	
		Value for model LGPDTH1	**Value for model LGPDTH2**	**Value for model BWPDTH1**	**Value model BWPDTH2**
4	Natural ventilation rate (per person)	10 l/s	10 l/s	10 l/s	10 l/s
5	Density (people/m^2)	0.01	0.03	0.05	0.02
6	Total occupied floor area (m^2)	112	103	41	96
7	Total occupied floor volume (m^3)	428	308	123	294
8	Daytime period	08:00 – 22:00	08:00 – 22:00	08:00 – 22:00	08:00 – 22:00
9	Evening period	18:00 – 22:00	18:00 – 22:00	18:00 – 22:00	18:00 – 22:00
10	Night-time-period	23:00 – 07:00	23:00 – 07:00	23:00 – 07:00	23:00 – 07:00
11	General lighting (W/m^2)	3.0	3.0	3.0	3.0
12	Exterior lighting (W)	60	60	60	60
13	Metabolic rate (Activity)	0.9	0.9	0.9	0.9
14	Metabolic rate (Clothing)	0.5clo	0.5clo	0.5clo	0.5clo
15	Infiltration rate (ac/h)	1.0	1.0	1.0	1.0
16	Outside air change rate by zone. Living room (ac/h)	3.0	3.0	3.0	3.0
17	Outside air change rate by zone. Bedroom (ac/h)	2.0	2.0	2.0	2.0
18	Window to wall ratio (%)	25.0	25.0	25.0	25.0
19	Window to floor ratio	16%	30%	16%	25%
20	Window height	1.2 m	1.2 m	1.2 m	1.2 m
21	Window width	1.2 m	1.2 m	1.2 m	1.5 m
	Window height (toilets)	0.6 m	0.6 m	0.6 m	0.6 m
	Window width (toilets)	0.6 m	0.6 m	0.6 m	0.6 m
22	Floor to ceiling height (m)	3.0	3.0	2.8m	3.0
23	External wall, no bridging (U-Value)	2.03 W/m^{2}K	2.03 W/m^{2}K	2.03 W/m^{2}K	2.03 W/m^{2}K
24	Ceiling, no bridging 150mm (U-Value)	2.53 W/m^{2}K	2.53 W/m^{2}K	2.53 W/m^{2}K	2.53 W/m^{2}K
25	Roof, no bridging (U-Value)	7.14 W/m^{2}K	7.14 W/m^{2}K	7.14 W/m^{2}K	7.14 W/m^{2}K

6.3 The simulations

The simulations were run for seven-day period corresponding to the individual measurement period, i.e. 18/03/2015 – 24/03/2015 for Lugbe (Figure 6.12) and 31/04/2015 – 06/05/2015 for Bwari (Figure 6.13). One building in each case study location was considered free-running and one air conditioned. The cooling set-back and set-point temperatures in the air-conditioned spaces, were set to 28°C and 30°C, but cooling was not active for the naturally ventilated spaces. This section will discuss all the eight spaces simulated: the living room spaces in Lugbe (LGLVPDTH1 and LGLVPDTH2); the bedroom spaces in Lugbe (LGBDPDTH1 and LGBDPDTH2,); the living room spaces in Bwari (BWLVPDTH1 and BWLVPDTH2) and the bedroom spaces in Bwari, (BWBDPDTH1 and BWBDPDTH2). In the simulated spaces, the dwelling code suffix H1 means naturally ventilated and those ending with H2 were air-conditioned.

6.3.1 The external temperatures at Lugbe and Bwari – Weather file

The weather file's outdoor temperature for Lugbe had a maximum outdoor temperature of 44°C on 22/03/2002 at 14:00 (Figure 6.12). The minimum temperature was 20.8°C on 23/03/2002 at 06:00 with a mean temperature of 30°C. The weighted running mean (see chapter 5) had a maximum temperature of 31.6°C and a mean temperature of 31°C. This shows the high outdoor temperatures that applied during the simulated dry season period.

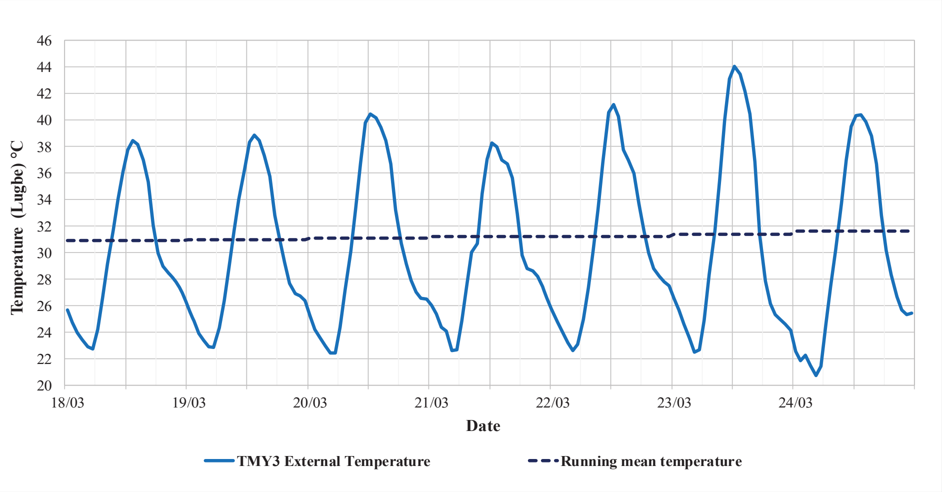


Figure 6.12: Abuja TMY3 weather file outdoor temperature used for Lugbe simulations

The weather file data for Bwari had a maximum outdoor temperature of 38°C on 02/05/2002 at 16:00 with an average temperature of 28ºC while the minimum outdoor temperature was 22°C on 02/05/2002 at 05:00 (Figure 6.13). Although the weather file temperatures used for Bwari were lower than the temperatures used for Lugbe, it still reported high average temperatures above 28°C.

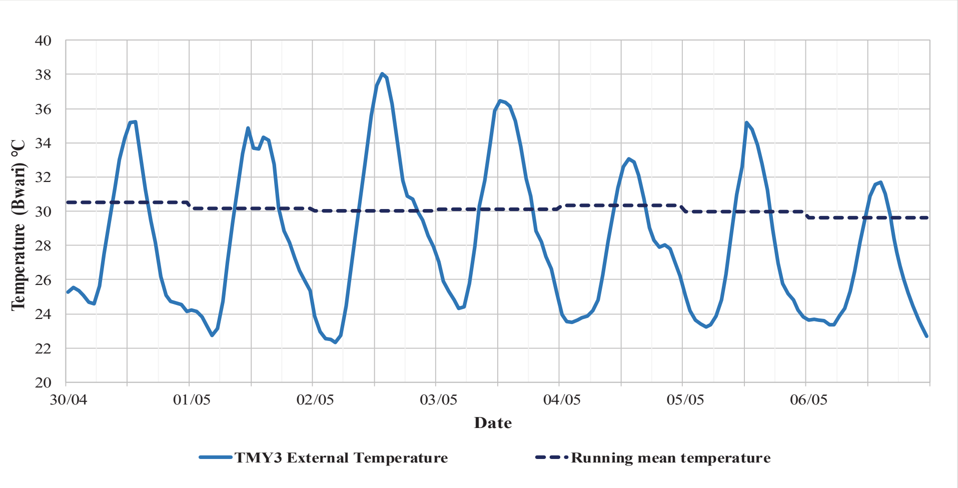


Figure 6.13: Abuja TMY3 weather file outdoor temperature for Bwari

6.3.2 The predicted indoor temperatures for Lugbe

Simulation for the models in Lugbe ran for a week from 18/03/2015 – 24/03/2015 in the naturally ventilated spaces (LGLVPDTH1 and LGBDPDTH1) and air-conditioned spaces (LGLVTPDTH2 and LGBDTPDTH2). The maximum predicted temperatures in the all the spaces in Lugbe were above 34ºC (Figure 6.14) with an average above 29ºC indicating high temperatures within the model. Table 6.4 summarizes the simulated indoor temperatures for the case study buildings in Lugbe. The results show the living room space were warmer than the bedroom in the naturally ventilated model but indicate higher internal temperatures in the bedroom than the living room in the air-conditioned model. This is explained by active air-conditioning in the living room space from 18:00-22:00, therefore contributing to the overall lower temperatures recorded in that space.

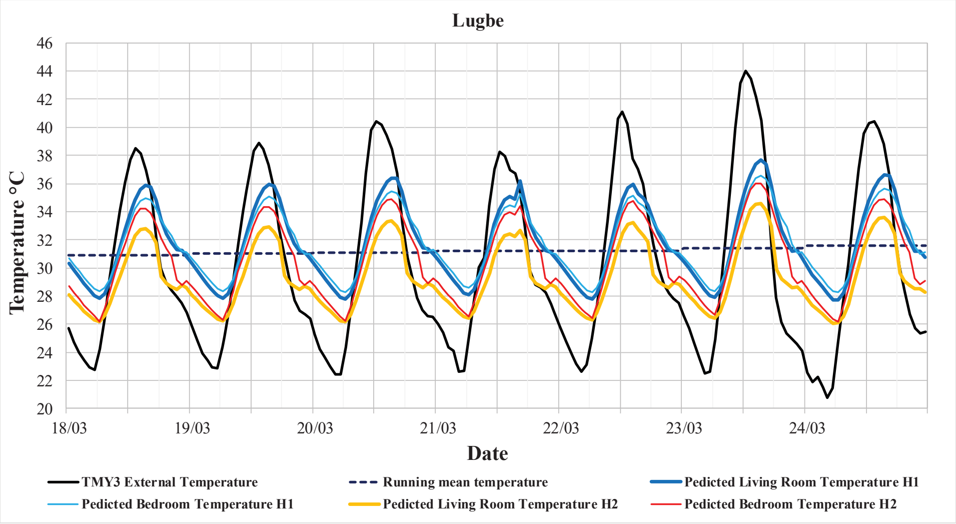


Figure 6.14: Predicted Living room and Bedroom temperature for the naturally ventilated (H1) and air-conditioned (H2) Model at Lugbe using Abuja TMY3 external temperature.

Table 6.4: Maximum, minimum and average predicted Living room and bedroom temperatures at Lugbe

	TMY3 Weather File Temp. °C	**Living room PDT Temp. °C H1**	**Bedroom PDT Temp. °C H1**	**Living room PDT Temp. °C H2**	**Bedroom PDT Temp. °C H2**
MAX	44.0	37.7	36.6	34.6	36.0
MIN	20.8	27.7	28.3	26.1	26.2
AVG.	30.2	31.0	31.7	29.3	30.4

PDT = Predicted

6.3.3 The predicted indoor temperatures for Bwari

The maximum predicted temperatures in the all the spaces in Bwari were above 33ºC (Figure 6.15) with an average above 29ºC average indoor temperatures above 28ºC across all naturally ventilated spaces (BWLVPDTH1 and BWBDPDTH1) and air-conditioned spaces (BWLVTPDTH2 and BWBDTPDTH2). Table 6.5 summarizes the simulated indoor temperatures across the spaces in Bwari, indicating high temperatures within the building.

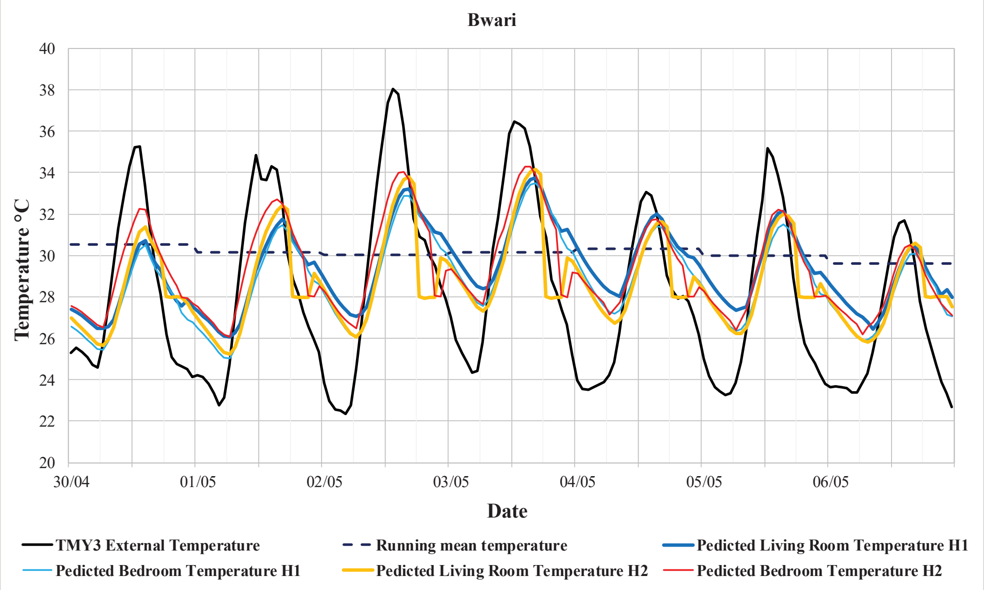


Figure 6.15: Predicted Living room and Bedroom temperatures for the naturally ventilated (H1) and air-conditioned (H2) Model for Bwari using Abuja TMY3 external temperature.

Table 6.5: Maximum, minimum and average predicted Living room and bedroom temperatures at Bwari

Bwari	**TMY3 Weather File Temp. °C**	**Living room PDT Temp. °C H1**	**Bedroom PDT Temp. °C H1**	**Living room PDT Temp. °C H2**	**Bedroom PDT Temp. °C H2**
MAX	38.0	33.7	33.5	34.2	34.3
MIN	22.4	26.1	25.0	25.2	26.1
AVG.	28.2	29.3	28.8	28.6	29.3

PDT = Predicted

6.3.4 Thermal performance comparison between the naturally ventilated and air-conditioned model

To further understand the relationship between the simulated internal temperature and the weather file temperature at the case studies, a regression analysis of Lugbe was considered. The model in Lugbe was chosen because it was the warmest building during the simulation period, depicting a warm building worse-case scenario in the dry season. The analysis for the naturally ventilated model between the living room and the bedroom shown in Figure 6.16, suggests that the people in the living room might have higher ability to adapt to a higher range of temperature than those in the bedroom. The analysis also suggests that the predicted indoor temperature in the bedroom is higher than the living room with a difference around 0.5ºC when the external temperature is below 30ºC. However, the trend changes when the external temperature rises as the living room appears to be warmer than the bedrooms once external temperature exceeds 31ºC for Lugbe. Even when the external temperature rose above 40ºC, the difference between the external and internal living room temperature is not significant. The regression analysis shows there is a strong relationship between the outdoor and indoor temperature where in the living room $r^2 = 0.71$, $r^2 = 0.64$ for the bedroom.

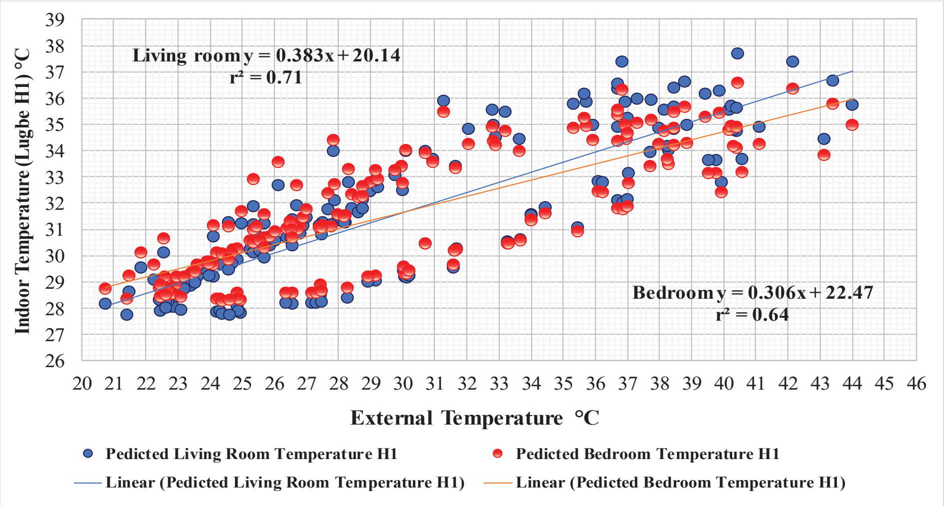


Figure 6.16: Relationship between the simulated internal temperature of the living rooms and the bedroom in the naturally ventilated model at Lugbe and the external temperature using Abuja TMY3.

The comparison between the naturally ventilated and the air-conditioned living room in Figure 6.17, shows that the naturally ventilated living space was warmer and has a higher temperature adaptation range. The analysis also shows that when the external temperature rises above 22ºC, the naturally ventilated living room temperature drifts towards extreme elevated temperature. The difference in the living room temperatures is around 2.0ºC when the external temperature rises above is 20ºC. The regression analysis shows there is a strong relationship between the outdoor and indoor temperature where in the living room $r^2 = 0.71$, $r^2 = 0.81$ for the bedroom.

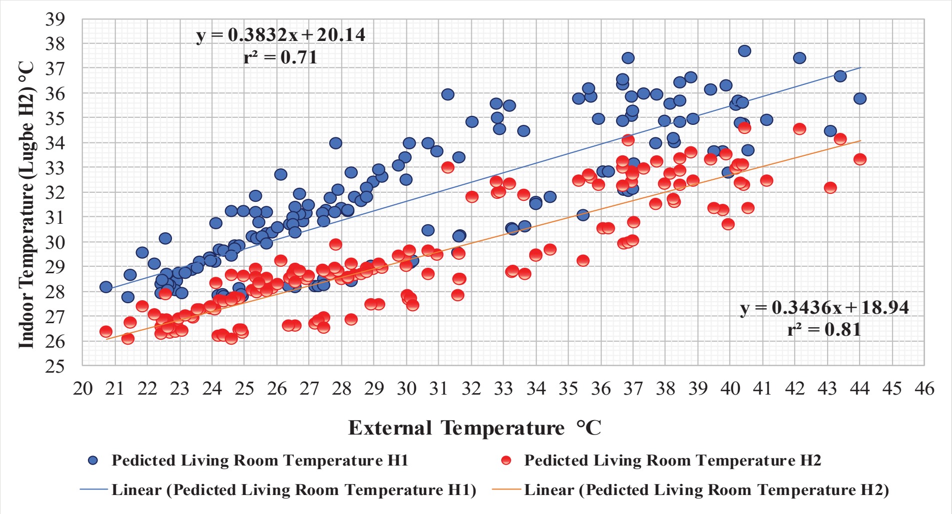


Figure 6.17: Relationship between the simulated naturally ventilated living room internal temperature and air-conditioned the living room temperature at Lugbe and the external temperature using Abuja TMY3.

Considering the naturally ventilated and air-conditioned bedrooms for analysis, it shows that naturally ventilated bedroom space was warmer than the air-conditioned bedroom space throughout the simulation period (Figure 6.18). It shows that when the external temperature rises above 20ºC, all the naturally ventilated predicted temperatures rose above 28ºC. The difference was around 2.0ºC when the external temperature was below 28ºC but when the external temperature rose above 30ºC, the difference reduced to around 0.5 ºC. The regression analysis shows there is a strong relationship between the outdoor and indoor temperature where in the naturally ventilated bedroom $r^2 = 0.64$, $r^2 = 0.77$ for the air-conditioned bedroom.

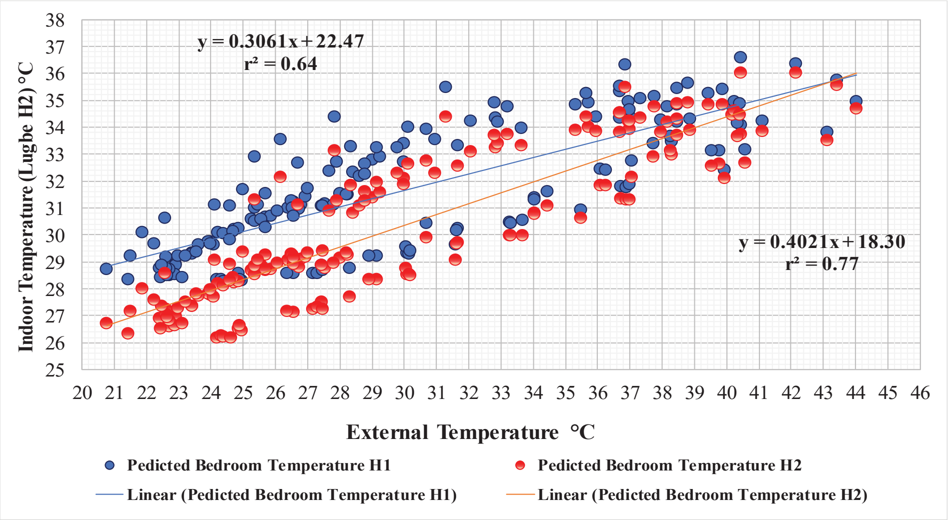


Figure 6.18: Relationship between the simulated naturally ventilated internal bedroom temperature and the air-conditioned bedroom temperature at Lugbe and the external temperature using Abuja TMY3.

In the air-conditioned model in Lugbe (Figure 6.19), the analysis shows that the predicted indoor temperature in the bedrooms is higher than the living room all through the day when compared to the external temperature. The trend remains constant even when the external temperature rises above 40ºC. There is a strong relationship between the outdoor and indoor temperature where in the living room $r^2 = 0.81$, $r^2 = 0.77$ for the bedroom.

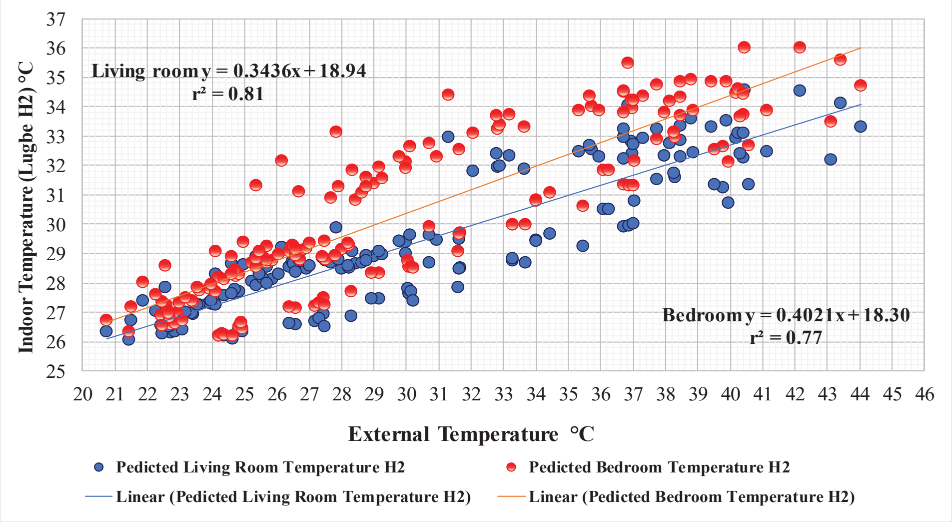


Figure 6.19: Relationship between the simulated internal temperature of the living rooms and the bedroom in the air-conditioned dwelling at Lugbe and the external temperature using Abuja TMY3.

Across all the houses at Lugbe, the average indoor temperature was within the comfort range (28-30ºC) until outdoor temperature increases more than 30.0ºC. The analysis suggests comfort is within a wider range at the naturally ventilated spaces than the air-conditioned spaces at Lugbe. The findings also suggest there is a stronger correlation between the simulated internal temperature and the external temperature at the case studies in Lugbe.

6.3.5 Comparison of modelled and measured data

The results from the simulations were compared using the results obtained from the indoor monitoring of the spaces. The one-week period of the monitoring was considered for the comparison. The hourly simulated data was compared with hourly averages of the 15 minutes monitored data. This range was adopted as a calibration criterion which is the maximum peak difference between the external recorded temperatures and the weather file temperature throughout the dry season period.

The comparison of the simulated and monitored temperatures showed the predicted peak temperatures align mostly with the measured peaks recorded during the monitoring. The differences between the maximum simulated and monitored temperature peaks were usually within a range of 2 – 3°C for most part the period.

6.3.6 Indoor (Measured and Predicted) and Weather file temperatures

The predicted temperatures show consistency with the measured temperatures in Lugbe and Bwari with average temperatures around 30°C in Lugbe and 29°C in Bwari (Figure 6.20 – 6.23 and Table 6.6 – 6.9). The external temperatures in Lugbe show the weather file had a maximum temperature above 40°C, which agrees with the measured temperature at 40°C. In Bwari, the measured outdoor temperature had a maximum of 38.6°C, which is consistent with the weather file temperature (38°C) for the same period. The weather file temperatures for Lugbe are warmer than those for Bwari as is the case for the measured external temperature.

6.3.6.1 Measured and Predicted indoor temperatures at Lugbe

The mean monitored living room temperatures in the naturally ventilated dwelling in Lugbe was 32°C which is very close to the predicted temperature of 31°C. The model predicted a maximum temperature of 37.7°C, around 1.5°C more the monitored temperatures. (Table 6.6).

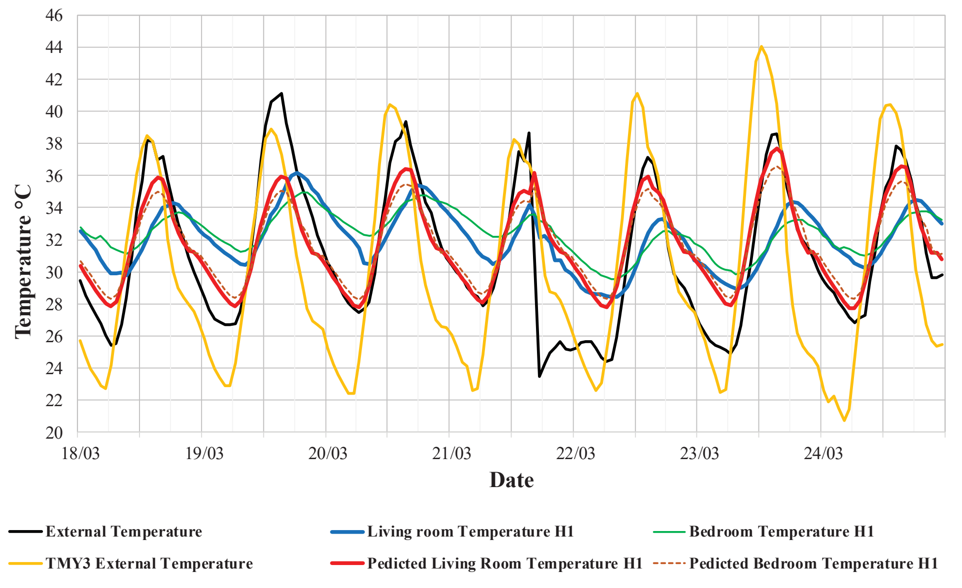


Figure 6.20: Measured and Predicted Living room and Bedroom temperatures at the naturally ventilated dwelling at Lugbe.

Table 6.6: Maximum, minimum and average measured and predicted Living room and bedroom temperatures at the naturally ventilated dwellings (H1) at Lugbe

Lugbe NV	**Ext. Temp. °C**	**Weather file Temp. °C**	**Measured Living room Temp. °C H1**	**Living room PDT Temp. °C H1**	**Measured Bedroom Temp. °C H1**	**Bedroom PDT Temp. °C H1**
MAX	41.1	44.0	36.2	37.7	34.9	36.6
MIN	23.5	20.8	28.4	27.7	29.5	28.3
AVG.	31.1	30.2	32.0	31.0	32.4	31.7

PDT = Predicted, NV = Naturally Ventilated

The maximum living room temperature measured in the air-conditioned dwelling in Lugbe was 32.7°C, which was around 2°C less than the predicted temperature (34.6°C) during the same period. The predicted maximum bedroom temperature was 3°C more than the measured temperature (Figure 6.21 and Table 6.7). The maximum predicted living room temperatures were higher than the predicted bedroom temperatures by more than 1°C but was no significant difference between the measured maximum and average living room and bedroom temperatures though the living room reported a minimum temperature that is around 2°C higher than the bedroom space (Table 6.7). The comparison between the measured and simulated internal temperatures for the naturally ventilated spaces at Lugbe shows the occupants have high adaptation potential when exposed to longer hours of high temperatures above 28°C.

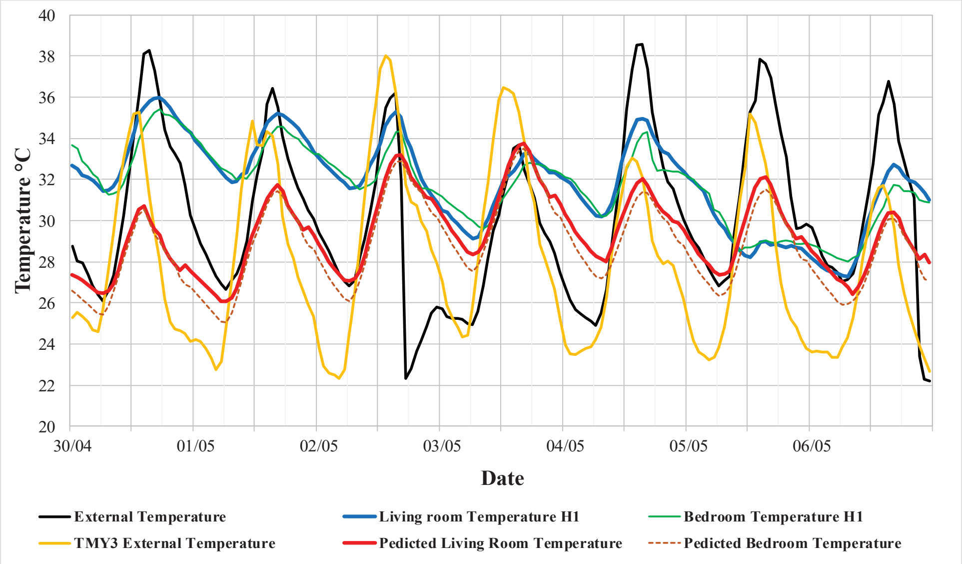


Figure 6.21: Measured and Predicted Living room and Bedroom temperatures at the air-conditioned dwelling at Lugbe.

Table 6.7: Maximum, minimum and average measured and predicted Living room and bedroom temperatures at the air-conditioned dwelling (H2) at Lugbe

Lugbe AC	**Ext. Temp. °C**	**Weather file Temp. °C**	**Living room Temp. °C H2**	**Living room PDT Temp. °C H2**	**Bedroom Temp. °C H2**	**Bedroom PDT Temp. °C H2**
MAX	41.1	44.0	32.7	34.6	32.9	36.0
MIN	23.5	20.8	29.8	26.1	27.0	26.2
AVG.	31.1	30.2	31.6	29.3	31.0	30.4

PDT = Predicted, AC = Air Conditioned

6.3.6.2 Measured and Predicted indoor temperatures at Bwari

The average measured living room temperatures in the naturally ventilated dwelling in Bwari was 31.9°C compared to 29.3°C in the simulated model while the maximum monitored temperature was 36°C compared to around 34°C in the model. Figure 6.22 and Table 6.8 shows that the monitored living room and bedroom space was warmer than the simulated corresponding spaces.

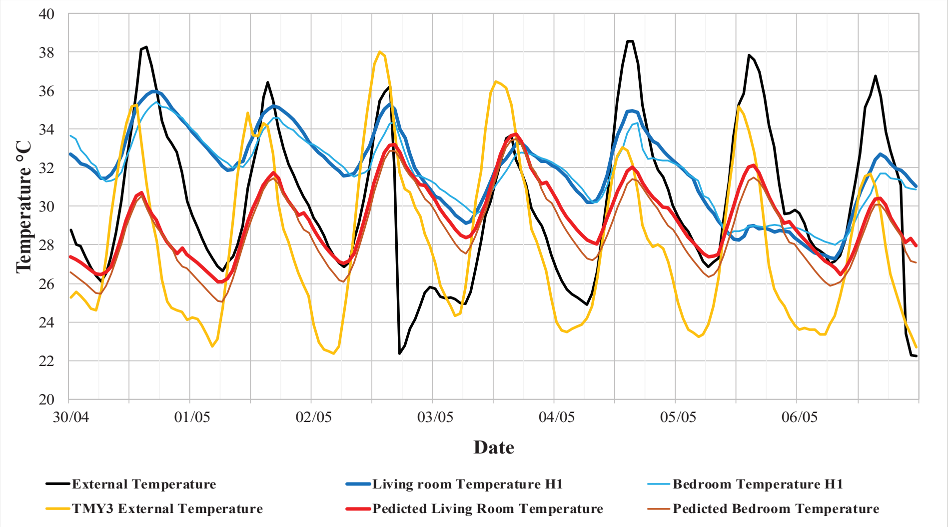


Figure 6.22: Measured and Predicted Living room and Bedroom temperatures at the naturally ventilated dwelling at Bwari.

Table 6.8: Maximum, minimum and average measured and predicted Living room and bedroom temperatures at the naturally ventilated dwellings (H1) at Bwari

Bwari NV	Ext. Temp. °C	Weather file Temp. °C	Living room Temp. °C H1	Living room PDT Temp. °C H1	Bedroom Temp. °C H1	Bedroom PDT Temp. °C H1
MAX	38.6	38.0	36.0	33.7	35.4	33.5
MIN	22.2	22.4	27.3	26.1	28.0	25.0
AVG.	30.1	28.2	31.9	29.3	31.7	28.8

PDT = Predicted, NV = Naturally Ventilated

The average living room temperatures in the air-conditioned dwelling in Bwari had temperatures around 29°C for the monitored dwelling which agrees with the temperature simulated (28.6°C) for the same space. However, the maximum measured temperature of 31.5°C contrasts with the 34.2°C reported in the simulated living space (Figure 6.23). The maximum predicted bedroom temperatures were 1°C higher than the monitored bedroom temperatures, though the difference between then was not more than 1°C (Table 6.10).

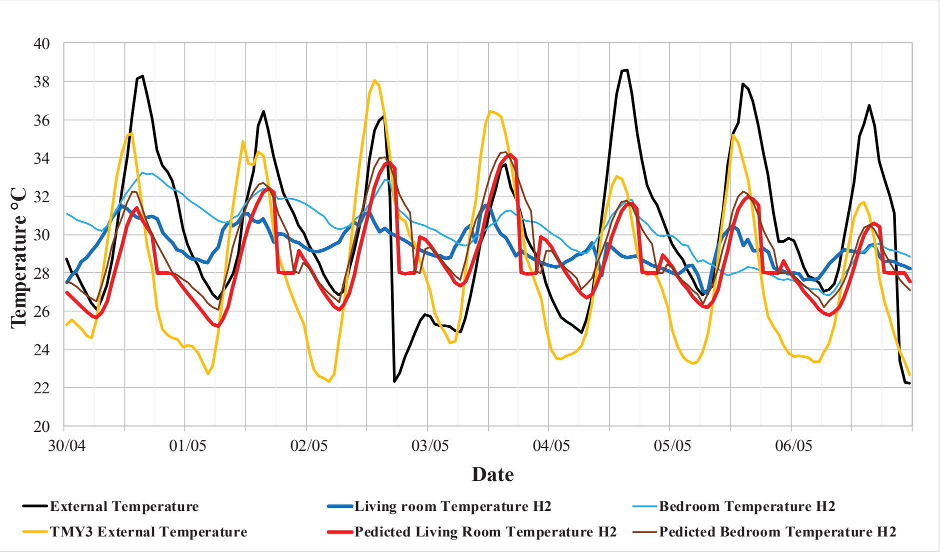


Figure 6.23: Measured and Predicted Living room and Bedroom temperatures at the air-conditioned dwelling at Bwari.

Table 6.9: Maximum, minimum and average measured and predicted Living room and bedroom temperatures at the air-conditioned dwelling (H2) at Bwari

Bwari AC	**Ext. Temp. °C**	**Weather file Temp. °C**	**Living room Temp. °C H2**	**Living room PDT Temp. °C H2**	**Bedroom Temp. °C H2**	**Bedroom PDT Temp. °C H2**
MAX	38.6	38.0	31.5	34.2	33.2	34.3
MIN	22.2	22.4	26.9	25.2	26.8	26.1
AVG.	30.1	28.2	29.3	28.6	30.2	29.3

PDT = Predicted, AC = Air Conditioned

Comparing the average predicted and measured temperatures in Table 6.8 and 6.9, shows that measured temperatures were higher than the predicted temperatures by around 1°C for both the naturally ventilated and air-conditioned houses in Lugbe and Bwari. This also shows that the houses in Lugbe were warmer than the houses in Bwari.

6.4 Overheating analysis (Comfort and discomfort periods)

As considered in Chapter 5, overheating analysis of the simulated temperatures in the indoor spaces at Lugbe and Bwari is analysed below using the static CIBSE criteria of 1% of hours above 28ºC for the living rooms and 1% of hours above 26ºC for the bedrooms. Furthermore, findings from evaluation of the overheating risk at the internal spaces at the case studies using the approved dynamic thermal comfort criteria (EN15251) are discussed below with 5% of hours above and below the Cat. III upper, Cat. II upper and lower indicators to identify warm discomfort and cold discomfort in all the spaces considered at the two case studies.

6.4.1 Analysis of overheating at Lugbe and Bwari using the static CIBSE model

Figures 6.24 to 6.26 below show analysis of the risk of overheating at Lugbe and Bwari. The Figures (6.24 and 6.25) explain the percentage of hours above 28ºC for the living rooms during the daytime and evening period while Figure 6.26 illustrates the percentage of hours over 26ºC for the bedrooms considered. For Lugbe and Bwari, the analysis shows that 100% of the living areas simulated were above 28ºC for more than 1% of the time. The analysis also suggests that 100% of the bedrooms exceeded 26ºC above 1% of the time for Lugbe and Bwari.

Considering all the four living areas simulated at Lugbe (Figure 6.24) and Bwari (Figure 6.25) from 08:00-22:00, shows that 100% of the living rooms rose above the 1% of hours over 28ºC marker of extremely hot dry season and 100% of the living room space was above the 1% of hours over 28ºC marker of extremely when looking at the evening time from 18:00-22:00 for Lugbe and Bwari. Considering 100% of the living room spaces rose above 1% of hours over 28ºC indicator of extremely hot summertime, 100% of the houses simulated are above the threshold most of the time for Lugbe and Bwari respectively indicating the occupants are experiencing extreme overheating during the day time and evening period. The analysis shows the living rooms in the houses at Lugbe and Bwari are experiencing higher temperatures than the Living rooms at Bwari. The finding from the analysis agrees with the findings from overheating analysis using static criteria for the monitored data considered in Chapter 5 (Table 6.11 and 6.12).

