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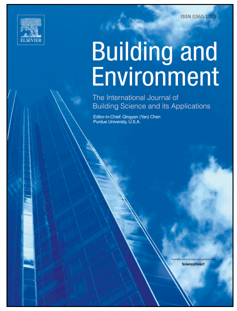

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Indoor comfort and adaptation in low-income and middle-income residential buildings in a Nigerian city during a dry season

Michael U. Adaji[1], Timothy O. Adekunle[2], Richard Watkins[3], Gerald Adler[3]

[1] School of Architecture, Computing, and Engineering (ACE), University of East London, Docklands Campus, London, UK, E16 2RD. Correspondence email: m.adaji@uel.ac.uk
[2] Department of Architecture, College of Engineering, Technology, and Architecture (CETA), University of Hartford, 200 Bloomfield Avenue, West Hartford, CT 06117, USA.
[3] Kent School of Architecture and Planning, University of Kent, Canterbury, UK.

Abstract

This paper investigates occupants' comfort, adaptation and their responses during the dry season in low-income to middle-income residential buildings in Abuja, Nigeria. The study aims to provide empirical data on occupants' comfort through evaluating 171 households in four different locations in Abuja. The study considered a combination of different research methods for data collection. Post-occupancy surveys were used to evaluate the buildings and residents' adaptation within the thermal environment. Thermal comfort surveys were also carried out in eight low-income residential households to assess occupants' perception of the thermal environment. Based on the short duration of the physical measurements, building simulation was also used to examine thermal comfort of occupants for an extended period. The Post Occupancy Evaluation (POE) results revealed over 70% of the occupants were dissatisfied with their thermal environment. The comfort surveys reported similar results with over 65% of the responses revealed being 'uncomfortably warm'. The results showed an overall mean temperature of all the measured case studies to be 31.7°C and the average temperature (predicted) of 30.7°C. The neutral temperatures were in a range of 28°C-30.4°C compared to the preferred temperature range of 27.5°C-29.4°C. The prevalence of thermal discomfort highlights the need to explore the possibilities of reducing internal temperatures, particularly by passive means (fabric, shading, insulation etc.) given the need to avoid or reduce the need for air conditioning to make the buildings energy-efficient for low to middle income groups.

Keywords: Occupants' adaptation, indoor thermal comfort, low-income, residential buildings, hot-humid climate, sub-Saharan Africa.

1. Introduction

Recent studies have mentioned the possibility of elevated temperatures within the indoor environment of different buildings (Lomas and Kane, 2013; Adekunle and Nikolopoulou, 2014, 2016), especially in residential buildings in various locations in sub-Saharan region (Ealiwa et al., 2001; Ogbonna and Harris, 2008; Akande and Adebamowo, 2010; Djongyang, et al., 2010; Djongyang, et al., 2012; Adunola and Ajibola, 2012; Nematchoua et al., 2014; Koranteng et al., 2015; Adaji et al., 2015) such as Abuja in Nigeria (Adaji, 2018). High temperatures in residential buildings in different regions can make occupants of such buildings thermally uncomfortable for a substantial period (Adunola and Ajibola, 2012; Akande and Adebamowo, 2010; Adekunle and Nikolopoulou, 2014, 2016; Adaji et al., 2015). Higher temperatures in buildings in moderate (Lomas and Kane, 2013; Adekunle and Nikolopoulou, 2016), tropical (Nicol, 2004; Al-Tamimi et al., 2011), hot and humid climates (Akande and Adebamowo 2010; Adaji et al., 2015) can affect thermal comfort and overall well-being of people. Various factors such as housing condition and quality (Jolaoso et al., 2012), thermal mass of building envelopes (Kendrick et al, 2012; Adekunle and Nikolopulou, 2016, 2019), regional climates (Nematchoua et al., 2014; Adekunle, 2019), design parameters like orientation (Al-Tamimi et al., 2011; Adekunle and Nikolopoulou, 2019) as well as non-integration of low-energy solutions (Nicol and Humphreys, 2002) to mitigate the effect of overheating can contribute to elevated temperatures in buildings.

In sub-Saharan nations like Nigeria, the housing condition of most residential buildings is substandard and largely of poor quality in both rural and urban centres (Abubakar, 2014). The increase in the quantity of housing needed by people has led to a major concern about the quick deterioration of the current housing stock (Jolaoso et al., 2012) and shortage in supply of housing units (Olayiwola et al., 2005). As a result, various builders in the region tend to focus more on quantity of housing units (Abubakar, 2014) rather than quality to meet the increasing demand for housing (Jolaoso et al., 2012; Adaji, 2018); thereby, compromising housing standards (Abubakar 2014; Adaji, 2018) which can also affect the users' comfort.

In most of the residential units in sub-Saharan Africa, occupants use operable windows and mechanical cooling mostly, fans and air conditioning, to improve the thermal environment of buildings (Adaji et al., 2015). According to the Federal Government of Nigeria's 2009 report on vision 2020, in Oyedepo, 2014, the analyses in the research showed that mechanical cooling is largely dependent on electricity supply in Nigeria of which the residential buildings sector consumes approximately 53.3% of electricity supply generated. However, due to the lack of a reliable and continuous power supply from the national grid, mechanical cooling systems in residential buildings cannot be depended on to meet the increasing demand for electricity supply (Adaji, 2018). Also, various cooling strategies (like air conditioning) require lots of energy to run and maintain (Nicol and Humphreys, 2002). Hence, relying on the continuous running of air conditioning is not cost-effective and sustainable for improving overall thermal comfort of people (Adaji, 2018). In addition to the lack of a constant power supply, people frequently turn to generators as a back-up power supply for their electrical appliances especially for mechanical cooling.

Ealiwa et al. (2001) carried out a thermal comfort field survey in several buildings in the Ghadames oasis, Libya representing a typical hot-dry climate in North Africa in the warm season. The study investigated natural ventilation systems in old traditional buildings and air conditioning systems in contemporary buildings. However, all the buildings in Ghadames were not evaluated in the study by Ealiwa et al., (2001), due to the limited time, but the survey was planned to select buildings that represent different locations in Ghadames and typical types and sizes (i.e. private and public, one-story building, flats or two-story building, etc.). The field study also investigated occupants' overall impression of the indoor thermal environments. The results revealed that people have an overall impression of higher standard of thermal comfort in old buildings than in new buildings.

An investigation of hygrometric thermal comfort was considered in different climatic zones of Cameroon (Nematchoua et al., 2014). The study (Nematchoua et al., 2014) found the comfort range varied according to regions and is highly dependent on climate and regional activity. Djongyang et al. (2012) presented an investigation on thermal comfort in sleeping environments in the sub-Saharan Africa region. The comfort equation used is based on the energy balance of the human body derived from Fanger's comfort model (Fanger, 1970). Comfort charts for the dry-tropical sub-Saharan Africa region were established using indoor climatic conditions collected over five years in Ouagadougou. The outcomes showed that the suitable monthly total insulation values for bedding systems in the dry-tropical regions range between 0.81 clo and 0.94 clo. The thermoneutral operative temperature range between 29°C and 32°C, while the thermoneutral air temperature range between 27°C and 30°C.

Similarly, Koranteng et al. (2015) carried out a study in sub-Saharan Africa to investigate the thermal performance of wall materials with different orientations to understand which performs better within the warm-humid climatic Region of Kumasi, Ghana. The study (Koranteng et al., 2015) concluded that material variances do not significantly have any effect on indoor comfort but rather the orientation of the building. Koranteng et al. (2015) further noted that buildings could be made comfortable for indoor occupants with the right materials and firm compliance and adherence to passive design principles.

Ogbonna and Harris (2008) investigated thermal comfort of people in different indoor thermal environments in sub-Saharan region. The study (Ogbonna and Harris, 2008) provided the range of indoor environmental conditions in which people in naturally ventilated buildings are thermally comfortable. Also, existing studies (Akande and Adebawomo, 2010; Adunola, 2012) have examined thermal comfort of occupants in residential buildings in sub-Saharan Africa. The findings showed that higher mean and neutral temperatures were found in the studies (Akande and Adebawomo, 2010; Adunola, 2012) than the values reported in other studies conducted in temperate climates (Lomas and Kane, 2013; Adekunle and Nikolopoulou, 2016). Strong relationships between the indoor and outdoor environmental variables were found in most of the studies carried out in sub-Saharan Africa (Akande and Adebamowo, 2010; Adunola, 2012; Adaji et al., 2015).

Thermal comfort standards such as the adaptive thermal comfort model (BSI, 2008) and ASHRAE model (ASHRAE, 2017) have been used to evaluate the risk of elevated temperatures within the thermal environments of different buildings (Lomas and Kane, 2013; Adekunle and Nikolopoulou, 2016; Adaji, 2018; Adekunle, 2019). The application of adaptive thermal standard in the hot-humid tropics has been examined (Nicol, 2004). The research revealed the importance of thermal comfort standards in assessing occupants' comfort within the region; while it also highlighted the implications of some environmental variables such as humidity and air movement for adaptive comfort model (Nicol, 2004). Published studies in the field have explained that various thermal comfort models help to assess the comfort temperatures (Nicol and Humphreys, 2012), risk of overheating (Lomas and Kane, 2013), and warm discomfort thresholds (Adekunle and Nikolopoulou, 2016) in various thermal environments of buildings. Some of the existing studies have used the thermal comfort standards as a benchmark to assess overheating and warm discomfort in buildings located in a hot and humid climate (Dili et al., 2011; Adaji, 2018). However, none of the studies conducted in residential buildings in sub-Saharan Africa considered a combination of post-occupancy survey, thermal comfort survey, physical measurements, and building simulation at the same time to examine thermal comfort and occupants' adaptation in the buildings.

This study used a combination of different research methods to enhance the diversity of data presented in this study as well as to capture more data for analysis and comparison (Ealiwa et al., 2001; Ogbonna and Harris, 2008; Akande and Adebawomo, 2010; Djongyang, et al., 2010; Djongyang, et al., 2012; Nematchoua et al., 2014; Koranteng et al., 2015; Adekunle and Nikolopoulou, 2016). The study also considered the methods with a view to examine and understand the conditions of occupants in different residential neighbourhoods in the study location during the dry season. This paper aims to understand the ideal and preferred conditions of thermal comfort in low-income residential buildings in the hot-humid climate of Abuja, Nigeria. Furthermore, the research was conducted to assess the various approaches residents explore to regulate and adapt within thermal environment of buildings located in the study location. The paper also aims an investigation such as this could assist the improvement and recommendations of diverse levels of tropical comfort considerations required in the standards.

1.1 Study area

The study area is Abuja in Nigeria and it lies at latitude 9° 07 'N and longitude 7° 48' E. Abuja is at an elevation of 840 m (2760 ft.) above the sea-level (Abubakar, 2014). The study area is a planned city largely developed in the 1980s and it is now designated as the Federal Capital Territory (FCT). It is the capital city of Nigeria and serves as the seat of the federal government of the country. Abuja falls within the Savannah zone vegetation of the West African sub region with patches of rain forest (World Climate Guide, 2014; Abubakar, 2014)). Due to the city location in the tropics, Abuja experiences two major seasonal conditions annually namely the rainy and dry seasons. The rainy season ranges from 305 to 762 mm (12–30 in.) precipitation and it begins in April and ends in October; while the dry season (the equivalent of summer in a temperate climate) starts in November and ends in March (World Climate Guide, 2014). However, within the dry season, 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 (Adaji et al., 2015). Abuja's distinctive geographical features such as the high altitudes and undulating terrain act as a moderating influence on the weather of the city (World Climate Guide, 2014; Abubakar, 2014). Temperatures can rise to 40°C during the dry season with dry winds lowering the temperature to as low as 12°C (Abubakar, 2014). Figure 1 shows the location map for Abuja city in Nigeria.