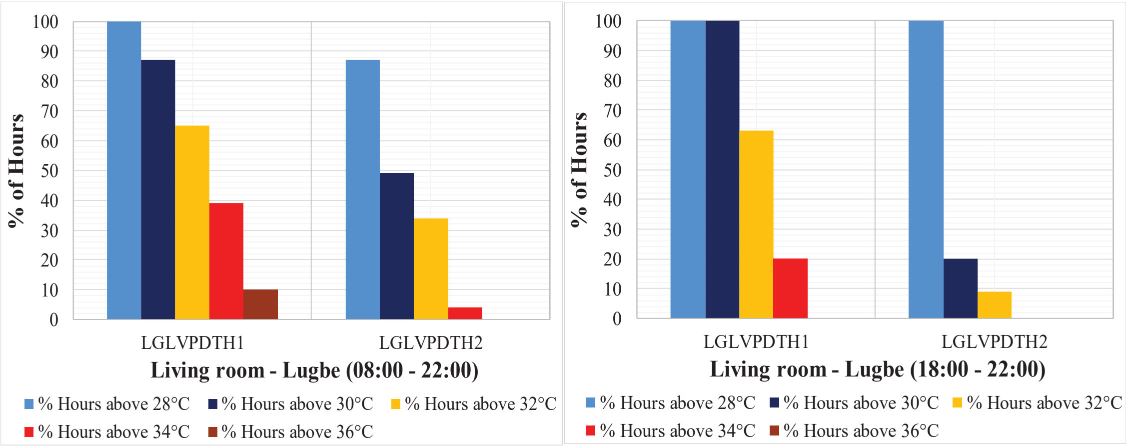


Figure 6.24: Predicted temperatures and overheating risks criteria for living rooms at Lugbe (08:00–22 :00, left and 18:00 – 22:00, right).

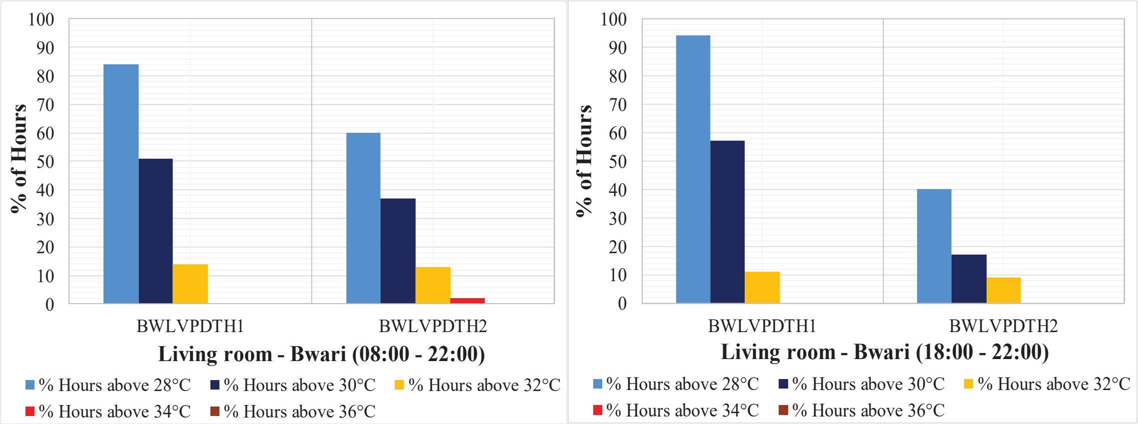


Figure 6.25: Predicted temperatures and overheating risks criteria for living rooms at Bwari (08:00–22 :00, left and 18:00 – 22:00, right).

Regarding the four bedrooms simulated from 23:00 to 07:00, 100% of the spaces rose above the 1% of hours above 26ºC marker for Lugbe and Bwari (Figure 6.26). The analysis shows the bedrooms in the houses at Lugbe are likely to experience higher temperatures than the bedrooms at Bwari. The finding from the analysis agrees with the findings from overheating analysis using static criteria for the monitored data considered in Chapter 5. The results further indicate the potential of regular occurrence of high indoor temperatures during the dry season in the bedrooms simulated which may affect the overall well-being of indoor occupants at night.

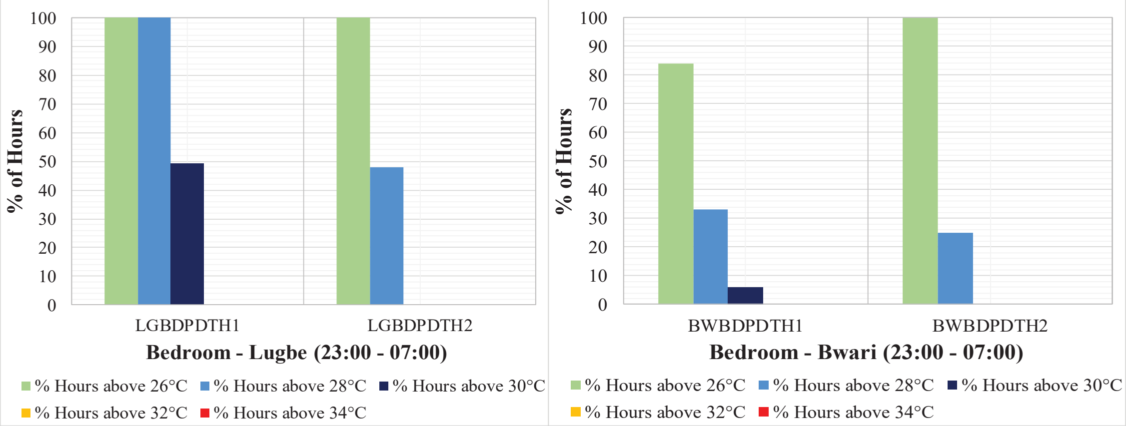


Figure 6.26: Predicted temperatures and overheating risks criteria for bedrooms at Bwari (left) and Bwari (right) from 23:00-07:00

Analysis of the overheating risk from simulation and monitoring at Lugbe and Bwari illustrated the high percentage of hours that exceeded the 1% of hours over 28°C threshold for all the living areas during the daytime and evening periods (Table 6.10 and 6.11), and it also exceeded the 1% of hours above 26°C indicator for 100% of the bedrooms (Table 6.12). Indoor conditions exceeded 28°C for more than 85% of the time in 100% of the living areas across the dwellings in Lugbe and Bwari during the day time.

Table 6.10: Summary of comparison between measured maximum, minimum and mean indoor daytime and evening period (08:00-22:00) temperatures and CIBSE static model and the adaptive comfort threshold during the dry season

Year	Indoor monitored and predicted living room spaces 08:00 – 22:00 (March – May 2015)			
Name of space-Living room	**CIBSE: total % of hours above 28°C**	**Above CIBSE % of hours threshold 30°C**	**Above CIBSE % of hours threshold 32°C**	**Above CIBSE % of hours threshold 34°C**
LGLVH1	100	89	59	25
LGLVPDTH1	100	87	65	39
LGLVH2	100	98	37	0
LGLVPDTH2	87	49	34	4
BWLVH1	98	80	58	27
BWLVPDTH1	84	51	14	0
BWLVH2	98	41	0	0
BWLVPDTH2	60	37	13	2

Table 6.11: Summary of comparison between measured maximum, minimum and mean indoor evening time (18:00-22:00) living room temperatures and CIBSE adaptive comfort threshold during the dry season

Year	Indoor monitored and predicted living room spaces 18:00 – 22:00 (March – May 2015)			
Name of space-Living room	**CIBSE: total % of hours above 28°C**	**Above CIBSE % of hours threshold 30°C**	**Above CIBSE % of hours threshold 32°C**	**Above CIBSE % of hours threshold 34°C**
LGLVH1	100	100	91	60
LGLVPDTH1	100	100	63	20
LGLVH2	100	100	54	0
LGLVPDTH2	100	20	9	0
BWLVH1	100	86	71	31
BWLVPDTH1	94	57	11	0
BWLVH2	100	11	0	0
BWLVPDTH2	40	17	9	0

The evening period in Lugbe had temperatures above 28°C for 100% of the time compared to more than 40% over 28°C recorded in Bwari (Table 6.12). During the night-time, both the measured and predicted temperatures exceeded the 1% above 26°C threshold for more 80% of the time in 100% of the bedrooms (Table 6.12).

Table 6.12: Summary of comparison between measured maximum, minimum and mean indoor night-time (23:00-07:00) bedroom temperatures and CIBSE adaptive comfort threshold during the dry season

Year	**Indoor monitored and predicted Bedroom spaces 23:00 – 07:00 (March – May 2015)**			
Name of space-Bedroom	**CIBSE: total % of hours above 26°C**	**Above CIBSE % of hours threshold 28°C**	**Above CIBSE % of hours threshold 30°C**	**Above CIBSE % of hours threshold 32°C**
LGLVH1	100	100	95	56
LGLVPDTH1	100	100	49	0
LGLVH2	100	87	62	3
LGLVPDTH2	100	48	0	0
BWLVH1	100	100	84	49
BWLVPDTH1	84	33	6	0
BWLVH2	100	86	52	3
BWLVPDTH2	100	25	0	0

Overall, the measured and predicted temperatures indoor temperatures exceeded the thresholds of moderately warm overheating risk. The predicted overheating risk results also shows that the naturally ventilated living room and bedroom spaces in all case studied were warmer than the air-conditioned space for the daytime, evening and night time, which agrees with the monitored overheating results.

6.4.2 Overheating risk analysis at Lugbe and Bwari using EN15251 Adaptive comfort model

Further analysis to examine the overheating predicted by the naturally ventilated simulation model in Lugbe and Bwari was carried out using the EN 15251 adaptive comfort model, the Category III (Cat. III) threshold 'moderate level of expectation' and Category II (Cat. II) threshold 'normal level of expectation level'. Comparing the predicted hourly temperatures with the running mean of the daily mean external temperature (T_{rm}) established a drift towards much warmer internal temperatures as T_{rm} increased. The variations in indoor temperatures for a certain T_{rm} value differ from one household to another. The results from the simulated naturally ventilated dwellings in Lugbe and Bwari were analysed and the temperatures in the living room spaces simulated in the case studies (LGPDTLVH1 and BWPDTLVH1) were above the Cat. II upper indicator for more than 5% of the time. However, the bedroom spaces in Lugbe and Bwari (LGPDTBDH1 and BWPDTBDH1) did not record temperature above Cat. II and Cat. III. The findings show an excessive occurrence of high temperatures above the approved Cat. II upper indicator in the living room spaces in the case studies but was uncomfortably cold in the bedrooms.

6.4.2.1 Analysis of overheating at Lugbe using EN15251 Adaptive comfort model

The overheating analysis for the naturally ventilated living room space in Lugbe, showed predicted temperatures rose above Cat. II upper threshold for more than 15% of the time and exceeded Cat. III upper indicator for more than 40% of the time during the daytime. The evening period (Figure 6.27) showed temperature rose above the Cat. II and Cat. III upper thresholds for more than 5% of the time. The naturally ventilated bedroom space also showed temperature rose above Cat. II upper threshold for more than 20% of the time (Figure 6.28).

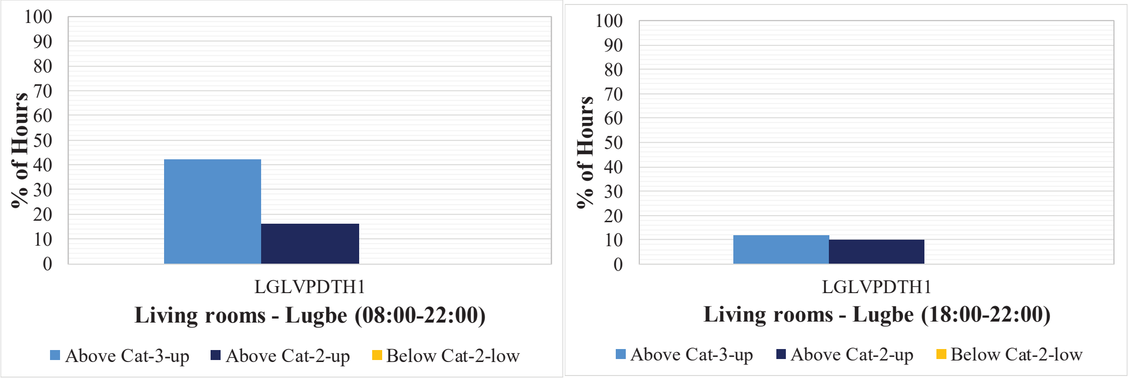


Figure 6.27: Percentage of hours of the living room predicted temperature in EN15251 Cat. II and Cat. III thermal comfort category at Lugbe (08:00–22 :00, left and 18:00 – 22:00, right).

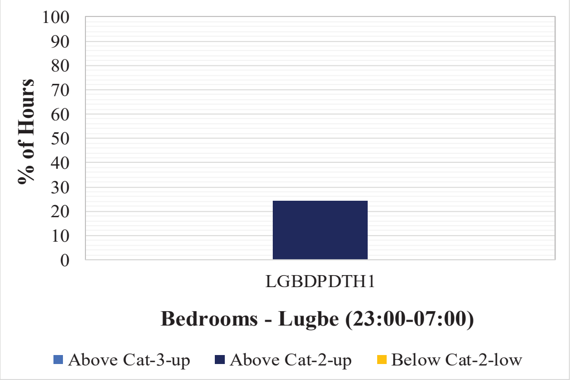


Figure 6.28: Percentage of hours of the living room predicted temperature in EN15251 Cat. II and Cat. III thermal comfort category at Lugbe (23:00–07:00).

6.4.2.2 Analysis of overheating at Bwari using EN15251 Adaptive comfort model

The naturally ventilated living room in Bwari showed predicted temperatures exceeded Cat. II upper threshold for more than 5% of the time and exceeded Cat. III marker for more than 1% of the time (Figure 6.29). In the bedroom, the temperature rose above the Cat. II upper threshold for more than 5% of the time indicating warm discomfort at night (Figures 6.30).

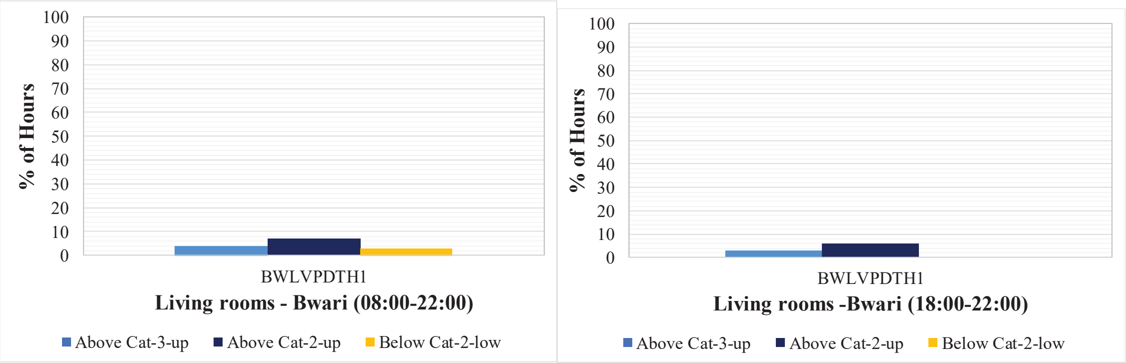


Figure 6.29: Percentage of hours of the living room predicted temperature in EN15251 Cat. II and Cat. III thermal comfort category at Bwari (08:00–22 :00, left and 18:00 – 22:00, right).

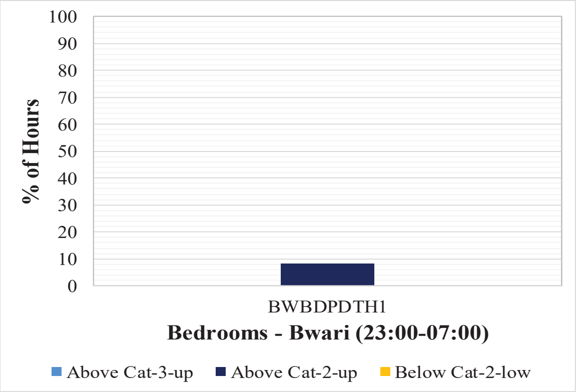


Figure 6.30: Percentage of hours of the living room predicted temperature in EN15251 Cat. II and Cat. III thermal comfort category at Bwari (23:00–07:00).

6.4.3 Measured and predicted temperature comparisons using EN 15251 adaptive overheating risks results at Lugbe

The predicted daytime and evening period naturally ventilated living room temperatures for Lugbe exceeded Cat. II upper threshold and exceeded Cat. III upper threshold which agrees with the monitored temperature over the same period (Figure 6.31). The evening period predicted temperatures exceeded the 5% of hours above the Cat. II threshold and were above the 1% of hours over the Cat. III marker, this agrees with the monitored temperature (Figure 6.31). It also shows the monitored spaces are warmer than predicted. The finding suggests extreme indoor conditions during the daytime and evening period in Lugbe.

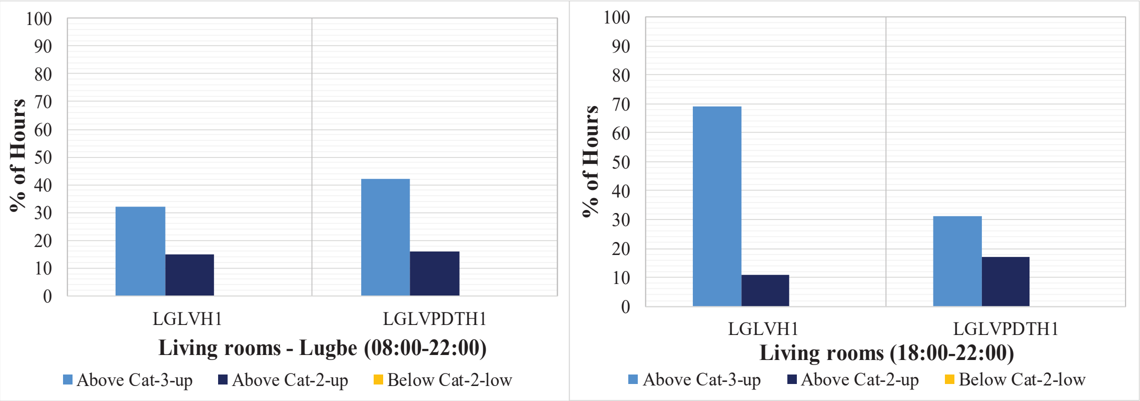


Figure 6.31: Percentage of hours of the living room predicted and measured temperatures in EN15251 Cat. II and Cat. III thermal comfort category at Lugbe (08:00–22 :00, left and 18:00 – 22:00, right).

The night-time adaptive overheating analysis in Lugbe showed temperatures rose above the 5% of hours above Cat. II upper threshold for the model, compared to the results obtained from the environmental monitoring where the temperatures exceeded Cat. II upper threshold for more than 5% of the time and exceeded the Cat. III upper threshold for more than 5% of the time. The predicted temperatures suggest warm discomfort in the bedroom which agrees with the results shown in the monitored temperatures (Figure 6.32 and Table 6.13).

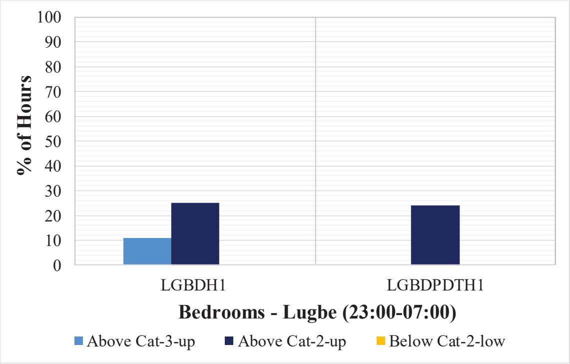
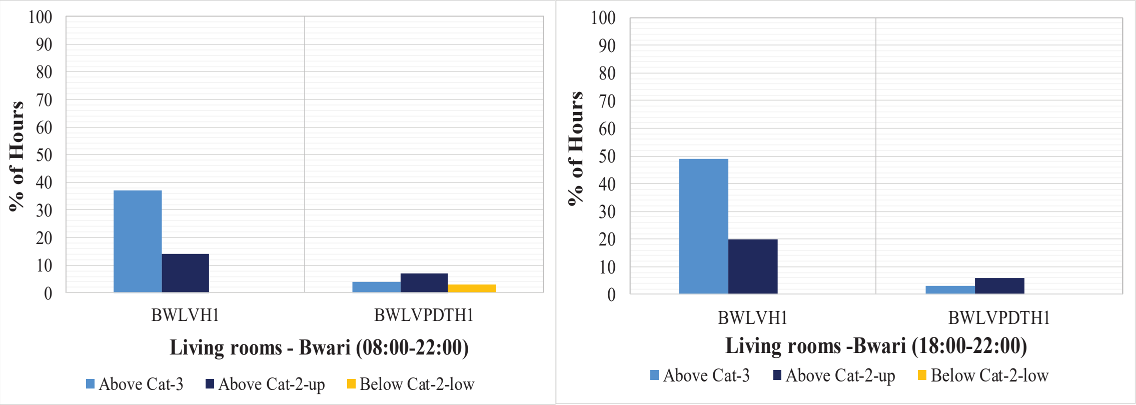


Figure 6.32: Percentage of hours of the living room predicted and measured temperature in EN15251 Cat. II and Cat. III thermal comfort category at Lugbe (23:00–07:00).

The predicted naturally ventilated living room temperature during the daytime and evening period (08:00-2:00) in Bwari, exceeded Cat. II upper threshold which agrees with the monitored temperatures during the same period (Figure 6.33 and Table 6.13). Although the monitored temperatures showed more hours above the Cat. II upper and Cat. III upper thresholds compared to the predicted temperatures. The predicted and monitored temperatures exceeded Cat. II upper threshold during the evening period (18:00-22:00). The predicted temperature also rose above Cat. III upper threshold which agrees with the monitored temperatures (Figure 6.33 and Table 6.14) indicating warm discomfort occurs in the naturally ventilated living room space in Bwari.

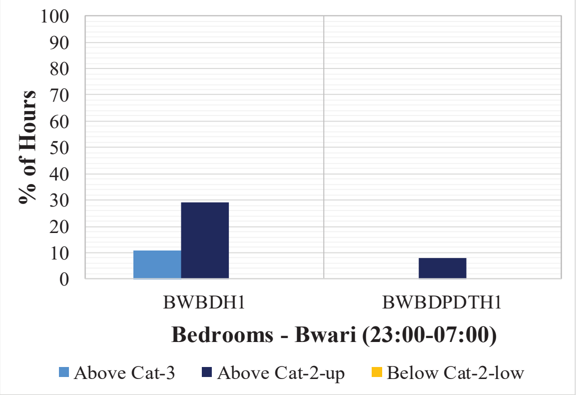


Living rooms - Bwari (08:00-22:00)

Living rooms -Bwari (18:00-22:00)

Figure 6.33. Percentage of hours of the living room predicted and measured temperatures in EN15251 Cat. II and Cat. III thermal comfort category at Bwari (08:00 – 22:00, left and 18:00 – 22:00, right).

The night-time adaptive overheating analysis at Bwari showed the predicted temperatures rose above the Cat. II upper threshold compared to the results obtained from the environmental monitoring where the temperatures exceeded Cat. II and Cat. III upper threshold. The predicted temperatures suggest warm discomfort occurs in the bedroom space (Figure 6.34 and Table 6.15).



Bedrooms - Bwari (23:00-07:00)

Figure 6.33: Percentage of hours of the living room predicted and measured temperature in EN15251 Cat. II and Cat. III thermal comfort category at Bwari (23:00–07:00).

Table 6.13: Summary of comparison between predicted and measured indoor daytime and evening period (08:00-22:00) living room temperatures and EN 15251 adaptive comfort threshold during the dry season

	Predicted Indoor monitored living spaces 08:00 – 22:00 (March – May 2015)	
Name of space-Living room	% of Hours above EN15251 Cat. II upper threshold (Hours)	% of Hours above EN15251 Cat. III upper threshold (Hours)
LGLVH1	15 (16)	32 (34)
LGLVPDTH1	16 (17)	42 (44)
BWLVH1	14 (15)	37 (39)
BWLVPDTH1	7 (7)	4 (4)

Table 6.14: Summary of comparison between predicted and measured indoor evening time (18:00-22:00) living room temperatures and EN 15251 adaptive comfort threshold during the dry season

	Predicted Indoor monitored living spaces 08:00 – 22:00 (March – May 2015)	
Name of space-Living room	% of Hours above EN15251 Cat. II upper threshold (Hours)	% of Hours above EN15251 Cat. III upper threshold (Hours)
LGLVH1	11 (6)	69 (24)
LGLVPDTH1	17 (6)	31 (11)
BWLVH1	20 (7)	49 (17)
BWLVPDTH1	6 (2)	3 (1)

Table 6.15: Summary of comparison between predicted and measured indoor evening time (23:00-07:00) living room temperatures and EN 15251 adaptive comfort threshold during the dry season

	Predicted Indoor monitored living spaces 23:00 – 07:00 (March – May 2015)	
Name of space-Bedroom	% of Hours above EN15251 Cat. II upper threshold (Hours)	% of Hours above EN15251 Cat. III upper threshold (Hours)
LGLVH1	25 (16)	11 (7)
LGLVPDTH1	24 (15)	0 (0)
BWLVH1	29 (18)	11 (7)
BWLVPDTH1	8 (5)	0 (0)

6.4.4 Comparisons between CIBSE static model and EN 15251 adaptive overheating risks model

Considering the CIBSE comfort model, extreme dry season overheating occurs in 100% of the spaces (living room and bedroom spaces) during the monitoring periods, while for the simulations overheating also occurs in 100% of the spaces.

For the overheating analysis using EN15251 simulations, 100% of the living area at Lugbe exceeded 5% of hours above the Cat. II upper indicator showing warm discomfort, and the bedroom space showed warm discomfort as temperatures rose above the 5% of hours above the Cat. II upper threshold. At Bwari, 100% of the living room space exceeded the 5% of hours threshold experiencing warm discomfort while the bedroom rose above the 5% of hours above the Cat. II threshold for more than 15% of the time indicating the space experienced warm discomfort.

Both the monitoring and modelling also highlight that warm discomfort was shown in 100% of the bedroom spaces. Categorising and comparing the percentage of hours that fall between the different thermal comfort categories, it is apparent 100% of all the spaces monitored at Lugbe exceeded 5% of the hours above the Cat. II upper threshold and 1% of hours above Cat. III threshold indicating warm discomfort, while 100% of the spaces monitored at Bwari exceeded the 5% of hours marker and 1% of hours above Cat. III threshold which suggest warm discomfort. For the simulations, 50% of all the spaces at Lugbe exceeded 5% of the hours above the Cat. II and 1% of hours above Cat. III upper thresholds. 100% of the bedroom spaces simulated at Bwari exceeded the 5% of hours above the Cat. II threshold which suggest warm discomfort occurs in the bedroom. These, although in line with the outcomes of the monitoring surveys, that indicate Bwari is cooler than Lugbe, greatly underestimate the occurrence of overheating, highlighting the limitations of modelling.

6.5 Conclusions

This chapter discussed the results from dynamic thermal simulations and compared the findings with the findings from environmental monitoring carried out in the dry season which have been considered in Chapter 5. The scope and method used for the simulations were explained. Two case study houses each in Lugbe and Bwari were simulated one as a free-running building while the other had cooling from air-conditioning, simulated for the period considered (30/04-06/05). The predicted temperatures gave representation of the internal temperatures at the case studies as some variables used for dynamic thermal simulation cannot be accurately measured in terms of quantity. For instance, it was difficult to measure occupancy character accurately for the simulations, when occupants close and opening windows or when they turn on the air-conditioning. However, the findings from the comparison between the measured and predicted data suggest a great proportion of alignment between the monitored temperatures and the predicted temperatures with the difference not exceeding 2.0ºC for most of the time. The comparison showed majority of the monitored temperatures and the simulated temperatures in all the internal spaces considered were aligned with a slight difference which suggests the reliability of the comparison done for this study.

The relationship between the predicted internal temperatures and external temperature at the case studies were discussed. The findings from the analysis provided a better understanding of the predicted internal temperature at which the occupants at the case studies will be comfortable when the external temperature rises above a certain threshold. It was discovered that the differences between the internal temperatures in Lugbe and Bwari tend to decrease as the external temperature increases.

Evaluation of the overheating risk using the static criteria and the adaptive criteria was discussed. The results predicted the possibility of dry season high internal temperatures across the case studies with tendency for frequent internal high temperatures at Lugbe than Bwari. The results also indicated that the living rooms are much warmer than bedrooms across the case studies, although the CIBSE model predicted warmer temperatures above 26°C for most of the time which suggest overheating may affect the indoor occupants from sleeping very well during night-time. Also, frequent internal high temperatures were observed within the internal spaces when the external temperature increases. The findings from this chapter further explain the adaptive thermal comfort (EN15251) criteria provide wider zones of comfort at which indoor occupants find comfortable at various locations. Regarding the two comfort models considered for evaluating the risk of overheating, it is apparent that the CIBSE comfort model is more sensitive in predicting extreme occurrences of overheating than the adaptive EN15251 model.

The comparative findings from all the surveys and thermal modelling considered in this chapter suggest that for evaluation of the overheating risk to be carried out in dwellings, further similar studies need to take into consideration the use of dynamic thermal simulation and environmental monitoring as part of the methodology. Finally, the results consistently suggest that the potential of dry season overheating of residential houses in Abuja may affect overall wellbeing of occupants. The next chapter will discuss the results from application of passive interventions through dynamic thermal simulations on a naturally ventilated and an air-conditioned model at Bwari.

CHAPTER 7

Passive cooling strategies and energy load reduction techniques

CHAPTER 7 Passive cooling strategies and energy load reduction techniques

This chapter looks at passive interventions by modifying the roof, ceiling, wall and shading device on a naturally ventilated and air-conditioned base model. For each intervention, the simulations show the effects on the daytime and evening period living room temperatures and the sleeping time, bedroom temperature for the naturally ventilated model. For the air-conditioned model, it shows the effect on the mechanical cooling load in the living room during the daytime and evening period and the bedroom when mechanical cooling is enabled.

This chapter considers some passive interventions that will be adopted on a base model to reduce external heat gain and indoor heat in residential buildings in Abuja. For the passive intervention simulations, two single storey base models were selected: the naturally ventilated model (BWPDTH1) and the air-conditioned model (BWPDTH2), representing a building in Bwari chosen because these reflected the real conditions when compared to the measured data. A summary of this chapter is shown as follows:

- 7.1 Design strategies for passive cooling for hot-humid tropical climate
- 7.2 Natural ventilation potential
- 7.3 Roof modifications: Naturally ventilated (air temperature) and air-conditioning (cooling loads) in the living room and bedroom spaces during the daytime, evening period and night-time.
- 7.4 Ceiling modifications: Naturally ventilated (air temperature) and air-conditioning (cooling loads) in the living room and bedroom spaces during the daytime, evening period and night-time
- 7.5 Wall modifications: Naturally ventilated (air temperature) and air-conditioning (cooling loads) in the living room and bedroom spaces during the daytime, evening period and night-time.
- 7.6 Shading device modifications: Naturally ventilated (air temperature) and air-conditioning (cooling loads) in the living room and bedroom spaces during the daytime, evening period and night-time.
- 7.7 Effects of passive intervention on daily cooling loads for a week
- 7.8 Optimum passive intervention effect on a naturally ventilated model and an air-conditioned model during the dry season
- 7.9 Optimum passive intervention effect on a naturally ventilated model for one year

The first section looks at the Design strategies for passive cooling for tropical climates. The second section looks at the effect of varying natural ventilation on indoor temperatures. The third section (7.3-7.6) explored a range of fabric passive intervention strategies and shading device projection for a week to align with the simulation periods used in Chapter 6. For any intervention, the sensitivity of the model is tested by increasing the thickness of the insulation from 25-500mm (Section 7.3-7.5). Section 7.6 tested the sensitivity of shading device projection from 150-1050mm on the base model. From each sensitivity study, an optimum thickness is chosen. These strategies were selected based on their availability in the Nigerian construction market and their real-life application. The fourth section (7.7) looks at the effect of insulation on daily cooling loads for a week in the living room and bedroom spaces. The fifth section (7.8) looks at the effect of the optimum passive intervention over the dry season. Lastly, the sixth section (7.9), looks at the effect of these optimum passive interventions for a year.

The roof, external walls and ceilings were selected for modification in the base model, as this is a significant route where heat enters the building. The high fabric U-Values as discussed in Chapter 6 (i.e. Roof: 7.1 W/m^{2}K, Ceiling 2.5 W/m^{2}K and Wall 2.0 W/m^{2}K) were a source of concern and the interventions were aimed at to reducing these U-Values considerably and thus lessen the cooling load for the air-conditioned model. The use of shading devices was also explored to test the potential for reducing solar gain.

7.1 Design strategies for passive cooling for hot-humid tropical climate

Passive cooling systems do not eliminate the use of a fan or a pump, when their application boosts performance (Givoni, 1994). In fact, several studies on the tropics such as Al-Obaidi et al. (2014b, 2014c) in Malaysia, enhance passive cooling with hybrid systems. Passive cooling strategies generally consist of all the preventive measures against overheating in the interior of buildings (Asimakopoulos, 1996). Passive cooling systems are energy-efficient and eco-friendly techniques used to improve the thermal comfort with nil or little power consumption as described in Section 2.13. They work either by removing heat from the building to a natural heat sink or by preventing heat from entering the living space from external heat sources. There are several passive cooling concepts that vary widely in working principle and performance. The practicability of these techniques depends greatly on the local climate. Further, ambiguities about their performance among stake holders lead to non-practice of these techniques even in favourable locations. Some of the design strategies for hot-humid tropical climates were selected and discussed in this study, they include: natural ventilation, reflective roof paints, radiant cooling, roof insulation, green roofs and solar chimneys.

7.1.1 Natural ventilation

A review of studies on natural ventilation through architectural elements and related techniques enables us to ascertain the most effective strategies for tropical regions. Previous research has looked at a range of different elements and techniques such as retrofitting buildings with vegetation (Nadia, et al., 2013, Perini, 2013), internal layout and division (Prianto and Depecker, 2002) building material (Kuznik et al., 2001) and shape of building structure (Kindangen, 1997) to achieve better ventilation and acceptable thermal conditions inside buildings. However, a review carried out by Aflaki et al. (2015), into the application of natural ventilation as a passive strategy in the tropical region, concentrates on studies that focus on elements related to ventilation openings with attention to size and location of apertures and specific concern on components on the building façades. These studies based on the principles of natural ventilation are classified into two categories namely: **cross ventilation** (wind force) (Al-Tamimi, 2011; Sahabuddin, 2012 – Malaysia; Gao and Lee, 2011; Burnett et al., 2011 – Hong Kong) and **stack ventilation** (thermal force) (Ai, et al., 2011 – Hong Kong; Wang, 1996 – China; Priyadarsini et al., 2004 – Singapore; Prajongsan, Sharples, 2012 – Thailand).

In Santamouris, et al., 2007, they suggested that night ventilation is one of the more efficient passive cooling techniques for low-income households especially for tropical regions. Golneshan and Yaghoubi (1990), Golneshan and Yaghoubi (2000), reported that the use of 12 ach/h during night with 1 ach during the day may provide comfortable indoor conditions. Given that the urban environment considerably decreases the cooling potential of night ventilation (Geros et al., 2005; Kolokotroni et al., 2006) the appropriate design of openings is very important.

Overall, studies show that natural ventilation is the dominant technique in tropical buildings compared to other passive design strategies. However, a lack of or reduced temperature change between day and night, high humidity levels and persistent cloud cover and security issues, constrain the use of natural ventilation as a strategy in tropical regions. These studies found that, natural ventilation can increase cooling significantly where steps have been taken in building design and construction to limit heat absorption from the surrounding environment. Aflaki, et al. (2015) concludes that specific cases in tropical regions of the world produced guidelines that are generalisable to all naturally ventilated buildings in tropical climates.

7.1.2 Reflective roofs paints

Asimakopoulos, (1996); Oberndorfer, et al. (2007); Aubrey, (2010) and Matthews, (2012) categorised the advantages and disadvantages of the reflective roof systems. All the researchers agreed that the best cool-roof is the use of reflective white paint (Al-Obaidi et al., 2014d). Passive cooling techniques through reflective roofs products in tropical climates considerably reduce the maximum solar heat gain by reflecting solar radiation by about 90% as well as reducing the Urban Heat Island (UHI) and energy consumption by lowering the energy demand for space conditioning (Al-Obaidi et al., 2014d). However, reflective roofs lose their reflectivity, owing to the accumulation of dirt and weathering conditions, particularly in large cities. This action will keep degrading the reflectiveness over extended periods. The use of reflective roofs is an effective strategy during hot months, but not during cold months. Moreover, highly reflective roofs result in visual discomfort and glare, and as such, their use is not advisable for areas near flight paths. Thus, the site topography and building regulations limit its application in some cases. However, the use of reflective roofs in countries with hot and humid climates such as Malaysia remains limited because of the lack of research to support this method (Al Yacouby, et al., 2011; Al-Obaidi, et al., 2014d).

These findings also show that an increase in urban population translates to the relentless use more energy, and therefore an increase in the level of greenhouse gas emissions and UHI. Therefore, energy-efficient methods, such as the reflective colour strategy, are necessary to reduce such emissions and mitigate the rising cost of energy. The colour of external surfaces (such that of the roof) has a remarkable counter-effect on the impact of solar radiation on buildings and the indoor temperature of buildings without air-conditioning systems. The strategy of using roof colour influence the thermal performance of a building, the reflection of incident solar radiation during daytime, and the emission of long-wave radiation during night time (Santamouris, 1990). This approach has the potential to provide a cooling possibility of 0.014kWh/m^2 a day. To enhance the efficiency of this approach, protecting the roof during the day is preferable. This can be achieved using different strategies, such as reflective, flat plate air cooler or movable insulation system. The potential of these methods significantly increases with movable insulation that lends a cooling potential of 0.266kWh/m^2 a day (Givoni, 1994). To effectively apply the technique of using colour methods, considering the physical factors that can potentially reduce the total heat gain is recommended. This technique is widely implemented in hot regions, but its application in the tropics remains imperfect.

7.1.3 **Radiant cooling**

The radiative cooling approach is a technique based on the idea that any objector surface at a temperature higher than 0K emits energy in the form of electromagnetic radiation. Given that more than half of heat transfer occurs through thermal radiation, radiant cooling systems is a viable mechanism for controlling surface temperature to reduce indoor thermal environment by removing sensible heat (ASHRAE, 2008). Asimakopoulos (1996), Mumma (2002), and Cavelius et al. (2007), reported that radiant cooling systems can work both day and night because this approach possesses the best view of the sky dome, making it an effective radiator. During the day, the roof can function as an absorbent of the heat from the room below (Alvarez etal.,1991). During the night, the roof is exposed to the night sky, losing heat through long-wave radiation and convection (Kamal, 2012). Radiant cooling appears to save more in costs and lifecycle costs in contrast to conventional methods of roof construction. The best radiative cooling products can considerably reduce the peak solar heat gain to 40 W/m^2. Furthermore, radiant exchange has fewer effects on air temperature, thereby requiring a supportive process to improve the strategy.