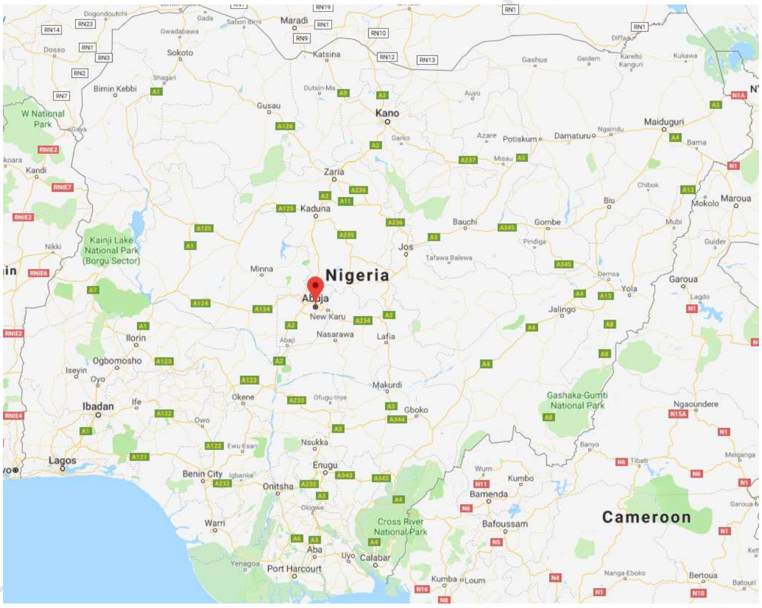


Figure 1: Map showing location of Abuja, the study area and capital city of Nigeria. Source: Google images/Abuja

1.1.1 Description Criteria adopted for post-occupancy survey location and comfort survey dwelling selection

The following criteria were adopted for the selection of the eight dwellings for environmental monitoring and comfort survey, and the post-occupancy study.

1. The buildings that are related to low income and low-middle income earners.

2. Houses built with conventional materials like sandcrete blocks for the walls, coarse and fine aggregate, Portland cement. They should either be roofed with either

galvanized corrugated iron roofing sheets or aluminium roofing sheets and seasoned wood.

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

4. Housing development built within the last 10 years.

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

6. A case study that has not been investigated

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

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

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

10. 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.

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. Four low/ low-middle income case study locations for the post-occupancy survey were finally identified and selected for this study (Figure 2) and they are Lugbe, Mpape, Dutse Alhaji, and Bwari. For the comfort survey and environmental monitoring, based on the criteria laid out in section 1.1.1. eight case dwellings in the four selected locations in Abuja were identified to investigate the thermal comfort of occupants with their means of ventilation (natural ventilation and air conditioning), purpose of construction (for low income group) and building type (low rise building), and housing development built within the last 10 years as their main criteria.

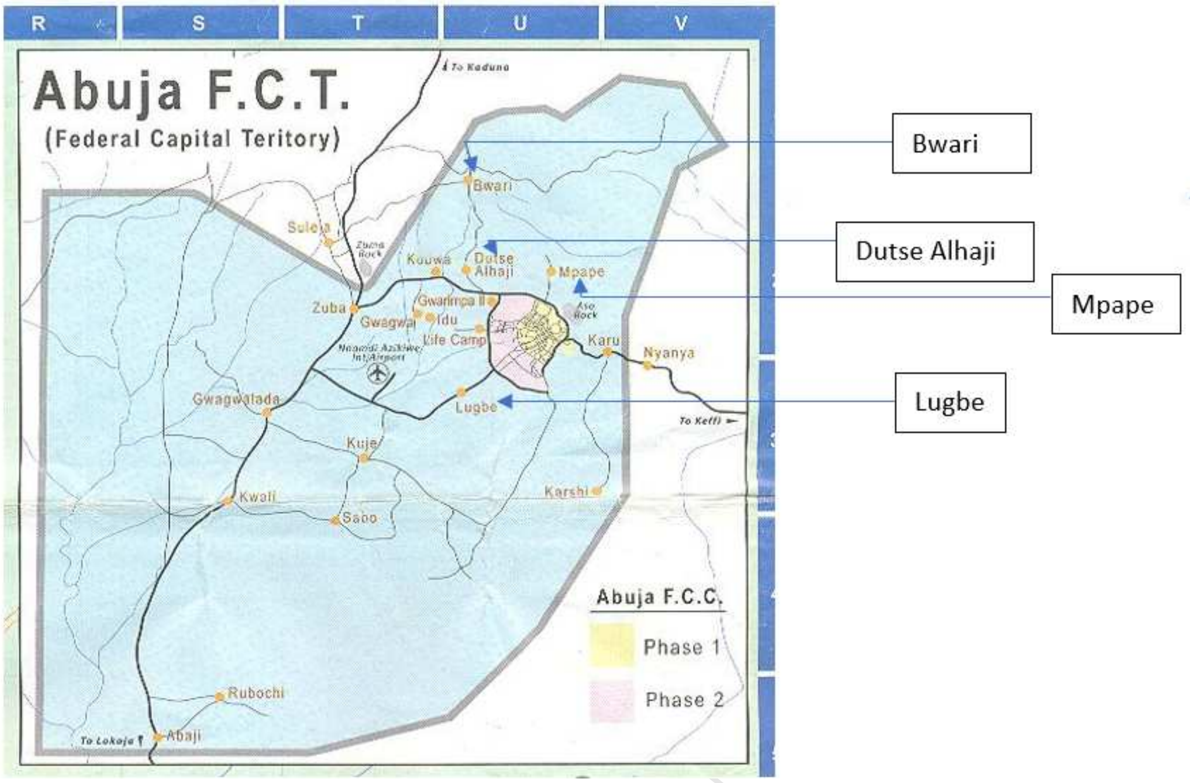


Figure 2: A map of Abuja showing the selected four case study locations. Source: Google images/Abuja

1.1.2 Residential buildings in the case study locations

Some of the residential buildings constructed during the accelerated stages of development in Abuja in the early 1980s were built using heavyweight materials like concrete, but most buildings in the city in the past and at present, are constructed with sandcrete blocks. (Abdulkareem, 2016). Consequentially, 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. (Adaji, 2018). Over 90% of physical infrastructures in Nigeria are being constructed using sandcrete blocks, making it an essential material in building construction. It is widely used in Nigeria, Ghana, and other African countries as load bearing and non-load bearing walling units. (Anosike and Oyebade. 2012). According to Abdulkareem (2016), he noted that most of the walling materials used in residential buildings in Abuja were constructed using hollow sandcrete blocks, which are more commonly used in contemporary building construction in the region (Abdulkareem, 2016). According to the 2006 National Bureau of Statistics (NBS) census report, updated in 2015, it noted that cement sandcrete blocks and bricks made 71.1% of the walling materials used in Abuja, of which around 65% were of sandcrete blocks. Also, mud and reed made 23.7%, metal and zinc sheet made 3.3%, wood and bamboo made 1.4%, and stone made 0.3%, while the remaining 0.2% comprised of other walling materials. As of the time of this survey, houses built with red bricks were initially selected for the survey, but access to the selected dwellings could not be obtained.

Thus, houses built with sandcrete blocks within the last 10 years was selected as this represented the overall housing stock of low-income earners in Abuja. However, the comparison between different walling materials (i.e., sandcrete cement blocks, red brick, and mud/reed) and their effect on indoor comfort and thermal properties in Abuja will be investigated in the future.

The housing schemes that were developed as part of Abuja's master plan over 30 years ago are still in use today as prototypes for low-income housing developments for low-income earners (Abdulkareem, 2016) since they form the bulk of the civil service and general workforce in Abuja (Jolaoso et al. 2012; Adaji, 2018). The socio-economic status in Nigeria plays an essential part in the selection and location of housing, where higher income earners go for high taste and good quality building while the low-income earners are often relegated to poor housing and unplanned locations. Jolaoso et al. (2012) noted that income status classification in Nigeria could be based on the level of income, geographical location, and political influence. The levels of household income may be classified as the lower, lower-middle, middle, and the high-income earners. However, for this study, only lower income and low-middle income earners will be reviewed.

1.1.3 Lower income earners

Lower income earners comprised of lower-level citizens, white-collar workers. These workers are typically not educated and lack the graduate degrees needed to advance to higher levels of employment or have a degree but remain unemployed but manage to put food on its table. This group also comprises of self-employed, semi and unskilled manual workers. They live mostly in the outskirts of cities and areas associated with poor planning and a high crime rate (Adaji, 2018; Lucky and Sam 2018).

Lower-income earners in Nigeria can be classified as a group of people who on average earn a reasonably small amount of money or in-kind reward for their corresponding labour. Income for these workers falls between 160,500 Naira and 200,000 Naira (Lucky and Sam, 2018). 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 (Ekong and Onye 2013) or $1-3 per day. This category falls in the poverty rate of 69% of the total population Lucky and Sam (2018).

Houses built in the lower-income areas are typically built with sandcrete blocks or clay bricks for walling material. The residential buildings are of low thermal performance with occupants always experiencing high indoor temperatures and discomfort. They are roofed with zinc sheets which tend to rust over time. 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 heights vary from 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.

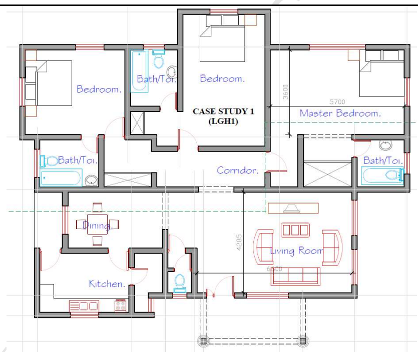
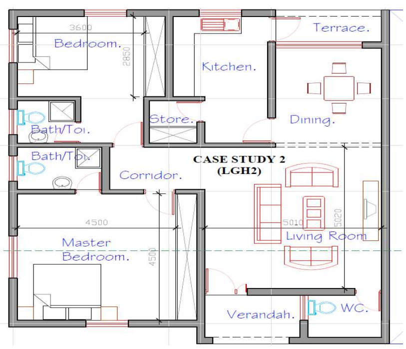
1.1.4 Lower-middle income earners

They typically have post-graduate degrees and work at high-level, white-collar positions. They are mostly civil servant, traders, and vocational professional: household income for these workers is often above n1m naira annually, 10% of Nigerian adult population is in this class. This group also comprises of supervisory, clerical and 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., 72, 000 Naira (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.They also live on the outskirts of the city but in well-developed estates and properly planned areas. Houses for this income group are usually of better quality compared to the low-income group. They use standard vibrated sandcrete blocks of 450mm x 230mm x 230mm for external walls, and 450mm x 150mm x 230mm for internal partitions walls (Abdulkareem, 2016) like toilets and bathrooms and are roofed with zinc 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. Local tradesmen living around the area usually build them.