In tropical countries such as Malaysia, the effective sky temperature can determine the performance of night radiation. The Building Sector Energy Efficiency Project (2013) showed that the maximum effective sky temperature is obtained at around 20°C from 3AM to 11AM. This result is a particularly good indication of the effectiveness of using radiative roofing system in this region. In general, horizontal surfaces are good radiators of heat back to the sky (Al-Obaidi, et al., 2014d). However, under tropical conditions, using different angles are more favourable. To delay the transfer of heat gain impact, traditional architecture designs in hot, dry, and sub-tropical climates serve as very worthy models of radiative cooling using vaulted roofs. To curb the amount of heat gain, a vault element is larger than its horizontal base, which is about three times larger than a hemispherical roof. Hence, this element serves as a large storage surface during the day and a large radiative surface at night (Asimakopoulos,1996). This process is typical of pitched tropical roofs with surface are as larger than its horizontal base. However, the storage surface value depends on the material properties, solar incident, and roof angles.

Finally, the application of the radiative approaches is quite effective. According to a study by the Lawrence Berkeley National Laboratory, the savings brought using radiant cooling energy in the US was around 30% in comparison with conventional techniques. Specifically, hot, arid regions saved about 42%, which is higher than cool, humid regions, which had savings of around 17% (Stetiu, 1999). In Singapore, Building System & Diagnostics Pte Ltd. (2011) compared three distinct types of roof, namely, new conventional roofs, aged conventional roofs, and cool roofs, in domestic and industrial buildings. The cool roof was found to reduce the annual cooling loads significantly.

7.1.4 Roof insulation using Phase Change materials (PCM) and Polyurethane

Heat flow through the roof contributes to the total heat gain of a building. The contribution becomes more severe for single storey houses covered with metal sheet roofing. A study by Benard et al. in Peru (1981) suggested that the indoor temperature could be regulated in the range between 22 and 30°C by placing thick Polyurethane insulators between the glass roof and paraffin Phase change materials (PCMs) at night, (Chou, et al. 2013). In Taiwan, Multilayer roofing which included one 150-mm thick insulator layer inserted in between two metal sheet layers has been investigated by Jun Han et al. (2013) in Taiwan.

In their research, the roof model using Polyurethane showed the best thermal performance improvement for the roof. Although the thermal effect of the paint colour was not as significant as that made by the type of insulator, light colours were still suggested to be used for engineers' design.

Chou, et al. (2013) presented an innovative design for metal–sheet roofing by utilizing the phase change effect of 7mm thick phase change material with 15mm polyurethane insulation under a 0.5mm corrugated a metal roof to improve its thermal performance, with the desired thermal comfort in the indoor space in test sample designs in Taiwan. The design was aimed at reducing the downward heat flux getting into the room through the roof. Experimental and numerical results both proved that the innovative design helped to control the indoor air temperature better by maintaining it at low temperature longer and shifting the peak temperature of the room compared with the presently widely used insulated metal–sheet roofing. As a result, the cooling/heating load for air conditioning was reduced. When 1 kg of PCM which had a melting temperature of 46.3°C and latent heat capacity of 90 kJ/kg was used to cover 48% of the roofing surface with ambient temperature 25°C, the energy saving rate reached 52.7% compared with the rate of 43.1% of the normal insulated roof. However, the numerical results could be used as a reference for designing work in related climate conditions. To sum up, the use of the innovative design could be a promising and advantageous solution for houses using metal-sheet roofing. The results show that the innovative design can effectively reduce the downward thermal flow through the roof into the house in tropical climates. Consequently, the cooling load of the house can be lower and more electricity for cooling can be saved.

In Puerto-Rico, a study by Alvarado and Martınez (2008) investigated the impact of a newly designed passive cooling system which can minimize heat transfer through concrete roofs. The passive cooling system consists of a corrugated aluminium sheet with a unique orientation to promote heat dissipation. A layer of polyurethane is also used to minimize heat transfer. Aluminium alone is not sufficient to meet the established design criteria because of its high thermal conductivity. Therefore, polyurethane was chosen as an insulating material because of its low thermal conductivity (0.020 W/m K). A layer of 19.5 mm of polyurethane was placed permanently below the aluminium foil to minimize heat conduction through the roof. The experimental results demonstrated that the newly designed aluminium–polyurethane insulation system with an optimal orientation reduces the bottom surface mean temperature of a cement-based roof significantly. The results also indicate that the roof insulation system can reduce the typical thermal load by over 70% while effectively controlling thermal fluctuations. This proof-of-concept study clearly demonstrates the significant impact of a simple and effective passive cooling system in reducing thermal loads in roofs.

7.1.5 Green roofs

A green roof is a green component of building industry which includes roof with solar panels or vegetation. It is also called eco-roof, living roof, and roof garden, (Omidreza, et al 2013). In terms of economic benefits, green roofs save money particularly in terms of run-off water and energy. However, the initial cost of green roofs is more than three to six times that of conventional roofs. However, green roofs provide the following advantages in term of energy. they reduce energy used for cooling and air-conditioning, due to the higher thermal mass of the roof system and combat heat island. Green roofs also have the same efficiency in term of heat flux as the brightest possible white roofs; increase the roof's life and save energy for manufacturing a new roof. Green roofs also reduce the ambient air temperature in daytime, reduces the ambient air temperature at night and save energy due to additional shading.

A review of energy aspects of green roofs by Omidreza, et al. (2013) shows that Green roofs have been regarded as an efficient solution for reducing cooling load (Morau, et al. 2012-Reunion Island; Spala, et al. 2008- Athens, Greece). Based on a study conducted in Singapore by Wong et al., it was revealed that green roofs can contribute to a reduction of the ambient air temperature. A maximum reduction of 4.2°C was recorded because of incorporating green roofs in their study Wong, et al. (2003). Comparing the global temperatures and mean radiant temperature revealed that green roofs emit less long-wave radiation than normal roofs Wong, et al. (2003). The maximum difference between mean radiant temperature and global temperatures appeared to be around 4.05 °C which is a good indicator of the efficiency of a green roof in combating the heat island effect, (Wong, et al 2003 in Omidreza, et al 2013).

A study by Chen (2013) in Taiwan reviewed policies regarding promoting green roofs development and compared them with other countries worldwide. The study concluded that there is no significant additional maintenance energy consumption in tropical areas. The reason is that in urban cities of tropical countries, there exists a high run-off. Another study by Ascione, et al. (2013) in Taiwan investigated maintenance energy use of green roofs, by considering different climates, intensity of rainfalls, types of building, various vegetations and several external coatings. The result of their study indicates that a scarce amount of rainfall increases maintenance energy consumption because it needs additional watering, (Omidreza, et al 2013). Furthermore, one study in Poland using Life Cycle Cost (LCC) analysis confirmed the above findings, (Sly, et al. 2012). Finally, Life Cycle Control (LCA) methodology was conducted on green roofs, Traverso, et al. 2012. Considering the contribution of production, maintenance, and end of life to the whole environmental burden of extensive green roofs it was concluded that previous research had not sufficiently investigated maintenance issues because they had overlooked the role of fertilizer in doing the LCA, (Peri, et al. 2012).

These architectural features also save energy due to better insulation, improves the thermal comfort of occupants in hot climate, reduces the building temperature up to 20 °C, (Peri, et al. 2012). It also hinders the solar radiations by absorbing 60% through photosynthesis, reduce the air-conditioning energy between 25% and 80%, and absorb lower irradiative temperature in comparison to other types of roofs.

7.1.6 Solar chimneys.

Solar chimneys are natural draft components, using solar energy to build up stack pressure and thus driving airflow through the chimney channel. Solar chimneys can improve the ventilation rate in naturally ventilated buildings in hot climates (Bansal, et al 1993; Bansal, et al 1994). It is found that the impact of solar chimneys is substantial in inducing natural ventilation at low wind speeds. Recent research has permitted optimization of the design and operation of solar chimneys (Padki and Sherif 1999; Rodrigues, et al., 2000; Letan, et al., 2003) and thus the improvement of indoor environmental conditions in overheated houses.

In Thailand, a study by Chungloo and Limmeechokchai (2007) showed that without the wind effect, a solar chimney can provide almost 100% of natural ventilation in a test cell by 1.13–2.26 of ACH, accounting for 7.5% to 15% compared to the high ACH with wind effect (Khedari et al., 2000a; Khedari et al., 2000b). Although the low values of ventilation rates show that by using only the solar chimney, the ventilation might be insufficient and as a requirement, the wind effect is included in the natural ventilation application.

At high ambient temperature and high solar intensity in the daytime, the solar chimney can reduce the indoor temperature by 1.0–3.5 °C compared with the ambient air of 32.0–40.0 °C, and 1.0–1.3 °C compared with the controlled cell of 32–38 °C. From the experimental results, water spraying on the roof together with the solar chimney reduces indoor temperatures by 2.0–6.2 °C compared with ambient air, and by 1.4–3.0 °C compared with the controlled cell. From the experimental result of utilizing the solar chimney during the period of high solar radiation and high ambient temperature, the difference between temperature at the inflow into the solar chimney and temperature at the outflow from the solar chimney tends to decrease. Water spraying on the metal ceiling does not only decrease temperature in the room but also increases the temperature difference and increases the related air flow rate from room to the solar chimney too.

All strategies can be included into heat avoidance techniques. Appropriate shading especially for apertures, building orientation and insulation vegetation surrounding building and relevant materials for façade are some intelligent strategies to prepare comfortable indoor temperature. These strategies are applicable in different climates and they are suggested for tropical climates where excessive amounts of solar radiation are not preventable.

From the various tropical climate passive cooling strategies discussed above, natural ventilation and the use of polyurethane insulation on the building envelope will be discussed further to explore their potential and applicability in the context of Nigeria.

7.2 Natural ventilation potential

The sensitivity of natural ventilation rates on indoor temperatures was considered to see if there is potential in adjusting the ventilation of the building during the day and night-time to cool it. Four scenarios were considered to look at the potential for natural ventilation. First, the effects of varying infiltration rates alone, without separate natural ventilation, in the living room and bedroom spaces of the naturally ventilated model in Bwari were considered (Table 7.1). The results showed that there was 0.6-0.8°C increase in the maximum internal air temperature when 5 ac/h was applied to the living room and bedroom spaces. When the infiltration rate was increased to 10 ac/h, the maximum increased by 1.6°C. This showed that minimizing the ventilating of the indoor spaces during the day time is desirable (Figure 7.1).

Table 7.1: Sensitivity of Tint Max to Air change rate for 24 hours (Infiltration only)

ac/h	Text. Max	Tlivingroom Max	ΔTliving room	Tbedroom Max	ΔTbedroom
0	38.0	33.0	-5.0	32.5	5.5
1	38.0	33.0	-5.0	32.7	5.3
2	38.0	33.2	-4.8	32.9	5.1
3	38.0	33.4	-4.6	33.1	4.9
4	38.0	33.6	-4.5	33.3	4.7
5	38.0	34.1	-4.0	33.6	4.5
10	38.0	34.6	-3.4	34.1	4.0

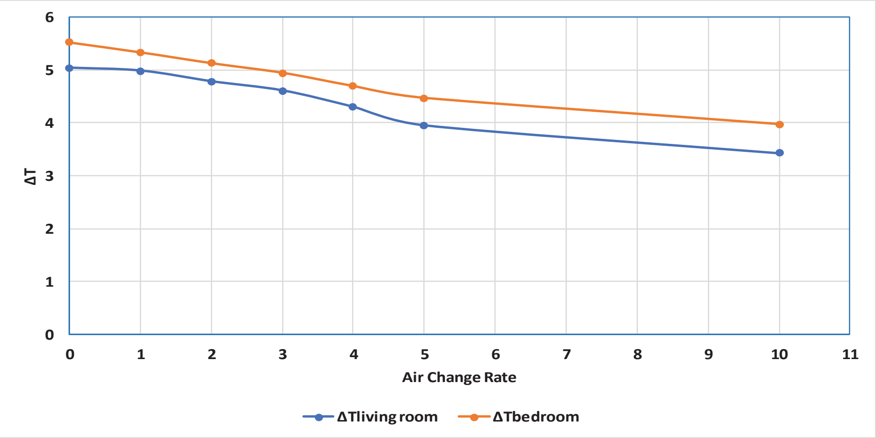


Figure 7.1: The effect of infiltration rate on indoor-outdoor temperature difference (natural ventilation set to zero)

Secondly, the living room space was ventilated from 08:00 – 22:00 and the bedroom space from 21:00 – 23:00 at 1 ac/h. This was done to simulate a real-life scenario of these spaces and to understand the effect of outdoor natural ventilation on indoor temperature. Occupants of residential buildings in Abuja tend to open their windows for long periods during the day even on warm days. However, the bedroom windows are often open for only a few hours before they go to bed mostly around 21:00 – 23:00. The results in Figure 7.2 show the indoor temperature over a 24-hour period. In the living room, there was an increase of 0.6°C in the maximum air temperature when 5 ac/h was applied, because of the flow of outdoor warm air into the building. There was no shift in the maximum bedroom temperature as the windows were only open for two hours, which is not enough time to fully exploit the cooler outdoor night-time temperature and have an effect on the daytime bedroom temperature.

Table 7.2: Sensitivity of Tint to Outside Air change rate @ 1 ac/h infiltration (24 hrs Reality Simulation)

ac/h	Text. Max	Tlivingroom Max	ΔTliving room	Tbedroom Max	ΔTbedroom
		Naturally ventilated from 08:00 – 22:00		Naturally ventilated from 21:00 – 23:00	
0	38.0	33.1	4.9	32.7	5.3
1	38.0	33.2	4.8	32.7	5.3
2	38.0	33.3	4.7	32.7	5.3
3	38.0	33.5	4.6	32.7	5.3
4	38.0	33.6	4.4	32.7	5.3
5	38.0	33.7	4.3	32.7	5.3
10	38.0	34.0	4.0	32.7	5.3

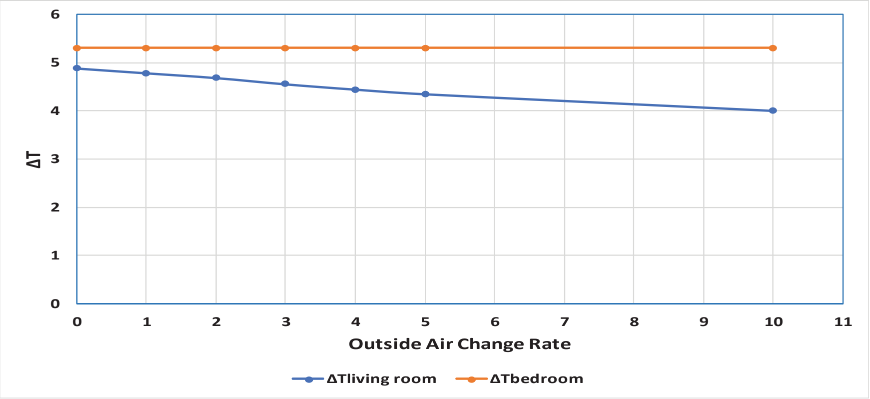


Figure 7.2: The effect of outdoor air change rates on indoor-outdoor temperature differences for 24-hours

The third scenario also looked at the living room space ventilated from 08:00 – 22:00 and the bedroom space from 21:00 – 23:00 at 1 ac/h, infiltration but this time focusing on the reported temperatures at the exact time frame for natural ventilation rather than a 24-hour scenario previously reported above. The results showed an increase of 0.6°C in the maximum living room air temperature when 5 ac/h was applied, in the maximum living room space and no change in the indoor bedroom temperature (Table 7.3 and Figure 7.3).

Table 7.3: Sensitivity of Tint to Outside Air change rate @ 1 ac/h infiltration (Reality simulation)

ac/h	Text. Max	Tlivingroom Max	ΔTliving room	Text. Max	Tbedroom Max	ΔTbedroom
	Naturally ventilated from 08:00 – 22:00			Naturally ventilated from 21:00 – 23:00		
0	38.0	33.1	4.9	30.0	31.3	-1.3
1	38.0	33.2	4.8	30.0	31.3	-1.3
2	38.0	33.3	4.7	30.0	31.3	-1.3
3	38.0	33.5	4.6	30.0	31.3	-1.3
4	38.0	33.6	4.4	30.0	31.3	-1.3
5	38.0	33.7	4.3	30.0	31.3	-1.3
10	38.0	34.0	4.0	30.0	31.3	-1.3

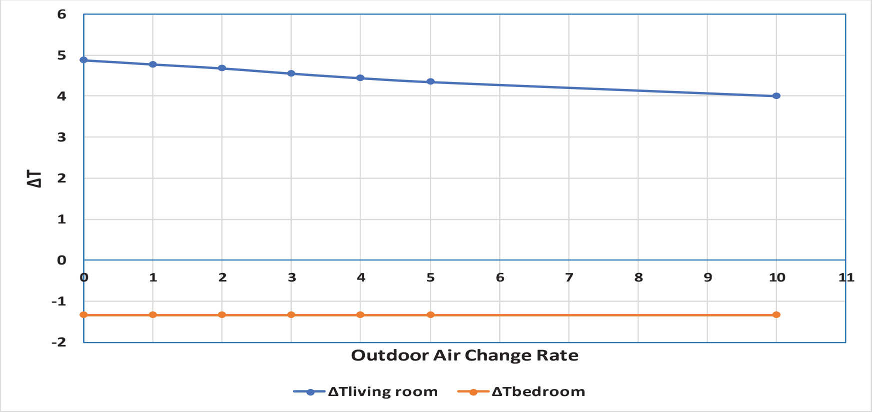


Figure 7.3: The effect of outdoor air change rates on indoor-outdoor temperature differences for naturally ventilated spaces from 08:00 – 22:00 for the living room and 21:00 – 23:00 for the bedroom.

The fourth scenario looked at the potential of naturally ventilating the indoor spaces during sleeping hours from 21:00 – 06:00. The results showed a potential in cooling the indoor spaces. When 5 ac/h was applied, the maximum living room air temperature reduced by 1.2°C and the maximum bedroom air temperature by 1.5°C (Table 7.4 and Figure 7.4). Although the fourth scenario showed more potential in reducing the indoor temperatures by over 1°C, there is difficulty in realising this in Abuja.

Table 7. 4: Sensitivity of Tint to Outside Air change rate @ 1 ac/h infiltration (Night time ventilation)

ac/h	Text. Max	Tlivingroom Max	ΔTliving room	Tbedroom Max	ΔTbedroom
		Naturally ventilated from 21:00 – 06:00		Naturally ventilated from 21:00 – 06:00	
0	30.0	31.7	-1.7	31.7	-1.7
1	30.0	31.4	-1.4	31.0	-1.0
2	30.0	31.1	-1.1	30.7	-0.8
3	30.0	30.8	-0.9	30.5	-0.6
4	30.0	30.6	-0.7	30.3	-0.4
5	30.0	30.5	-0.5	30.2	-0.3
10	30.0	29.6	0.4	29.4	0.6

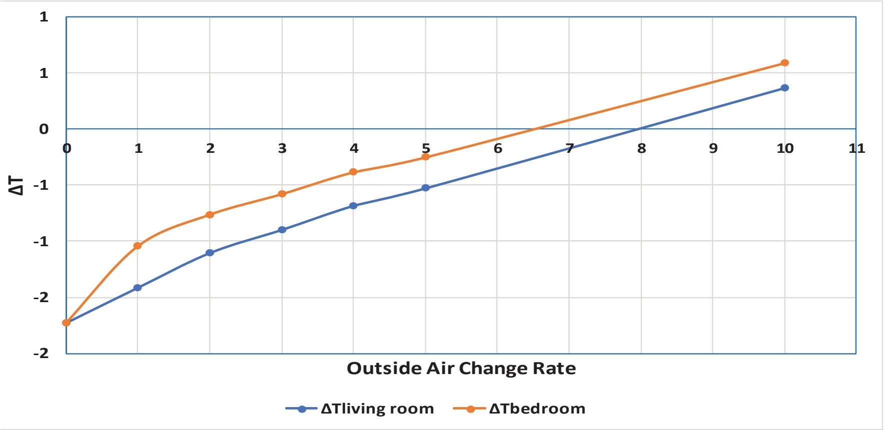


Figure 7.4: The effect of outdoor air change rates on indoor-outdoor temperature differences for the living room and bedroom spaces naturally ventilated from 21:00 – 06:00

There are three main barriers that will make night-time ventilation difficult to implement and these include: i) Noise, ii) Outdoor fumes and iii) Security. Most residents close their windows to prevent noise from generators at night, as this can make sleeping uncomfortable and even impossible. The fumes from generators are also a problem as this affects indoor air quality at night by making the air less pleasant. The third barrier to night time ventilation is security concerns. In Nigeria, opening windows at night is often seen as an invitation or opportunity for thieves to seek entrance into the space. Owing to these barriers, passive interventions using natural ventilation will not be pursued in this study and the focus will be on interventions with few barriers, that are less problematic and more acceptable to people. These interventions will not need people to change their way of operating the building. The interventions can be done on the building fabric. The next section (the first of four sections), looks at the effects of the application of insulation as a passive cooling strategy on the building fabric i.e. roofs, ceiling and walls and their cooling load reduction potential with regards to air-conditioned buildings for a week.

7.3 Design optimisation: Roof modifications

Polyurethane (PUR) roof insulation board (Figure 7.5) was applied underneath the metal roof at thicknesses from 25-500mm. A large range was used to find the most appropriate thickness for roof insulation in a naturally ventilated and air-conditioned building. The effect of the insulation on the cooling load for the air-conditioned building is revealed in the simulation results.

Figure 7.5: Polyurethane insulation under a metal roof

7.3.1 Naturally ventilated model – Living room space – Roof insulation

The roof insulation board reduced the predicted indoor temperatures, from a maximum of 33.7°C to 30.6°C, a 3.1°C drop when 75mm roof insulation board was used in living room naturally ventilated from 08:00 – 22:00 (Table 7.5). The predicted average temperature reduced by 1.5°C drop 30.0°C to 28.5°C using the same insulation thickness. Table 7.5 and Figure 7.5 summarize the effects of the different roof insulation thickness on the base model. When considering the percentage of hours above 28°C, Table 7.6 shows a drop-in percentage from 84% for the base model to 66% when using 75mm roof insulation board.

Table 7.5: Summary of roof insulation intervention in the naturally ventilated living room space model occupied 08:00 – 22:00, showing the predicted indoor temperatures.

PUR Roof Insulation thickness	**Max Temp. BWPDTLVH1**	**Min Temp. BWPDTLVH1**	**Avg. Temp. BWPDTLVH1**
500	29.9	26.1	28.1
400	29.9	26.1	28.2
300	29.9	26.1	28.2
200	30.0	26.1	28.2
100	30.4	26.1	28.4
75	30.6	26.1	28.5
50	30.7	26.1	28.6
25	31.2	26.2	28.9
0	33.7	26.3	30.0

Table 7.6: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in the naturally ventilated living room model naturally ventilated from 08:00 – 22:00.

	Base Roof	Roof PUR 25 mm	Roof PUR 50 mm	Roof PUR 75 mm	Roof PUR 100 mm	Roof PUR 200 mm	Roof PUR 300 mm	Roof PUR 400 mm	Roof PUR 500 mm
Hours above 28°C	88	77	73	69	67	61	61	61	61
% of Hours above 28°C	84	73	70	66	64	58	58	58	58

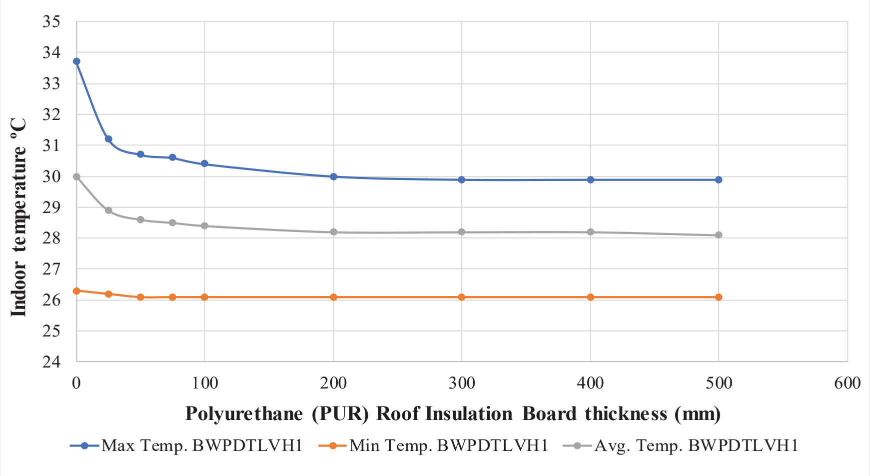


Figure 7.6: **Roof insulation** impact on temperature: **Nat. Vent.: Living Room: 8:00 – 22:00**.

Considering the evening period from 18:00-22:00 for the living room space, the maximum base model temperature dropped from 32.8°C to 30°C, a 2.8°C fall when 75mm roof insulation board was applied to the roof (Table 7.7). The average predicted temperature dropped by 1.5°C from 30.0°C to 28.5°C using the same insulation thickness. Table 7.7 and Figure 7.8 summarizes of the effects of the different roof insulation thickness on the base model. When considering the percentage of hours above 28°C for the evening period, Table 7.8 shows a fall from 91% for the base model to 69% when using 75mm roof insulation board.

Table 7.7: Summary of roof insulation intervention in the naturally ventilated living room space model occupied 18:00 – 22:00, showing the predicted indoor temperatures.

PUR Roof Insulation thickness (mm)	Max Temp. BWPDTLV-H1	Min Temp. BWPDTLV-H1	Avg. Temp. BWPDTLV-H1
500	29.3	26.6	28.1
400	29.3	26.6	28.1
300	29.4	26.6	28.1
200	29.5	26.7	28.2
100	29.8	26.7	28.4
75	30.0	26.8	28.5
50	30.2	26.8	28.6
25	30.7	26.9	28.9
0	32.8	27.2	29.8

Table 7.8: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in the naturally ventilated living room model, occupied from 18:00 – 22:00.

	Base Roof	**Roof PUR 25 mm**	**Roof PUR 50 mm**	**Roof PUR 75 mm**	**Roof PUR 100 mm**	**Roof PUR 200 mm**	**Roof PUR 300 mm**	**Roof PUR 400 mm**	**Roof PUR 500 mm**
Hours above 28°C	32	27	25	24	23	23	22	22	21
% of Hours above 28°C	91	77	71	69	66	66	63	63	60

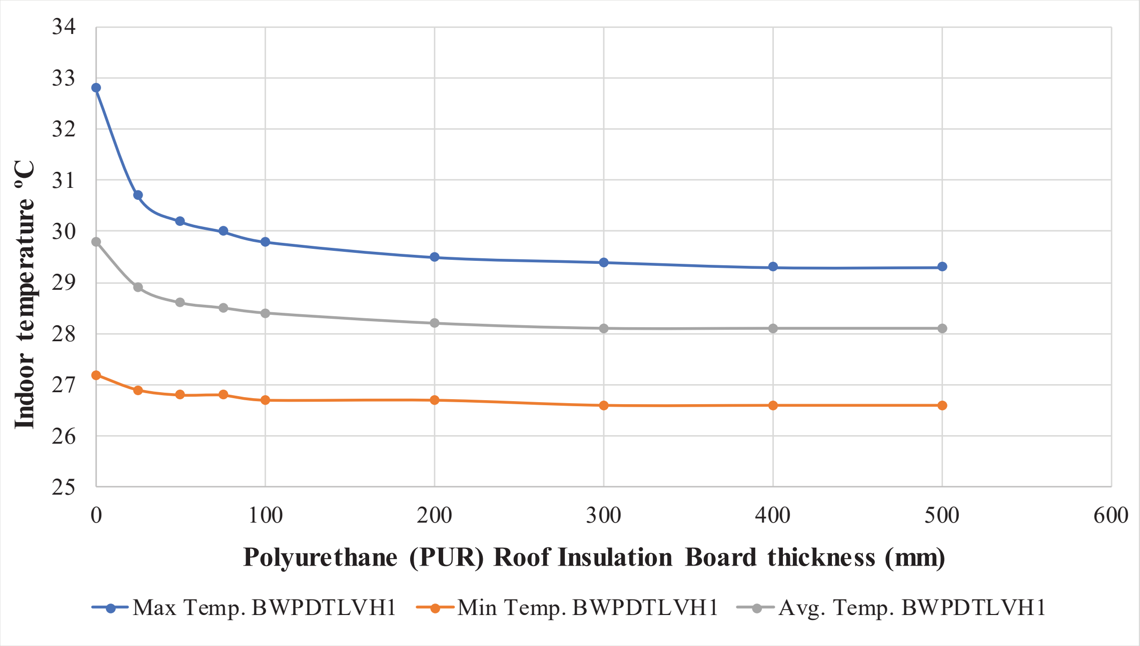


Figure 7.7: **Roof insulation** impact on temperature: **Nat. Vent.: Living Room: 18:00 – 22:00.**

7.3.2 Naturally ventilated model – Bedroom space – Roof insulation

Table 7.10 shows the maximum base model bedroom temperature, during the sleeping period reduced 2°C (from 30.4°C to 28.4°C) when 75mm roof insulation was applied on the bedroom space during the sleeping period (Table 7.9 and Figure 7.8). When considering the percentage of hours above 28°C for the same period, Table 7.10 shows a drop from 33% for the base model to 10% when using 75mm roof insulation board.

Table 7.9: Summary of roof insulation intervention in the naturally ventilated bedroom space model occupied 23:00 – 07:00, showing the predicted indoor temperatures.

PUR Roof Insulation thickness (mm)	**Max Temp. BWPDTH1**	**Min Temp. BWPDTH1**	**Avg. Temp. BWPDTH1**
500	28.0	25.3	26.4
400	28.0	25.3	26.5
300	28.1	25.3	26.5

PUR Roof Insulation thickness (mm)	Max Temp. BWPDTH1	Min Temp. BWPDTH1	Avg. Temp. BWPDTH1
200	28.2	25.3	26.5
100	28.3	25.3	26.6
75	28.4	25.5	26.7
50	28.6	25.4	26.7
25	28.8	25.4	26.8
0	30.4	25.0	27.4

Table 7.10: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in the naturally ventilated living room model, occupied from 23:00 – 07:00.

	Base Roof	Roof PUR 25 mm	Roof PUR 50 mm	Roof PUR 75 mm	Roof PUR 100 mm	Roof PUR 200 mm	Roof PUR 300 mm	Roof PUR 400 mm	Roof PUR 500 mm
Hours above 28°C	21	8	6	6	4	3	2	2	1
% of Hours above 28°C	33	13	10	10	6	5	3	3	2

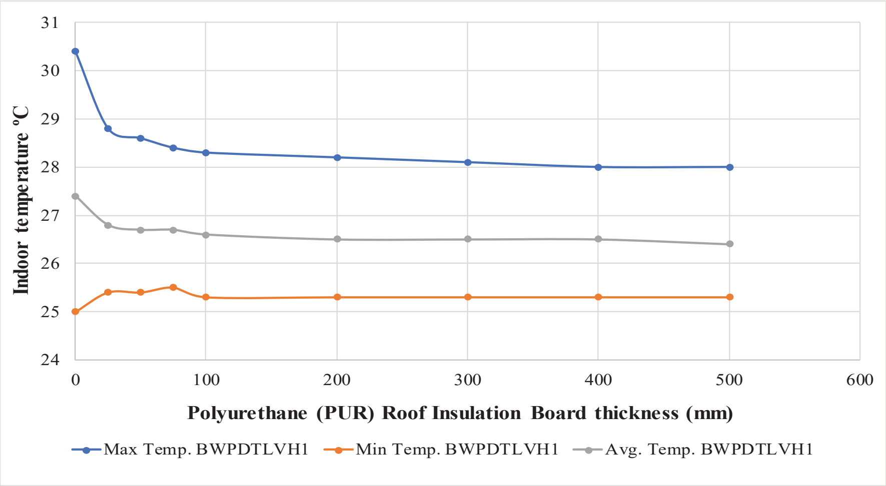


Figure 7.8: **Roof insulation** impact on temperature: **Nat. Vent.: Bedroom: 23:00 – 07:00**.

7.3.3 Air-conditioned model – Living room space – Roof insulation

In the air-conditioned model when mechanical cooling was enabled in the living room from 08:00-22:00 and 18:00-22:00, there was a significant change in the cooling load. Table 7.11 and Figure 7.9 shows a reduction of 43kWh in the living room cooling load for 08:00-22:00 when 75mm roof insulation was applied in the air-conditioned model. Considering the cooling load from 18:00-22:00, Table 7.12 and Figure 7.10 show a reduction of 11kWh when 75mm roof insulation was applied on the air-conditioned model.

Table 7.11: Summary of predicted cooling loads (sensible + latent) when using roof insulation intervention in a modelled air-conditioned living room space, occupied and air-conditioned from 08:00 – 22:00.

PUR Insulation thickness	Cooling load kWh (Roof)
500	14
400	15
300	16
200	17
100	21
75	23
50	25
25	32
0	66

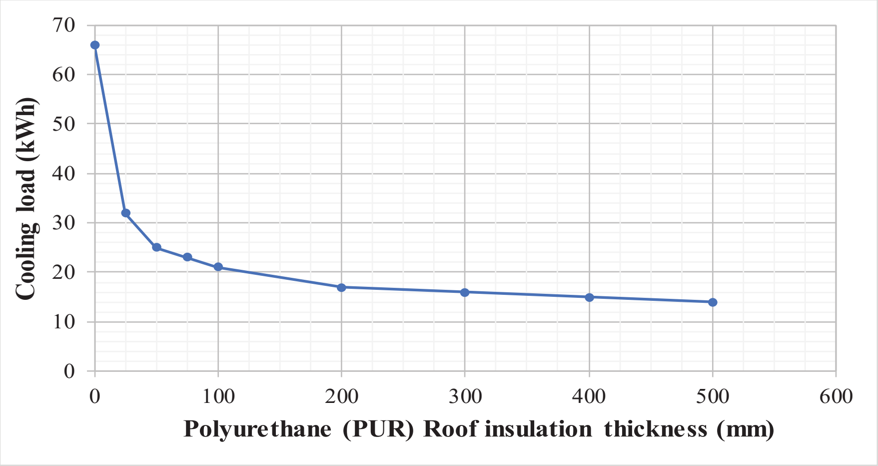


Figure 7.9: Predicted cooling loads illustrating the effect of using PUR insulation board in an air-conditioned living room space occupied and air-conditioned from 08:00 – 22:00.

Table 7.12: Summary of predicted cooling loads (sensible + latent) when using roof insulation intervention in a modelled air-conditioned living room space, occupied and air-conditioned from 18:00 – 22:00.

PUR Insulation thickness	Cooling load kWh (Roof)
500	11
400	11
300	12
200	12
100	13
75	14
50	15
25	17
0	25

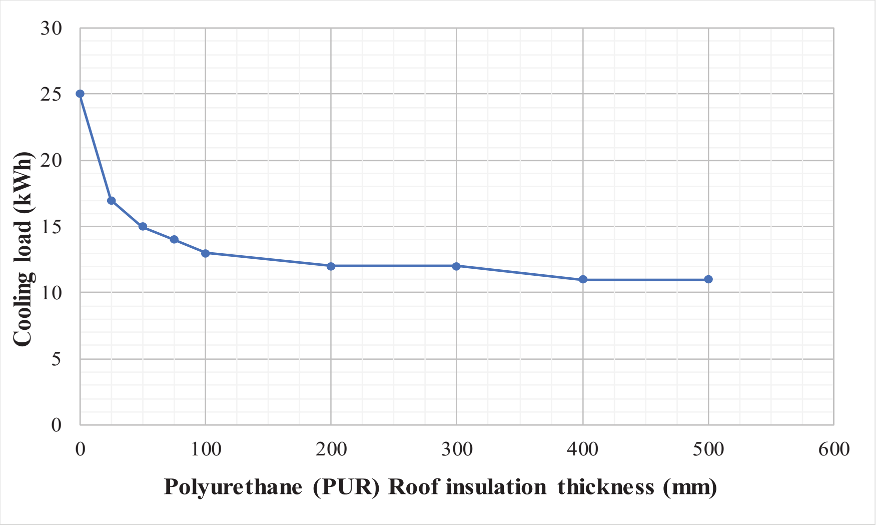


Figure 7.10: Predicted cooling loads illustrating the effect of using PUR insulation board on an air-conditioned living room space occupied and air-conditioned from 18:00 – 22:00.

7.3.4 Air-conditioned model – Bedroom space – Roof insulation

In the air-conditioned model when mechanical cooling was enabled in the bedroom from 21:00-23:00, Table 7.13 and Figure 7.11 show a reduction of 5Wh from the base model bedroom cooling load (7kWh) when 75mm roof insulation was applied on the air-conditioned model.

Table 7.13: Summary of predicted cooling loads (sensible + latent) when using roof insulation intervention in a modelled air-conditioned bedroom space, cooled from 21:00 – 23:00.

PUR Insulation thickness	Cooling load kWh (Roof)
500	1
400	1
300	2
200	2
100	2
75	2
50	3
25	4
0	7

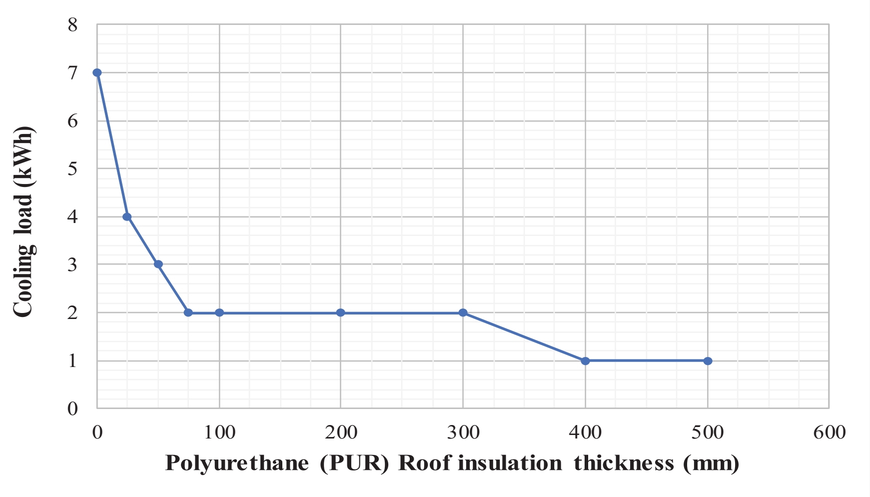
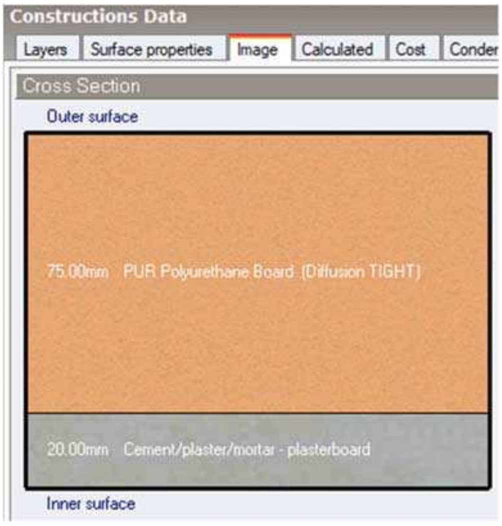


Figure 7.11: Predicted cooling loads illustrating the effect of using PUR insulation board on an air-conditioned bedroom space cooled from 21:00 – 23:00.