1.1.5 Description of case studies

The dry season surveys considered in this paper were carried out in four locations (Lugbe, Mpape, Dutse Alhaji and Bwari) in Abuja. Post-occupancy evaluation was carried out in different residential buildings at the four locations. Environmental monitoring of variables and respective thermal comfort surveys during the dry season were conducted at the selected buildings in each of the locations. Due to the approval required from the occupants to evaluate the buildings and willingness to participate in the comfort surveys, physical measurements and comfort surveys were only considered eight buildings in the study location to investigate the thermal comfort of occupants. The buildings were selected based on their overall representation of the typical type of housing in the area, means of ventilation (natural ventilation and air conditioning), purpose of construction (for low income group) and building type (low rise building). The mean U-value of 2.03 W/m^2K is computed for the external walls of all the case study buildings. Table 1 below summarises the main features of the case study buildings in different study locations within Abuja. This section discusses the selected case study dwellings for the comfort survey for this study.

Table 1: Main features of the case study buildings evaluated in the four locations in Abuja

Case study	Designation area/purpose of construction	Location	Means of ventilation	Building type and additional information	Floor plan, elevation, and U-values of building components
Case Study 1, Lugbe (LGH1)	Designated low-income area/developed for low-income earners	Located within the Light Gold Estate in Lugbe, Abuja	Naturally ventilated	Low-rise construction, 3-bedroom, north facing, detached bungalow built with sandcrete blocks, covered with aluminium roofing sheets with no insulation.	  External walls: 230mm, U-values of 2.028 W/m^{2}K; Internal walls: U-values of 1.025 W/m^{2}K; Roof: U-values of 7.142 W/m^{2}K; Cement plaster ceiling board: 20mm, U-values of 2.532 W/m^{2}K
Case Study 2, Lugbe (LGH2)	Designated low-income area/built for low-income earners	Located within the Trade Moore Estate in Lugbe, Abuja	Air conditioned	Low-rise construction, 2-bedroom, north-east facing, semi-detached bungalow built with sandcrete blocks, covered with longspan aluminium roofing sheets with no insulation.	

Case study	**Designation area/purpose of construction**	**Location**	**Means of ventilation**	**Building type and additional information**	**Floor plan, elevation, and U-values of building components**
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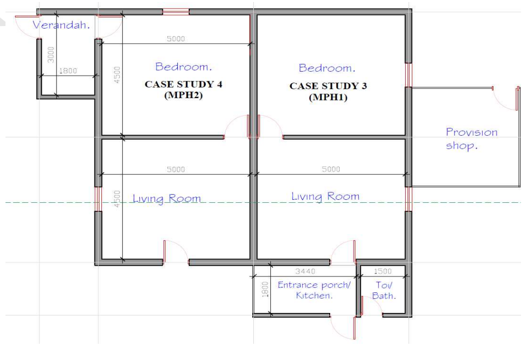
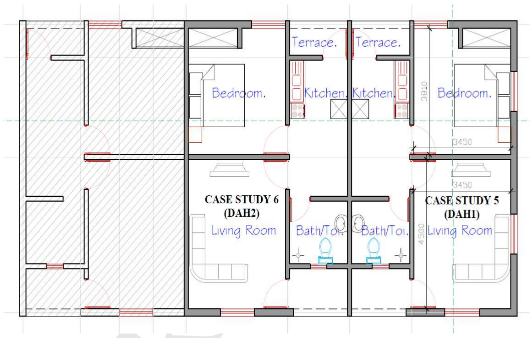
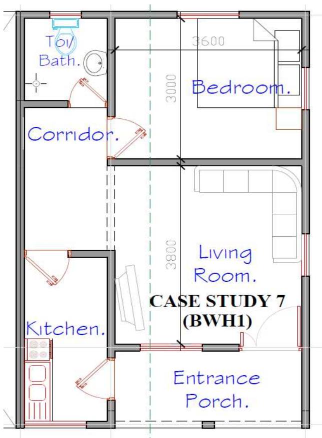
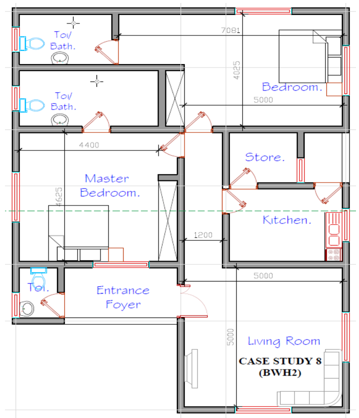
Case Study 3 (MPH1) and 4, Mpape (MPH2)	Designated low-income and high-density area/built for low-income earners	Located in Mashafa Street Mpape, Abuja	Naturally ventilated	Low-rise construction, 1-bedroom, south-east facing, semi-detached bungalow built with sandcrete blocks, covered with corrugated iron roofing sheets with no insulation.	  External walls: 230mm, U-values of 2.028 W/m^{2}K; Internal walls: U-values of 1.025 W/m^{2}K; Roof: U-values of 7.142 W/m^{2}K; Cement plaster ceiling board: 10mm, U-values of 2.688 W/m^{2}K

Case study	Designation area/purpose of construction	Location	Means of ventilation	Building type and additional information	Floor plan, elevation, and U-values of building components
Case Study 5 (DAH1) and Case Study 6, Dutse Alhaji (DAH2)	Designated low-income and high-density area/built for low-income earners	Located in Dutse Alhaji, Abuja	DAH1 - Naturally ventilated. DAH2 – Air conditioned	Low-rise construction, 1-bedroom semi-detached flats (DAH1 and DAH2) built with sandcrete blocks, covered with corrugated iron roofing sheets with no insulation.	  External walls: 230mm, U-values of 2.028 W/m^2K; Internal walls: U-values of 1.025 W/m^2K; Roof: U-values of 7.142 W/m^2K; Cement plaster ceiling board: 20mm, U-values of 2.532 W/m^2K
Case Study 7 Bwari (BWH1)	Designated low-income and high-density area/built for low-income earners	Located in Bwari, Abuja	Naturally ventilated	Low-rise construction, 2-bedroom flat, south-west facing, semi-detached bungalow built with sandcrete blocks, covered with zinc iron roofing sheets with no insulation.	

Case study	Designation area/purpose of construction	Location	Means of ventilation	Building type and additional information	Floor plan, elevation, and U-values of building components
					 External walls: 230mm, U-values of 2.028 W/m^{2}K; Internal walls: U-values of 1.025 W/m^{2}K; Roof: U-values of 7.142 W/m^{2}K; Cement plaster ceiling board: 20mm, U-values of 2.532 W/m^{2}K
Case Study 8, Bwari (BWH2)	Designated for high-density low neighbourhood/built for low-income earners	Located in Bwari, Abuja	Air-conditioned	Low-rise construction, 2-bedroom bungalow, north-west facing built with sandcrete blocks, covered with aluminium corrugated iron roofing sheets with no insulation.	  External walls: 230mm, U-values of 2.028 W/m^{2}K; Internal walls: U-values of 1.025 W/m^{2}K; Roof: U-values of 7.142 W/m^{2}K; Cement plaster ceiling board: 20mm, U-values of 2.532 W/m^{2}K

2. Research methodology

The methodology for the study includes environmental monitoring, post-occupancy and thermal comfort surveys. Since the period of the monitoring was not an extended one, the study also considered building simulation to capture more data for data analysis. The research methodology also provides the opportunity to compare both measured and simulated data on an equal basis as well as over an extended period. Existing studies have explored some of the research techniques considered in the paper (Ogbonna and Harris, 2008; Akande and Adebamowo, 2010; Adekunle and Nikolopoulou, 2014; Adaji et al., 2015). A few studies have explored all the research methods outlined in the study at the same time to improve the quality of data presented in the published work (Adekunle and Nikoloupou, 2016; Adaji, 2018).

The surveys were aimed at obtaining a comprehensive understanding of occupants' thermal comfort sensation within the buildings and occupant's energy demands and use. For the monitoring, sensors were installed to measure environmental variables within the thermal environment. The building simulation was considered to understand the thermal behaviour of the case study buildings. As stated in the existing research, post-occupancy studies are crucial for evaluating the thermal condition in buildings (Nicol and Roaf, 2005); while the thermal comfort surveys help to understand as well as analyse the nature and occurrence of occupants' complaints of experiencing warmth or sensation through the day that cannot be achieved with environmental monitoring (Nicol and Roaf, 2005; Adekunle and Nikolopoulou, 2014).

2.1 Post-occupancy survey

The post-occupancy evaluation (POE) focused on all the dwellings located in the four locations considered during the survey. The questionnaire features about 31 questions, and it is divided into three main sections. The first section includes background information about respondents' location, gender, age, socio-economic status, educational and occupancy status. The second section focuses on the building attributes and energy consumption including house type, number of rooms in the building and duration of occupancy. The third section considers indoor thermal conditions and evaluates how residents explore control and make themselves comfortable by opening and closing windows or doors, and clothing type. Overall, 216 questionnaires were distributed to residents. Approximately 179 questionnaires (83%) were returned, and of these, 171 questionnaires (79%) were correctly completed. The questionnaires were self-administered by residents, but adequate information was provided to all residents before the questionnaires were administered. The testing procedure was also considered to check the questionnaire before it was administered to residents of the case studies. Figure 3 shows the distribution of the questionnaire to residents that participated in the POE.

Figure 3: Distribution of the post-occupancy questionnaire to residents of the case studies

2.2 Environmental monitoring

The environmental monitoring of variables was conducted during the dry season from 11/03/15 to 18/04/15. Environmental variables such as air temperature and relative humidity were recorded using HOBO sensors placed on the internal walls at a height of 1.1m above the ground floor level. The field measurements were considered in eight buildings in Abuja. Two spaces (living room and bedroom) were measured in each case study building. The outdoor environmental conditions measured were air temperature and relative humidity using Tiny Tag T/RH sensors inside a radiation shield and global solar radiation on the horizontal. Data were recorded at every 15 minutes. Figure 4 shows the installation of the sensor used to measure the outdoor environmental variables at the study locations.

Figure 4: Installation with radiation shield of Tinytag data logger used to measure outdoor environmental variables

2.3 Thermal comfort survey

Thermal comfort questionnaires were administered to the occupants of the dwellings monitored. The residents were asked to complete the 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). Further information on clothing insulation and activity was also collected. The comfort survey was designed as a daily diary evaluating occupants' responses to discomfort and how they achieve comfort at various times of the day (morning, afternoon and evening) for the duration of the environmental monitoring. These data were used for analysis and comparison with the measured data collected concurrently during the surveys.

2.4 Building modelling and simulation

The study also used building modelling and simulation to ensure valid comparison and identification of overheating under similar conditions. The simulation was carried out using the DesignBuilder. The research technique was vital as it gave an insight into the most realistic outcomes of passive cooling interventions in the selected case study buildings representing residential buildings in Abuja, Nigeria. A pilot model was carried out 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. In this paper, the simulated results obtained from the case study buildings in two of the warmest case study locations were considered for discussion.