7.4 Design optimisation: Ceiling modifications

The ceiling was modified by using polyurethane (PUR) insulation board on the default cement plaster boards generally used in Nigeria (Figure 7.12). The board was thickness varied from 25 to 500mm in the simulations on the base model, to find the most appropriate thickness for ceiling insulation in a naturally ventilated and air-conditioned building. The effect on the cooling load for the air-conditioned building is also discussed in this section.



75.00mm PUR Polyurethane Board (Diffusion TIGHT)

20.00mm Cement/plaster/mortar - plasterboard

Figure 7.12: Polyurethane insulation above cement plaster boards

7.4.1 Naturally ventilated model – Living room space – Ceiling insulation

Considering the naturally ventilated living room space from 08:00-22:00 in Bwari, the ceiling insulation board reduced the predicted maximum internal temperatures, from 33.7°C to 30.4°C, a 3.3°C drop when 75mm ceiling insulation board was applied (Table 7.14). Table 7.14 and Figure 7.13 also shows the summary of the effects of the various ceiling insulation thickness on the indoor temperature. When considering the percentage of hours above 28°C, Table 7.15 shows this reducing from 84% for the base model to 63% when using 75mm ceiling insulation board.

Table 7.14: Summary of ceiling insulation intervention in the naturally ventilated living room space model occupied 08:00 – 22:00, showing the predicted indoor temperatures.

PUR Ceiling Insulation thickness (mm)	Max Temp. BWPDTLV-H1	Min Temp. BWPDTLV-H1	Avg. Temp. BWPDTLV-H1
500	29.9	26.0	28.1
400	29.9	26.0	28.1
300	30.0	26.0	28.1
200	30.1	26.0	28.2
100	30.3	26.0	28.3
75	30.4	26.0	28.3
50	30.6	26.0	28.5
25	31.1	26.0	28.7
0	33.7	26.3	30.0

Table 7.15: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in air-conditioned living room model, occupied from 08:00 – 22:00.

	Base Ceil.	Ceil. PUR 25 mm	Ceil. PUR 50 mm	Ceil. PUR 75 mm	Ceil. PUR 100 mm	Ceil. PUR 200 mm	Ceil. PUR 300 mm	Ceil. PUR 400 mm	Ceil. PUR 500 mm
TEMP>=28°C	88	76	68	66	64	59	60	59	59
% Hours above 28°C	84	72	65	63	61	56	57	56	56

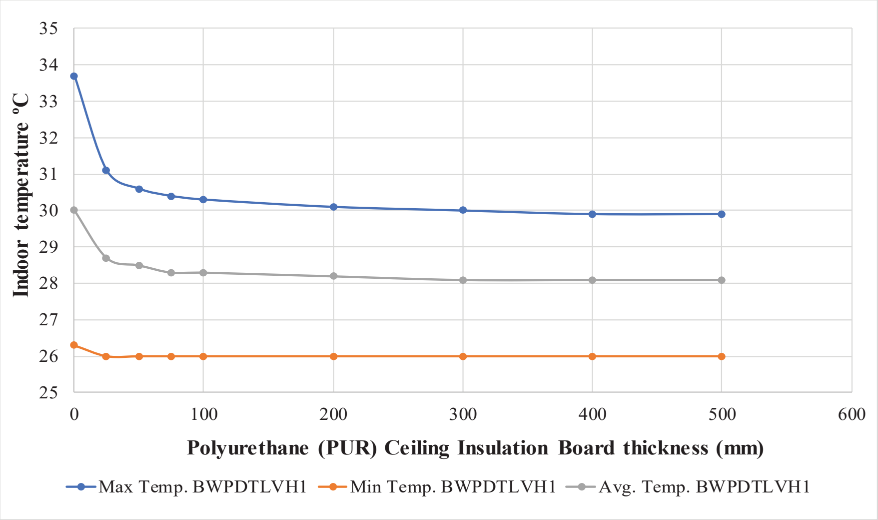


Figure 7.13: **Ceiling insulation** impact on temperature: **Nat. Vent.: Living Room: 08:00 – 22:00**.

Considering the evening period from 18:00-22:00 for the living room space, the maximum base model temperature dropped from 32.8°C to 29.9°C, a 2.9°C drop when 75mm ceiling insulation board was applied on the roof (Table 7.16). The predicted average temperature dropped by 1.4°C drop from 29.8°C to 28.4°C using the same insulation thickness. Table 7.23 and Figure 7.14 show the summary of the effect of varying the ceiling insulation thickness in the base model. When considering the percentage of hours above 28°C for the evening period, Table 7.17 shows a drop from 91% for the base model to 69% when using 75mm ceiling insulation board.

Table 7.16: Summary of ceiling insulation intervention in the naturally ventilated living room space model occupied 18:00 – 22:00, showing the predicted indoor temperatures.

PUR Ceiling Insulation thickness	Max Temp. BWPDTLVH1	Min Temp. BWPDTLVH1	Avg. Temp. BWPDTLVH1
500	29.4	26.5	28.1
400	29.4	26.5	28.1
300	29.4	26.5	28.1
200	29.5	26.6	28.2
100	29.8	26.6	28.3
75	29.9	26.6	28.4
50	30.1	26.7	28.5
25	30.6	26.8	28.8
0	32.8	27.2	29.8

Table 7.17: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in air-conditioned living room model, occupied from 18:00 – 22:00.

	Base Ceil.	Ceil. PUR 25 mm	Ceil. PUR 50 mm	Ceil. PUR 75 mm	Ceil. PUR	Ceil. PUR	Ceil. PUR	Ceil. PUR	Ceil. PUR

					100 mm	**200 mm**	**300 mm**	**400 mm**	**500 mm**
TEMP>=28°C	32	27	25	24	23	23	22	22	21
% Hours above 28°C	91	77	71	69	66	66	63	63	60

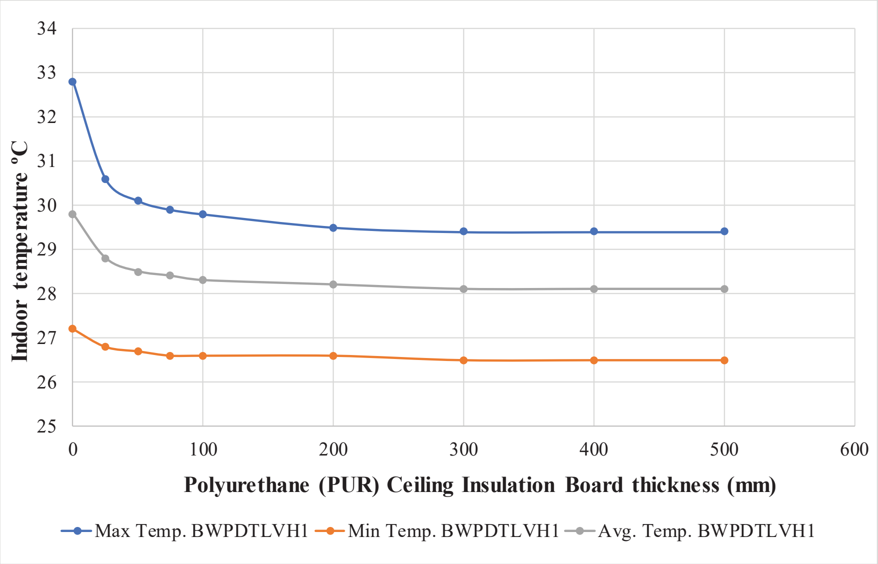


Figure 7.14: **Ceiling insulation** impact on temperature: **Nat. Vent.: Living Room: 18:00 – 22:00**.

7.4.2 Naturally ventilated model – Bedroom space – Ceiling insulation

Table 7.18 shows a 1.2°C from the maximum base model temperature (30.4°C) to 29.2°C when 75mm ceiling insulation is applied on the bedroom space during the sleeping period (Table 7.25 and Figure 7.13). When considering the percentage of hours above 28°C for the same period, Table 7.26 shows a drop from 33% for the base model to 10% when using 75mm ceiling insulation board.

Table 7.18: Summary of ceiling insulation intervention in the naturally ventilated bedroom space model, occupied 23:00 – 07:00, showing the predicted indoor temperatures.

PUR Ceiling Insulation thickness	**Max Temp. BWPDTLVH1**	**Min Temp. BWPDTLVH1**	**Avg. Temp. BWPDTLVH1**
500	29.2	24.8	26.6
400	29.2	24.8	26.6
300	29.2	24.8	26.6
200	29.2	24.8	26.6
100	29.2	24.8	26.6
75	29.2	24.8	26.6
50	29.2	24.9	26.6
25	29.3	24.9	26.7
0	30.4	25.0	27.4

Table 7.19: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in naturally ventilated bedroom model, occupied from 23:00 – 07:00.

	Base Ceil.	Ceil. PUR 25 mm	Ceil. PUR 50 mm	Ceil. PUR 75 mm	Ceil. PUR 100 mm	Ceil. PUR 200 mm	Ceil. PUR 300 mm	Ceil. PUR 400 mm	Ceil. PUR 500 mm
TEMP>=28°C	21	8	8	7	7	7	7	7	7
% Hours above 28°C	33	13	13	11	11	11	11	11	11

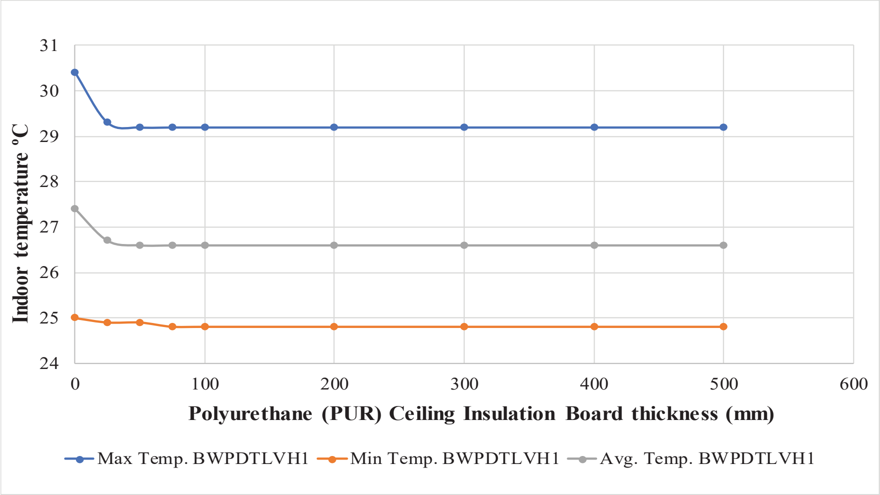


Figure 7.15: **Ceiling insulation** impact on temperature: **Nat. Vent.: Bedroom: 23:00 – 07:00**.

7.4.3 Air-conditioned model – Living room space – Ceiling insulation

Table 7.20 and Figure 16 shows a reduction of 43kWh in the living room cooling load from 08:00-22:00 when 75mm ceiling insulation was applied on the air-conditioned model. Considering the cooling load from 18:00-22:00, Table 7.21 and Figure 17 show a reduction of 11kWh from 25kWh when 75mm ceiling insulation was applied on the air-conditioned model.

Table 7.20: Summary of predicted cooling loads (sensible + latent) when using ceiling insulation intervention in a modelled air-conditioned living room space, occupied and air-conditioned from 08:00 – 22:00.

PUR Insulation thickness	Cooling load kWh (Ceiling)
500	16
400	16
300	16
200	17
100	20
75	21
50	23
25	29
0	66

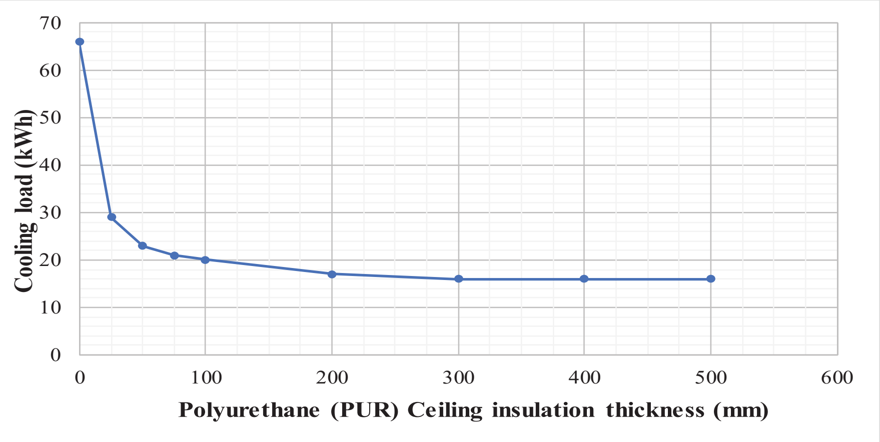


Figure 7.16: Predicted cooling loads illustrating the effect of using PUR ceiling insulation board on an air-conditioned living room space occupied and air-conditioned from 08:00 – 22:00.

Table 7.21: Summary of predicted cooling loads (sensible + latent) when using ceiling insulation intervention in a modelled air-conditioned living room space model, occupied and air-conditioned from 18:00 – 22:00.

PUR insulation thickness	Cooling loads kWh (Roof)
500	12
400	12
300	12
200	13
100	14
75	14
50	15
25	17
0	25

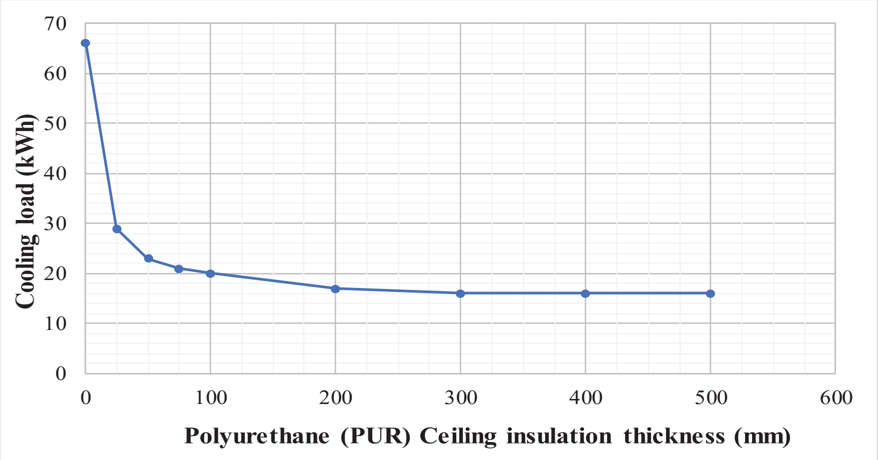


Figure 7.17: Predicted cooling loads illustrating the effect of using PUR ceiling insulation board on an air-conditioned living room space occupied and air-conditioned from 18:00 – 22:00.

7.4.4 Air-conditioned model – Bedroom space – Ceiling insulation

Table 7.22 and Figure 7.18 show a reduction of 2kWh from the base model bedroom cooling load (7kWh) when 75mm roof insulation was applied on the air-conditioned model.

Table 7.22: Summary of predicted cooling loads (sensible + latent) when using roof insulation intervention in a modelled air-conditioned bedroom space model cooled from 21:00 – 23:00.

PUR Insulation thickness	Cooling load kWh (Ceiling)
500	4
400	4
300	4
200	5
100	5
75	5
50	5
25	5
0	7

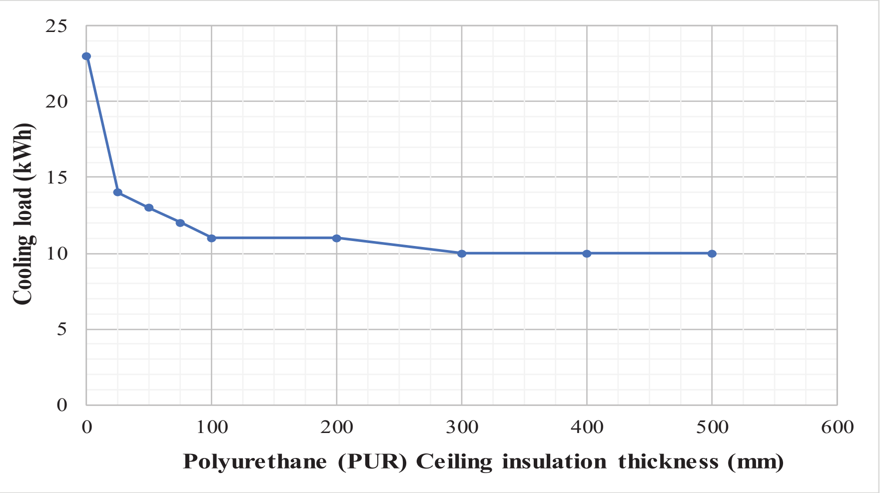


Figure 7.18: Predicted cooling loads illustrating the effect of using PUR insulation board on an air-conditioned bedroom space cooled from 21:00 – 23:00.

7.5 Design optimisation: Wall modifications

The walls were modified by applying polyurethane (PUR) insulation board on the default sandcrete modelled exterior wall used in Nigeria (Figure 7.19). The board thickness varied from 25 to 500mm which was simulated in the base model, to find the most appropriate thickness for wall insulation in a naturally ventilated and air-conditioned building. The effect of this passive cooling intervention on a naturally ventilated model and an air-conditioned model is shown in this section.

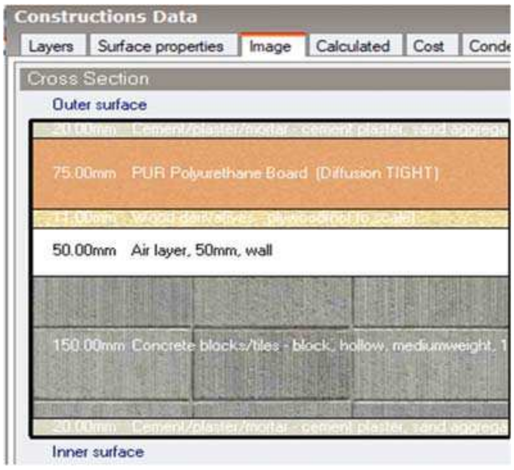


Figure 7.19: Polyurethane insulation above cement plaster boards

7.5.1 Naturally ventilated model – Living room space – Wall insulation

Considering the naturally ventilated living room space from 08:00-22:00, the wall insulation board reduced the predicted maximum internal temperatures, from 33.7°C to 33.0°C, a 0.7°C fall when 75mm ceiling insulation board was applied (Table 7.23). Table 7.23 and Figure 7.20 also summarizes the effects of the various wall insulation thicknesses on the indoor temperature. When considering the percentage of hours above 28°C, Table 7.24 show a drop in percentage from 84% for the base model to 80% when using 75mm wall insulation board.

Table 7.23: Summary of wall insulation intervention in the naturally ventilated living room space model occupied 08:00-22:00, showing the predicted indoor temperatures.

PUR Wall Insulation thickness	Max Temp. BWPDTLVH1	Min Temp. BWPDTLVH1	Avg. Temp. BWPDTLVH1
500	32.8	26.3	29.6
400	32.8	26.3	29.6
300	32.9	26.3	29.6
200	32.9	26.3	29.7
100	33.0	26.3	29.7
75	33.0	26.3	29.7
50	33.1	26.3	29.7
25	33.2	26.3	29.8
0	33.7	26.3	30.0

Table 7. 24: Summary of the predicted effects of wall insulation intervention on indoor temperatures above 28°C in naturally ventilated living room model, occupied from 08:00-22:00.

	Wall Roof	Wall PUR 25 mm	Wall PUR 50 mm	Wall PUR 75 mm	Wall PUR 100 mm	Wall PUR 200 mm	Wall PUR 300 mm	Wall PUR 400 mm	Wall PUR 500 mm
Hours above 28°C	88	86	84	84	84	84	84	84	84
% Hours above 28°C	84	82	80	80	80	80	80	80	80

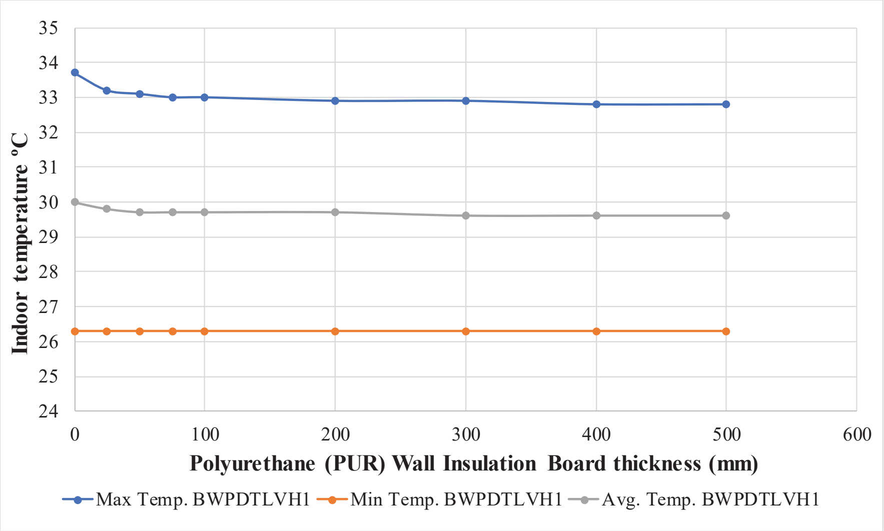


Figure 7.20: **Wall insulation** impact on temperature: **Nat. Vent.: Living Room: 08:00 – 22:00**.

Considering the evening period from 18:00-22:00 for the living room space, the maximum base temperature dropped from 32.8°C to 32.1°C, a 0.7°C drop, when 75mm wall insulation board was applied (Table 7.25). The predicted average temperature dropped by 0.4°C from 29.8°C to 29.4°C using the same insulation thickness. Table 7.25 and Figure 7.21 summarizes the effects of the various ceiling insulation thicknesses on the base model. When considering the percentage of hours above 28°C for the evening period, Table 7.26 shows a drop from 91% for the base model to 69% when using 75mm ceiling insulation board.

Table 7.25: Summary of wall insulation intervention in the naturally ventilated living room space model, occupied 18:00 – 22:00, showing the predicted indoor temperatures.

PUR Wall Insulation thickness	Max Temp. BWPDTLVH1	Min Temp. BWPDTLVH1	Avg. Temp. BWPDTLVH1
500	31.9	27.1	29.3
400	32.0	27.1	29.3
300	32.0	27.1	29.3
200	32.0	27.1	29.4
100	32.1	27.1	29.4
75	32.1	27.1	29.4
50	32.2	27.1	29.5
25	32.3	27.1	29.5
0	32.8	27.2	29.8

Table 7.26: Summary of the effects of wall insulation intervention on indoor temperatures above 28°C in naturally ventilated living room model, occupied from 18:00 – 22:00

	Wall Roof	Wall PUR 25 mm	Wall PUR 50 mm	Wall PUR 75 mm	Wall PUR 100 mm	Wall PUR 200 mm	Wall PUR 300 mm	Wall PUR 400 mm	Wall PUR 500 mm
Hours above 28°C	15	13	11	11	11	11	11	11	11
% Hours above 28°C	43	37	31	31	31	31	31	31	31

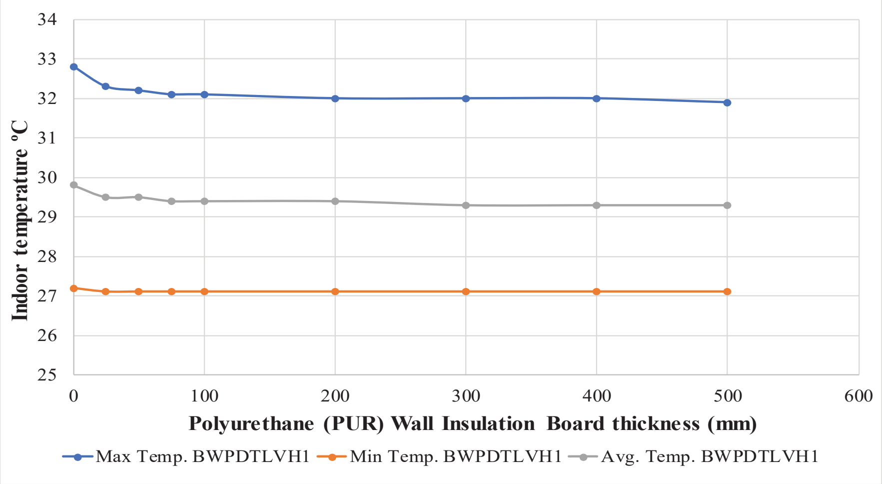


Figure 7.21: **Wall insulation** impact on temperature: **Nat. Vent.: Living Room: 18:00 – 22:00**.

7.5.2 Naturally ventilated model – Bedroom space – Wall insulation

Table 7.36 shows a 1.6°C drop in temperature from the maximum base model temperature (30.4°C) to 28.8°C when 75mm wall insulation is applied on the air-conditioned bedroom space during the sleeping period (Table 7.27 and Figure 7.21). When considering the percentage of hours above 28°C for the same period, Table 7.28 shows a drop from 33% for the base model to 13% when using 75mm wall insulation board.

Table 7.27: Summary of wall insulation intervention in the naturally ventilated bedroom space model occupied 23:00 – 07:00, showing the predicted indoor temperatures.

PUR Wall Insulation thickness	Max Temp. BWPDTLVH1	Min Temp. BWPDTLVH1	Avg. Temp. BWPDTLVH1
500	28.6	25.3	26.7
400	28.6	25.3	26.7
300	28.6	25.3	26.7
200	28.6	25.3	26.7
100	28.8	25.4	26.8
75	28.8	25.4	26.8
50	28.9	25.4	26.9
25	29.1	25.4	27.0
0	30.4	25.0	27.4

Table 7.28: Summary of the predicted effects of wall insulation intervention on indoor temperatures above 28°C in naturally ventilated bedroom model, occupied from 23:00 – 07:00

	Wall Roof	**Wall PUR 25 mm**	**Wall PUR 50 mm**	**Wall PUR 75 mm**	**Wall PUR 100 mm**	**Wall PUR 200 mm**	**Wall PUR 300 mm**	**Wall PUR 400 mm**	**Wall PUR 500 mm**
Hours above 28°C	21	9	8	8	6	6	6	6	6
% Hours above 28°C	33	14	13	13	10	10	10	10	10

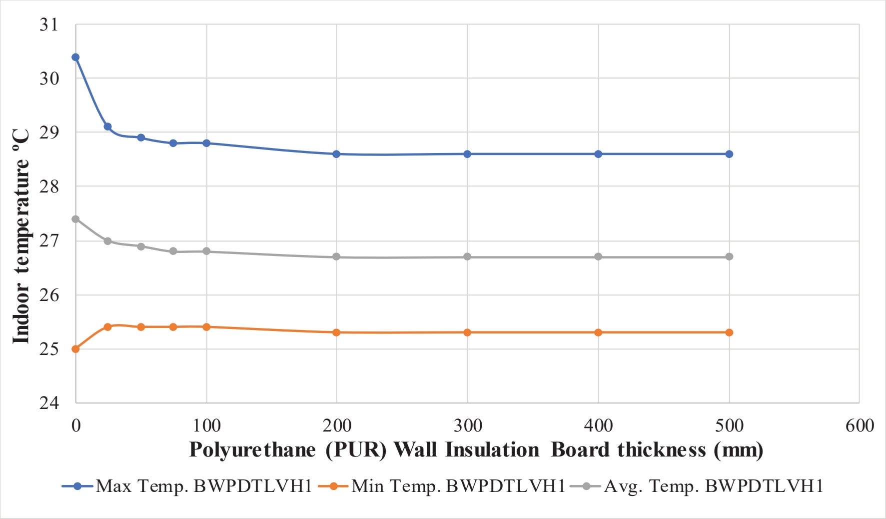


Figure 7. 22: **Wall insulation** impact on temperature: **Nat. Vent.: Bedroom: 23:00 – 07:00**.

7.5.3 Air-conditioned model – Living room space – Wall insulation

Table 7.29 and Figure 7.23 show a reduction of 27Wh from 66kWh for the base model in the living room cooling load from 08:00-22:00 when 75mm wall insulation was applied in the air-conditioned model. Considering the cooling load from 18:00-22:00, Table 7.30 and Figure 7.24 show a reduction of 11kWh when 75mm wall insulation was applied in the air-conditioned model.

Table 7.29: Summary of cooling loads (sensible + latent) when using wall insulation intervention in a modelled air-conditioned living room space, occupied and air-conditioned from 08:00 – 22:00.

PUR Insulation thickness	**Cooling load kWh (Wall)**
500	37
400	37
300	37
200	38
100	39
75	39
50	41
25	43
0	66

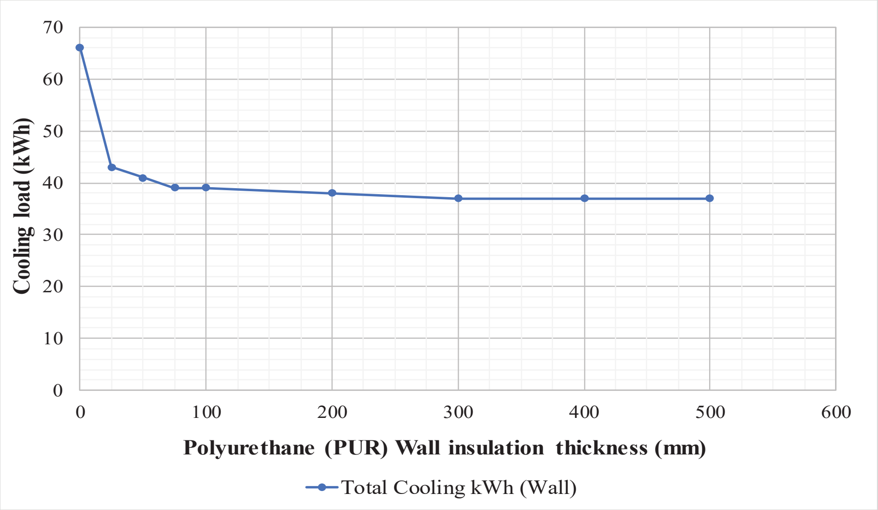


Figure 7.23: Predicted cooling loads illustrating the effect of using PUR wall insulation board on an air-conditioned living room space occupied and air-conditioned from 08:00 – 22:00.

Table 7.30: Summary of predicted cooling loads (sensible + latent) when using ceiling insulation intervention in a modelled air-conditioned living room space model, occupied and air-conditioned from 18:00 – 22:00.

PUR Insulation thickness	Cooling load kWh (Wall)
500	7
400	7
300	7
200	8
100	8
75	9
50	9
25	11
0	25

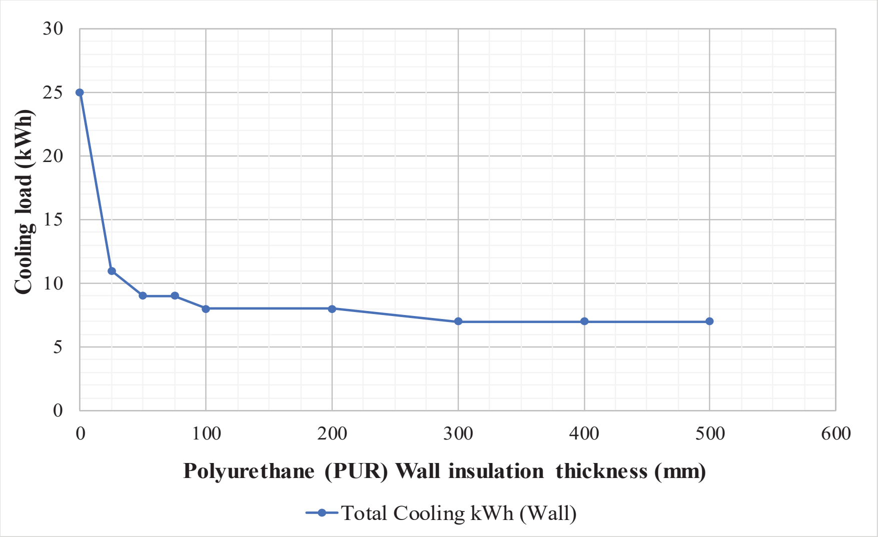


Figure 7.24: Predicted cooling loads illustrating the effect of using PUR wall insulation board on an air-conditioned living room space occupied and air-conditioned from 18:00 – 22:00.

7.5.4 Air-conditioned model – Bedroom space – Wall insulation

Considering the cooling load from 21:00-23:00, Table 7.31 and Figure 7.25 show a reduction of 2kWh from the base model (7kWh) when 75mm wall insulation was applied to the air-conditioned model.

Table 7.31: Summary of predicted cooling loads when using wall insulation intervention in a modelled air-conditioned bedroom space model cooled from 21:00 – 23:00.

PUR Insulation thickness	Cooling load kWh (Wall)
500	4
400	4
300	5
200	5
100	5
75	5
50	5
25	5
0	7

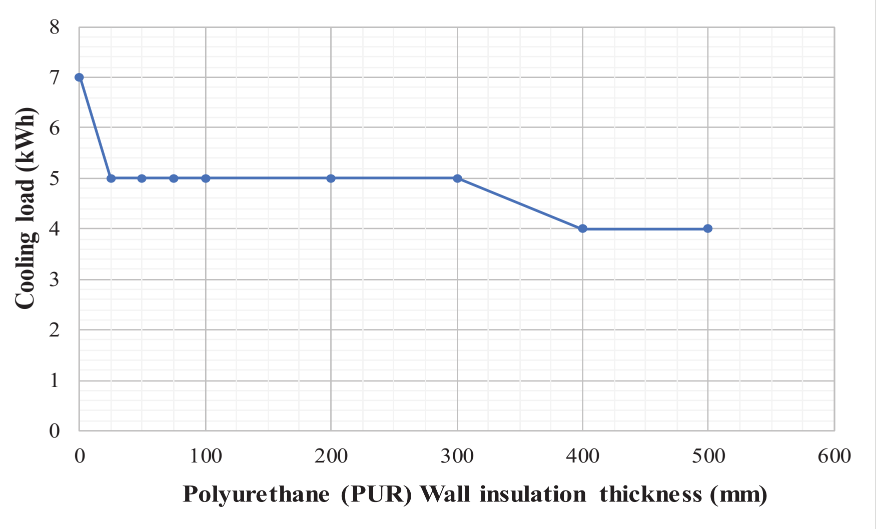


Figure 7.25: Predicted cooling loads illustrating the effect of using PUR wall insulation board in an air-conditioned bedroom space cooled from 21:00 – 23:00.

7.6 Design optimisation: Shading device modifications

On the exterior living rooms and bedrooms windows on the naturally ventilated and air-conditioned models, shading devices were applied using an exterior projection varying from 150 to 1050mm to find the most suitable projection that would reduce indoor temperatures. In the simulations, the naturally ventilated building had bedroom windows orientated towards the North-East and South-East, while the living room had an exterior window oriented towards the South-East. Sunlight entered the building during the simulated period especially the air-conditioned model, because it has windows on all four sides of the house. In the air-conditioned model, the living room had one of its windows oriented to the east and the other to the south while the bedroom had one of its windows oriented towards the west and the other to the north. The shading device was made up of 50mm thick concrete horizontal overhang and vertical side fins, offset 100mm from the window (Figure 7.26 and 7.27). This study applies a horizontal and vertical shading device. This section will discuss the effects of the shading devices on the naturally ventilated model and air-conditioned model.

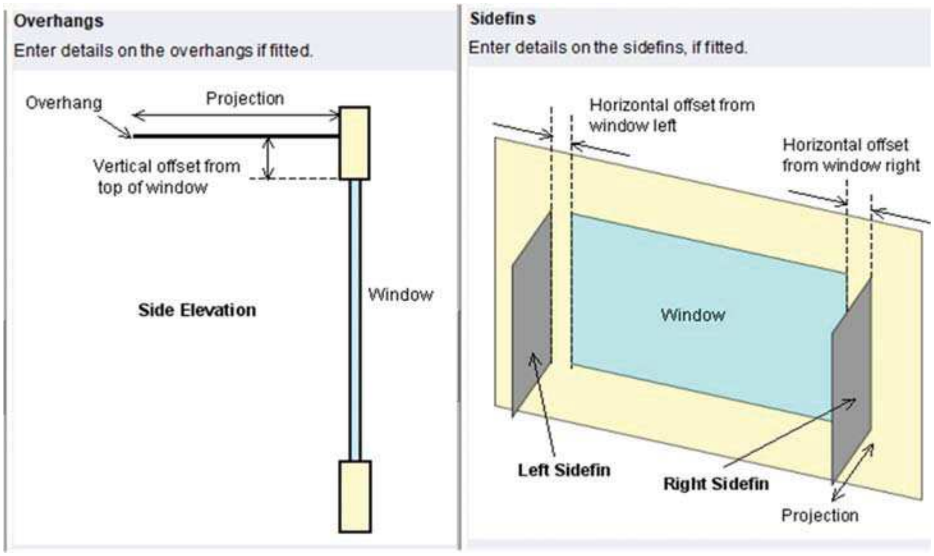


Figure 7.26: 50mm thick concrete horizontal overhang (Right) and vertical side fins (Left).

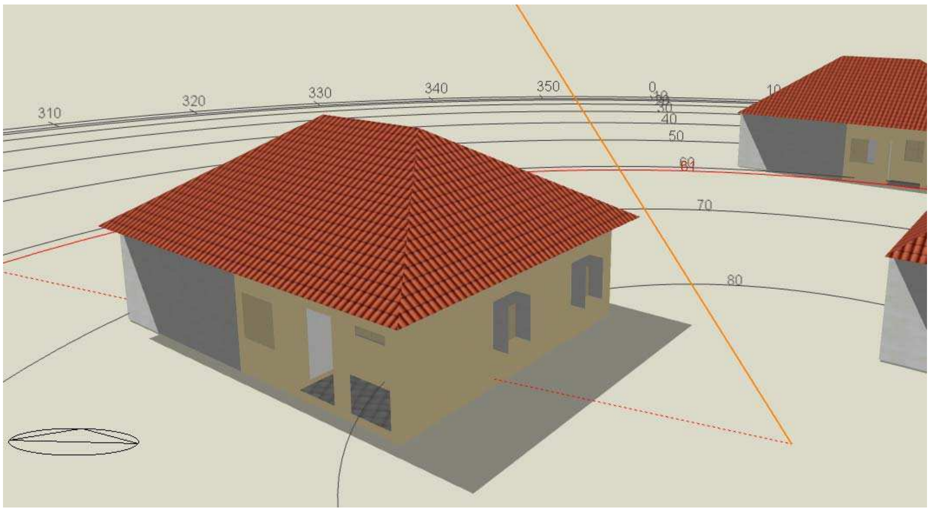


Figure 7.27: Shading device on the naturally ventilated model at 14:00

7.6.1 Naturally ventilated model – Living room space – Shading device

Considering the effects on the indoor daytime period from 08:00-22:00 when using shading devices (Table 7.32 and Figure 7.28), shows a 1.1°C reduction from the base model temperature (33.7°C) was achieved when a 1050mm projection shading device was applied. When considering the percentage of hours above 28°C for the daytime period, Table 7.33 shows a drop from 84% for the base model to 81% when using 150-1050mm shading device extension.