Concerning the outdoor weather data, a comprehensive Test Meteorological Year (TMY3) weather file for Abuja developed by a commercial based weather company was uploaded into DesignBuilder as it was not preinstalled on many of the platforms that generated weather files. The weather file was generated from real weather data collected for several months over a certain period. The outdoor weather file was analysed and compared with daily data collected from government agencies in Nigeria. The preliminary analysis showed strong similarities between the generated data used for the simulations and the data from the government agencies. The study also carried out the calibration and validation of the simulated results in line with the procedure outlined in the existing studies (Adekunle and Nikolopoulou, 2016; Adaji, 2018).

2.5 The assessment criteria for the risk of overheating

The assessment of the risk of overheating in the case study buildings was considered using the CIBSE thermal comfort model (CIBSE, 2015) and the EN15251 thermal comfort standard (BSI, 2008). For the CIBSE model, the criterion focuses on the percentage of hours of temperatures above 28°C in all the spaces. Since the case study buildings are located in a hot-humid climate, the assessment of overheating using the CIBSE "static" model also considered the percentage of hours of temperatures above 30°C and 32°C for analysis and discussion. For the EN15251 thermal comfort model, the standard focuses on Cat. II and Cat. III lower and upper markers for discussion and comparison. Some of the existing studies (Lomas and Kane, 2013; Adekunle and Nikolopoulou, 2016) in the field have also used the similar criteria (CIBSE, EN15251) discussed in this paper for the assessment of the risk of overheating in buildings.

3. Data analysis

The analysis of data considered in this study is presented in various sub-sections below.

3.1 Analysis of post-occupancy survey

About 43 questionnaires were completed and returned by the residents of Lugbe, of which 26 (60.5%) were from male and 17 from female (39.5%). From Mpape, 44 questionnaires were returned, of which 33 (75%) were from male and 11 from female (25%). Dutse Alhaji's residents had 43 questionnaires returned with 33 (76.7%) male and 10 (23.3%) female responses; while Bwari returned 25 (61%) male and 16 (16%) female responses. The analysis showed over 67% of the respondents were above the age of 30 as shown in Table 2. The data collected on socio-economic status of the respondents were also analysed. Table 3 shows a breakdown of respondents' socio-economic status. From Table 3, the analysis revealed the respondents in Lugbe almost have an even split between low and low-middle income groups, while over 65% of the respondents in Dutse Alhaji and Bwari were in the low-income range. However, in Mpape, 100% of the respondents indicated that they were low-income earners. In all, 70% of the total votes were in the low-income range with 120 votes, while 43 votes were low-middle income, representing 25% of the respondents' vote. On the one hand, the analysis shows that nearly all of the residents in Mpape are low-income earners and they are mostly self-employed. On the other hand, most of the residents in the remaining case study locations are either public servants or privately employed therefore having better economic status when compared to the residents in Mpape. Tables 2 and 3 provide the summary of gender, age, and socio-economic status of the residents.

Table 2: Gender and age distribution of post-occupancy questionnaires for the case studies.

Case study	Gender (frequency/ percentage distribution)		Age (frequency/percentage distribution)			
	Male	Female	18 – 30	31 – 45	46 – 59	60 and above
Lugbe	26 (61%)	17 (40%)	17 (35%)	24 (60%)	2 (5%)	0 (0)
Mpape	33 (75%)	11 (25%)	13 (30%)	27 (61%)	4 (9%)	0 (0)
Dutse Alhaji	33 (77%)	10 (23%)	14 (33%)	23 (53%)	6 (14%)	0 (0)
Bwari	25 (61%)	16 (39%)	11 (27%)	24 (59%)	5 (12%)	1 (2)

Table 3: Summary of respondents' socio-economic status during post-occupancy survey

		Lugbe (n=43)		Mpape (n=44)		Dutse Alhaji (n=43)		Bwari (n=41)		Combined (n=171)	
		S.S.	%	S.S.	%	S.S.	%	S.S.	%	S.S.	%
Socio-economic status	**Low-income**	18	41.9	44	100	31	72.1	27	65.8	120	70.2
	Low-medium	22	51.1	0	0.0	11	35.6	10	24.4	43	25.1
	Medium	3	7.0	0	0.0	1	2.3	4	9.8	8	4.7

S.S. = Sample Size

3.2 Analysis of environmental monitoring

The outdoor temperature recorded in Lugbe during the dry season varied from 23.5°C to a maximum of 41.1°C, which was the highest during the entire period of monitoring in the dry season (Table 4). The relative humidity ranged from 19% to a maximum of 91% and an average of 56%. The external temperature for Mpape varied from 21.5°C to a maximum of 37.5°C with an average outdoor temperature of 29.4°C shown in Table 4, while the relative humidity varied from 14% to a maximum of 99.3% on 31/04/2015. In Dutse Alhaji, the outdoor temperature ranged from 23.0°C to a maximum of 38.4°C, with a relative humidity that varied from 10% to a maximum of 93% and an average of 37% throughout the monitoring period. Lastly, the outdoor temperature in Bwari varied from 30°C to a maximum of 38.6°C and an average of 30.9°C throughout the monitoring period. The case study location (Bwari) also recorded a relative humidity that varied from 31.4% to a maximum of 97% and the highest average of 68.7% during the entire monitoring period in the dry season. The analysis showed Lugbe is the warmest case study location in Abuja. Also, the mean value of outdoor solar radiation varied from 4.30mV reported in Dutse Alhaji to 3.51mV recorded in Mpape. The study revealed the highest mean solar radiation was measured in Dutse Alhaji while the maximum outdoor solar radiation value was observed in Lugbe. Table 4 summarises the maximum, minimum and average outdoor temperatures at the case study locations.

Table 4: 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)				Relative humidity (%)				Max (°C)	Min (°C)	Solar radiation (mV)		
	Max Temp.	Min Temp	Avg. Temp	Temp Range	Max RH	Min RH	Avg. RH	RH Range	Date/ time	Date/ time	Max value	Min value	Avg. value
Lugbe	41.1	23.5	31.1	22.4	91.2	18.7	56.1	67.7	19/03/15 16:00	21/03/15 18:00	16.48	-0.09	3.83
Mpape	37.5	21.5	29.4	16.0	99.3	14.1	50.1	85.2	06/04/15 16:00	31/03/15 03:00	16.66	-0.08	3.51
Dutse Alhaji	38.4	23.0	30.3	15.4	92.7	9.9	36.6	82.8	14/04/15 16:00	15/04/15 06:00	16.01	-0.10	4.30
Bwari	38.6	22.2	30.1	16.4	97.0	31.4	68.7	65.6	04/05/15 16:00	07/05/15 00:00	16.03	-0.13	3.53

3.3 Analysis of comfort survey

During the comfort survey in the dry season, about 210 questionnaires were administered and 159 were received (75.7% response). The comfort surveys showed most of the occupants were feeling warm with most of the distribution of votes varying from ‘slightly’ warm’ to ‘hot’. The analysis showed that the occupants in Lugbe LGH1 feel ‘warm’ for 50% of the time, while the residents in Lugbe LGH2 feel ‘warm’ for 25% of the time. Also, the occupants in Dutse Alhaji DAH1 feel ‘warm’ for 76.9% of the time compared to 25% of the time the respondents feel warm in Dutse Alhaji DAH2. The 25% warm votes reported in Lugbe LGH2 and Dutse Alhaji DAH2 can be attributed to the use of air conditioning in these dwellings, though the ‘slightly warm’ votes in Lugbe LGH2 and Dutse Alhaji DAH2 were about 53.6% and 56% respectively.

The analysis showed that most of the residents of the case study buildings spent about 12 hours inside the houses per day. The study revealed that most of the survey participants had lived in the case study buildings for at least 36 months as at the time the surveys were carried out. The analysis revealed 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 study buildings recorded temperatures above the comfort range.

3.4 Analysis of building modelling and simulation

The models for the case study buildings were simulated for a one-week period from 30th May – 6th April for the TMY3 file for Abuja during the dry season (summer period). This paper focused on the modelling and simulation of the case study buildings in the warmest location (Lugbe) and a moderately warm location, Bwari. For this simulation study, LGH1 and BWH1 were considered free-running while LGH2 and BWH2 were supplemented with air-conditioning system. Assumptions were made on general lighting, task and display lighting, and the outside air change rate. The input parameters for the case study buildings in Lugbe are analysed below (Table 5).

The simulations were considered for seven-day period corresponding to the period of physical measurements at the case study location, i.e. 18/03/2015 – 24/03/2015 for Lugbe and 31/04/2015 – 06/05/2015 for Bwari. The simulations were also run for the whole dry season period from 01/02/2015 – 06/05/2015. 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. However, this paper will discuss the simulated data from all the living room spaces in Lugbe and Bwari (LGH1-LR, LGH2-LR, BWH1-LR and BWH2-LR) as well as the bedroom spaces in Lugbe and Bwari (LGH1-BR, LGH2-BR, BWH1-BR and BWH2-BR). In the simulated spaces, the dwelling code suffix H1 means naturally ventilated and those ending with H2 were air-conditioned.

Table 5: Summary of parameters input for the base modelling (LGH1 and LGH2)

Input parameters	Lugbe		Bwari	
	Value for model LGH1	**Value for model LGH2**	**Value for model BWH1**	**Value for model BWH2**
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
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
Ventilation	Natural ventilation-no heating/ cooling	Natural ventilation/ supplemented with air conditioning	Natural ventilation-no heating/ cooling	Natural ventilation/ supplemented with air conditioning
Natural ventilation rate (per person)	10 l/s	10 l/s	10 l/s	10 l/s
Density (people/m^2)	0.01	0.03	0.05	0.02
Total occupied floor area (m^2)	112	103	41	96
Total occupied floor volume (m^3)	428	308	123	294
Daytime & evening period	08:00 – 22:00	08:00 – 22:00	08:00 – 22:00	08:00 – 22:00
Evening period	18:00 – 22:00	18:00 – 22:00	18:00 – 22:00	18:00 – 22:00
Night-time-period	23:00 – 07:00	23:00 – 07:00	23:00 – 07:00	23:00 – 07:00
General lighting (W/m^2)	3.0	3.0	3.0	3.0
Exterior lighting (W)	60	60	60	60
Metabolic rate (Activity)	0.9	0.9	0.9	0.9
Metabolic rate (Clothing)	0.5clo	0.5clo	0.5clo	0.5clo

Input parameters	Lugbe		Bwari	
	Value for model LGH1	Value for model LGH2	Value for model BWH1	Value for model BWH2
Infiltration rate (ac/h)	1.0	1.0	1.0	1.0
Outside air change rate by zone. Living room (ac/h)	3.0	3.0	3.0	3.0
Outside air change rate by zone. Bedroom (ac/h)	2.0	2.0	2.0	2.0
Window to wall ratio (%)	25.0	25.0	23.0	30.0
Window to floor ratio	16%	30%	16%	25%
Window height	1.2 m	1.2 m	1.2 m	1.2 m
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
Floor to ceiling height (m)	3.0	3.0	2.8m	3.0
External wall, no bridging (U-Value)	2.03 W/m^2K	2.03 W/m^2K	2.03 W/m^2K	2.03 W/m^2K
Ceiling, no bridging 150mm (U-Value)	2.53 W/m^2K	2.53 W/m^2K	2.53 W/m^2K	2.53 W/m^2K
Roof, no bridging (U-Value)	7.14 W/m^2K	7.14 W/m^2K	7.14 W/m^2K	7.14 W/m^2K
Floor (U-Value)	1.4 W/m^2K	1.4 W/m^2K	1.4 W/m^2K	1.4 W/m^2K
Window (U-Value)	5.78 W/m^2K	5.78 W/m^2K	5.78 W/m^2K	5.78 W/m^2K
Orientation	North facing	North-east facing	South-west facing	North-west facing

3.4.1 Base model for case study 1: LGH1 (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. The spaces were also the most occupied spaces in the building. 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. The building has nine zones with the living room and the master bedroom representing the largst spaces and the most occupied throughout the day. Figure 5 shows the generated model for LGH1.

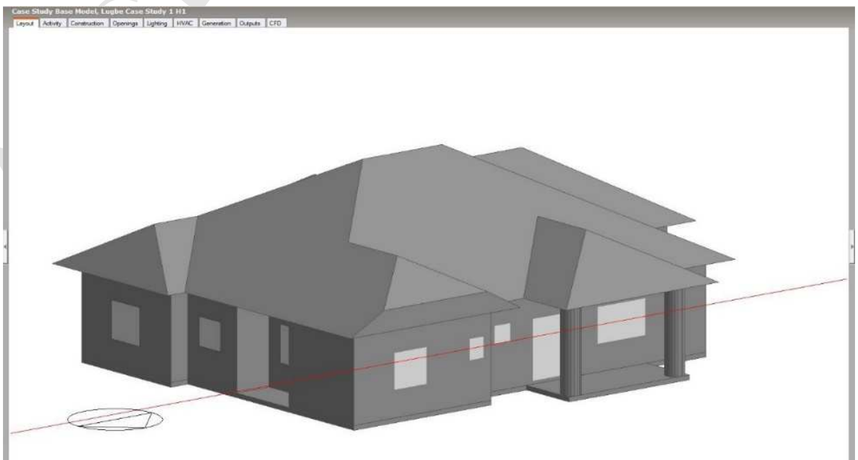


Figure 5: Generated Model for naturally ventilated case study dwelling Lugbe

3.4.2 Base model for case study 2: LGH2 (Air- conditioned)

This model was a two-bedroom north-east facing air-conditioned dwelling with a kitchen and dining room. The living room and master bedroom were selected for simulation (Figure 6). The building has seven zones with the living room and the master bedroom representing the air-conditioned spaces in the building. It has a main external 2.1 x 1.2 m steel door in the living room and another 2.1 x 0.9 m steel door in the kitchen and 1.2 x 1.2 m external window. Figure 5 shows the generated model for LGH2.

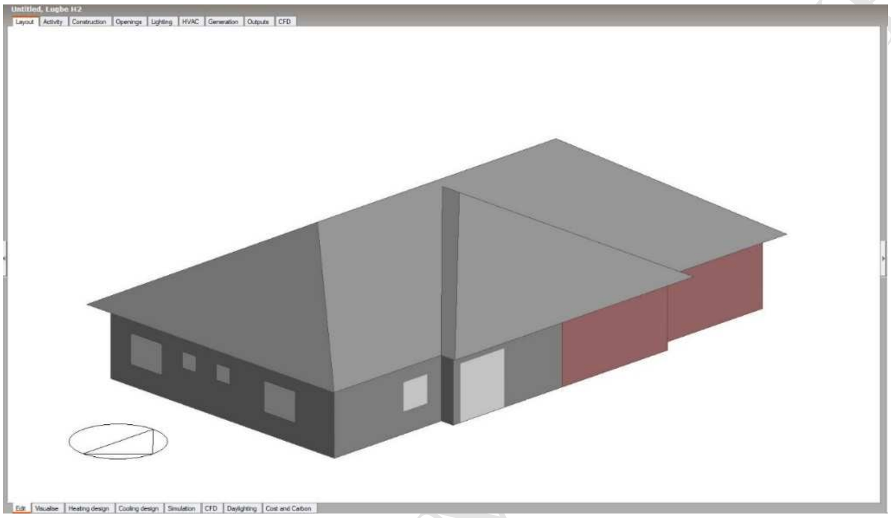


Figure 6: Generated Model for the air-conditioned case study dwelling in Lugbe

3.4.3 Base model for case study 1: BWH1 (Naturally ventilated)

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 2.1m x 0.9 m wooden doors. The floor to ceiling height is 2.8 m (Figure 7). The building has six zones with the living room and the master bedroom representing the largest spaces. The case study building is typically occupied during the day (Figure 7).

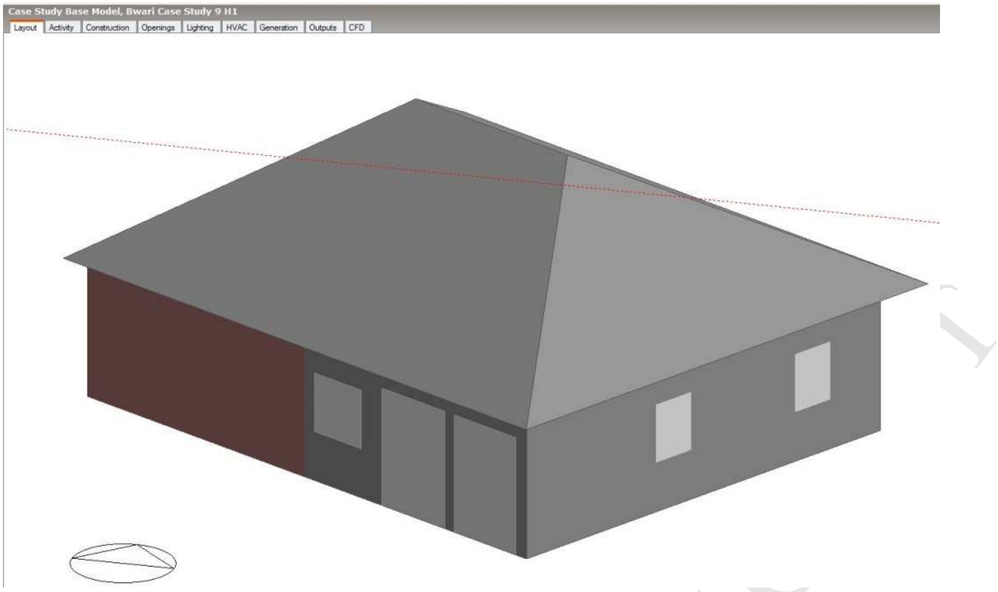


Figure 7: Generated Model for naturally ventilated case study dwelling in Bwari

3.4.4 Base model for case study 2: BWH2 (Air- conditioned)

This is north-west facing detached model is a two-bedroom house with a kitchen. The floor to ceiling height is 3.0 m (Figure 8). The building has seven zones with the living room and the master bedroom representing the air-conditioned spaces in the building.

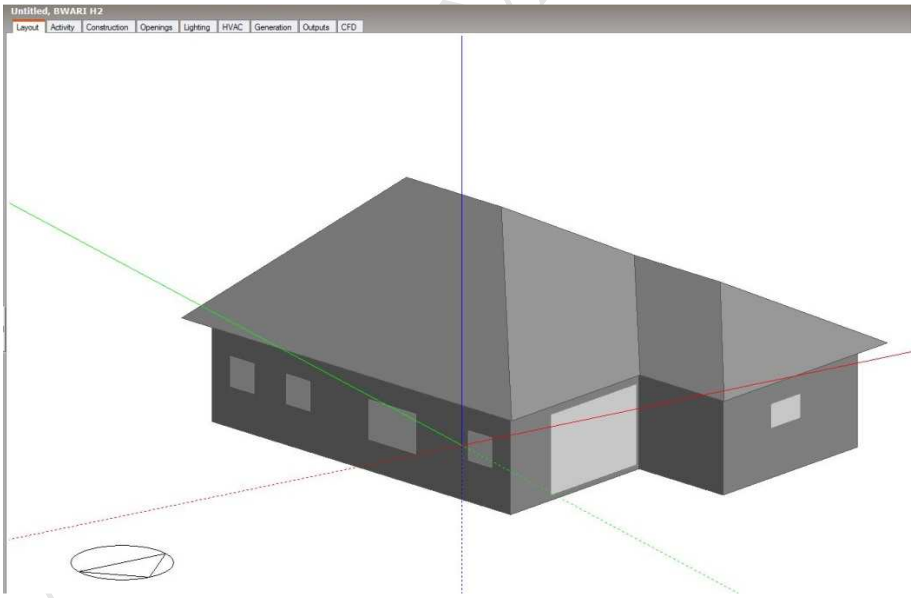


Figure 8: Generated Model for the air-conditioned case study dwelling in Bwari

4. Results and discussions

4.1 Post-occupancy survey

The POE results showed that most low-income earners were also found to use less air conditioning for cooling compared to low-middle and middle-income earners as over 48% of the houses in Dutse Alhaji and 53% of the houses in Bwari do not have air conditioning. The finding contrasts with the results obtained from Lugbe. More than 80% of houses in Lugbe have air conditioning compared to 84% of houses in Mpape that do not have air-conditioning as shown in Table 6. The result across the case study buildings shows a strong relationship between low-income areas and the availability of air-conditioning ($r = 0.837$, $p<0.005$).

Table 6: Summary of respondents' use of air conditioning during the POE

		Lugbe (n=43)		Mpape (n=44)		Dutse Alhaji (n=43)		Bwari (n=41)		Combined (n=222)	
		S.S.	%	S.S.	%	S.S.	%	S.S.	%	S.S.	%
Houses with AC	**Yes**	35	81.4	7	15.9	22	51.2	19	46.3	118	53.2
	No	8	18.6	37	84.1	21	48.8	22	53.7	104	46.8

Table 7 shows the responses regarding use of indoor controls like open widows, electric fans and air conditioning for indoor comfort control ranged from 'slightly much' to 'very much' with the votes skewed to the 'slightly much' response. The results showed that between 50% and 80% of the residents either used open widows, electric fans or air conditioning at some point to change the thermal environment of the buildings from an uncomfortable to a more comfortable state. The votes for the level of satisfaction with the use of controls were spread across 'dissatisfied' to 'satisfied', with up to 80% of respondents indicating to be in this range, (Table 7). With the satisfaction votes skewing towards slightly dissatisfied and neutral responses, the result suggests that most people were either 'slightly dissatisfied', 'neutral' or 'slightly satisfied' with their use of controls through the dry season regardless of their socio-economic status. Although a different outcome was obtained from the respondents that use of alternative energy of sources (i.e. diesel or petrol-powered generators) for cooling. The study identified that the lack of constant power supply might be a contributing factor to higher slightly dissatisfied to neutral responses reported on control satisfaction at the case study buildings. The results also showed that residents in Lugbe tend to take more cold water as a means of achieving thermal comfort during the day as they have more electricity supply to operate their refrigerators compared to the residents of the other case studies.