Table 7.32: Summary of shading device intervention in the naturally ventilated living room space model, occupied 08:00 – 22:00, showing the predicted indoor temperatures.

Shading Device Extension	Max Temp. BWPDTLVH1	Min Temp. BWPDTLVH1	Avg. Temp. BWPDTLVH1
1050	32.6	25.9	29.3
900	32.7	25.9	29.3
750	32.8	25.9	29.4
600	32.9	25.9	29.4
450	33.1	25.9	29.5
300	33.3	26.0	29.7
150	33.5	26.1	29.8
0	33.7	26.3	30.0

Table 7.33: Summary of the effects of shading device intervention on indoor temperatures above 28°C in naturally ventilated living room model, occupied from 08:00 – 22:00.

	Shading device Base	SD 150 mm	SD 300 mm	SD 450 mm	SD 600 mm	SD 750 mm	SD 900 mm	SD 1050 mm
Hours above 28°C	88	85	85	85	85	85	85	85
% Hours above 28°C	84	81	81	81	81	81	81	81

SD-Shading Device

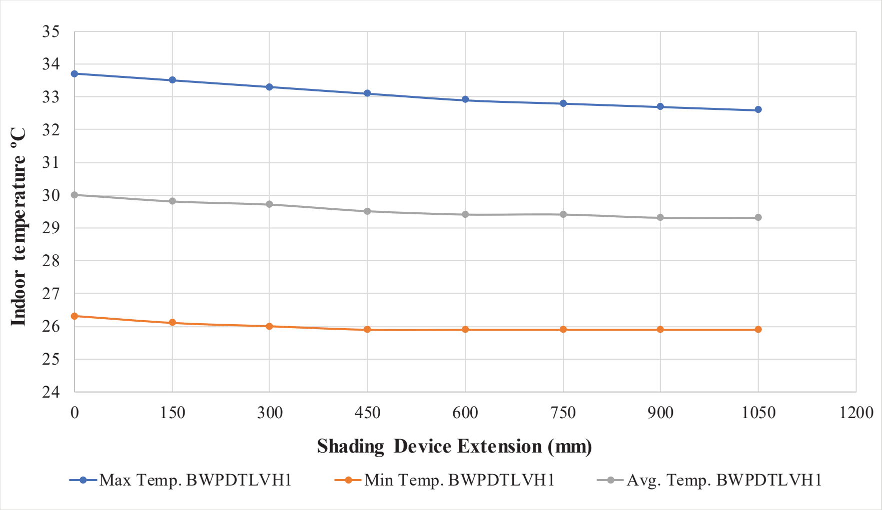


Figure 7.28: **Shading Device** impact on temperature: **Nat. Vent.: Living Room: 08:00 – 22:00**.

Considering the effects on the indoor daytime period from 18:00-22:00 when using shading devices (Table 7.34 and Figure 7.29), shows a 0.3°C reduction from the maximum base model temperature (32.8°C) was achieved when 750mm projection shading device extension was applied. When considering the percentage of hours above 28°C for the daytime period, Table 7.35 shows a 5% drop throughout from 91% for the base model to 86% when applying 150-1050mm shading device extension.

Table 7.34: Summary of shading device intervention in the naturally ventilated living room space model, occupied 18:00-22:00, showing the predicted indoor temperatures.

Shading Device Extension	Max Temp. BWPDTLVH1	Min Temp. BWPDTLVH1	Avg. Temp. BWPDTLVH1
1050	32.5	27.1	29.7
900	32.5	27.1	29.7
750	32.5	27.1	29.7
600	32.6	27.1	29.7
450	32.6	27.1	29.7
300	32.6	27.1	29.7
150	32.6	27.1	29.7
0	32.8	27.2	29.8

Table 7.35: Summary of the predicted effects of shading device intervention for indoor temperatures above 28°C in naturally ventilated living room model, occupied from 18:00 – 22:00.

	Shading device	SD 150 mm	SD 300 mm	SD 450 mm	SD 600 mm	SD 750 mm	SD 900 mm	SD 1050 mm
Hours above 28°C	32	30	30	30	30	30	30	30
% Hours above 28°C	91	86	86	86	86	86	86	86

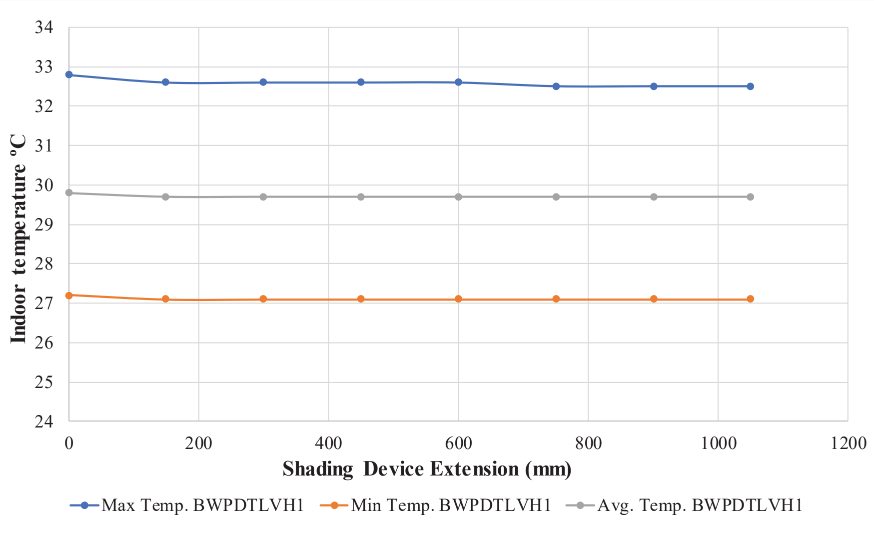


Figure 7.29: **Shading Device** impact on temperature: **Nat. Vent.: Living Room: 18:00 – 22:00**.

7.6.2 Naturally ventilated model – Bedroom space – Shading device

Considering the effects on the indoor sleeping period from 23:00-07:00 when applying shading devices (Table 7.36 and Figure 7.30), shows a 0.7°C reduction from the maximum base model temperature

(30.4°C) was predicted when a 300mm projection shading device extension was applied. When considering the percentage of hours above 28°C for the daytime period, Table 7.37 shows an 11 percentage points drop in temperature from 33% for the base model to 22% when applying a 300mm shading device projection.

Table 7.36: Summary of shading device insulation intervention in the naturally ventilated bedroom space model, occupied 23:00 – 07:00, showing the recorded maximum, minimum and average indoor temperatures.

Shading Device Extension	**Max Temp. BWPDTLVH1**	**Min Temp. BWPDTLVH1**	**Avg. Temp. BWPDTLVH1**
1050	29.7	25.2	27.0
900	29.7	25.2	27.0
750	29.7	25.2	27.0
600	29.7	25.2	27.0
450	29.7	25.2	27.0
300	29.7	25.2	27.0
150	29.8	25.2	27.0
0	30.4	25.0	27.4

Table 7.37: Summary of the effects shading device intervention for indoor temperatures above 28°C in naturally ventilated bedroom model, occupied from 23:00 – 07:00.

	Shading device Base	**SD 150 mm**	**SD 300 mm**	**SD 450 mm**	**SD 600 mm**	**SD 750 mm**	**SD 900 mm**	**SD 1050 mm**
Hours above 28°C	**21**	**14**	**14**	**13**	**13**	**13**	**12**	**12**
% Hours above 28°C	**33**	**22**	**22**	**21**	**21**	**21**	**20**	**20**

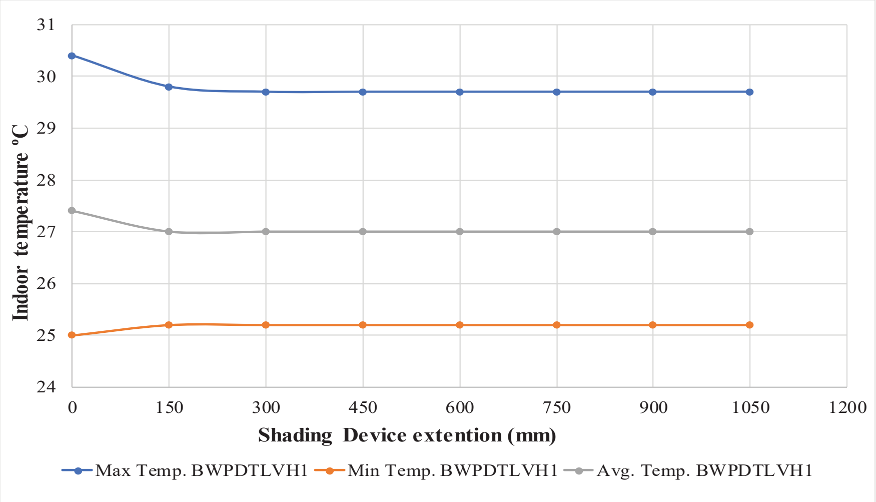


Figure 7.30: **Shading Device** impact on temperature: **Nat. Vent.: Bedroom:** 23:00 – 07:00.

7.6.3 Air-conditioned model – Living room space – Shading device

Considering the cooling load from 08:00-22:00, Table 7.38 and Figure 7.31 show a reduction of 8kWh from the base model (66kWh) when a 600-1050mm shading device was applied to the air-conditioned model.

Table 7.38: Summary of cooling loads when applying shading device intervention on an air-conditioned Living room space model cooled from 08:00-22:00.

Shading Device Extension	Cooling Load kWh (Shading device)
1050	58
900	58
750	58
600	58
450	59
300	61
150	63
0	66

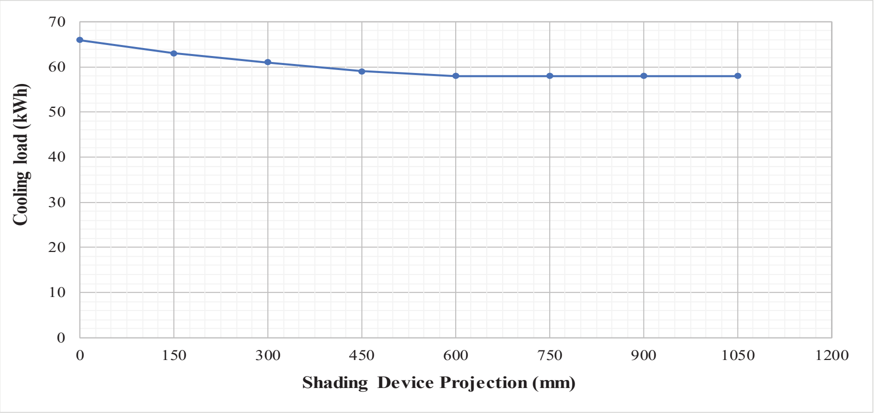


Figure 7.31: Predicted cooling loads illustrating the effect of using a shading device on an air-conditioned living room space cooled from 08:00 – 22:00.

Considering the cooling load from 18:00-22:00, Table 7.39 and Figure 7.32 shows a reduction of 18kWh from the base model (66kWh) when a 900-1050mm shading device projection was applied to the air-conditioned model.

Table 7.39: Summary of cooling loads when applying shading device intervention on an air-conditioned Living room space model cooled from 18:00 – 22:00.

Shading Device Extension	Cooling Load kWh (Shading device)
1050	7
900	7
750	8
600	9
450	12
300	16
150	18
0	25

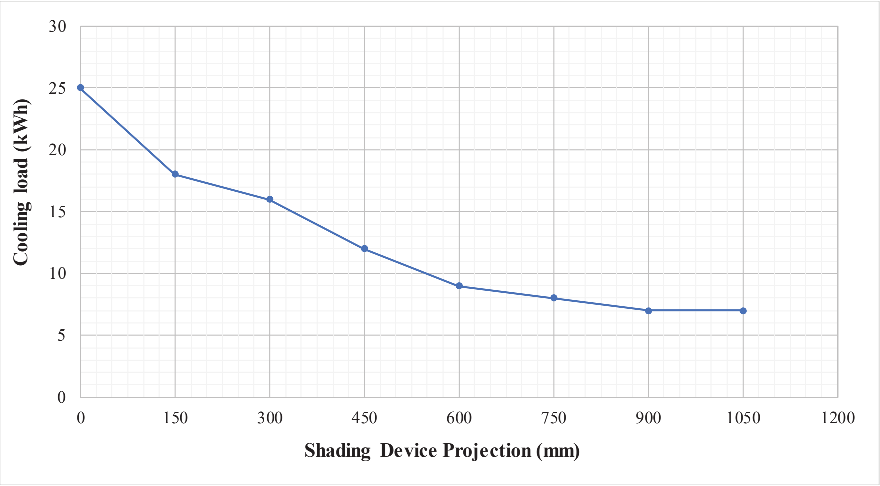


Figure 7.32: Predicted cooling loads illustrating the effect of using a shading device on an air-conditioned living room space cooled from 18:00 – 22:00.

Considering the cooling load from 21:00-23:00, Table 7.40 and Figure 7.33 shows a reduction of 8kWh from the base model (23kWh) when 1050mm shading device extension was applied on the air-conditioned model.

Table 7.40: Summary of cooling loads when shading device is applied on a modelled air-conditioned bedroom space model cooled from 21:00 – 23:00.

Shading Device Extension	**Cooling Load kWh (Shading device)**
1050	5
900	6
750	6
600	6
450	6
300	6
150	6
0	7

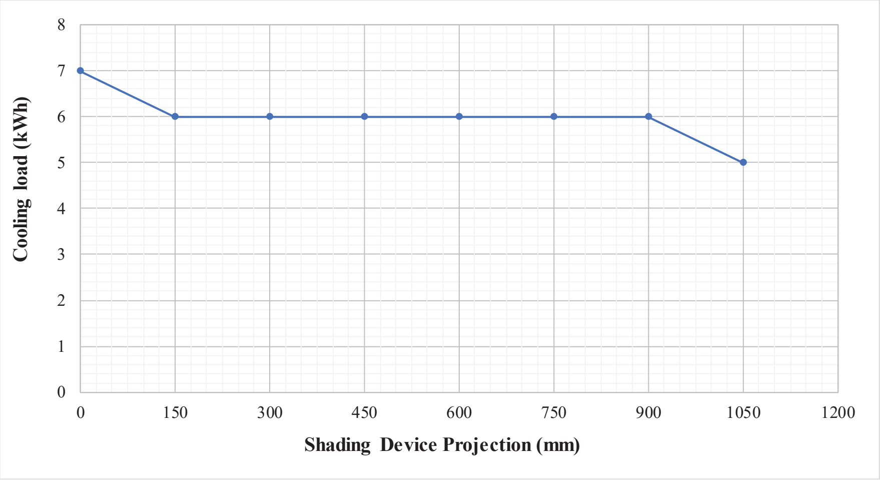


Figure 7.33: Predicted cooling loads illustrating the effect of using a shading device on an air-conditioned bedroom space cooled from 21:00 – 23:00.

7.7 Daily cooling load for the various passive cooling (insulation) interventions in the living room and bedroom

The cooling load for the air-conditioned model when cooling was enabled during the daytime i.e. 08:00-22:00, showed a large drop from 66kWh for the base model to 14 and 16kWh respectively when 75-500mm roof or ceiling insulation was applied in the living rooms (Table 7.41 and Figure 7.34). The wall insulation led to a 29kWh cooling load reduction when 75-500mm insulating boards were applied. The roof and ceiling insulation were more effective than the wall insulation during the daytime. However, during the evening period (18:00-22:00) the wall insulation showed the most reduction from 25kWh for the base model to 9kWh, a 16kWh reduction when 75mm wall insulation was applied compared to 11kWh reduction showed when 75mm roof and ceiling insulation was applied for the same period (Table 7.42 and Figure 7.35). The bedroom space also had cooling loads reduced to 11kWh and less when 75mm insulation was applied on the roof and ceiling, but the wall insulation gave only a 3kWh reduction when 75mm insulation was applied (Table 7.43 and Figure 7.36).

Table 7.41: Summary of cooling loads when applying roof, ceiling and wall insulation on an air-conditioned Living room model cooled from 08:00 – 22:00.

PUR Insulation thickness	Cooling load kWh Roof insulation	Cooling load kWh Ceiling insulation	Cooling load kWh Wall insulation
500	14	16	37
400	15	16	37
300	16	16	37
200	17	17	38
100	21	20	39
75	23	21	39
50	25	23	41
25	32	29	43
0	66	66	66

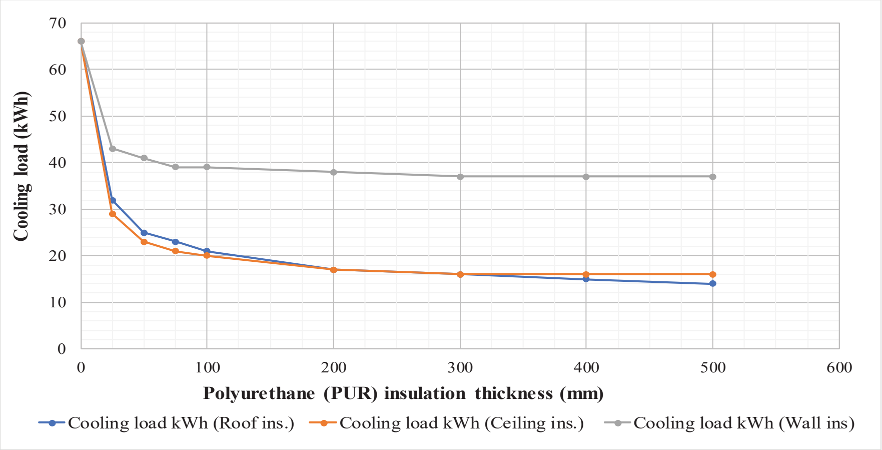


Figure 7.34: Summary of cooling loads with roof, ceiling and wall insulation on an air-conditioned living room space cooled from 08:00 – 22:00.

Table 7.42: Summary of cooling loads when applying roof, ceiling and wall insulation on an air-conditioned Living room model cooled from 18:00 – 22:00.

PUR Insulation thickness	Cooling load kWh Roof insulation	Cooling load kWh Ceiling insulation	Cooling load kWh Wall insulation
500	11	12	7
400	11	12	7
300	12	12	7
200	12	13	8
100	13	14	8
75	14	14	9
50	15	15	9
25	17	17	11
0	25	25	25

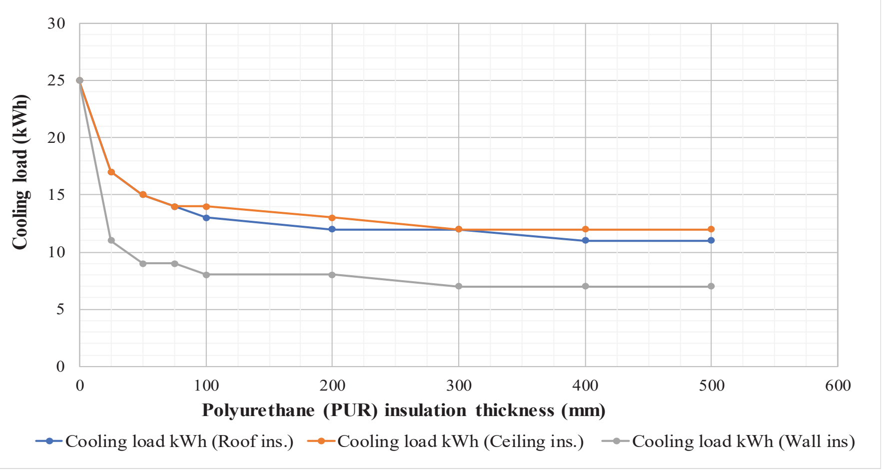


Figure 7.35: Summary of cooling loads with roof, ceiling or wall insulation on an air-conditioned living room space cooled from 18:00 – 22:00.

Table 7.43: Summary of cooling loads when applying roof, ceiling or wall insulation on an air-conditioned Bedroom model cooled from 23:00 – 07:00.

PUR Insulation thickness	Cooling load kWh Roof insulation	Cooling load kWh Ceiling insulation	Cooling load kWh Wall insulation
500	1	4	4
400	1	4	4
300	2	4	5
200	2	5	5
100	2	5	5
75	2	5	5
50	3	5	5
25	4	5	5
0	7	7	7

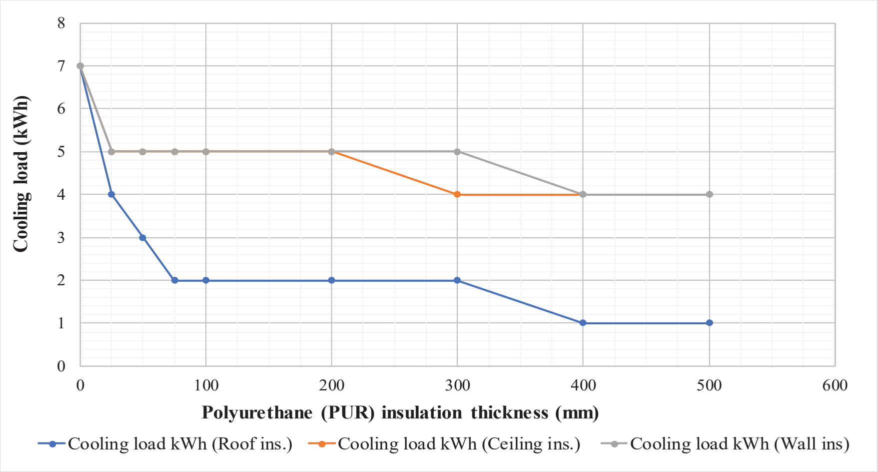


Figure 7.36: Summary of cooling loads with roof, ceiling or wall insulation on an air-conditioned bedroom space cooled from 23:00 – 07:00.

7.8 Comprehensive optimum passive cooling interventions

The results from the simulation of the various PUR insulation applications to the roof, ceiling and external walls showed how effective the insulation is. However, since the effect of the roof and ceiling insulation were identical, i.e. either could be cheaper, the ceiling insulation was no longer pursued as an intervention in this study; only the roof and wall insulation were incorporated into the optimum passive intervention. A selection of the various insulation thicknesses applied on the roof and walls was simulated to reduce the indoor maximum temperatures to 28°C from a daytime maximum temperature of 33.7°C. This is the lowest comfortable temperature reported and discussed in Chapter 5. Although shading devices showed smaller indoor temperature reductions, they were significant and included in the passive application. Some simulation was run here to explore the potential of including thermal mass into the optimum passive interventions. A 20% thermal mass was adopted as a passive cooling intervention to help reduce the indoor temperature to the comfortable temperature range. This section discusses the comprehensive, combined passive cooling interventions chosen for a naturally ventilated and air-conditioned model.

7.8.1 Impact of Passive cooling interventions on naturally ventilated living room model

Figures 7.37 and 7.38 show the effect of passive cooling interventions on the maxima and minima naturally ventilated living room temperature during the daytime and evening period for a week. The passive intervention analysis of the living room space occupied from 08:00-22:00, showed a 5°C reduction from the predicted base model maximum air temperature of 33.7°C to 28.8°C. This was achieved when 75mm roof and wall insulation was applied together with 450mm external shading device projection on the window and 20% thermal mass made of 100% concrete (Table 7.44 and Figure 7.38).

Table 7.44 also shows a 2.5°C reduction in the average temperature from the base model (30.5°C) with same passive application.

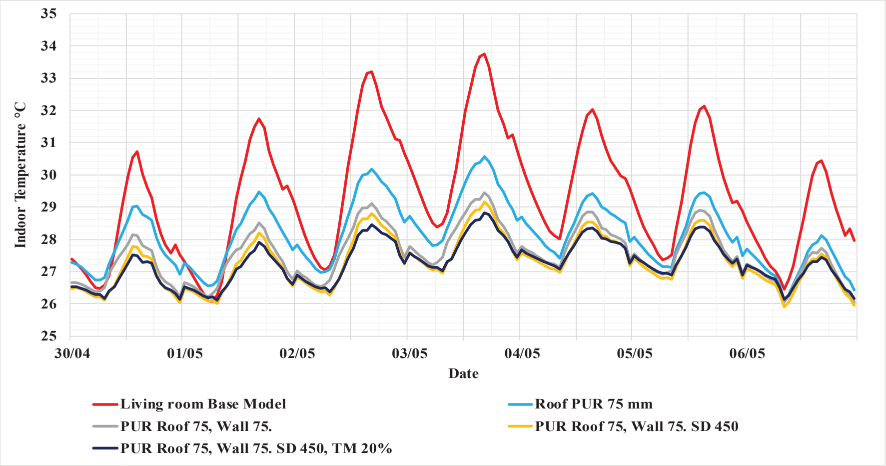


Figure 7.37: Summary of the proposed passive intervention on the living room space in naturally ventilated model during the daytime, 08:00 – 22:00, showing the effect on indoor predicted temperatures.

Table 7.44: Summary of insulation intervention in a naturally ventilated living room space occupied from 08:00 – 22:00, showing the effect on predicted indoor temperatures.

	Passive Cooling Intervention	Max Temp. BWPDTLVH1	Min Temp. BWPDTLVH1	Avg. Temp. BWPDTLVH1
1	Living room Base	33.7	26.3	30.0
2	Roof PUR 75 mm	30.6	26.1	28.5
3	PUR Roof 75, Wall 75.	29.5	26.1	27.9
4	PUR Roof 75, Wall 75. SD 450	29.1	25.9	27.6
5	PUR Roof 75, Wall 75. SD 450, TM 20%	28.7	26.1	27.5

Note: SD - Shading Device, TM – Thermal Mass.

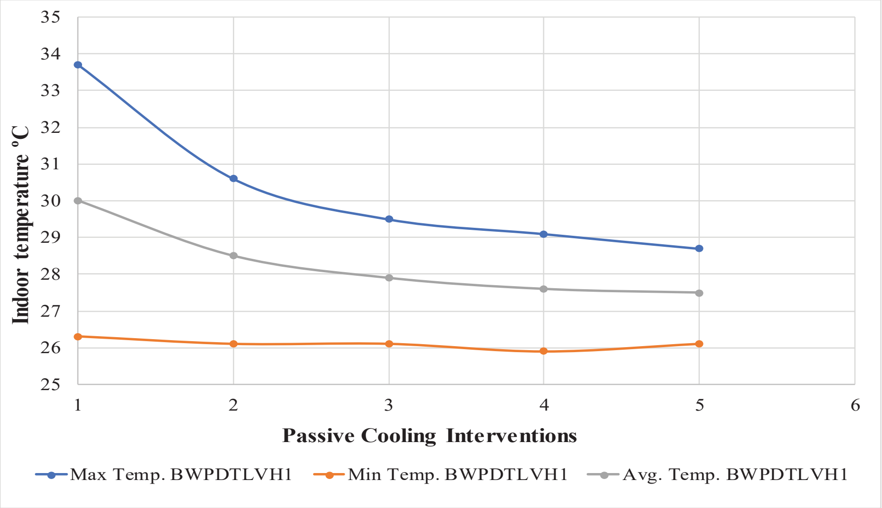


Figure 7.38: Predicted indoor temperatures illustrating the effect on indoor climate using varying passive cooling intervention on a naturally ventilated living room space occupied from 08:00 – 22:00.

The passive intervention analysis for the naturally ventilated living room space occupied for the evening period from 18:00-22:00 (Figure 7.39), showed a 4.6°C reduction from the predicted base model maximum air temperature of 32.8°C to 28.2°C. This was achieved when 75mm roof and wall insulation was applied together with 450mm external shading device extension on the window and 20% thermal mass (Table 7.45 and Figure 7.40). Table 7.45 also shows a 2.5°C reduction in the average temperature from the base model (29.8°C) with same passive application.

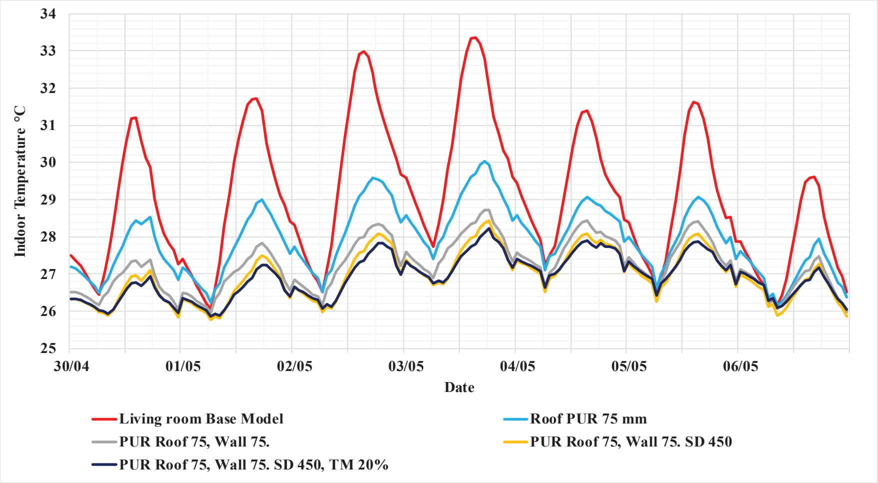


Figure 7.39: Summary of the proposed insulation intervention in the living room space in naturally ventilated model during the evening time, 18:00 – 22:00, showing the effect on indoor predicted temperatures.

Table 7.45: Summary of insulation intervention in a naturally ventilated living room space occupied from 18:00 – 22:00, showing the effect on indoor predicted maximum, minimum and average temperatures.

	Passive Cooling Intervention	**Max Temp. BWPDTLVH1**	**Min Temp. BWPDTLVH1**	**Avg. Temp. BWPDTLVH1**
1	Living room Base	32.8	27.2	29.8
2	Roof PUR 75 mm	30.0	26.8	28.5
3	PUR Roof 75, Wall 75	28.7	26.4	27.6
4	PUR Roof 75, Wall 75. SD 450	28.4	26.2	27.4
5	PUR Roof 75, Wall 75. SD 450, TM 20%	28.2	26.2	27.3

Note: SD - Shading Device, TM – Thermal Mass.

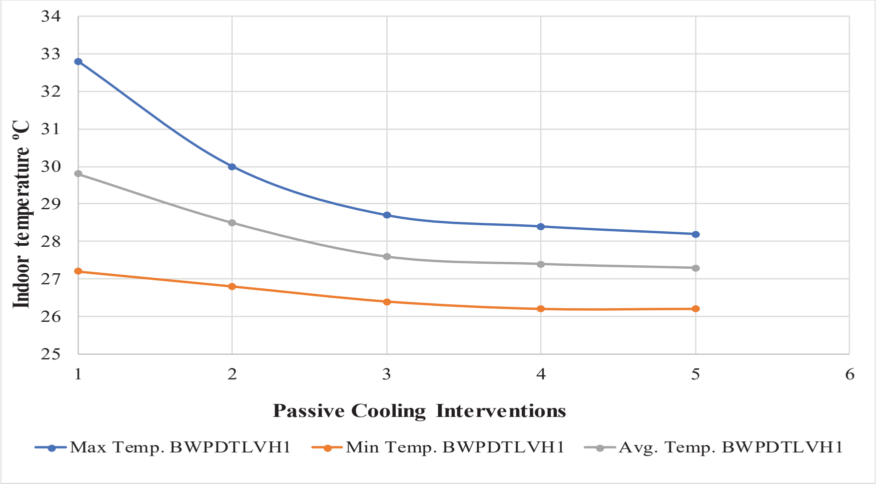


Figure 7.40: Predicted indoor temperatures illustrating the effect on indoor climate using varying passive cooling interventions on a naturally ventilated living room space occupied from 18:00 – 22:00.

7.8.2 Comprehensive passive cooling application on naturally ventilated bedroom model

Figure 7.41 shows the effect of passive cooling interventions on the maxima and minima of the naturally ventilated bedroom temperature during the night-time (23:00-07:00) for a week. The passive intervention analysis of the bedroom showed a 3.8°C drop from the predicted base model maximum air temperature of 30.4°C to 26.6°C. This was achieved when 75mm roof and wall insulation were applied together with 450mm external shading device extension on the window and 20% thermal mass (Table 7.46 and Figure 7.42). Table 46 also shows a 1.7°C reduction in the average temperature from the base model (27.4°C) with same passive application over the same period.

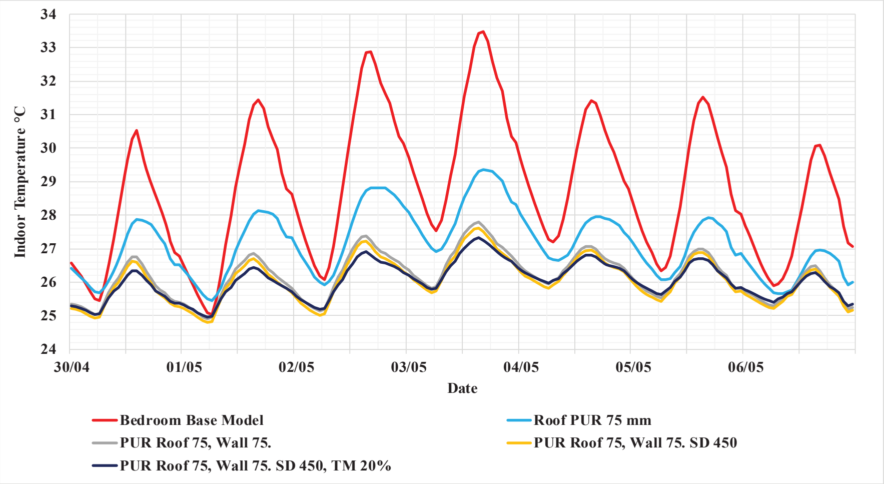


Figure 7.41: Summary of the proposed insulation intervention in the bedroom space in naturally ventilated model during the night-time, 23:00 – 07:00, showing the effect on indoor predicted temperatures.

Table 7.46: Summary of insulation intervention in a naturally ventilated living room space occupied from 23:00 – 07:00, showing the effect on indoor predicted maximum, minimum and average temperatures.

	PUR Roof Insulation thickness	**Max Temp. BWPDTBDH1**	**Min Temp. BWPDTBDH1**	**Avg. Temp. BWPDTBDH1**
1	Bedroom Base	30.4	25.0	27.4
2	Roof PUR 75 mm	28.4	25.5	26.7
3	PUR Roof 75, Wall 75.	26.8	24.9	25.7
4	PUR Roof 75, Wall 75. SD 450	26.6	24.8	25.6
5	PUR Roof 75, Wall 75. SD 450, TM 20%	26.6	25.0	25.7

Note: SD - Shading Device, TM – Thermal Mass.

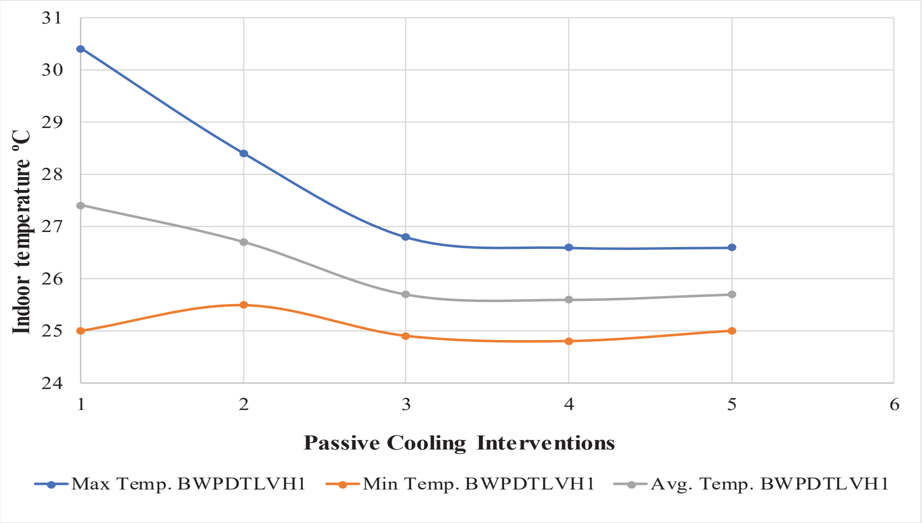


Figure 7.42: Predicted indoor temperatures illustrating the effect on indoor climate using varying passive cooling intervention on a naturally ventilated bedroom space occupied from 23:00 – 07:00.

7.8.3 Passive cooling application on air-conditioned model living room model

Considering the day period when mechanical cooling was enabled (18:00-22:00), Table 7.47 and Figure 7.52 show a summary of the various passive cooling interventions on the cooling load. The cooling load dropped from 66kWh to 0 when 75mm roof and wall insulation, 450 mm shading device and 20% thermal mass was applied on the model.

Table 7.47: Summary of cooling loads (sensible + latent) for selected passive cooling interventions in a modelled air-conditioned living space cooled from 08:00 – 22:00 for one week.

	Passive Cooling Intervention	**Cooling load kWh**
1	Living room Base Model	66
2	Roof PUR 75 mm	32
3	PUR Roof 75, Wall 75	2
4	PUR Roof 75 Wall 75, SD 450	0
5	PUR Roof 75 Wall 75, SD 450, TM 20%	0

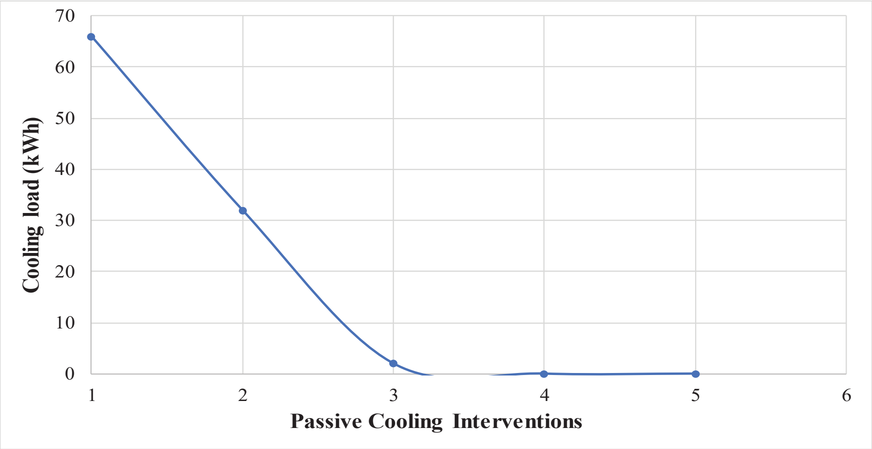


Figure 7.52. Cooling loads reported illustrating the effect on indoor climate using selected passive cooling intervention in an air-conditioned living room space cooled from 08:00 – 22:00.

Considering the evening period when mechanical cooling was enabled (18:00-22:00), there was a reduction in the cooling load from 25kWh to 0kWh when a 75mm roof and wall insulation was applied together with 450mm shading device on the living room windows and 20% thermal mass on the base model. (Table 7.48 and Figure 7.43).

Table 7.48: Summary of cooling loads (sensible + latent) for selected passive cooling interventions in a modelled air-conditioned living space cooled from 18:00 – 22:00.