Table 7: Summary of respondents' use of indoor controls during the POE in dry season

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

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Bwari (n=41)		Combined (n=222)	
		S.S.	%	S.S.	%	S.S.	%	S.S.	%	S.S.	%
	Very satisfied	1	2.3	0	0.0	0	0.0	0	0.0	3	1.4

S.S. = Sample Size

Across the buildings surveyed during the POE, the results showed an overwhelming response for the warm/hot part of the scale in the dry season. More than 76% of the occupants were feeling ‘warm’ and ‘hot’ (Table 8) and with over 50% of ‘warm’ votes. The occupants in Dutse Alhaji had the highest levels of warm/hot sensation responses with over 86% and a highest mean thermal sensation value of 6.0 as shown in Table 8. Over 70% of the respondents in other case studies indicated to be warm or hot.

A 7-point scale (from 1 for very uncomfortable to 7 for very comfortable) was used for the overall thermal comfort. There was an almost even distribution of the comfort votes in Lugbe where 49.5% were dissatisfied, i.e. only slightly skewed towards discomfort. However, 81% of the respondents in Dutse Alhaji indicated they were uncomfortable within the thermal environment. The results revealed that the thermal environment has been influenced by the air conditioning in these buildings, as houses in Lugbe have more air conditioning compared to those in Dutse Alhaji. The findings of the thermal comfort showed an overwhelming response for the uncomfortable/very uncomfortable part of the scale in the dry season across all the case studies (Table 8). At least 70% of the occupants perceived to be ‘uncomfortable’ or ‘very uncomfortable’ at Mpape, Dutse Alhaji and Bwari with the mean vote focusing around being uncomfortable. However, in Lugbe there is a noticeable spread of thermal comfort votes with more than 90% of the responses spread almost evenly across the ‘very uncomfortable’ to ‘slightly uncomfortable’ part of the scale. The mean vote focusing around neutrality.

The thermal preference was evaluated on a 5-point scale (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 case study dwellings (Table 8). More than 80% of the occupants preferring to be ‘much cooler’ and ‘cooler’ and the mean responses across all case study locations focuses around the ‘cooler’ part of the scale (Table 9).

The thermal satisfaction was measured on a 7-point scale (1 for very dissatisfied to 7 for very satisfied). The findings revealed at least 70% of the occupants were not satisfied with their thermal environment (Table 8). A further breakdown of the thermal satisfaction responses within all the case studies shows that the occupants’ in Dutse Alhaji had the highest dissatisfied responses. More than 90% of the occupants’ indicating they were either ‘very dissatisfied’, ‘dissatisfied’ or slightly dissatisfied’ compared to the lowest of 39.5% recorded in Lugbe. Lugbe also had the highest neutral and thermal satisfaction responses of 23.3% and 37.2% respectively, (Table 8) and a mean thermal preference response of 3.9 (Table 9).

Table 8: Summary of respondents’ indoor thermal conditions during the POE in dry season

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Bwari (n=41)		Combined (n=171)	
		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
	Cool	0	0.0	0	0.0	1	2.3	0	0.0	1	0.6
	Slightly cool	1	2.3	0	0.0	2	4.7	0	0.0	3	1.8

		Lugbe (n=43)		Mpape (n=44)		Dutse Alh. (n=43)		Bwari (n=41)		Combined (n=171)	
		S.S.	%	S.S.	%	S.S.	%	S.S.	%	S.S.	%
	Neutral	1	2.3	1	2.3	1	2.3	3	7.3	6	3.5
	Slightly warm	9	20.9	12	27.3	2	4.7	7	17.1	30	17.5
	Warm	28	65.1	22	50.0	22	51.2	21	51.2	93	54.4
	Hot	4	9.3	9	20.5	15	34.9	10	24.4	38	22.2
Indoor Thermal comfort	**Very uncomfortable**	1	2.3	10	22.7	7	16.3	8	19.5	26	15.2
	Uncomfortable	8	18.6	20	45.5	22	51.2	21	51.2	71	41.5
	Slightly uncomfort.	11	25.6	7	15.9	6	14.0	7	17.1	31	18.1
	Neutral	12	27.9	3	6.8	3	7.0	2	4.9	20	11.7
	Slightly comfortable	8	18.6	4	9.1	5	11.6	3	7.3	20	11.7
	Comfortable	3	7.0	0	0.0	0	0.0	0	0.0	3	1.8
	Very comfortable	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Thermal preference	**Much cooler**	12	27.9	26	59.1	27	62.8	20	48.8	85	49.7
	Cooler	23	53.5	12	27.3	10	23.3	13	31.7	58	33.9
	No change	8	18.6	6	13.6	6	14.0	7	17.1	27	15.8
	Warmer	0	0.0	0	0.0	0	0.0	1	2.4	1	0.6
	Much warmer	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Thermal Satisfaction	**Very dissatisfied**	1	2.3	4	9.1	13	30.2	4	9.8	22	12.9
	Dissatisfied	7	16.3	22	50.0	18	41.9	11	26.8	58	33.9
	Slightly dissatisfied	9	20.9	12	27.3	8	18.6	12	29.3	41	24.0
	Neutral	10	23.3	6	13.6	4	9.3	12	29.3	32	18.7
	Slightly satisfied	11	25.6	0	0.0	0	0.0	2	4.9	13	7.6
	Satisfied	4	9.3	0	0.0	0	0.0	0	0.0	4	2.3
	Very satisfied	1	2.3	0	0.0	0	0.0	0	0.0	1	0.6

Table 9: Mean responses for the thermal sensation, thermal comfort, thermal preference and thermal satisfaction during the POE in dry season

		Thermal sensation		Thermal comfort		Thermal preference		Thermal satisfaction		Gender	
Location	**N(%)**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**Male (%)**	**Female (%)**
Lugbe	43 (78)	5.8	0.751	3.6	1.254	1.91	0.684	3.9	1.394	66.6	33.3
Mpape	44 (80)	5.9	0.754	2.3	1.18	1.55	0.73	2.5	0.848	66.6	33.3
Dutse A.	43 (80)	6.0	1.144	2.5	1.202	1.51	0.736	2.1	0.936	50.0	50.0
Bwari	41 (79)	5.9	0.848	2.3	1.078	1.73	0.837	2.9	1.081	66.6	33.3

Applying Pearson correlation to find relationship between thermal satisfaction and thermal comfort, the result shows that thermal satisfaction and thermal comfort are correlated in Mpape, ($R = 0.562$, $p < 0.05$) with no correlations found in other case studies. The respondents that are thermally dissatisfied where also thermally uncomfortable ($r = 0.880$, $p<0.005$). Further analysis revealed that more than 80% of the buildings surveyed do no use air conditioning regularly during the dry season for adjusting the thermal environment of the indoor spaces. The outcome might be due to lack of finances to acquire air-conditioning, lack of constant power supply, and the high cost of electricity especially using alternative power supply systems.

Considering the overall urban design of Mpape, the finding shows the buildings were clustered and this may be a contributing factor, as fresh air is not properly circulated within the buildings. This finding may also contribute to higher thermal dissatisfaction reported at Mpape as it can reduce the indoor air quality within the thermal environment. 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 ($r = 0.877$, $p<0.005$). However, at Lugbe, the lowest level of dissatisfaction was recorded by the middle-income earners with the low-middle earners responses focusing around neutrality ($R = 0.045$, $p < 0.05$). Correlations are found between socio-economic status and thermal comfort in Dutse Alhaji and Bwari during the dry season, where significance was noted as $r = 0.384$, $p < 0.05$ in Dutse Alhaji, and $R = 0.577$, $p < 0.05$ in Bwari. The findings revealed that the low-income and low-middle-income earners are less comfortable within the thermal environment when compared to the middle-income earners.

4.2 Environmental monitoring

The measured outdoor temperature had a running mean temperature, $T_{rm,}$ for the dry season (Figures 9 and 10) as defined by BSENI 15251 (BSI, 2008)[1] varied from 32°C on 23/03/2015 to a maximum of 33.3°C on 21/03/2015 in Lugbe. In Mpape the running mean temperature varied from 29.3°C on 01/04/2015 to a maximum of 31°C on 06/04/2015, and it varied from 30.8°C 11/04/2015 to a maximum of 31.4°C on 17/04/2015 in Dutse Alhaji. In Bwari, the temperature varied from 31°C on 04/05/2015 to a maximum of 32°C on 01/05/2015 during the period of monitoring in the dry season.

Concerning the measured temperatures within the indoor spaces of the case study buildings, higher maximum and minimum day-time temperatures were observed at Lugbe. At (LGH1 – naturally ventilated), a maximum temperature of 36.2°C which was the warmest of all the naturally ventilated case study buildings compared to 32.7°C recorded in LGH2 (air-conditioned building) as shown in Figure 9. The result showed that LGH1 is the warmest monitored building in Lugbe with a mean temperature of 32°C (Table 10). The average indoor temperature between 08:00 and 22:00 in the monitored living areas in Lubge was 32.1°C while 31.2°C was recorded in the bedrooms from 23:00 – 07:00 (Table 11). The living rooms recorded the warmest temperatures in the buildings 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. (Table 10).

A maximum daytime temperature of 33.5°C was recorded in both the naturally ventilated monitored buildings in MPH1 and MPH2 at Mpape (Table 10 and Figure 11), where MPH2 was the warmest with a mean temperature of 30.1°C, though it was just 0.4°C more than MPH1. The average temperature between 08:00 and 22:00 in the monitored living areas in was 30.2°C and 30.8°C from 18:00 – 22:00. The living room recorded the hottest temperature in the buildings 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 29.7°C for the bedrooms.

[1] The running mean of external temperature (T_{rm}) is described 'as an exponentially weighted running mean of the daily average outdoor temperature'. Θ_{ed} is the series. It is computed from the formula: $\Theta_{rm} = (1 - \alpha).\{ \Theta_{ed-1} + \alpha. \Theta_{ed-2} + \alpha^2 \Theta_{ed} - 3 \ldots\}$. Where, Θ_{rm} = Running mean temperature for today, Θ_{rm-1} = Running mean temperature for previous day, Θ_{ed-1} = daily mean external temperature for the previous day, Θ_{ed-2} = daily mean external temperature for the day before and so on. a is a constant between 0 and 1, usually, $\alpha = 0.8$ (Nicol et al., 2009; Lomas and Giridharan, 2012; Adekunle and Nikolopoulou, 2016).

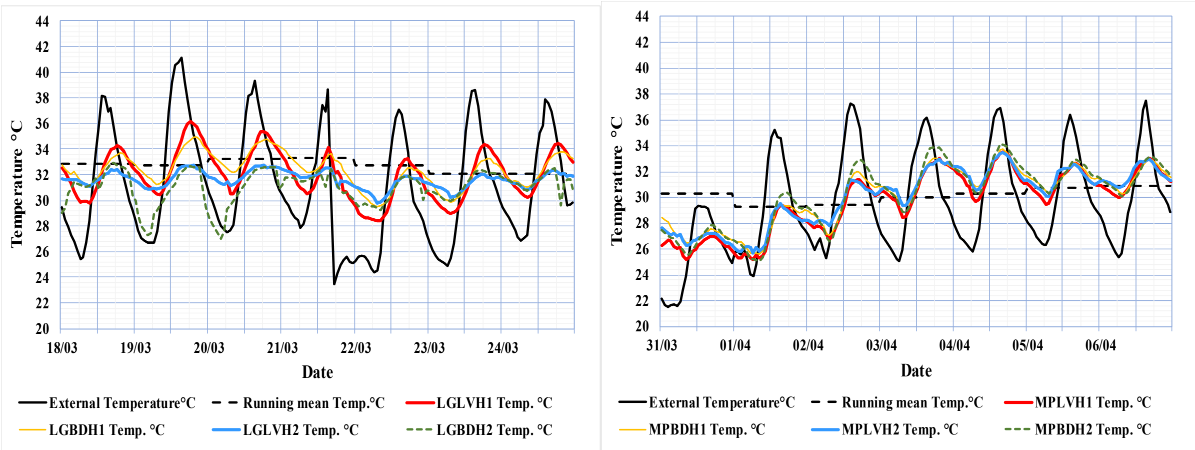


Figure 9: Living rooms and bedrooms monitored in two different buildings in Lugbe (Left) and Mpape (Right) during the dry season

In Dutse, DAH2 (air-conditioned), a maximum temperature of 37.2°C was recorded in the building compared to a maximum of 35.7°C recorded in DAH1 (naturally ventilated building). The finding contradicts from the general assumption that air-conditioned buildings should be much cooler than 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 and the mean value was 34.8°C between 18:00 and 22:00 (Table 10). The warmest temperature was recorded in the living room in the buildings with a mean of 33.6°C and a maximum temperature of 36.4°C. The average temperature between 23.00 and 07.00 was 31.8°C for the bedrooms. The findings showed that the spaces in DAH2 are not cross-ventilated, therefore reducing the possibility of air circulating properly within the indoor spaces and increasing the indoor temperature. The additional comments obtained from the survey participants revealed that the air conditioning was not functioning well for several days of the survey due to a breakdown of the system. The occupant also commented that there was poor electricity supply in the area during the survey period.

In Bwari, a maximum temperature of 36.0°C was recorded in BWH1 (naturally ventilated) monitored building while a maximum temperature of 31.5°C was observed in BWH2 (air-conditioned as shown in Figure 10. BWH1 was the warmest building in Bwari with a mean temperature of 31.9°C, which was 2.6°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 from 18:00 – 22:00 and 29.2°C in BWH2 (Table 10). The average temperature between 23:00 and 07:00 was 30.7°C for the bedrooms with a maximum of 33.6°C (Table 11 and Figure 12). On the one hand, the living room in BWH1 was warmer than the bedroom. On the other hand, the bedroom was warmer than the living room in BWH2.

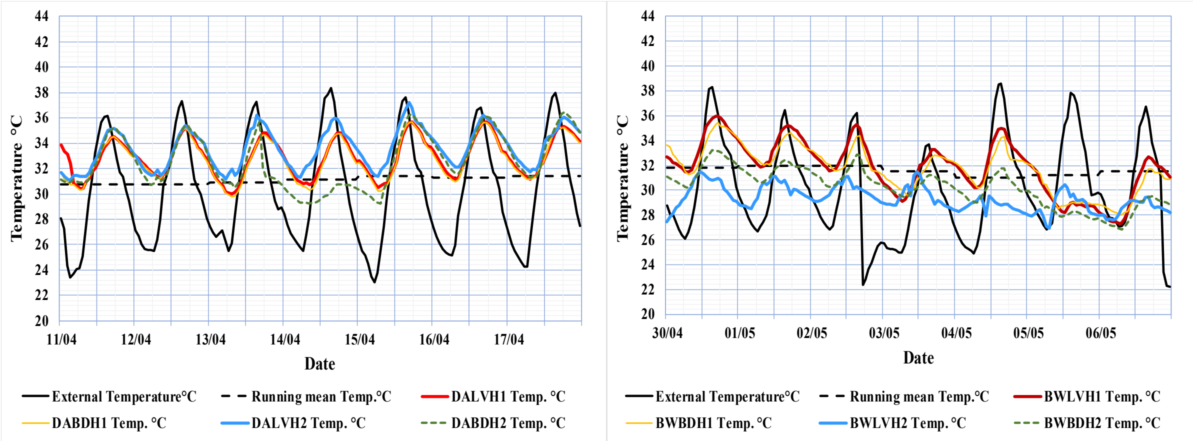


Figure 10: Living rooms and bedrooms monitored in two different buildings in Dutse Alhaji (Left) and Bwari (Right) during the dry season

Table 10: Summary of monitored indoor daytime 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-LR	36.2	28.4	32.4	36.2	30.7	33.9	36.2	28.4	32.0
LGH2-LR	32.7	29.8	31.7	32.7	31.1	32.1	32.7	29.8	31.6
MPH1-LR	33.5	25.2	30.1	33.4	26.2	30.8	33.5	25.2	29.7
MPH2-LR	33.5	25.8	30.4	33.3	26.5	30.8	33.5	25.7	30.1
DAH1-LR	35.7	30.0	33.3	35.7	33.4	34.6	35.7	30.0	32.9
DAH2-LR	37.2	31.4	34.2	36.8	34.0	35.2	37.2	31.1	33.6
BWH1-LR	36.0	27.3	32.3	36.0	28.7	32.9	36.0	27.3	31.9
BWH2-RR	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
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 11: 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-BR	34.4	29.6	32.2	34.9	29.5	32.4
LGH2-BR	32.6	27.0	30.2	32.9	27.0	31.0
MPH1-BR	32.5	25.7	29.7	33.8	25.6	30.1
MPH2-BR	32.9	25.2	29.6	34.2	25.03	30.2
DAH1-BR	34.3	30.0	31.9	35.7	29.8	32.8
DAH2-BR	35.2	29.3	31.7	36.5	29.2	32.6
BWH1-BR	34.6	28.1	31.6	35.4	28.0	31.7
BWH2-BR	32.3	26.9	29.9	33.2	26.8	30.2

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
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
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.

Across the period of monitoring across all case studies, the findings revealed there is a relationship between the outdoor temperatures and the living room ($r = 0.6$, $p<0.005$) and bedroom temperatures ($r = 0.5$, $p<0.005$). About 80% of the reported temperatures in the living rooms were warmer than the temperatures observed in the bedroom due to higher hours of occupation during the day. The indoor relative humidity during the survey in dry season had a minimum and maximum of 27% and 72% for Lugbe, 15% and 67% for Mpape, 15% and 66% in Dutse Alhaji and 37% and 80% for Bwari. The results showed that all the values reported for relative humidity at the case studies exceed or fall below the comfort limit of 40% - 60% for the associated temperatures.

The study showed that LGH1 (naturally ventilated living room) was the hottest space in the naturally ventilated case study buildings. DAH2 (air-conditioned living room) was the warmest space in the air-conditioned case study buildings. The occupants in Lugbe and Dutse Alhaji experienced higher temperatures compared to the occupants in the remaining case study buildings. The lack of air circulation within the case studies at Lugbe and Dutse Alhaji might be a contributing factor to higher temperatures reported in the buildings.

4.3 Thermal comfort survey

The thermal sensation analysis shows a distribution clustered above the central categories with more than two-thirds of the responses feeling ‘uncomfortably warm’ with a moderately even distribution of votes varying between ‘neutral’ and ‘warm’ (Table 12). While Table 13 shows the mean values and standard deviation of thermal sensation in each case study buildings

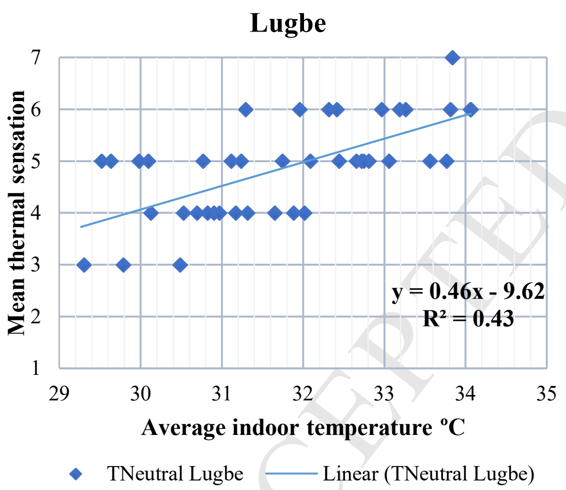
Table 12: Summary of responses on thermal sensation during the comfort survey.

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

Table 13: Mean responses of thermal sensation during the comfort survey in the dry season

Case study	Thermal sensation	
	Dry season	
	Mean	SD
LGH1 (NV)	5.4	1.15
LGH2 (AC)	5.0	0.84
MPH1 (NV)	5.3	1.27
MPH2 (NV)	5.8	0.79
DAH1 (NV)	5.9	0.80
DAH2 (AC)	5.0	0.82
BWH1 (NV)	5.4	1.27
BWH2 (AC)	3.7	1.76

Linear regression analysis was used to calculate neutral and preferred temperatures (Figure 11) and the results showed the temperatures were in a range of 28°C to 30°C. The finding showed that occupants in this region can adapt to elevated temperatures. The results revealed that the residents in Lugbe indicated a higher neutral temperature of 29.6°C and preferred temperature of 28.3°C, compared to the occupants in Dutse Alhaji with a lower neutral temperature of 28.2°C and lower preferred temperature of 25.4°C.



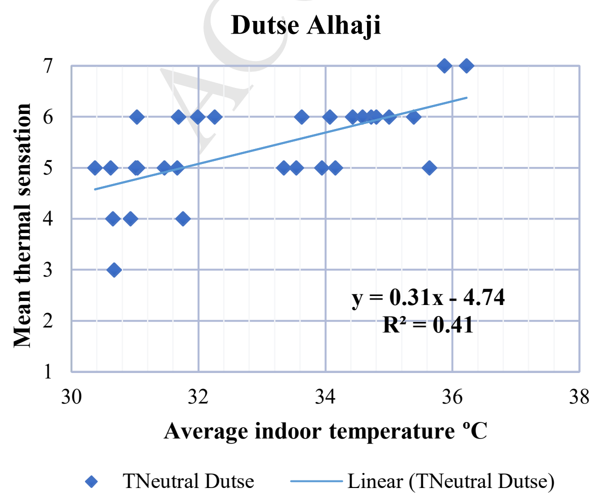


Figure 11: Relationship between the mean thermal sensation and the average indoor temperature at Lugbe (left) and Dutse Alhaji (right) during the dry season

4.4 Evaluation of the risk of overheating

The results on the evaluation of the risk of overheating are presented below.

4.4.1 The Static CIBSE comfort model

The assessment of risk of overheating using the CIBSE comfort model revealed the temperatures exceed the 28°C for 100% of the monitored hours in all the living rooms (that is, 100%). The monitored temperatures also exceed the 26°C for 100% of the time in all the bedrooms. Considering the day (08:00 – 22:00), the measured temperatures also exceed the 28°C in 100% of the living rooms. At night-time (23:00 – 07:00), the monitored temperatures were also above the 28°C mark in 100% of the bedrooms monitored at the buildings (Figure 12).