	Passive Cooling Intervention	Total Cooling load kWh
1	Living room Base Model	25
2	Roof PUR 75 mm	17
3	PUR Roof 75, Wall 75	0
4	PUR Roof 75 Wall 75, SD 450	0
5	PUR Roof 75 Wall 75, SD 450, TM 20%	0

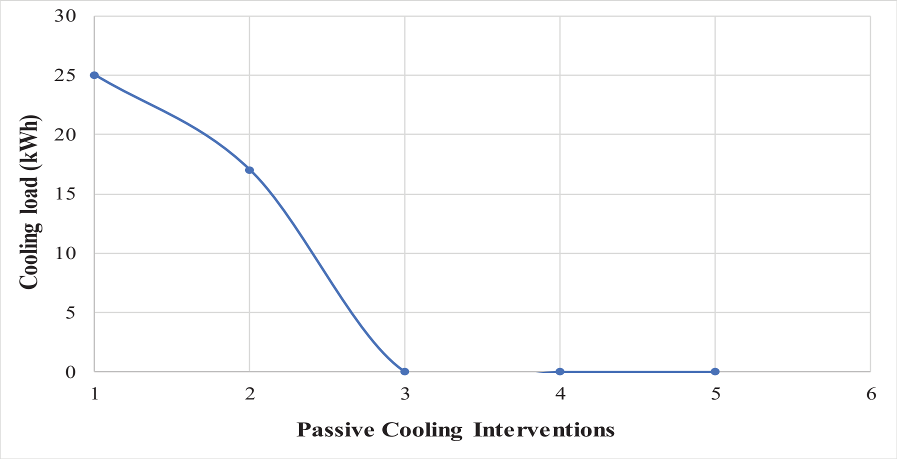


Figure 7.43: Cooling loads reported illustrating the effect on indoor climate using selected passive cooling intervention in an air-conditioned living room space cooled from 18:00 – 22:00.

7.8.4 Comprehensive passive cooling application on air-conditioned model bedroom model

There was a reduction in the cooling load from 7kWh to 0kWh when 75mm roof and wall insulation was applied together with 450mm shading device on the living room windows and 20% thermal mass on the base model. (Table 7.49 and Figure 7.44).

Table 7.49: Summary of cooling loads (sensible + latent) for selected passive cooling interventions in a modelled air-conditioned living space cooled from 21:00 – 23:00.

	Passive Cooling Intervention	Cooling load kWh
1	Living room Base Model	7
2	Roof PUR 75 mm	3
3	PUR Roof 75, Wall 50	0
4	PUR Roof 75 Wall 75, SD 450	0
5	PUR Roof 75 Wall 75, SD 450, TM 20%	0

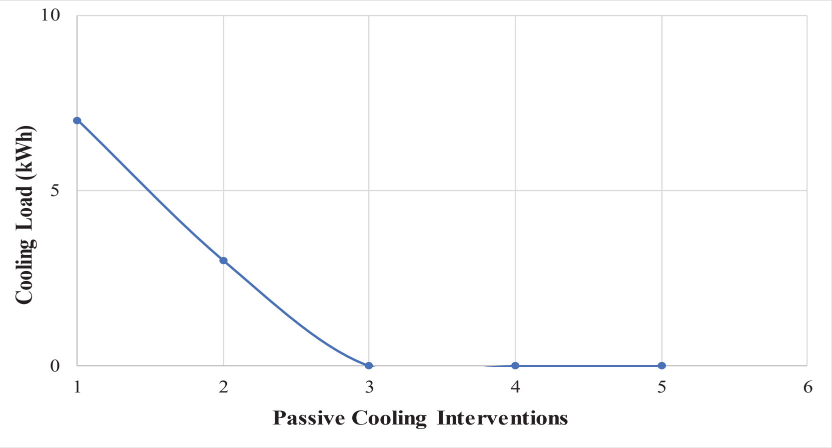


Figure 7.44: Cooling loads reported illustrating the effect on indoor climate using selected passive cooling intervention in an air-conditioned bedroom space cooled from 23:00 – 07:00.

7.9 Overall Dry season comparison between base model and optimum passive intervention in a naturally ventilated and air-conditioned model

The passive interventions discussed in section 7.8 show that for the naturally ventilated model, the passive intervention combination with 75mm roof and wall insulation, 450 mm exterior window shading devices and 20% thermal mass was the most effective intervention. For the air-conditioned model, 75mm roof and wall insulation, 450 mm exterior window shading devices and 20% thermal mass was also the most effective intervention. These interventions were adopted to form the optimum passive cooling interventions for the naturally ventilated and air-conditioned models during the daytime, evening time and night-time and now form the proposed optimum passive interventions for this study. This section discusses the effects of the optimum passive intervention for the dry season period considered from 01/02/2017-06/05/2017 for simulation, on a naturally ventilated base and a model that was cooled during the daytime and evening (08:00 – 22:00), evening (18:00 – 22:00) and night-time (21:00 – 23:00).

7.9.1 Overall Dry season comparison between the naturally ventilated base model and optimum passive cooling model.

The model simulated the naturally ventilated living room space ventilated from 08:00 – 22:00 throughout the dry season. It showed the maximum predicted air temperatures reduced by 5.5°C from 36.2°C to 30.7°C when the optimum passive intervention was applied (Table 7.50). The evening period (18:00-22:00) shows a 4.9°C reduction from 34.6°C for the base model maximum air temperature to 29.7°C when optimum interventions were applied (Table 7.51). For the night-time period, the maximum air temperature reduced from 31.4°C for the predicted base model to 27.7°C, a 3.7°C drop when the optimum passive intervention was applied (Table 7.52). Table 7.50, 7.51 and 7.52 also shows a summary average and minimum temperatures for the effects of the optimum passive intervention on the base model during the dry season.

Table 7.50: Summary of predicted temperature comparison between the base model and optimum passive cooling intervention in a naturally ventilated living room space during the dry season period

	Base Model - Living room (08:00 – 22:00)	**Living room - Optimum passive cooling interventions (08:00 – 22:00)**
MAX	36.2	30.7
MIN	25.0	26.2
AVG.	30.4	28.3

Table 7.51: Summary of predicted temperature comparison between the base model and optimum passive cooling intervention in a naturally ventilated living room space occupied from 18:00 – 22:00.

	Base Model - Living room (18:00 – 22:00)	**Living room - Optimum passive cooling interventions (18:00 – 22:00)**
MAX	34.6	29.7
MIN	26.7	26.0
AVG.	31.2	28.3

Table 7.52: Summary of predicted temperature comparison between the base model and optimum passive cooling intervention in a naturally ventilated living room space occupied from 23:00 – 07:00.

	Base Model - Living room (23:00 – 07:00)	**Living room - Optimum passive cooling interventions (23:00 – 07:00)**
MAX	31.4	27.7
MIN	23.2	24.3
AVG.	27.8	26.4

7.9.2 Overall Dry season cooling load comparison between the air-conditioned base model and optimum passive cooling.

The cooling loads when air-conditioning was enable from 08:00-22:00 showed a significant drop from 1,332kWh for the base model to 0kWh when the optimum passive interventions were applied (Table 7.53). There was also a significant drop in the cooling load during the evening period from 525kWh for the base model to 0kWh when the optimum passive interventions were applied (Table 7.54). During the night cooling period (21:00-23:00), there was also a significant drop in the cooling load from 345kWh to 8kWh when the optimum passive interventions were applied, (Table 7.55).

Table 7.53: Summary of cooling load (sensible + latent) comparison between the base model and optimum passive cooling intervention in a modelled air-conditioned living space cooled from 08:00 – 22:00.

Cooling load, Base Model Living room (kWh) (08:00 – 22:00)	Cooling load, Optimum passive interventions Living room (kWh) (08:00 – 22:00)
1332	0

Table 7.54: Summary of cooling load (sensible + latent) comparison between the base model and optimum passive cooling intervention in a modelled air-conditioned living space cooled from 18:00 – 22:00.

Cooling load, Base Model Living room (kWh) (18:00 – 22:00)	Cooling load, Optimum passive interventions Living room (kWh) (18:00 – 22:00)
525	0

Table 7.55: Summary of cooling load (sensible + latent) comparison between the base model and optimum passive cooling intervention in a modelled air-conditioned bedroom space cooled from 21:00 – 23:00.

Cooling load, Base Model Living room (kWh) (21:00 – 23:00)	Cooling load, Optimum passive interventions Living room (kWh) (21:00 – 23:00)
345	8

7.10 Thermal performance of the naturally ventilated base model compared to optimum passive cooling model for a year.

Considering the simulated naturally ventilated living room and bedroom space for a year, it showed the maximum predicted air temperatures reduced by 5.5°C from 36.2°C to 30.7°C when the optimum passive intervention was applied (Table 7.56). For the night-time period, the maximum air temperature reduced from 31.4°C for the predicted base model to 27.7°C, a 3.7°C drop when the optimum passive intervention was applied (Table 7.57). Table 7.56, and 7.57 also show the average and minimum temperatures for the effects of the optimum passive intervention on the base model for a year.

Table 7.56: Summary of predicted temperature comparison between the base model and optimum passive cooling intervention in a naturally ventilated living room space occupied from 08:00 – 22:00.

	Base Model - Living room (08:00 – 22:00)	Living room - Optimum passive cooling interventions (08:00 – 22:00)
MAX	36.2	30.7
MIN	21.0	22.3
AVG.	28.3	26.8

Table 7.57: Summary of predicted temperature comparison between the base model and optimum passive cooling intervention in a naturally ventilated Bedroom space occupied from 23:00 – 07:00.

	Base Model - Bedroom (23:00 – 07:00)	Bedroom - Optimum passive cooling interventions (23:00 – 07:00)
MAX	31.4	27.7
MIN	20.0	21.1
AVG.	27.2	24.3

When considering the percentage of hours above 28°C in the living room for a year, Table 7.58 shows this reducing from 51% for the base model to 26% when the optimum passive intervention is applied for a year. When considering the percentage of hours above 28°C in the bedroom for a year, Table 7.59 shows a drop from 38% to zero when the optimum passive cooling intervention is applied. Figure 7.45 and 7.46 show the effect of the optimum passive cooling application for a year on the living room and bedroom temperatures.

Figure 7.47 and 7.48 show the reduction in the effect of outdoor temperature on the naturally ventilated indoor temperatures throughout the year. For the living room base model, there was a strong relationship between the indoor and outdoor temperature ($r^2 = 0.6$). This reduced substantially when the optimum passive interventions were applied to the living room spaces ($r^2 = 0.32$) (Figure 7.47). Similarly, the relationship between the external temperature and the base model bedroom space ($r^2 = 0.56$) reduced when the optimum passive interventions were applied ($r^2 = 0.36$) (Figure 7.48).

Table 7.58: Summary of the effects of optimum passive interventions on the indoor temperatures above 28°C in naturally ventilated Living room model from 08:00 – 22:00 for a year.

	Base Model - Living room (08:00 – 22:00)	**Living room - Optimum passive cooling interventions (08:00 – 22:00)**
Hours above 28°C	4453	2259
% Hours above 28°C	51	26

Table 7.59: Summary of the effects of optimum passive interventions on the indoor temperatures above 28°C in naturally ventilated Bedroom model from 23:00 – 07:00 for a year.

	Base Model - Living room (23:00 – 07:00)	**Living room - Optimum passive cooling interventions (23:00 – 07:00)**
Hours above 28°C	3335	0
% Hours above 28°C	38	0

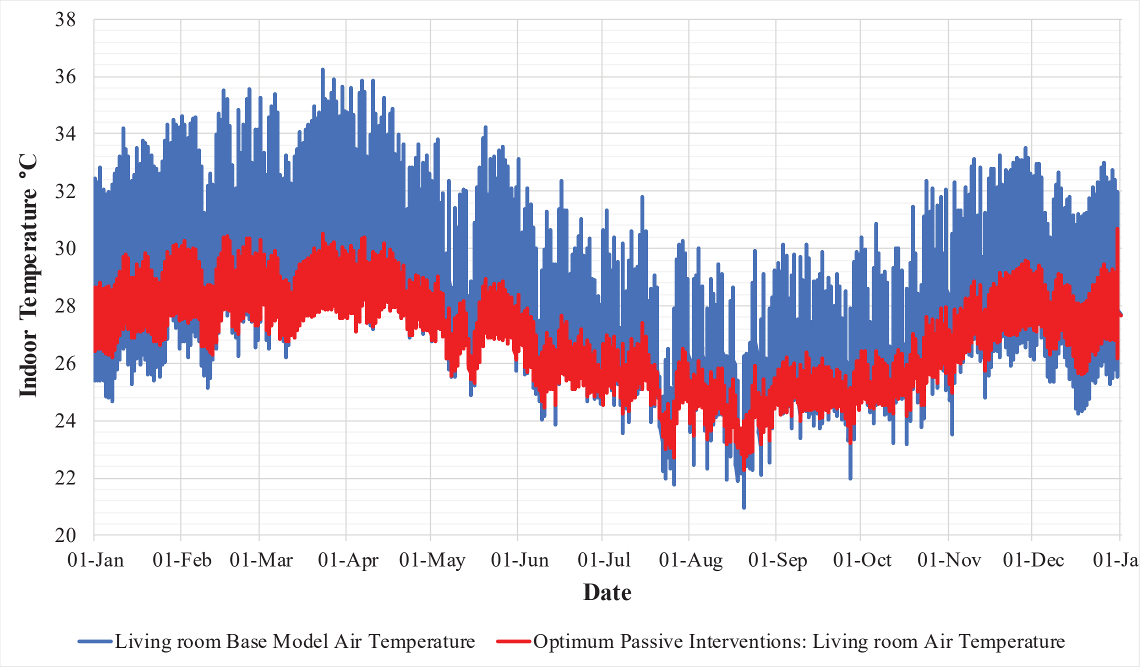


Figure 7.45: Relationship between the predicted naturally ventilated living room air temperature and the predicted optimum passive intervention air temperature at Bwari

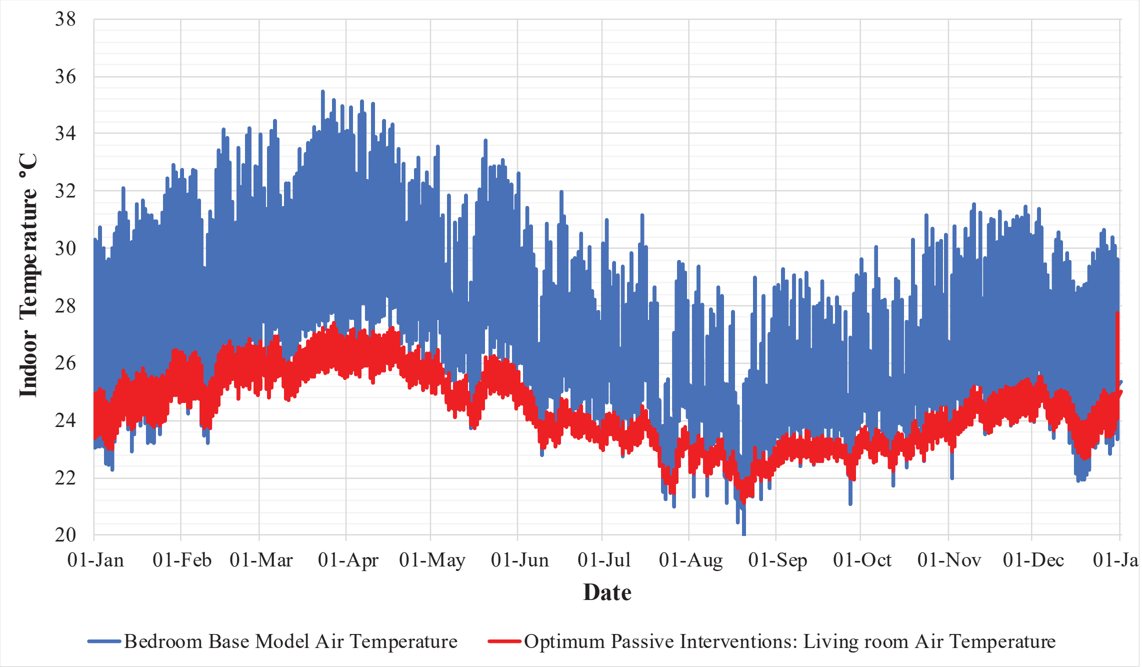


Figure 7.46: Relationship between the predicted naturally ventilated bedroom air temperature and the predicted optimum passive intervention air temperature at Bwari

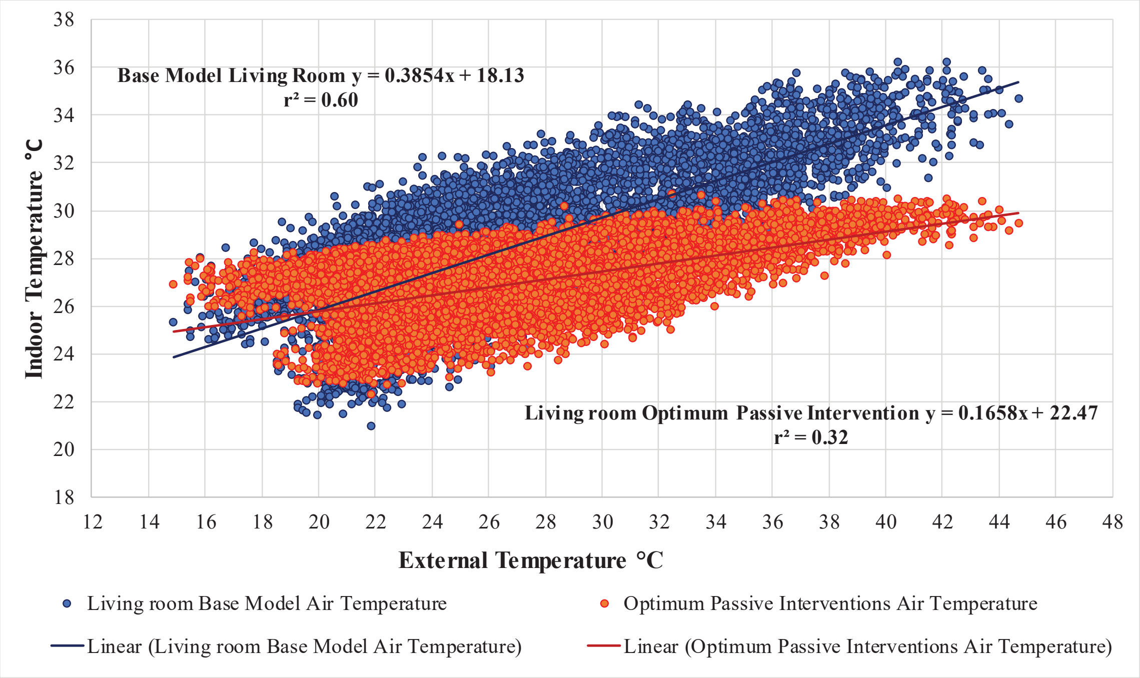


Figure 7.47: Relationship between the predicted naturally ventilated living room air temperature, the predicted living room optimum passive intervention air temperature at Bwari and the external temperature using Abuja TMY3

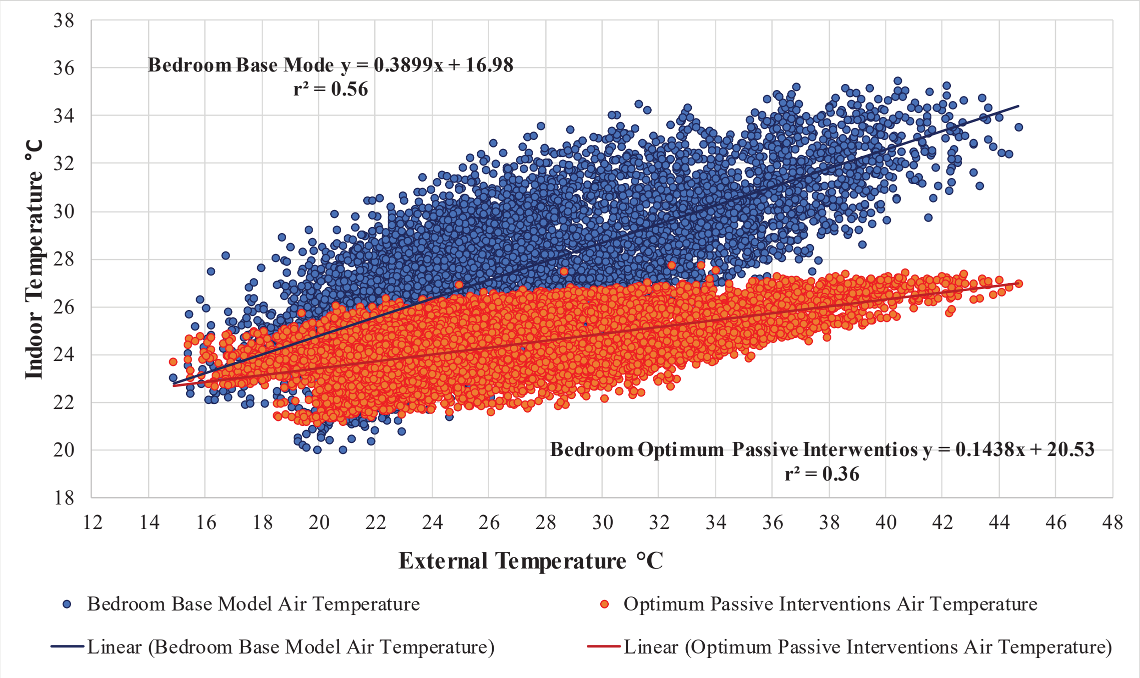


Figure 7.48: Relationship between the predicted naturally ventilated bedroom air temperature, the predicted living room optimum passive intervention air temperature at Bwari and the external temperature using Abuja TMY3

7.11 Conclusion

This chapter discussed the results from the application of passive interventions on the base model using dynamic thermal simulations and compared the findings with the base model temperatures for Bwari discussed in Chapter 6.

The scope and method used for the simulations were explained. Two case studies each were simulated as naturally ventilated and air-conditioned for the periods considered which included one-week (30/April – 06/May), dry season (01/February – 06/May) and a year for the naturally ventilated model. The results show that applying the recommended optimum passive interventions (75mm roof and wall insulation, 450mm shading device and 20% thermal mass) during the daytime and evening periods for a week, had a significant effect in reducing the maximum living room temperatures by 5°C. The night-time bedroom temperatures were reduced by 3.8°C from the base model air temperature when the optimum passive interventions were applied. This would improve the sleeping period for occupants at night. The air-conditioned model saw a 100% reduction (66kWh to 0) in the cooling load from the base model cooling loads when the optimum passive interventions were applied to the living room (75mm roof and wall insulation, 450mm shading device and 20% thermal mass) during the daytime and evening period. The bedroom cooling load was reduced by 100% (7kWh to 0kWh) when the optimum passive interventions were applied. The reduction in the cooling load was possible because the optimum passive interventions alone maintained the maximum indoor temperatures at 28°C for most of the time.

During the dry season simulations, the percentage of temperatures above 28°C for the naturally ventilated living room space dropped by 23% during the daytime and dropped by 42% during the evening period. For the sleeping period in the bedroom, the percentage of temperatures above 28°C was reduced by 17%. Considering the simulation period for a year for the naturally ventilated model in Bwari, the percentage of hours above 28°C was reduced by 50% in the living room while a 100% reduction was achieved in the bedroom when the optimum passive interventions were applied.

This study shows that the most effective passive cooling application for the naturally ventilated model is the application of 75mm roof and wall insulation, 450mm shading device and 20% thermal mass, as an optimal passive cooling intervention. This is effective in reducing indoor temperatures throughout the dry season and the year. The financial savings of the optimum passive interventions and the barriers to their implementation are discussed in the next chapter.

CHAPTER 8

Costing and barriers to passive cooling implementation

CHAPTER 8 Costing and barriers to passive cooling implementation

8.1 Introduction

Results and discussions from the previous chapter suggest that cooling energy can be reduced for air-conditioned buildings and high temperatures can also be reduced for all by using insulation on a building's envelope. This should be encouraged. Unfortunately, there is not enough awareness of the advantages of using passive cooling strategies in the Nigerian building construction industry today to make the buildings more sustainable. The little that is known about environmental design is often met with barriers that inhibit the propagation of the use of passive cooling. This chapter will look at the possible energy savings that can be made when using passive strategies on a house with air-conditioning and a petrol generator as a base case and discuss the challenges and possible barriers to achieving this potential.

8.2 Costing and estimation

This section will discuss the energy saving when using the optimal interventions to reduce electricity demand and use of generators over a week in the dry season.

8.2.1 Cost of cooling energy saved using optimal passive intervention model

To get an insight into the cost of energy saved using the optimal passive interventions in an air-conditioned model, the current cost for energy use in residential building in Abuja per week and the dry season is needed. In Abuja, 24.3 Naira (£0.05) (abujaelectricity.com) will buy 1kWh. However, the price in reality in Abuja is nearer 50 Naira/kWh. We consider the case of the air-conditioned model in Bwari, cooled from 08:00-22:00 as a scenario. As discussed in Chapter 7, 66kWh a week and 1332kWh for the dry season would be saved if optimum passive cooling were applied. The cost of this energy for a week and the dry season were estimated by calculating the energy used by the heat pump in the air-conditioning system, then the cost of the electricity brought from the grid also the cost when a generator is used to power the air-conditioning.

8.2.1.1 Energy for the heat pump

The amount of energy needed to drive the heat pump in the air-conditioning unit was calculated by dividing the cooling load by an assumed Coefficient of Performance (CoP) of 3. The previous chapter showed that the cooling load for the monitored week would be reduced by 66 kWh and by 1332 kWh for the dry season if the optimum passive cooling interventions were applied on the air-conditioned model. Hence, 22 kWh of energy are needed to drive the heat pump for the monitored week and 444 kWh are needed for the whole dry season.

8.2.1.2 Cost of energy from the grid for air-conditioning

At 50.00 Naira/kWh the cost of energy for a week in the dry season would be:

The cost of energy for air-conditioning for a week:

22 kWh x 50 = 1,100 Naira

The cost of energy for air-conditioning for the dry season:

444 kWh x 50 = 22,200 Naira.

The cost of using electricity from the grid to power the air-conditioning unit per week would be 1,100 Naira (£2.30) and the dry season would be 22,200 Naira (£46.40).

8.2.1.3 Cost of energy from petrol generators for air-conditioning

To calculate the energy cost for generating power for air-conditioning from a petrol generator, the efficiency of conversion from petrol to electricity was assumed to be 20%. Thus,

> The total energy in petrol input for a week is 110 kWh (i.e. 22 kWh x 5) and the total energy in petrol input for the dry season is 2220 kWh (i.e. 444 kWh x 5).

The calorific value for petrol was taken as 45.8 MJ/Kg (12.7 kWh/kg) so the petrol requirements for a week and the dry season will be:

A week: 110/12.7 = 8.7 kg petrol

Dry season: 2220/12.7 = 174.8 kg petrol

The density of petrol was taken as 0.75 kg/litre. This gives the volume of petrol needed for a week and the dry season:

Volume of petrol for week = 8.75/0.75 = 11.6 litres

11.6 litres of petrol will be used to power an air-conditioning unit powered by a petrol generator for a week.

Volume of petrol for the dry season = 174.8/0.75 = 233.1 litres

233.1 litres of petrol will be used to power an air-conditioning unit by a petrol generator for the dry season.

The cost of a litre of petrol in Nigeria is taken as 145 Naira (December 2017). This gives the cost of using petrol generators for air-conditioning in Nigeria:

For a week: 11.6 x 145 = 1,680 Naira (£3.51)

For the dry season: 233.1 x 145 = 33,800 Naira (£70.71)

In summary, 1,682 Naira (£3.51) would buy the 11.6 litres of petrol needed to power the generator over the week. For the dry season, 33,800 Naira (£70.71) would buy the 233.1 litres of petrol needed to power the generator.

The combined cost of using mechanical cooling during the dry season

Electricity is available only intermittently. A more realistic cost is obtained by assuming electricity is available for 70% of the time for air-conditioning during the dry season period and a generator is used for the other 30% of the time. The real cost of air-conditioning using the power from the grid and petrol generator for the dry season will be:

From the grid: 70% of 22,200 Naira = 15,540 Naira

From the generator: 30% of 33,800 Naira =10,140 Naira

Total: 25,680 Naira

Therefore, 25,680 Naira (£53.72) would be saved if optimum passive interventions were applied to the fabric of an air-conditioned building.

The dry season (i.e. 01/02/2017-06/05/2017) lasts approximately three months (95 days) so the mean monthly cost during the dry season is:

25,680 Naira x 30/95 = 8,110 Naira (£16.69) per month

This cost of cooling should be put in context with the minimum wage in Nigeria: 18,000 Naira per month (£37.66). This cost of cooling therefore represents 45% of the minimum wage and avoiding this cost would be significant for many.

8.3 Deductions from interviews and observations: The social barrier

Interviews were conducted with an academic, a developer and an architect in Abuja to give an insight into the housing situation and context in Abuja. The interview with the developer revealed that people now build for quantity rather than quality. He reiterated the ideology that in the modern and urban areas people believe they can procure comfort and indoor cooling and all they think about is aesthetics while in the villages and rural areas they consider comfort not aesthetics. In the interview, with the academic from the University of Jos, Nigeria, in the department of Architecture, she said that architects and designers now design and build houses without climatic consideration. Passive cooling strategies and environmental comfort are not being taught in schools of architecture unlike in well-known schools of architecture in developed countries. There is a lack of climatic awareness to the current design approach and this is greatly affecting occupants' comfort, in fact increasing discomfort. Additionally, by not adhering to the right approach to design, there is a great tendency to expose building surfaces to direct sunlight which will eventually increase internal temperature.

In the third interview with an architect in Abuja, he noted that there is a deficiency in the sustainable passive approach in current designs and mode of construction in the country, especially in Abuja. The city is supposed to be an example for the whole country to follow when it comes to the latest designs and construction techniques. There is also a lack of awareness and movement towards passive designs as a means of combating or regulating the challenges posed by the warm climate in Abuja. Most people prefer to use air-conditioning to achieve indoor comfort, sadly, no matter the cost. Even if they can't afford one, they tend to save towards buying one rather than considering passive cooling as an alternative to indoor cooling.

All the interviewees agreed that the reason for the lack of awareness towards indoor comfort, passive design and construction is the people's attitude to accepting any form of change easily. They tend to resist any new development without approval from the government or a prominent individual in the community. The interviewees also noted there is little or no will from the government to encourage passive design and construction agenda's. According to them, it would take a dedicated intervention by the government to persuade people to take the issue of comfort and sustainable building seriously. This could also be achieved through government policies and updating the current building codes to encourage or even enforce sustainable passive building strategies in Nigeria.

8.4 Barriers facing passive cooling strategies, the optimal intervention model

Currently, Nigeria does not have a tradition of a sustainable building agenda or building energy regulations[1] in place to contribute and facilitate a more sustainable passive cooling implementation.

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[1] In August 2017, the Federal Government of Nigerian published the first edition of a National Energy Efficiency Code. The Energy Efficiency code does not give a detailed guide on applying energy saving measures, but does give some minimum values, e.g. wall U-value. It is something of a missed opportunity as it does not address dwelling design as a whole. This could have guided and regulated building designers and contractors on the production of energy efficient and passive buildings.

Rather the lack of these regulations forms barriers to the implementation of passive cooling strategies. The numerous barriers presented explain why the implementation of passive residential building strategies towards energy conservation and energy efficiency improvements usually require special motivation through governmental action, private initiatives and occupants' behavioural change. The number of barriers is large and according to some estimates, it is higher in the buildings' sector than in any other sector. This section will discuss potential barriers that hinder implementation of passive intervention and these include economic/financial barriers, lack of appropriate research, development and production technologies, behavioural and social constraints and information barriers.

8.4.1 Lack of policy and legislation

Lack of policy and legislation to address the inefficient or non-existent sustainable strategies in Nigeria is a very key barrier to the development of sustainable building strategies that reduce indoor heat gains and cooling load. Policy and legislation could help to change behaviour towards a sustainable and energy efficient economy. Private and public institutions should be encouraged to make their own policy to promote sustainability through passive cooling solutions and efficient energy use. The government could make it mandatory for public, large and small scale private organizations to establish passive strategy and energy management departments or units.

8.4.2 Economic/financial barriers

Purchasing more sustainable and efficient building materials usually involves higher costs which many consumers do not want, and low-income consumers cannot afford because they have limited capital. This is one of the most important barriers facing the application of passive strategies in Nigeria because of lack of funding. Currently, the energy prices and market often do not encourage the use of sustainable load reduction materials involving efficient technologies. Although it is very beneficial to apply sustainable techniques to save energy in buildings, cost consideration is a prime challenge.

8.4.3 Lack of appropriate research development and building production technologies

There is a lack of research materials and data that will guide the development of policy that will strengthen and encourage sustainable passive approaches in Nigeria. Adequate research materials and data are highly deficient and, thus the availability of this is necessary because it would guide policy development and reinforce energy use efficiency. There is a lack of material to conduct training in energy efficiency. Although there are Nigerian companies manufacturing e.g. insulation materials, their businesses are not well established, and the products are often imported and thus more expensive. As a result, Nigeria is currently unable to develop a sustainable building material environment, which would have created a market and encouraged the development of local skills in all areas of passive building such as building energy standard development and implementation, sustainable research, energy conservation and efficiency.

8.4.4 Behavioural and organisational constraints

Behavioural characteristics of occupants in Nigeria tend to hinder sustainable passive practices. Small but easy opportunities and strategies for sustainable building implementation are often ignored and changing behaviour or lifestyle is very difficult. Some of the behavioural characteristics of individuals relating to this barrier are: a tendency to ignore small energy saving opportunities (e.g. closing windows when using air-conditioning), and the loss of a traditional appreciation of environmentally sensitive design coupled with the perhaps: unquestioning acceptance of western techniques and materials. Nigerians have a habit of not accepting something new, a conservative trend, except it has been experienced or tested by someone, seen to be effective and affordable or forced upon them by the government. Any research data on passive cooling and its advantages should be published and made available for people to see that passive strategies are can be affordable and effective. Government should encourage and enlighten people of the advantages of passive strategies making it available to all i.e. the low, middle and high-income earners at an affordable price. This barrier is common to most countries and to many developing countries due to corruption, political instability, low income and poor standard of living.

8.4.5 Lack of awareness and information barriers

Many Nigerians in public and private sectors are not aware of passive cooling strategies. Hence, awareness creation would go a long way to help people understand the concept and change their behaviour. Lack of information about the potential of sustainable passive cooling building strategies as load reduction and energy efficiency solutions is a major barrier in Nigeria. Very often, the provision of energy services or provision of access to the national grid is considered a priority without recognizing the advantages of always combining these with the application of good environmental design to reduce the electricity required. Inadequate information and understanding are significant barriers faced in Nigeria, in the process of achieving passively cooled buildings and possible future development of sustainable building and energy saving regulations and implementation.

8.5 Possible solutions to overcome these barriers

This section will discuss the possible solutions to overcoming the barriers mentioned above.

8.5.1 Overcoming the economic and financial barriers.

Overcoming economic and financial barriers can be achieved by developing and investing in sustainable building energy strategies, by the government of Nigeria and also international bodies could help in financial support now. This can be managed by the government through the assigned energy regulation agency by setting up innovative financial schemes (sustainable funds, loan guarantee mechanism, etc.), and involving the local financial sector to support the implementation of energy standard measures.

Secondly, fiscal instruments and incentives, capital subsidies, grants, subsidized loans and rebates are one of the most frequently used instruments for encouraging passive strategies and increasing energy efficiency in buildings. Subsidies are very commonly used to overcome the major barrier of high cost. They are used to finance better insulation such as roof insulation in the UK. Subsidized loans are used in several European countries, e.g. Austria and Netherlands, to support energy service companies (The Building Performance Institute Europe-BPIE, 2010). Apart from overcoming the high cost of purchasing barrier, this option can also effectively overcome the energy subsidy barrier confronting most developing countries. Rather than subsidizing energy costs for short-term benefits, subsidizing energy regulatory measures will bring about long-term benefits and energy efficiency in building.

8.5.2 Overcoming the information barrier by using an information policy instrument.

This instrument can be highly effective if combined with regulatory measures. Public information campaigns can be described as policy instruments designed by government agencies with the intention to change individual behaviours, attitudes, values, or knowledge. Programme types include counselling, consumption feedback, elementary school programmes and mass media motivational campaigns on the benefits of passive cooling strategies and sustainable building and effective implementation. Creating local sustainable building and energy information centres, establishing good information systems, strengthening data collection networks would effectively help to overcome this barrier.

8.5.3 Lack of research development and production technologies.

Research and building technology subsidies can help to facilitate the introduction of new technologies, improve economics and enable especially poor households to engage in passive strategies and energy efficient investments. For this reason, they are especially useful in developing countries where financial limitations constitute one of the major barriers for sustainable energy regulations implementation. For example, this study reported that using 75mm PUR (polyurethane) insulation under the roof or on the ceiling could reduce indoor temperatures by 4 – 5°C, therefore reducing the dependence on air-conditioning or even fans. It would also lead to savings on electricity and petrol bills for air-conditioning and generators and relieve the burden on the grid. Once there is an awareness of the advantages and potential of passive cooling among the populace, it will encourage the government to subsidize these products to make them more available.

It would encourage more research into passive cooling interventions to develop effective, reliable but cheaper alternatives for the country. This will create a market for cost effective, sustainable passive and load/ heat reduction building components and encourage local skills. It will also enhance better enforcement of possible building energy regulation, development and implementation. Besides, these types of subsidies can be very effective if combined with regulatory measures. In Nigeria, energy expenditure represents a much larger share of the household income, but energy subsidies often lower the energy price artificially, which does not encourage the practice of building energy regulations as funds are directed towards energy subsidies rather than energy regulation implementation. Sustainable and passive building research grants and subsidies should be considered as one of the most important opportunities for encouraging sustainable practices in Nigeria.

8.6 Conclusions

The optimum passive interventions reduced indoor temperatures and cooling loads as seen in the previous chapter. This chapter discussed how the financial impact of these interventions was significant by putting the cost of energy without passive cooling interventions in the context of the minimum wage in Nigeria (N18, 000 per month (£37.66)). If optimum passive cooling interventions were applied, an energy saving cost of 8,110 Naira per month (£16.97). A total of some 25,000 Naira (£53.60) and 2220 kWh of energy would be saved during the dry season if optimum passive interventions were applied to the fabric of the air-conditioned building. The results show that the optimum passive interventions were effective in providing an alternative form of indoor cooling during the hot dry season and save energy and mechanical cooling cost. Although only the cooling energy savings were calculated for a dwelling using air-conditioning, there would be a wider financial impact of using these interventions alongside the health and comfort benefits e.g. the saving on the maintenance cost of air-conditioners and the reduction in noise and air pollution and the effect on health.

In Nigeria, presently there is no extensive and comprehensive sustainable building agenda or building energy regulations in place to contribute and facilitate sustainable passive cooling implementation, rather the lack of these regulations form barriers to implementation of passive cooling strategies. The number of barriers in the building sector is daunting. These barriers hinder future implementation of passive intervention, i.e. economic/financial barriers, lack of appropriate research and development and production technologies, behavioural and social constraints and information barriers. The next chapter will discuss the main results, overall conclusions and recommendations for this study.

CHAPTER 9

Conclusions and Recommendations

CHAPTER 9 Conclusions

This study has looked at the thermal comfort of occupants in low-income residential buildings in Abuja, Nigeria and the potential of passive cooling interventions to reduce indoor temperatures and energy cooling loads especially during the hot-dry season. The financial implication of these passive interventions was also discussed. To investigate occupants' thermal comfort and assess the impact of passive cooling interventions, the study has proceeded in five parts.

i. A post occupancy survey was carried out in five locations in Abuja to evaluate the thermal conditions in buildings. They added breadth and support the results from the ten more detailed individual case studies.

ii. Environmental monitoring was carried out with two weather stations established to measure the outdoor conditions. These measured outdoor air temperature, relative humidity and solar radiation simultaneously at quarter hourly intervals over the dry and rainy seasons. The indoor air temperature and relative humidity were also measured in naturally ventilated and air-conditioned dwelling case study dwellings to determine the actual conditions occupants were experiencing.

iii. A thermal comfort survey was carried using a thermal comfort questionnaire, issued to the occupants of the dwellings monitored and they were asked to complete the questionnaires three times a day to assess their thermal comfort state.

iv. Out of the ten houses monitored, four houses comprising two naturally ventilated and air-conditioned building at two locations (Lugbe and Bwari) were selected and modelled for simulation. The simulations investigated the thermal performance of the selected case study houses during the dry season. The naturally ventilated and air-conditioned model in Bwari was further modified with various passive cooling interventions to determine the impact on indoor air temperatures and the cooling energy loads.

v. To get an insight into why housing is the way it is in Nigeria, professionals (an academic, a developer and an architect) were interviewed to get their views.

The main findings of this work fall into five broad categories: the post-occupancy survey, environmental monitoring, comfort surveys, simulations and passive intervention to reduce indoor air-temperatures and the impact of optimum passive cooling interventions on the cooling energy loads. The main results are listed below:

9.1 Main results from the post-occupancy survey

For this study, five case study locations in Abuja, (i.e. Lugbe, Mpape, Dutse Alhaji, Kubwa and Bwari) were identified and used for the post-occupancy survey. The results below refer to the findings from all case study areas unless otherwise stated.

9.1.1 General sample description from the post-occupancy survey

- 64% of the respondents identified as low-income earners while 32% were low-middle income earner.
- 40% of the residents surveyed payed £7- £11 per month for electricity bills from the grid while 49% of the surveyed residents pay £11 - £14.50 above per month for electricity from the grid.
- 66% of the residents surveyed used personal petrol generators for alternative electricity
- 69% of the residents paid more than £7 per month for alternative source of electricity.
- 53% of the occupants surveyed used air-conditioning for indoor cooling
- 60% of the occupants open the living room window during the day and 42% open their windows at night.

9.1.2 Post-occupancy thermal sensation survey – Dry season and Rainy season

- In the dry season, 77% of the residents indicated that they felt ‘warm’ or ‘hot’ during the daytime.
- In the rainy season, there was a noticeable shift of thermal sensation with 75% of the responses across all case studies at either ‘slightly cool’, ‘neutral’ or ‘slightly warm’ during the daytime.

9.1.3 Post-occupancy thermal comfort survey – Dry season and Rainy season

- In the dry season, 86% of the total votes from the respondents across all case studies indicated that they were not comfortable during the daytime with their thermal environment with only 9% indicating ‘slightly comfortable’ or ‘comfortable’.
- In the rainy season, there was a shift towards the comfortable part of the scale. 28% of the respondents across all the case studies indicated that they were comfortable.

9.1.4 Post-occupancy thermal preference survey – Dry season and Rainy season

- In the dry season, the results showed that the great majority clearly indicated a desire to be cooler; 83% of the occupants preferred to be ‘much cooler’ and ‘cooler’ with a mean response of 1.7.
- In the rainy season, 48% of the occupants preferred to be ‘cooler’ with a mean response of 2.3

9.1.5 Post-occupancy thermal acceptability survey – Dry season and Rainy season

- In the dry season, about 40% of the respondents found their thermal environment acceptable. This result contrasts with ASHRAE's recommendation that at least 80% of occupants must find their thermal environment acceptable.
- In the rainy season, over 80% of the respondents found their thermal environment acceptable, twice the number reported in the dry season and satisfying the ASHRAE's recommendation.

9.2 Main results from Environmental Survey analysis

Outdoor monitoring

- In the dry season, each case study was monitored for a week and the maximum outdoor temperature varied slightly from week to week 37.5-41.1°C. The minimum external temperature ranged from 21.5-24.9°C
- In the rainy season, each case study was monitored for a week and the maximum outdoor temperature varied slightly from week to week (29.7-32.6°C). The minimum external temperature ranged from 20.6-21.9°C

Indoor monitoring

- Most discomfort was reported during the dry season and the average indoor temperature across all the case studies was above 30°C during the daytime and evening period (08:00-22:00).
- At night-time (23:00-07:00) the average indoor temperature across all case studies was also above 30°C and there was very little difference between the naturally ventilated and air-conditioned dwelling (on average, 0.1°C).

9.3 Main results Comfort survey

- In the dry season, most of the occupants (90%) felt ‘slightly warm’, ‘warm’ to ‘hot’ for more than 50% of the time.
- There was a shift in the thermal sensation mean votes during the rainy season to the cool and neutral part of the scale
- The thermal comfort votes show that more than 70% of the occupants were feeling uncomfortable across all dwellings.
- The mean distribution of occupants’ responses across all case studies from the dry season surveys shows they prefer to be ‘much cooler’ or ‘cooler’; which was also found in the post-occupancy survey.
- 60% of the occupants found their thermal environment in the dry season unacceptable. However, 87% were content with their thermal environment during the rainy season. Again, this is similar to the result from the post-occupancy survey.

Preferred and Neutral temperatures from the Comfort Survey

- Neutral temperatures ranged from 28 – 30.4°C and preferred temperatures between 27°C – 28.5°C were reported across all ten case studies during the comfort survey.
- Overheating risk analysis for the ten monitored case studies (both naturally ventilated and air-conditioned): CIBSE static model
- In the dry season, 100% of the living room spaces across all the case studies recorded temperatures that rose above 1% of hours above the 28°C threshold during the daytime and evening period (08:00-22:00) for more than 80% of the time and evening period for more than 86% of the time (18:00-22:00).
- The night-time period recorded temperatures that rose above the 1% of hours over 26°C threshold for more than 95% of the time in the bedrooms monitored at the case study buildings.

Overheating risk analysis for the five monitored case studies (Naturally ventilated only): EN15251 adaptive model

- 100% of the monitored naturally ventilated living room spaces across all case studies exceeded the 5% above Cat. II upper threshold for more than 10% of the time and the 1% above Cat. III upper threshold for more than 14% of the time during the daytime and evening period (08:00-22:00)
- 100% of the monitored bedroom spaces exceeded the 5% above Cat. II upper threshold for more than 10% of the time and 80% of the spaces rose above 1% of Cat. III upper threshold for more than two hours during the sleeping period (23:00-07:00).

9.4 Main results from Simulation

Overheating risk analysis for the four modelled case studies (Naturally ventilated and air-conditioned models): CIBSE static model

- 100% of the living room spaces across all the case studies had predicted temperatures that rose above 1% of hours over the 28°C threshold for more than 60% of the time during the daytime and evening period (08:00-22:00) and over 40% of the time during evening period (18:00-22:00).
- The night-time predicted temperatures rose above the 1% of hours over 26°C threshold in 100% of the bedrooms in the four buildings for more than 84% of the time.

Overheating risk analysis for the two modelled case studies (Naturally ventilated only): EN15251 adaptive model

- In the daytime and evening period (08:00-22:00), 100% of the simulated naturally ventilated living room space in Lugbe and Bwari exceeded the 5% above Cat. II upper threshold for more than 7% of the time and the 1% above Cat. III upper threshold for more than 4% of the time.

- Warm discomfort was predicted in the naturally ventilated bedroom space in Lugbe and Bwari during the sleeping period from 23:00-07:00 during the dry season. The temperature rose above the Cat. II upper threshold for more 8% of the time at night.
- The overheating in the indoor spaces predicted by the simulation is in agreement with the results in the monitored overheating risks, showing warm discomfort occurs in all the spaces monitored.

9.5 Main results from passive cooling intervention

- For the naturally ventilated and the air-conditioned model, the optimum passive intervention adopted for this study was 75mm roof and wall polyurethane insulation, 450mm shading device and 20% thermal mass.

Optimum passive cooling interventions on a naturally ventilated and air-conditioned model for a week during the dry season

- For the naturally ventilated mode, the maximum indoor air temperature during the daytime and evening period (08:00-22:00) was reduced by 5°C from the base model temperature (33.7°C) to 28.7°C when the optimum passive cooling intervention was applied.
- For the night-time period, the maximum indoor temperature was reduced by 3.8°C from the base model air-temperature (30.4°C) to 26.6°C.
- For the air-conditioned model, the cooling load during the daytime was reduced by 66kWh from the base model total cooling load (66kWh) i.e. to zero, when optimum passive cooling intervention was applied to the air-conditioned model and simulated for week.
- For the night-time the cooling load was reduced to zero from the base model cooling load (7kWh).

Optimum passive interventions on an air-conditioned model during the dry season

- The cooling load during the daytime was reduced by 1332kWh from the base model cooling load (1332kWh) when optimum passive cooling intervention was applied on an air-conditioned model and simulated for the dry season period.
- The cooling load at night-time achieved a drop of 240kWh from the base model total cooling load (345kWh) when optimum passive cooling intervention was applied on an air-conditioned model and simulated for dry season period.

Energy and cost savings when optimum passive intervention was applied to the air-conditioned model during the dry season

- An energy saving cost of 8,110 Naira per month (£37.66) (977kWh per month of energy for cooling) was achieved when the optimum passive cooling intervention was applied.
- For the whole dry season, 25,000 Naira (£53.60) was predicted to be saved.

9.6 Research hypotheses

The research looked at three hypotheses to help answer the research questions, and it was found that:

1. There is a significant difference between thermal comfort and socio-economic status of residents in Abuja. This was found to be true for residents in Dutse Alhaji ($r = 0.38$, $p < 0.05$) and Bwari ($r = 0.58$, $p < 0.05$).
2. The indoor temperature in naturally ventilated buildings can be substantially reduced by applying interventions such as insulation and shading to reduce heat gain.
3. The indoor cooling loads in air-conditioned buildings can also be significantly reduced by applying interventions such as insulation and shading to reduce heat gain.

9.7 Limitations of the study

The study was limited to only ten dwellings for environmental monitoring and thermal comfort survey during the survey period. Also, two dwellings out of the ten selected buildings were monitored at the same time for a week. Initially, the study sought to monitor all ten dwellings simultaneously. Unfortunately, there was a limited number of temperature and relative humidity data loggers to monitor all the dwellings at the same time for longer periods rather than two dwellings for a week. The study experienced some security challenges, making some areas difficult and dangerous to survey. This partially limited access to more houses for the post-occupancy survey, although there was no reason to suggest that the added buildings would have given different results. The study would have liked to measure CO_2 levels in the dwellings, however, the available CO_2 data loggers are powered only by electricity and due to the limited power supply in the Abuja, a battery powered logger would have been preferred. The study was also limited by understanding the lifestyles of the occupants and their understanding of the research subject. Giving honest account and input of their adaptation behaviour may be problematic due to limits of human cognition and limitations of knowledge about the issues under investigation. These constitute major sources of errors for self-completed questionnaire surveys. Finally, the study had to make assumptions about the ventilation rate of the buildings because it could not be measured. The actual ventilation rate is unknown.

9.8 Conclusions

The main aim of the research was to investigate the indoor thermal comfort conditions of occupants in low-income residential building in Abuja, Nigeria and identify the potential overheating and propose passive cooling strategies. The research proposed an optimal passive cooling intervention for naturally ventilated and air-conditioned buildings in Abuja to reduce indoor air-temperature, overheating risks and mechanical cooling loads for air-conditioning. This intervention reduced indoor temperature by 5°C during the daytime and evening period and by almost 4°C during the night time. The study also showed that when the comfort temperature was set at 28°C in an air-conditioned building and the interventions were applied, a 100% reduction in cooling load was achieved.

However, this push for a more sustainable approach to tackling high indoor temperatures, overheating and global warming is really lacking in sub-Saharan countries like Nigeria, where there is little or no national sustainable drive or agenda. Journals, articles, books, and conferences on thermal comfort are often organised by government agencies, but, that is where it stops. There is a need to continually push for more research in this area, to investigate thermal comfort of residents in Nigeria for longer periods throughout the year. This is necessary because the more we understand the lifestyles of people with regards to their comfort, the better we understand the issue how and to solve them. More people need to be informed on the best practical solutions to the concerns raised during the study. Further studies will also help in giving guidance on adopting current and new passive strategies to suit low-income earners in the tropical climates around the world. Enacting policies that would help implement and subsidise passive strategies in Nigeria would go a long way in the countries reluctant push to achieve sustainability.

There must be a national push to achieve sustainability, and this will be encouraged by the results in this study, proving that passive cooling application and affordability in Nigeria is possible. It will also go a long way in persuading those, even policy makers that are sceptical about the possibility of passive cooling strategies in Nigeria. This section discussed the need for more research into real life passive cooling strategies and applications. Since the study shows that design strategies for passive cooling reduced indoor temperature and energy for cooling in residential dwellings, then passive cooling application in Nigeria is possible and achievable.

Post-occupancy survey, environmental monitoring and comfort surveys

The results from post-occupancy surveys showed that the occupants felt much warmer within the living room and bedrooms of their homes in the dry season compared to the wet season. Essentially the majority were uncomfortably warm in the dry season as shown in a range of comfort indices.

The results from environmental monitoring showed that the warm dry season's external temperature averaged 31.1ºC and reached 41.1 ºC while the minimum was 23.5ºC. The high external temperatures were a cause of high mean internal temperatures. Although these means were within the neutral temperature range (28-30.4ºC), high hourly temperatures were recorded for long hours within the internal spaces. An overheating analysis using the predicted temperatures from the building simulation data supported this, showing that overheating occurs in all the houses and the occupants would be predicted to be thermally dissatisfied with their thermal environment.

Dynamic thermal modelling and passive cooling intervention

Simulation modelling of an air-conditioned house and a naturally ventilated house allowed a range of thermal interventions to be investigated. Design optimisation allowed optimum interventions to be determined. The results showed that applying the chosen set of optimum cooling passive interventions, viz. 75mm roof and wall insulation, 450mm shading device and 20% thermal mass, had a significant effect in reducing the living room temperatures when the optimum passive interventions were applied, thus significantly improving the sleeping period for occupants at night. For the naturally ventilated model, the maximum indoor air temperature during the daytime and evening period (08:00-22:00) was reduced by 5°C from the base model temperature (33.7°C) to 28.7°C when the optimum passive cooling intervention was applied. Also, for the night-time period, the maximum indoor temperature was reduced by 3.8°C from the base model air-temperature (30.4°C) to 26.6°C when the optimum passive intervention was applied.

The air-conditioned model saw a 100% reduction (1332kWh to 0) in the living room cooling load for the whole dry season from the base model for the daytime and evening period when the optimum passive interventions were applied. The bedroom cooling load was also reduced substantially by 70% (345 to 105kWh) when the optimum passive intervention was applied. The reduction in these temperatures and cooling load was possible because the optimum intervention lowered the maximum indoor temperatures near to 28°C for most of the time.

Cost and energy saving on optimum passive cooling intervention

When the optimum passive cooling interventions were applied, 977kWh per month of energy for cooling was saved worth 8,560 Naira per month (£17.86). This saving is significant and would help residents in Abuja especially those in the low-income group who earn the minimum wage of 18,000 Naira (£37.30) per month. A total of 25,000 Naira (£53.60) and 2220kWh of energy was predicted to be saved during the whole of the dry season when the optimum passive intervention was applied to the fabric of the air-conditioned building. The results show that the optimum passive interventions were effective in providing an alternative form of indoor cooling during the hot dry season and saved energy and mechanical cooling cost. Although only the cooling energy saved was calculated, other benefits of reduced or eliminated air-conditioning would accrue, particularly through reduced air and noise pollution, lowered impact on health and reduced maintenance expenditure.

Barriers to passive cooling implementation in Nigeria

In Nigeria, presently there is no extensive and comprehensive sustainable building agenda or a tradition of building energy regulations in place to contribute and facilitate sustainable passive cooling implementation. Rather the lack of these regulations forms barriers to implementation of passive cooling strategies and the number of barriers in the building sector is daunting. These barriers hinder future implementation of passive interventions, i.e. economic/financial barriers, lack of appropriate research and development and production technologies, behavioural and social constraints and information barriers.

9.9 Recommendations for future work

The research had found several key areas for future research.

1) Local construction materials should be studied as these may well have better insulating properties than the currently used materials, e.g. sandcrete blocks. Materials like adobe and rammed earth mud bricks will also be cheaper to produce and therefore more proper for the lower income sector and have a lower environmental impact.

2) There is a need for the development of a local adaptive thermal comfort standard that responds better to the different climate zones and seasons in Nigeria.

3) The air tightness of low-income residential buildings is poorly understood. If occupants can be given better control of ventilation there is the potential to reduce the ventilation cooling load. The potential for heat recovery could also be exploited.

4) There is a need to assess in detail the balance of the benefits of passive interventions and their costs against the reduction in air and noise pollution and associated health benefits.

5) There is limited research on cool roof materials in Nigeria. The application and maintenance of cool roof materials (i.e. reflective white and Infra-red paints, and green roofs) as a passive cooling strategy in Nigeria should be investigated to explore its potential, long term financial and environmental benefits to Nigeria and real-life application.

6) Finally, this study found evidence of poorer satisfaction with the thermal environment in the areas with highly clustered buildings, viz Mpape and Dutse Alhaji. A study of the relationship between the morphology of dense housing settlements and indoor temperatures and thermal stress levels could provide guidance for planning control to improve community well-being.

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APPENDIX

APPENDIX 1 – Analysis of Post-Occupancy Survey

Table A1.1: Summary of respondents' gender and age distribution, post-occupancy survey

		Post-Occupancy survey											
		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S	%	S.S	%	S.S	%	S.S	%	S.S	%	S.S	%
Gender	**Male**	26	60.5	33	75.0	33	76.7	39	76.5	25	61.0	156	70.3
	female	17	39.5	11	25.0	10	23.3	12	23.5	16	39.0	66	29.7
Age (Years)	**18-30**	17	39.5	13	29.5	14	32.5	15	29.4	11	26.8	70	31.5
	31-45	24	59.8	27	61.4	23	53.5	34	66.7	24	58.5	132	59.5
	46-59	2	4.7	4	9.1	6	14.0	2	3.9	5	12.2	19	8.6
	>60	0	0.0	0	0.0	0	0.0	0	0.0	1	2.4	1	0.5

Table A1.2: Summary of respondents' building occupancy, post-occupancy survey

		Post-Occupancy survey											
		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222))	
		S.S	%	S.S	%	S.S	%	S.S	%	S.S	%	S.S	%
No. of bedroom	**1**	7	16.3	25	56.8	13	30.2	11	21.6	12	29.3	68	30.6
	2	23	53.5	16	36.4	20	46.5	25	49.0	16	39.0	100	45.0
	3	9	20.9	3	6.8	9	21.0	9	17.6	9	21.9	39	17.6
	4	3	7.0	0	0.0	1	2.3	4	7.9	4	9.8	12	5.4
	>4	1	2.3	0	0.0	0	0.0	2	3.9	0	0.0	3	1.4
No. of People in apartm.	**1**	3	7.0	5	11.4	6	14.0	1	2.0	3	7.3	18	8.1
	2	6	14.0	22	50.0	3	30.2	11	21.5	9	22.0	61	27.5
	3	17	39.5	9	20.5	8	18.6	17	33.3	10	24.4	61	27.5
	4	13	30.2	6	13.6	9	20.9	8	15.7	14	34.1	50	22.5
	>4	4	9.3	2	4.5	7	16.3	14	27.5	5	12.2	32	14.4
Years in apartm.	**>1**	3	7.0	5	11.4	6	14.0	9	17.6	8	19.5	31	14.0
	1-3	18	41.8	24	54.5	18	41.8	19	37.3	16	39.0	95	42.8
	4-5	11	25.6	13	29.6	15	34.9	16	31.4	14	34.2	69	31.0
	>5	11	25.6	2	4.5	4	9.3	7	13.7	3	7.3	27	12.2

Table A1.3: Summary of respondents' indoor thermal conditions during the dry season at daytime, post-occupancy survey

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S	**%**	**S.S**	**%**	**S.S**	**%**	**S.S**	**%**	**S.S**	**%**	**S.S**	**%**
Thermal sensation	**Cold**	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
	Cool	5	11.6	0	0.0	1	2.3	1	2.0	0	0.0	6	2.7
	Slightly cool	2	4.7	0	0.0	1	2.3	1	2.0	2	4.9	6	2.7
	Neutral	7	16.3	0	0.0	2	4.7	1	2.0	1	2.4	4	1.8
	Slightly warm	16	37.2	7	15.9	2	4.7	10	19.6	8	19.5	34	15.3
	Warm	13	30.2	24	54.5	17	39.5	7	13.7	18	43.9	82	36.9
	Hot	0	0.0	13	29.5	21	48.8	31	60.8	12	29.3	90	40.5
Indoor Thermal comfort	**Very uncomfort.**	6	14.0	13	29.5	7	16.3	3	5.9	5	12.2	34	15.3
	Uncomfort.	15	34.9	19	43.2	22	51.2	12	23.5	25	61.0	93	41.9
	Slightly uncomfort.	14	32.6	11	25.0	6	14.0	26	51.0	8	19.5	65	29.3
	Neutral	3	7.0	0	0.0	3	7.0	3	5.9	2	4.9	11	5.0
	Slightly comfortable	3	7.0	0	0.0	5	11.6	5	9.8	1	2.4	14	6.3
	Comfortable	1	2.3	0	0.0	0	0.0	2	3.9	0	0.0	4	1.8
	Very comfortable	1	2.3	0	0.0	0	0.0	0	0.0	0	0.0	1	0.5
Humidity	**Very dry**	2	4.7	0	0.0	3	7.0	8	15.7	1	2.4	14	6.3
	dry	17	39.5	21	47.7	16	37.2	12	23.5	15	36.6	81	36.5
	Slightly dry	12	27.9	15	34.1	14	32.6	11	21.6	12	29.3	64	28.8
	Neutral	7	16.3	8	18.2	10	23.3	8	15.7	13	31.7	46	20.7
	Slightly humid	1	2.3	0	0.0	0	0.0	5	9.8	0	0.0	6	2.7
	humid	4	9.3	0	0.0	0	0.0	4	7.8	0	0.0	8	3.6
	Very humid	0	0.0	0	0.0	0	0.0	3	5.9	0	0.0	3	1.4
Thermal preference	**Much cooler**	11	25.6	24	54.5	25	58.1	21	41.2	23	56.1	104	46.8
	Slightly cooler	27	62.8	19	43.2	18	41.9	28	54.9	15	36.6	107	48.2
	No change	5	11.6	1	2.3	0	0.0	2	3.9	2	4.9	10	4.5
	Slightly warmer	0	0.0	0	0.0	0	0.0	0	0.0	1	2.4	1	0.5
	Much warmer	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0

Table A1.4: Summary of respondents' indoor thermal conditions during the dry season at night-time, post-occupancy survey

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S	**%**	**S.S**	**%**	**S.S**	**%**	**S.S**	**%**	**S.S**	**%**	**S.S**	**%**
Thermal sensation	**Cold**	2	4.7	0	0.0	1	2.3	0	0.0	0	0.0	3	1.4
	Cool	1	2.3	0	0.0	0	0.0	3	5.9	2	4.9	6	2.7
	Slightly cool	6	14.0	2	4.5	3	7.0	6	11.8	2	4.9	19	8.6
	Neutral	16	37.2	4	9.1	6	14.0	4	7.8	3	7.3	33	14.9
	Slightly warm	8	18.6	20	45.5	9	20.9	15	29.4	10	24.4	62	27.9
	Warm	4	9.3	18	40.9	20	46.5	13	25.5	20	48.8	75	33.8
	Hot	6	14.0	0	0.0	4	9.3	10	19.6	4	9.8	24	10.8
Indoor Thermal comfort	**Very uncomfort.**	1	2.3	0	0.0	1	2.3	3	5.9	0	0.0	5	2.3
	Uncomfort.	17	39.5	19	43.2	16	37.2	16	31.4	12	29.3	80	36.0
	Slightly uncomfort.	11	25.6	21	47.7	18	41.9	14	27.5	21	51.2	85	38.3
	Neutral	3	7.0	3	6.8	5	11.6	10	19.6	6	14.6	27	12.2
	Slightly comfortable	7	16.3	1	2.3	2	4.7	4	7.8	1	2.4	15	6.8
	Comfortable	3	7.0	0	0.0	1	2.3	4	7.8	1	2.4	9	4.1
	Very comfortable	1	2.3	0	0.0	0	0.0	0	0.0	0	0.0	1	0.5
Humidity	**Very dry**	1	2.3	0	0.0	1	2.3	5	9.8	0	0.0	2	0.9
	dry	6	14.0	3	6.8	7	16.3	19	37.3	1	2.4	22	9.9
	Slightly dry	10	23.3	26	59.1	13	30.2	12	23.5	15	36.6	83	37.4
	Neutral	8	18.6	14	31.8	21	48.8	8	15.7	21	51.2	76	34.2
	Slightly humid	7	16.3	1	2.3	0	0.0	5	9.8	4	9.8	20	9.0
	humid	7	16.3	0	0.0	1	2.3	2	3.9	0	0.0	13	5.9
	Very humid	4	9.3	0	0.0	0	0.0	0	0.0	0	0.0	6	2.7
Thermal preference	**Much cooler**	8	18.6	3	6.8	7	16.3	1	2.0	5	12.2	24	10.8
	Slightly cooler	13	30.2	34	77.3	33	76.7	41	80.4	24	58.5	145	65.3
	No change	20	46.5	7	15.9	3	7.0	9	17.6	8	19.5	47	21.2
	Slightly warmer	2	4.7	0	0.0	0	0.0	0	0.0	3	7.3	5	2.3
	Much warmer	0	0.0	0	0.0	0	0.0	0	0.0	1	2.4	1	0.5

Table A1.5 – Summary of respondents' indoor thermal conditions during the rainy season at daytime, post-occupancy survey

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S	%	S.S	%	S.S	%	S.S	%	S.S	%	S.S	%
Thermal sensation	**Cold**	0	0.0	0	0.0	1	2.3	3	5.9	0	0.0	4	1.8
	Cool	8	18.6	2	4.5	2	4.7	6	11.8	3	7.3	21	9.5
	Slightly cool	7	16.3	20	45.5	7	16.3	15	29.4	15	36.6	64	28.8
	Neutral	7	16.3	17	38.6	7	16.3	10	19.6	3	7.3	44	19.8
	Slightly warm	11	25.6	5	11.4	18	41.9	12	23.5	12	29.3	58	26.1
	Warm	8	18.6	8	18.6	8	18.6	5	9.8	7	17.1	28	12.6
	Hot	2	4.7	0	0.0	0	0.0	0	0.0	1	2.4	3	1.4
Indoor Thermal comfort	**Very uncomfort.**	0	0.0	0	0.0	0	0.0	0	0.0	1	2.4	1	0.5
	Uncomfort.	8	18.6	10	22.7	11	25.6	4	7.8	8	19.5	41	18.5
	Slightly uncomfort.	10	23.3	19	43.2	14	32.6	13	25.5	16	39.0	72	32.4
	Neutral	12	27.9	7	15.9	11	25.6	13	25.5	3	7.3	46	20.7
	Slightly comfortable	5	11.6	7	15.9	3	7.0	15	29.4	12	29.3	42	18.9
	Comfortable	8	18.6	1	2.3	4	9.3	5	9.8	1	2.4	19	8.6
	Very comfortable	0	0.0	0	0.0	0	0.0	1	2.0	0	0.0	1	0.5
Humidity	**Very dry**	0	0.0	0	0.0	0	0.0	1	2.0	0	0.0	1	0.5
	dry	1	2.3	0	0.0	1	2.3	4	7.8	0	0.0	2	0.9
	Slightly dry	2	4.7	3	6.8	2	4.7	26	51.0	1	2.4	12	5.4
	Neutral	19	44.2	17	38.6	14	32.6	12	23.5	19	46.3	95	42.8
	Slightly humid	11	25.6	19	43.2	22	51.2	8	15.7	17	41.5	81	36.5
	humid	4	9.3	5	11.4	4	9.3	0	0.0	3	7.3	24	10.8
	Very humid	6	14.0	0	0.0	0	0.0	0	0.0	1	2.4	7	3.2
Thermal preference	**Much cooler**	3	7.0	6	13.6	5	11.6	15	29.4	7	17.1	36	16.2
	Slightly cooler	15	34.9	34	77.3	33	76.7	31	60.8	25	61.0	138	62.2
	No change	22	51.2	4	9.1	4	9.3	5	9.8	8	19.5	43	19.4
	Slightly warmer	3	7.0	0	0.0	0	0.0	0	0.0	1	2.4	4	1.8
	Much warmer	0	0.0	0	0.0	1	2.3	0	0.0	0	0.0	1	0.5

Table A1.6: Summary of respondents' indoor thermal conditions during the rainy season at night-time, post-occupancy survey

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Kubwa (n=51)		Bwari (n=41)		Combined (n=222)	
		S.S	**%**	**S.S**	**%**	**S.S**	**%**	**S.S**	**%**	**S.S**	**%**	**S.S**	**%**
Thermal sensation	**Cold**	3	7.0	4	9.1	3	7.0	8	15.7	3	7.3	21	9.5
	Cool	12	27.9	16	36.4	10	23.3	17	33.3	15	36.6	70	31.5
	Slightly cool	14	32.6	16	36.4	11	25.6	7	13.7	9	22.0	57	25.7
	Neutral	5	11.6	6	13.6	10	23.3	11	21.6	5	12.2	37	16.7
	Slightly warm	7	16.3	2	4.5	9	20.9	6	11.8	5	12.2	29	13.1
	Warm	1	2.3	0	0.0	0	0.0	1	2.0	4	9.8	6	2.7
	Hot	1	2.3	0	0.0	0	0.0	1	2.0	0	0.0	2	0.9
Indoor Thermal comfort	**Very uncomfort.**	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
	Uncomfort.	0	0.0	2	4.5	2	4.7	4	7.8	2	4.9	7	3.2
	Slightly uncomfort.	13	30.2	19	43.2	20	46.5	1	2.0	14	34.1	73	32.9
	Neutral	14	32.6	15	34.1	12	27.9	7	13.7	8	19.5	63	28.4
	Slightly comfortable	9	20.9	2	4.5	4	9.3	14	27.5	10	24.4	36	16.2
	Comfortable	5	11.6	6	13.6	4	9.3	11	21.6	6	14.6	36	16.2
	Very comfortable	2	4.7	0	0.0	1	2.3	15	29.4	1	2.4	7	3.2
Humidity	**Very dry**	0	0.0	0	0.0	1	2.3	1	2.0	0	0.0	2	0.9
	dry	2	4.7	0	0.0	1	2.3	3	5.9	0	0.0	2	0.9
	Slightly dry	1	2.3	1	2.3	20	46.5	14	27.5	0	0.0	6	2.7
	Neutral	10	23.3	14	31.8	12	27.9	19	37.3	18	43.9	76	34.2
	Slightly humid	22	51.2	20	45.5	8	18.6	8	15.7	9	22.0	82	36.9
	humid	4	9.3	6	13.6	1	2.3	6	11.8	10	24.4	36	16.2
	Very humid	4	9.3	3	6.8	0	0.0	0	0.0	4	9.8	18	8.1
Thermal preference	**Much cooler**	2	4.7	1	2.3	2	4.7	2	3.9	2	4.9	9	4.1
	Slightly cooler	13	30.2	28	63.6	29	67.4	25	49.0	23	56.1	118	53.2
	No change	23	53.5	15	34.1	11	25.6	13	25.5	11	26.8	73	32.9
	Slightly warmer	4	9.3	0	0.0	0	0.0	11	21.6	4	9.8	19	8.6
	Much warmer	1	2.3	0	0.0	1	2.3	0	0.0	1	2.4	3	1.4

Table A 1.7: Summary of respondents' indoor control votes during the dry season comfort survey

		Lugbe		Mpape		Dutse Alhaji		Kubwa		Bwari	
		LGH 1 %	**LGH 2 %**	**MPH 1 %**	**MPH 2 %**	**DAH 1 %**	**DAH 2 %**	**KBH1 %**	**KBH 2 %**	**BWH 1 %**	**BWH 2 %**
		N=14	**N=28**	**N=18**	**N=31**	**N=13**	**N=16**	**N=14**	**N=13**	**N=7**	**N=33**
Open Windows Living room	Yes	85.7	25	88.9	0	76.9	6.3	42.9	42.9	70.2	45.2
	No	14.3	75	11.1	100	23.1	93.7	57.1	57.1	29.8	54.8
Electric Fan Living room	Yes	71.4	25	72.2	74.2	100	0	14.3	14.3	57.1	14.3
	No	28.6	75	27.8	25.8	0	100	85.7	85.7	42.9	85.7
AC Living room	Yes	0	39.3	0	0	0	62.5	50	50	0	26.2
	No	0	60.7	100	100	100	37.5	50	50	100	73.8
Open Windows Bedroom	Yes	78.6	39.3	94.4	74.2	84.6	50	7.1	7.1	14.3	35.7
	No	21.4	60.7	5.6	25.8	15.4	50	92.9	92.9	85.7	64.3
Electric Fan Bedroom	Yes	78.6	17.9	72.2	16.1	84.6	-	0	0	50	9.5
	No	21.4	82.1	27.8	83.9	15.4	-	100	100	50	90.5
AC Bedroom	Yes	0	50	0	0	0	37.5	7.1	7.1	0	2.4
	No	0	50	100	10	100	62.5	92.9	92.9	100	97.6
Use of indoor controls	Very little	0	0	5.6	0	0	0	0	0	0	0
	Little	0	0	11.1	3.2	0	0	0	7.7	0	4.8
	Slightly little	0	0	0	6.5	7.7	0	7.1	15.4	0	23.8
	Neutral	0	3.6	5.6	3.2	7.7	0	7.1	7.7	0	21.4
	Slightly much	7.1	10.7	5.6	29	46.2	18.8	7.1	0	0	23.8
	Much	85.8	71.4	61.1	48.4	30.8	68.8	50	69.2	85.7	11.9
	Very much	7.1	14.3	11.1	9.7	7.7	12.4	28.7	0	14.3	14.3
Satisfaction with of control	Very dissatisfied	0	0	0	0	0	0	0	0	28.6	0
	Dissatisfied	42.9	7.1	22.2	0	30.8	0	7.1	0	28.6	4.8
	Slightly dissatisfied	35.7	3.6	27.8	7.7	53.8	0	0	15.4	14.3	14.3
	Neutral	14.3	17.9	27.8	7.7	7.7	0	0	23.1	14.3	28.6
	Slightly satisfied	7.1	39.3	5.6	46.2	7.7	0	28.6	15.4	14.3	40.5
	Satisfied	0	32.1	16.7	30.8	0	87.5	64.3	38.5	0	11.9
	Very satisfied	0	0	0	7.7	0	12.5	0	7.7	0	0

Table A1.8: Summary of comparison between measured maximum, minimum and mean indoor daytime time (08:00-22:00) temperatures and CIBSE adaptive comfort threshold during the dry season

Year	Indoor monitored living spaces 08:00 – 22:00 (March – May 2015)							
Name of space-Living room	**CIBSE: total hours above 28°C**	**CIBSE: total % above 28°C**	**Above CIBSE hours threshold 30°C**	**Above CIBSE % threshold 30°C**	**Above CIBSE threshold 32°C**	**Above CIBSE % threshold 32°C**	**Above CIBSE threshold 34°C**	**Above CIBSE % threshold 34°C**
LGLVH1	105	100	93	89	62	59	26	25
LGLVH2	105	100	103	98	39	37	0	0
MPLVH1	82	78	62	59	30	29	0	0
MPLVH2	84	80	66	63	35	33	0	0
DALVH1	105	100	104	99	76	72	48	46
DALVH2	105	100	105	100	92	88	68	65
KBLVH1	105	100	105	100	42	40	0	0
KBLVH2	105	100	105	100	80	76	0	0
BWLVH1	103	98	84	80	61	58	28	27
BWLVH2	103	98	43	41	0	0	0	0

Table A1.9: Summary of comparison between measured maximum, minimum and mean indoor evening time (18:00-22:00) living room temperatures and CIBSE adaptive comfort threshold during the dry season

Year	Indoor monitored living spaces 18:00 – 22:00 (March – May 2015)							
Name of space-Living room	**CIBSE: total hours above 28°C**	**CIBSE: total % above 28°C**	**Above CIBSE hours thresh-old 30°C**	**Above CIBSE % thresh-old 30°C**	**Above CIBSE thresh-old 32°C**	**Above CIBSE % thresh-old 32°C**	**Above CIBSE thresh-old 34°C**	**Above CIBSE % thresh-old 34°C**
LGLVH1	35	100	35	100	32	91	21	60
LGLVH2	35	100	35	100	19	54	0	0
MPLVH1	30	86	25	71	14	40	0	0
MPLVH2	30	86	25	71	13	37	0	0
DALVH1	35	100	35	100	35	100	29	83
DALVH2	35	100	35	100	35	100	35	100
KBLVH1	35	100	35	100	25	71	0	0
KBLVH2	35	100	35	100	35	100	0	0
BWLVH1	35	100	4	11	0	0	0	0
BWLVH2	35	100	30	86	24	69	9	26

Table A 1.10: Summary of comparison between measured maximum, minimum and mean indoor night-time (23:00-07:00) bedroom temperatures and CIBSE adaptive comfort threshold during the dry season

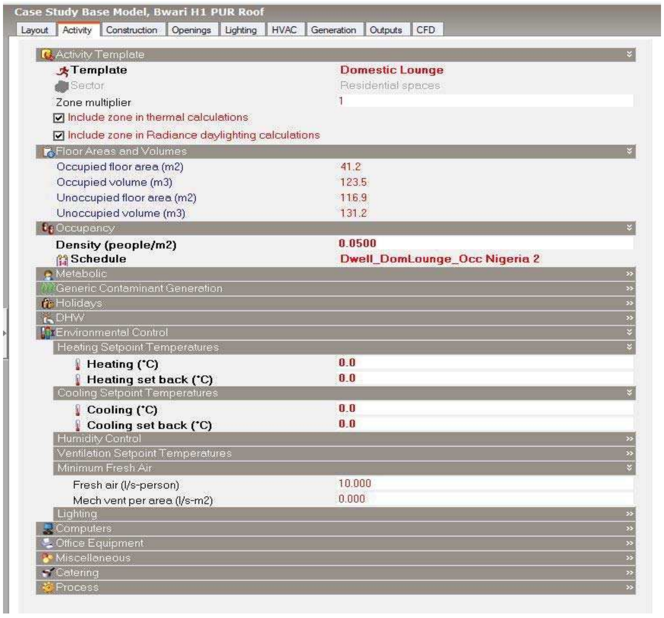
Year	**Indoor monitored living spaces 23:00 – 07:00 (March – May 2015)**							
Name of space-Bedroom	**CIBSE: total hours above 26°C**	**CIBSE: total % above 26°C**	**Above CIBSE hours threshold 28°C**	**Above CIBSE % threshold 28°C**	**Above CIBSE threshold 30°C**	**Above CIBSE % threshold 30°C**	**Above CIBSE threshold 32°C**	**Above CIBSE % threshold 32°C**
LGBDH1	63	100	63	100	60	95	35	56
LGBDH2	63	100	55	87	39	62	2	3
MPBDH1	60	95	48	76	37	59	5	8
MPBDH2	60	95	45	71	36	57	6	10
DABDH1	63	100	63	100	62	98	29	46
DABDH2	63	100	63	100	54	86	24	38
KBBDH1	63	100	63	100	53	84	2	3
KBBDH2	63	100	63	100	62	98	27	43
BWBDH1	63	100	63	100	53	84	31	49
BWBDH2	63	100	54	86	33	52	2	3

APPENDIX 2 – Simulation parameters and overheating risk analysis

This appendix presents overview of the development of base models using six inputs: layout, activity, construction, openings, lighting and HVAC. However, the layout input had been discussed in Chapter 6. This appendix also presents the summary of results from the overheating risk analysis at Lugbe and Bwari using CIBSE static and EN 15251 adaptive model.

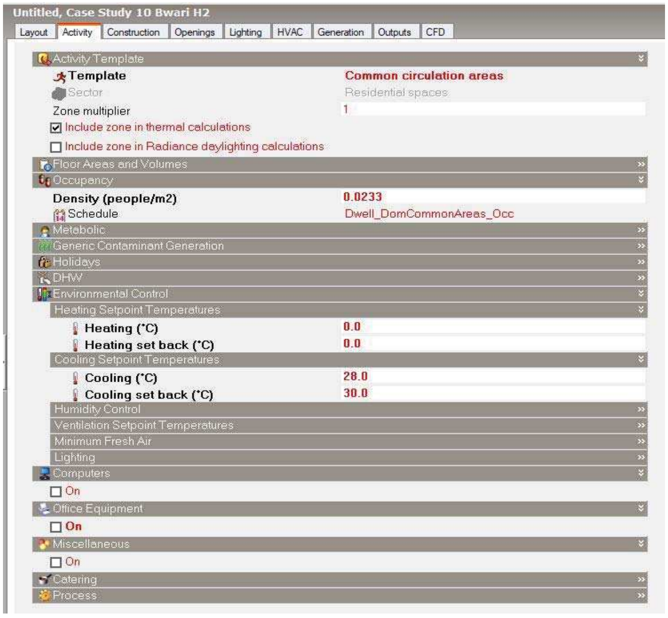
Figure A2.1: Activities

The dwellings in Lugbe had the largest floor areas with LGPDTH1 and LGPDTH2 had an occupied area of 319m^2 and 103m^2 respectively, while BWPDTH1 (Figure 6.12) had the smallest occupied area of 41m^2 and 95m^2 were recorded in BWPDTH1 (Figure 6.13). The infiltration rate was assumed to be 1 ach since the external walls had some cracks and the windows were not fully sealed. The outside air change (ach) rate for indoor spaces in the cross ventilated dwelling was assumed to be 3ac/h for cross ventilated spaces and 2 ac/h for single side ventilated spaces.



Template: Domestic Lounge
Sector: Residential spaces
Zone multiplier: 1
☑ Include zone in thermal calculations
☑ Include zone in Radiance daylighting calculations
Occupied floor area (m2): 41.2
Occupied volume (m3): 123.5
Unoccupied floor area (m2): 116.9
Unoccupied volume (m3): 131.2
Density (people/m2): 0.0500
Schedule: Dwell_DomLounge_Occ Nigeria 2
Heating (°C): 0.0
Heating set back (°C): 0.0
Cooling (°C): 0.0
Cooling set back (°C): 0.0
Fresh air (l/s-person): 10.000
Mech vent per area (l/s-m2): 0.000

Activity tab for BWPDT-H1

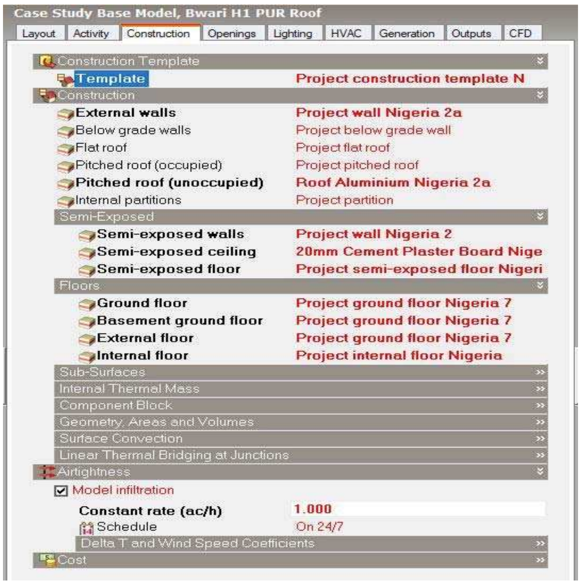


Template	Common circulation areas
Sector	Residential spaces
Zone multiplier	1
☑ Include zone in thermal calculations	
☐ Include zone in Radiance daylighting calculations	
Density (people/m2)	0.0233
Schedule	Dwell_DomCommonAreas_Occ
Heating (°C)	0.0
Heating set back (°C)	0.0
Cooling (°C)	28.0
Cooling set back (°C)	30.0
Computers: ☐ On	
Office Equipment: ☐ **On**	
Miscellaneous: ☐ On	

Activity tab for BWPDT-H2

Figure A2.2: Construction

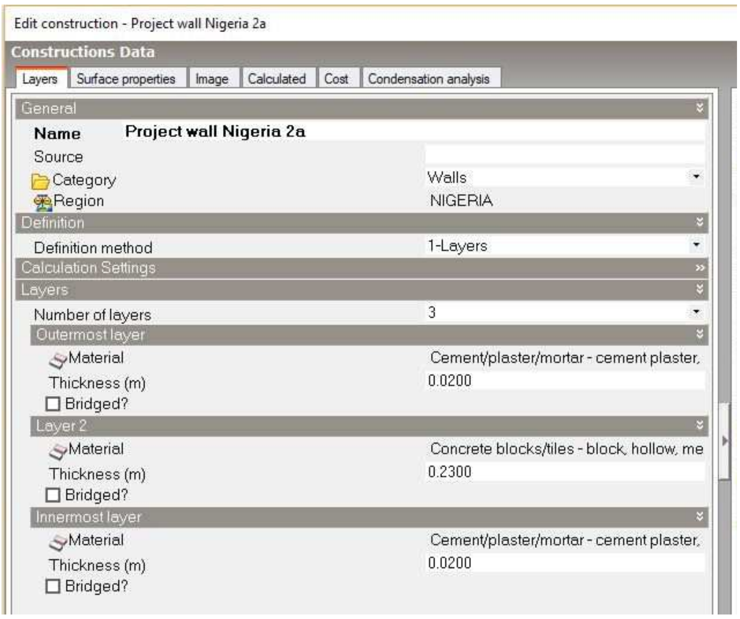
The ‘general best practice template’ in the construction template was modified to suit the Nigerian construction elements like the external and internal walls since there was no available data on Nigeria pre-installed in the software (Figure 6.14).



Template	Project construction template N
External walls	Project wall Nigeria 2a
Below grade walls	Project below grade wall
Flat roof	Project flat roof
Pitched roof (occupied)	Project pitched roof
Pitched roof (unoccupied)	Roof Aluminium Nigeria 2a
Internal partitions	Project partition
Semi-exposed walls	Project wall Nigeria 2
Semi-exposed ceiling	20mm Cement Plaster Board Nige
Semi-exposed floor	Project semi-exposed floor Nigeri
Ground floor	Project ground floor Nigeria 7
Basement ground floor	Project ground floor Nigeria 7
External floor	Project ground floor Nigeria 7
Internal floor	Project internal floor Nigeria
☑ Model infiltration	
Constant rate (ac/h)	1.000
Schedule	On 24/7

Construction model template

The external walls were modelled to represent the Nigerian sandcrete blocks which mainly comprised three layers of 20mm cement plaster on the outer and inner surfaces with the block comprising the middle component (Figure 6.15 and 6.16).


Edit construction - Project wall Nigeria 2a

Constructions Data

General

Name **Project wall Nigeria 2a**

Source

Category: Walls

Region: NIGERIA

Definition

Definition method: 1-Layers

Calculation Settings

Layers

Number of layers: 3

Outermost layer

Material: Cement/plaster/mortar - cement plaster,

Thickness (m): 0.0200

☐ Bridged?

Layer 2

Material: Concrete blocks/tiles - block, hollow, me

Thickness (m): 0.2300

☐ Bridged?

Innermost layer

Material: Cement/plaster/mortar - cement plaster,

Thickness (m): 0.0200

☐ Bridged?

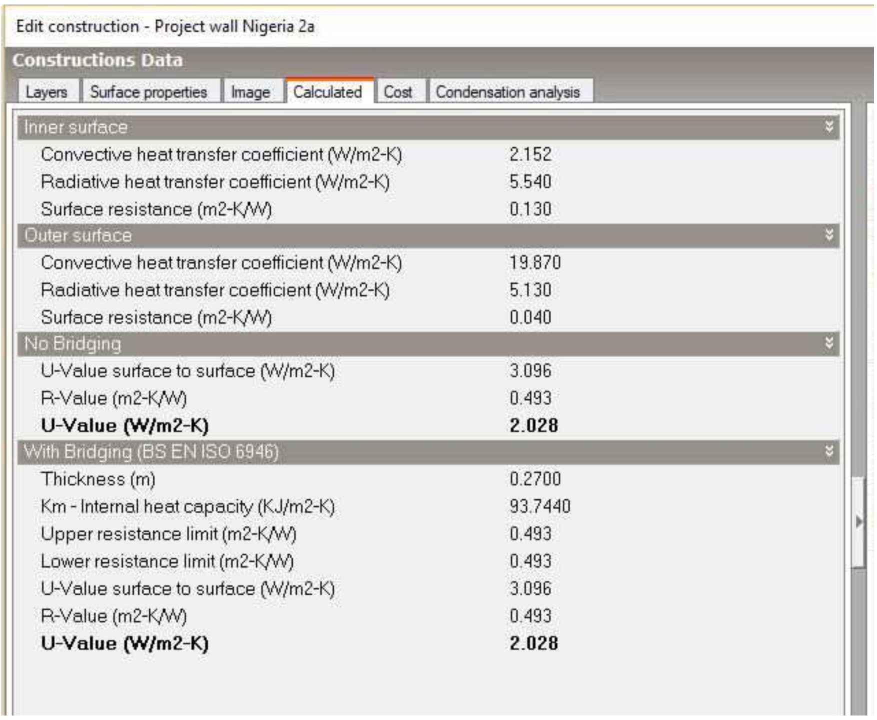
Layer components of the modelled sandcrete hollow blocks


Edit construction - Project wall Nigeria

Constructions Data

Image of the modelled sandcrete hollow blocks

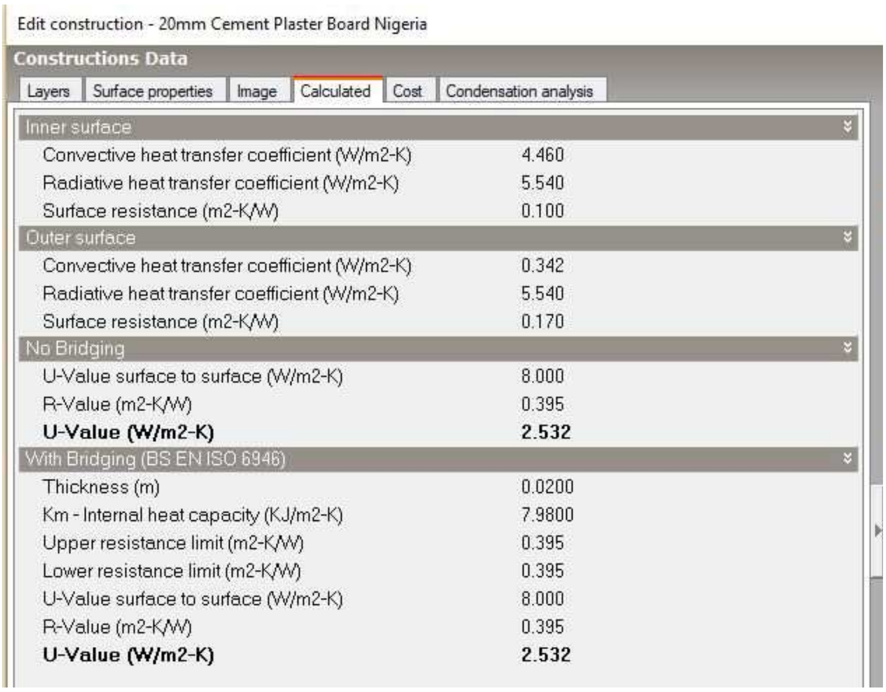
The external hollow sandcrete blocks used in this study had a very high U Value of 2.0W/m^{2}K (Figure 6.17).



Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	3.096
R-Value (m2-K/W)	0.493
U-Value (W/m2-K)	**2.028**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.2700
Km - Internal heat capacity (KJ/m2-K)	93.7440
Upper resistance limit (m2-K/W)	0.493
Lower resistance limit (m2-K/W)	0.493
U-Value surface to surface (W/m2-K)	3.096
R-Value (m2-K/W)	0.493
U-Value (W/m2-K)	**2.028**

U Value of the modelled sandrete hollow blocks

The modelled cement plaster ceiling board is a representation of ceiling types across all case studies which also had a high calculated U Value of 2.5W/m^{2}K, (Figure 6.18).

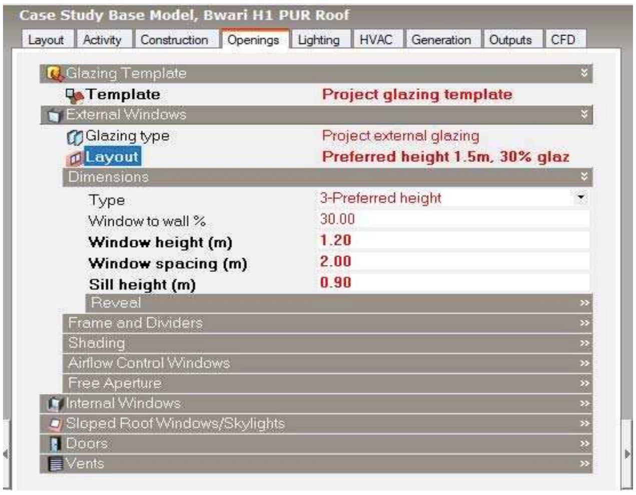


Inner surface	
Convective heat transfer coefficient (W/m2-K)	4.460
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.100
Outer surface	
Convective heat transfer coefficient (W/m2-K)	0.342
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.170
No Bridging	
U-Value surface to surface (W/m2-K)	8.000
R-Value (m2-K/W)	0.395
U-Value (W/m2-K)	**2.532**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.0200
Km - Internal heat capacity (KJ/m2-K)	7.9800
Upper resistance limit (m2-K/W)	0.395
Lower resistance limit (m2-K/W)	0.395
U-Value surface to surface (W/m2-K)	8.000
R-Value (m2-K/W)	0.395
U-Value (W/m2-K)	**2.532**

U – Value of the modelled ceiling cement plasterboard

Figure A2.3: Openings

The external windows were modelled as a single glazed window glass with a 25% - 30% window to wall ratio across the modelled case studies. The window height and length were 1.2 x 1.2m for all the windows (Figure 6.19) except for the toilet windows that were modelled as 0.6 x 0.6m.

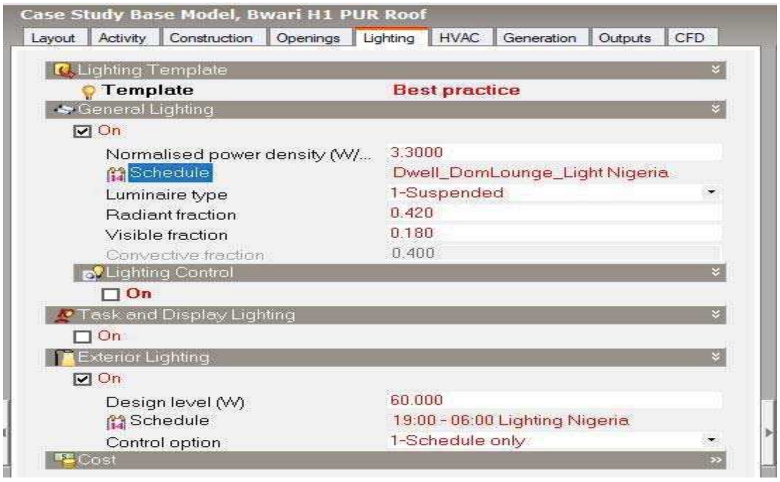


Template	Project glazing template
Glazing type	Project external glazing
Layout	Preferred height 1.5m, 30% glaz
Type	3-Preferred height
Window to wall %	30.00
Window height (m)	1.20
Window spacing (m)	2.00
Sill height (m)	0.90

Selected sample of opening tab used for modelling BWPDTH1

Figure A2.4: Lighting

The best practice template was selected and modified for lighting. The lighting schedule was set to turn on the light from 19:00 – 22:00 for indoor lighting and 19:00 – 06:00 for external lighting, (Figure 6.20).

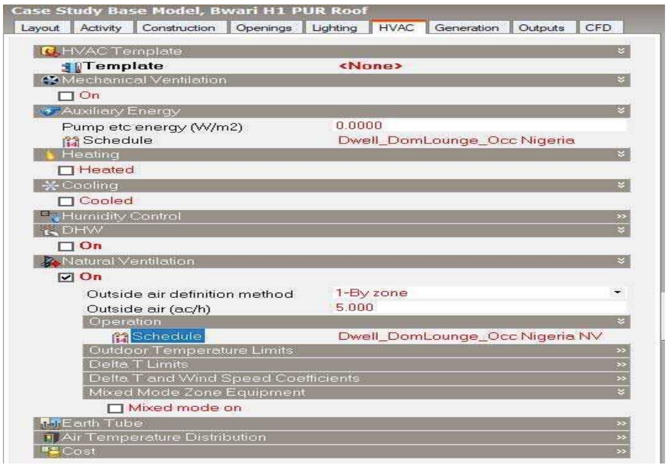


Lighting Template
Template: Best practice
General Lighting
☑ On
Normalised power density (W/...: 3.3000
Schedule: Dwell_DomLounge_Light Nigeria
Luminaire type: 1-Suspended
Radiant fraction: 0.420
Visible fraction: 0.180
Convective fraction: 0.400
Lighting Control
☐ On
Task and Display Lighting
☐ On
Exterior Lighting
☑ On
Design level (W): 60.000
Schedule: 19:00 - 06:00 Lighting Nigeria
Control option: 1-Schedule only
Cost

Selected sample of lighting tab for model BWPDT-H1

Figure A2.5: HVAC

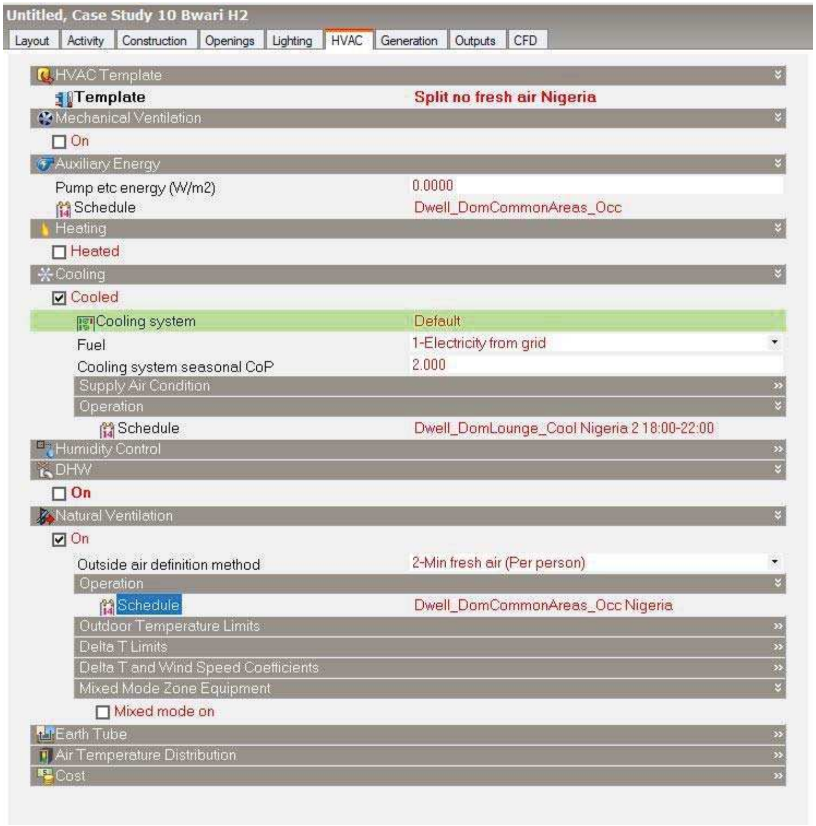
The occupancy schedule for HVAC settings for the naturally ventilated models used a 08:00 – 22:00 schedule for opening and closing of windows during the day for the living room spaces (Figure 6.20) and 23:00 – 07:00 for bedrooms (Figure 6.21) to represent the way occupants use their windows in real life scenarios.



HVAC Template
Template: <None>
Mechanical Ventilation
☐ On
Auxiliary Energy
Pump etc energy (W/m2): 0.0000
Schedule: Dwell_DomLounge_Occ Nigeria
Heating
☐ Heated
Cooling
☐ Cooled
Humidity Control
DHW
☐ On
Natural Ventilation
☑ On
Outside air definition method: 1-By zone
Outside air (ac/h): 5.000
Operation
Schedule: Dwell_DomLounge_Occ Nigeria NV
Outdoor Temperature Limits
Delta T Limits
Delta T and Wind Speed Coefficients
Mixed Mode Zone Equipment
☐ Mixed mode on
Earth Tube
Air Temperature Distribution
Cost

Selected sample of HVAC, none AC/ naturally ventilated model for BWPDT-H1.

The HVAC settings for the air-conditioned model used a cooling schedule of 08:00 – 22:00 to represent dwellings that were occupied throughout the day and 18:00 – 22:00 for dwellings that the occupants leave for work in the morning and come back to around 18:00 (Figure 6.22).



HVAC Template

Template: Split no fresh air Nigeria

Mechanical Ventilation

☐ On

Auxiliary Energy

Pump etc energy (W/m2): 0.0000

Schedule: Dwell_DomCommonAreas_Occ

Heating

☐ Heated

Cooling

☑ Cooled

Cooling system: Default

Fuel: 1-Electricity from grid

Cooling system seasonal CoP: 2.000

Supply Air Condition

Operation

Schedule: Dwell_DomLounge_Cool Nigeria 2 18:00-22:00

Humidity Control

DHW

☐ On

Natural Ventilation

☑ On

Outside air definition method: 2-Min fresh air (Per person)

Operation

Schedule: Dwell_DomCommonAreas_Occ Nigeria

Outdoor Temperature Limits

Delta T Limits

Delta T and Wind Speed Coefficients

Mixed Mode Zone Equipment

☐ Mixed mode on

Earth Tube

Air Temperature Distribution

Cost

Selected sample of HVAC, air-conditioned model for BWPDTH2.

APPENDIX 3 – Letter of Invitation to Participate in a Survey

COVER LETTER

The Owner/Occupier
x
x
x
Abuja, Nigeria
x

27th January 2015

Dear Sir/Madam

Research into "Thermal comfort through passive cooling in residential buildings" in Abuja, Nigeria

I am a second year PhD student in the Kent School of Architecture undertaking a four-stage research project into indoor residential buildings in Abuja, Nigeria. This research will investigate the current thermal conditions in residential buildings to ascertain what the indoor heat and comfort conditions are in residential buildings. It will further investigate ways of improving these conditions through natural cooling strategies suitable for residential housing in Abuja.

Please would you like to assist me with the various stages of the research? Completing the enclose questionnaire should not take more than 10-15 minutes of your time and will greatly aid my research. The study is expected to start by March and be completed by April 2015 for the summer period and for the rainy season it will start by June and end by July 2015. Replies that come in late would also be assessed. There is an enclosed stamped and addressed envelope for your convenience.

Also, please note that completion of the questionnaire does not commit you to partaking in any future stages of the research and you do not have to provide your name or additional contact details if you do not wish to. Should you be willing to become further involved in the project, including receiving details of the results when they are published, I have also enclosed a consent form, which it would be helpful if you could return with the questionnaire. Similarly, please also find attached a Participant Information Sheet, which provides further details about the research.

If there are any questions concerning this research, questionnaire, or your likely participation, please I can be contacted without hesitation at any point in time

Thank you for your impending participation in this research project, it is highly appreciated.

Yours faithfully

Michael Adaji
Mua2@kent.ac.uk / +44(0) 758 7735851

COMFORT SURVEY CONSENT FORM

To be adapted as appropriate to the specific research project

Title of project:

Name of investigator:

Participant Identification Number for this project:

Please initial box

1. I confirm I have read and understand the information sheet dated………(version…….) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. *(Insert contact number here of lead researcher/member of research team, as appropriate).* ☐
3. I understand that my responses will be anonymised before analysis. I give permission for members of the research team to have access to my anonymised responses. *(Also add here a statement about publication of anonymised direct quotes if this will be done).* ☐
4. I agree to take part in the above research project. ☐

Name of participant	Date	Signature
Name of person taking consent *(if different from lead researcher)* *To be signed and dated in presence of the participant*	Date	Signature
Lead researcher	Date	Signature

Copies:

When completed: 1 for participant; 1 for researcher site file; 1 (original) to be kept in main file

Participant's information sheet

Thermal comfort in hot-humid climate through passive cooling in low-income residential buildings in Abuja, Nigeria

I am a second year PhD student in the Kent School of Architecture carrying out a research into thermal comfort through passive cooling in Abuja, Nigeria. The aim of this research is to improve the indoor thermal conditions in residential buildings in Abuja. The research is privately funded and conducted by me alone. It is being supervised by the Kent School of Architecture and has been approved by the University's Research Ethics Advisory Group.

The research will be carried out at the following stages:

The first stage a comfort survey, which will assess occupants comfort and general information;

The second stage is a detailed assessment of occupants' comfort for a week, about their activity level, how they feel and what they do to make themselves comfortable at different times of the day notably morning, afternoon and the evening

The third stage will involves taking measurements of temperature and humidity in different spaces in your building for a week

Please you are invited to participate in the first stage of this research and, depending on the information about your property's features to be provided on the form, you may be invited to participate in the second and the third stages respectively. This survey will run approximately from 16th March to 20th April 2015 for the summer season and 22nd June to 27th July 2015 for the rainy season. Your property has been selected to receive the questionnaire based on its location, construction and/or design, which lead me to believe that the property may have some potential of a low-income class features(s). Should you choose to participate further in this study, I will contact you if your property is appropriate for the final stage.

To (the best of) my knowledge, this level of in depth research on natural ways of cooling residential buildings in Abuja has not been previously carried out. By participating in this study, you will help in identifying what the current indoor comfort conditions in houses are and support the different natural ways of improving it.

Participation in the project is voluntary and you are naturally free to withdraw at any time without giving any reason, please see the consent form for further details. Any foreseeable risk or disadvantage to you if you were to participate in the research cannot be predicted by me if you were to participate in the research. The work is non-invasive and, in the very unlikely event of any damage to you or your property, my actions will be covered by public liability insurance. However, should you have questions about the research or about your rights as a participant, or in the event of a complaint, please contact my supervisor Dr Richard Watkins at the Kent School of Architecture – R.Watkins@kent.ac.uk Tel. No…………………

The information I collect about your property will be stored in paper files in a lockable filing cabinet and in password-protected electronic files. These will be for my use only although property-specific data may be discussed with my academic supervisors. It is likely that I would need to keep this information until at least 2018. My PhD is due to finish September 2017. The results of the research may be suitable for publication or archiving but, if either of these was the case, I would contact you again to obtain relevant permissions. Similarly, anonymity would be preserved in any personal responses given before analysis, although the information given may be linked to your specific property and I would contact you for permission if I wanted to credit any quote to you.

Thank you for taking the time out to read this information sheet. It is highly appreciated. Please if you have any questions and concerns about the research or your likely participation, you are free to bring them up, on the other hand do not hesitate to contact me at any time

Michael Adaji

Mua2@kent.ac.uk / +44(0)758 7735851

29th October 2014

APPENDIX 4 – Post-Occupancy Questionnaire

POST-OCCUPANCY SURVEY

A Questionnaire designed for post-occupancy evaluation in residential buildings in Nigeria: A case study of Abuja. Please fill in, tick or circle as many as you can

SECTION A: **Background Information**

1. Address (Location): ____

2. Date:___________________

3. Time:___________________

Morning:	**Afternoon:**	**Evening:**

4. Sex:

Male	**Female**

5. Age:

18 – 30 years	**31 – 45 years**	**46 – 59 years**	**60 and above**

6. Marital status:

Single	**Married**	**Prefer not to say**

7. Employment status:

Public servant	**Private employee**	**Self-employed**	**Student**	**Unemployed**

8. Socio-economic status:

Low-income	**Lower medium-income**	**Upper medium-income**

9. What is the highest level of your educational attainment?

No formal education	**Completed primary**	**Secondary**	**Post-secondary**	**Post-graduate**

10. What is your current tenure status?

Rented (tenancy)	**Owner occupier**

SECTION B: **BUILDING ATTRIBUTES/ ENERGY CONSUMPTION**

11. What is your house type?

Single-Family Bungalow	Semi-detached Bungalow	Detached	Semi-detached building	Duplex

If “Other”, please state: ____________________

12. How many bedrooms do you have in your apartment?

1	2	3	4	More than 4

13. How many people live in this apartment?

1	2	3	4	More than 4

14. How long have you been living in your apartment?

Less than 1 year	1 – 3 years	4 – 5 years	More than 5years

15. On average, how much do you spend on electricity bill per month from the national grid?

Below N1,000 (£3.64)	N1,000 – N1,999 (£3.64 - £7.27)	N2,000 – N2,999 (£7.27 - £10.91)	N3,000 – N3,999 (£10.91- £14.54)	Above N4,000 (£14.54)

16. What is your alternative source of electricity supply, if any?

Personal Power Generating sets	Power Generating Plant in the estate	Solar Panels (photovoltaic)	Other	None

17. On average, how much do you spend per month on alternative source of electricity?

Below N1,000 (£3.64)	N1,000 – N1,999 (£3.64 - £7.27)	N2,000 – N2,999 (£7.27 - £10.91)	N3,000 – N3,999 (£10.91- £14.54)	Above N4,000 (£14.54)

18. What is your major source of cooking fuel?

Electricity	Gas	Kerosene	Firewood	Other

If “Other”, please state: ____________________

19. What is your major source of water supply?

Public mains	Borehole	Well	Water vendors

If “Other”, please state: ____________________

SECTION C: **INDOOR THERMAL CONDITIONS**

Control vote

20. Are you using anything to keep yourself comfortable, if yes which space are you using it?

Space/ Control	**Open Windows**	**Open Doors**	**Electric fan**	**A/C**	**Hand fan**
Living room					
Bedroom					
Dining room					

21. How often do you use the controls stated in (20) above?

Very little	**Little**	**Slightly little**	**Neutral**	**Slightly much**	**Much**	**Very much**

22. Are you satisfied with the level of control?

Very dissatisfied	**Dissatisfied**	**Slightly dissatisfied**	**Neutral**	**Slightly satisfied**	**Satisfied**	**Very satisfied**

23. Thermal sensation:

What do you think about the thermal sensation in the room(s) during the:	**Cold**	**Cool**	**Slightly cool**	**Neutral**	**Slightly warm**	**Warm**	**Hot**
	1	2	3	4	5	6	7
Dry season in the daytime?							
Dry season at night?							
Rainy season in the daytime?							
Rainy season at night?							
Overall indoor temperature							

24. Daylight:

What do you think about the day lighting in the room(s) during the:	**Very dim**	**Dim**	**Slightly dim**	**Neutral**	**Slightly bright**	**Bright**	**Very bright**
	1	2	3	4	5	6	7
Dry season in the daytime?							
Rainy season in the daytime?							

25. Humidity:

What do you think about the humidity in the room(s) during the:	**Very dry**	**Dry**	**Slightly dry**	**Neutral**	**Slightly humid**	**Humid**	**Very humid**
	1	2	3	4	5	6	7
Dry season in the daytime?							
Dry season at night?							
Rainy season in the daytime?							
Rainy season at night?							
Overall humidity							

26. Air movement:

What do you think about the air movement in the room(s) during the:	Very little 1	Little 2	Slightly little 3	Neutral 4	Slightly much 5	Much 6	Very much 7
Dry season in the daytime?							
Dry season at night?							
Rainy season in the daytime?							
Rainy season at night?							
Overall air movement							

27. Air quality:

What do you think about the air quality in the room(s) during the:	Very stuffy 1	Stuffy 2	Slightly stuffy 3	Neutral 4	Slightly good 5	Good 6	Very good 7
Dry season in the daytime?							
Dry season at night?							
Rainy season in the daytime?							
Rainy season at night?							
Overall air quality							

28. Indoor environmental rating:

What do you think about the environment in the room(s) during the:	Very uncomfor-table 1	Uncomfor-table 2	Slightly uncomfor-table 3	Neutral 4	Slightly comfort-table 5	Comfort-table 6	Very comfort-table 7
Dry season in the daytime?							
Dry season at night?							
Rainy season in the daytime?							
Rainy season at night?							
Overall thermal comfort							

29. Thermal preference:

How would you prefer air temperature during the:	Much cooler 1	Slightly cooler 2	No change 3	Slightly warmer 4	Much warmer 5
Dry season in the daytime?					
Rainy season in the daytime?					
Dry season in the night?					
Rainy season at night?					
Overall satisfaction					

30. The Typical Clothing You Wear Indoors at Home:

Using the table below please indicate what items of clothing you would typically wear when indoors. Please only choose one set that most typifies your indoor clothing at the listed time of the year.

<Circle all that apply in the season column>

ITEM OF CLOTHES:	DRY SEASON	RAINY SEASON
Shorts	1	1
Singlet	1	1
Track/ Jogging suits	1	1
Trousers/ slacks	1	1
Jeans	1	1
Short sleeved shirt or blouse	1	1
Long sleeved shirt or blouse	1	1
Short sleeved pullover	1	1
Long dress	1	1
Knee length dress	1	1
Skirt	1	1
Thin tights	1	1
Standard underwear	1	1
Other major item	1	1

31. What has been your activity level in the last 15 minutes?

Watching TV	Cooking	Standing	Walking	Washing	Reading

If “Other”, please state: ____________________

32. Approximately, what are your energy bills/ month (electricity)?

	Jan	Feb	Mar	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Monthly Amount (N)												
kWh												

APPENDIX 5 – Comfort Survey Questionnaire

DAILY DIARY

(Comfort Survey)

A daily diary designed for thermal comfort evaluation of occupants in residential buildings in Nigeria: A case study of Abuja. Please fill, tick or circle as many as you can

1. Address (Location):____

2. Date:__________________

3. Time:__________________

Morning:	Afternoon:	Evening:

4. Gender:

Male	Female

5. Age of respondent:

18 – 30 years	31 – 45 years	46 – 59 years	60 and above

6. In what room are you currently filling in this survey?

Living room	Bedroom	Kitchen	Dining room

7. Where have you spent most of your time in the last hour?

Living room	bedroom	Kitchen

If “Other”, please state: ____________________

8. Have you just come into the building in the last…?

15 minutes	30 minutes	45 minutes	1 hour	More than 1 hr.

9. What has been your activity within the last hour?

Watching TV	Cooking	Standing	Walking	Washing	Reading

If “Other”, please state: ____________________

10. Do you feel comfortable now?

Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Comfortable	Very comfortable

11. Would you like to be:

Cooler	No change	Warmer

12. How would you rate the overall acceptability of the temperature at this moment?

Acceptable	Not acceptable

13. How do you feel about the thermal sensation in your building at this moment?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

14. How do you feel about the air movement (ventilation) in your building at this moment?

Very Little	Little	Slightly little	Neutral	Slightly much	Much	Very much

15. How do you feel about the air (humidity) in the building at this moment?

Very dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Very humid

16. How do you feel about the day lighting level at this moment?

Very dim	Dim	Slightly dim	Neutral	Slightly bright	Bright	Very bright

17. How do you feel about the air quality at this moment?

Very stuffy	Stuffy	Slightly stuffy	Neutral	Slightly good	Good	Very good

18. How do you prefer air temperature at this moment?

Much cooler	Slightly cooler	No change	Slightly warmer	Much warmer

19. Occupant's activity level during the last 15 minutes?

Watching TV	cooking	Standing	Walking	Washing	reading

If "Other", please state: ________________________

20. In the last 30 minutes please identify the kind of drinks you have taken

Cold drinks	Hot drinks	No drinks

If "Other", please state: _____________________

Control vote

21. Are you using anything to keep yourself comfortable at this moment, if yes where are you using it?

Space/ Control	Open Windows	Open Doors	Electric fan	A/C	Hand fan
Living room					
Bedroom					
Dining room					

22. How often do you use these controls stated in (21) above at this moment?

Very little	Little	Slightly little	Neutral	Slightly much	Much	Very much

23. Are you satisfied with the level of control at this moment?

Very dissatisfied	Dissatisfied	Slightly dissatisfied	neutral	Slightly satisfied	Satisfied	Very satisfied

24. Please circle the clothing you are wearing at the moment. <circle all that apply>

ITEM OF CLOTHES:	SCORE
Shorts	1
Singlet	1
Track/ Jogging suits	1
Trousers/ slacks	1
Jeans	1
Short sleeved shirt or blouse	1
Long sleeved pullover	1
Short sleeve pullover	1
Long dress	1
Knee length dress	1
Skirt	1
Thin tights	1
Standard underwear	1
Other major item	1

25. Do you feel well at the moment?

Yes	No

If No, **(25a)** is this making you feel hot or cold?

Yes	No

(25b) for how many days have you been feeling unwell?
(1-7)? _____

26. Please make any further comment about the comfort in this building, i.e. indoor air temperature, humidity, air freshness, etc.

____
____
____
____
____