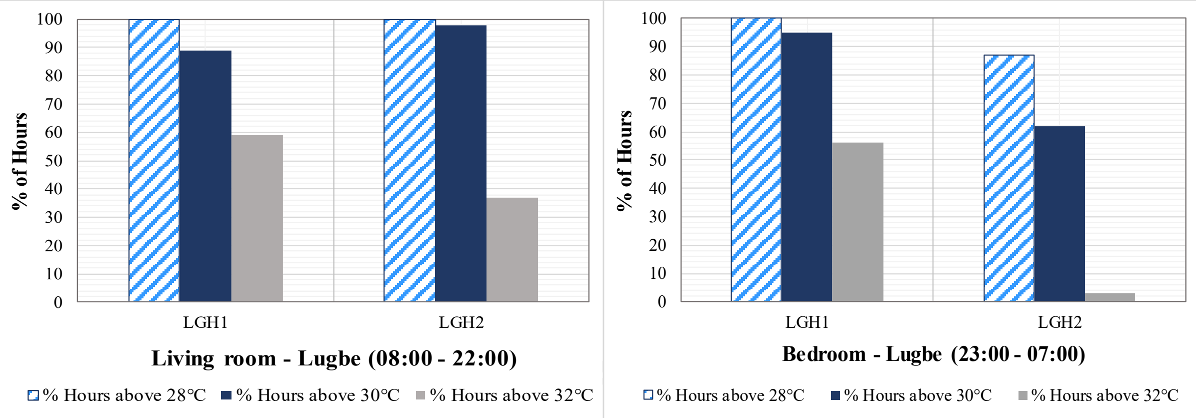


Figure 12: The Static CIBSE Comfort Model for the monitored temperatures at Lugbe

4.4.2 The dynamic adaptive comfort model in Lugbe

Regarding the adaptive thermal comfort for assessment of the risk of overheating, in the living room (LGH1-LR), the recorded temperatures exceed the Cat. II upper threshold for more than 70% of the time. The temperatures also exceed the Cat. III upper threshold for more than 10% of the time during the day and evening period (08:00-22:00). The bedroom in LGH1 recorded temperatures exceed the Cat. II upper threshold for more than 30% of the time and rose above the Cat. III upper marker for 10% of the time. The results showed extreme indoor thermal conditions within the case study buildings at Lugbe during the daytime and night time (Figure 13).

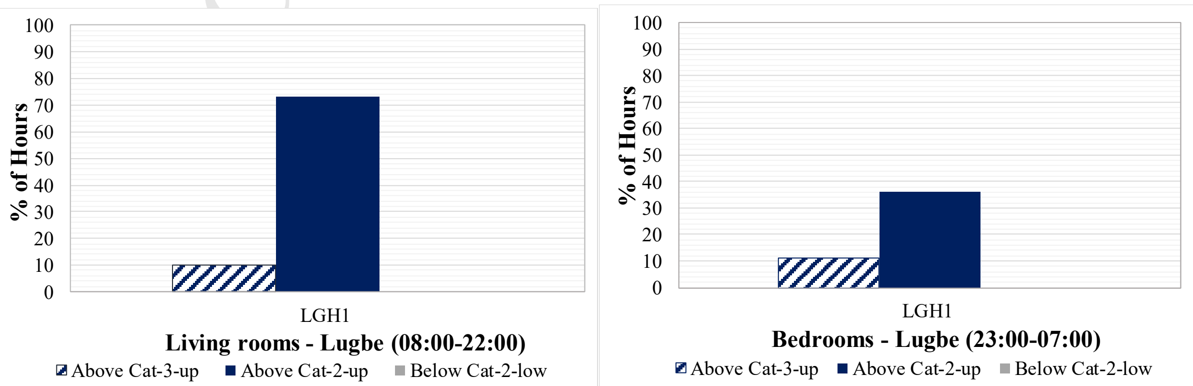


Figure 13: The dynamic EN15251 adaptive comfort model - Percentage of hours of the monitored temperatures in the living room and bedroom at Lugbe using dynamic EN15251 adaptive comfort model.

In Bwari, the adaptive thermal comfort for assessment of the risk of overheating, in the living room (BWH1-LR), the recorded temperatures exceed the Cat. II upper threshold for more than 35% of the time. The temperatures also exceed the Cat. III upper threshold for more than 10% of the time during the day and evening period (08:00-22:00). The bedroom in BWH1 recorded temperatures exceed the Cat. II upper threshold for more than 25% of the time and rose above the Cat. III upper marker for 10% of the time. The results showed extreme indoor thermal conditions within the case study buildings at Bwari during the daytime and night-time (Figure 14).

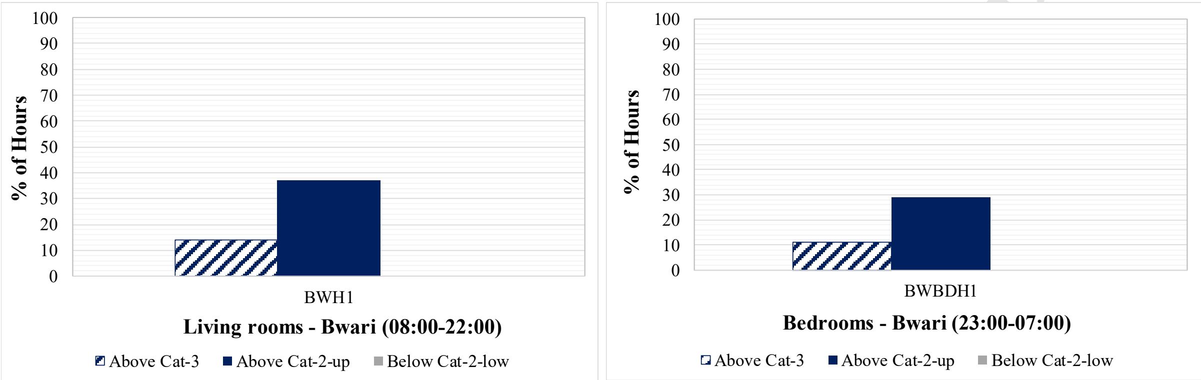


Figure 14: The dynamic EN15251 adaptive comfort model - Percentage of hours of the monitored temperatures in the living room and bedroom at Bwari using dynamic EN15251 adaptive comfort model.

4.5 Building modelling and simulation

4.5.1 Outdoor weather data

The simulated temperature for Lugbe had a maximum outdoor temperature of 44°C on 22/03/2002 at 14:00 (Figure 15). 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 had a maximum temperature of 31.6°C and a mean temperature of 31°C. The analysis showed the high outdoor temperatures that applied during the simulated dry season period.

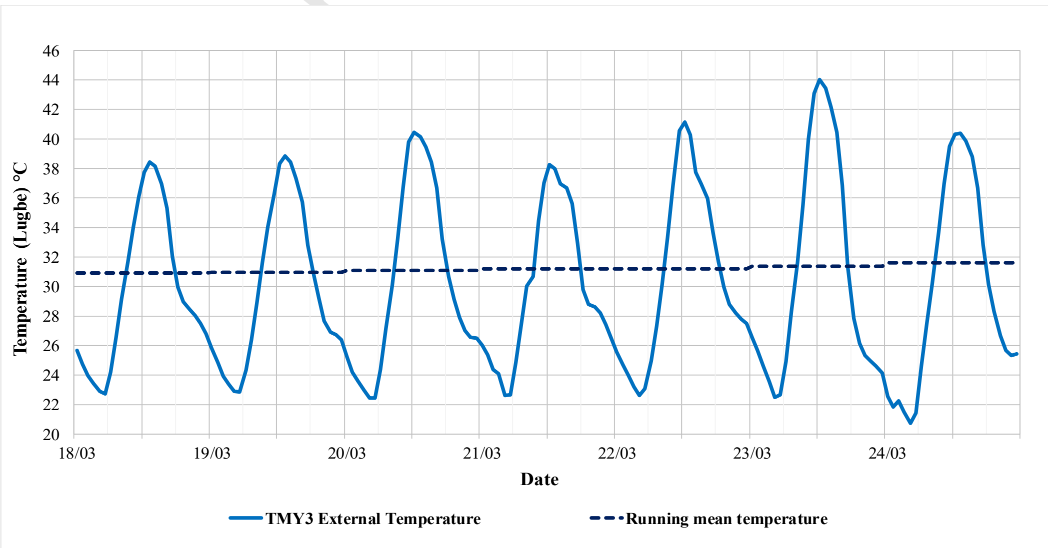


Figure 15: Abuja TMY3 weather file outdoor temperature used for Lugbe simulations

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 16). Although the weather file temperatures used for Bwari were lower than the temperatures used for Lugbe, the analysis still showed the average temperatures above 28°C.

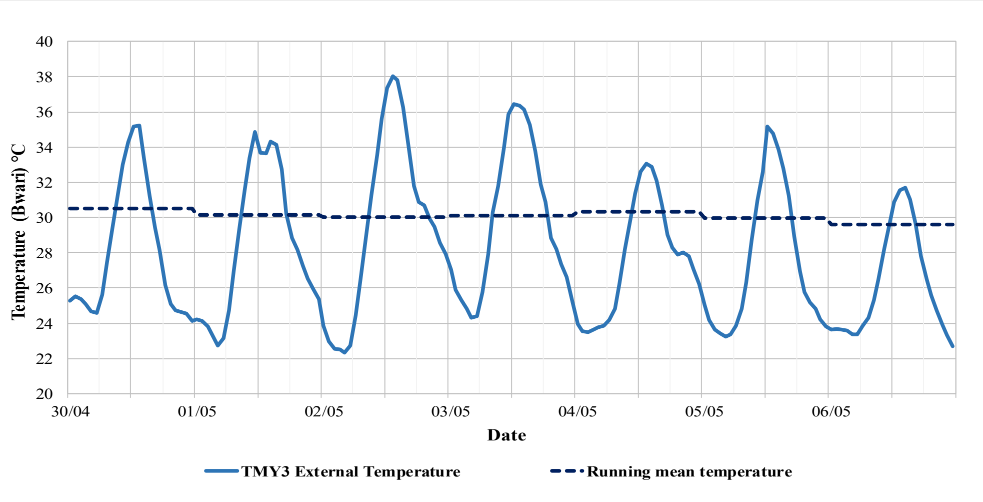


Figure 16: Abuja TMY3 weather file outdoor temperature for Bwari

4.5.2 The predicted indoor temperatures for Lugbe and Bwari

Since the results showed that the case study buildings in Lugbe are one of the warmest. Moreover, the warmest period of monitoring was considered in Lugbe, therefore the study focused on simulations of LGH1 and LGH2 in Lugbe to understand the thermal environment of the buildings for the same period of the environmental monitoring and the whole dry season. Simulations for the models in Lugbe were carried out for a week from 18/03/2015 – 24/03/2015 in the naturally ventilated spaces (LGH1-LR and LGH1-BR) and air-conditioned spaces (LGH2-LR and LGH2-BR). The maximum predicted temperatures in the all the spaces in Lugbe were above 34ºC (Figure 17) with an average above 29ºC indicating high temperatures within the buildings. Table 14 summarizes the simulated indoor temperatures for the case study buildings in Lugbe. The results showed the living room is warmer than the bedroom in the naturally ventilated model (LGH1). However, higher internal temperatures are predicted in the bedroom than the living room in the air-conditioned model (LGH2). The model (LGH2) shows an active air-conditioning in the living room from 18:00-22:00, therefore contributing to the overall lower temperatures in the space (LGH2-LR).

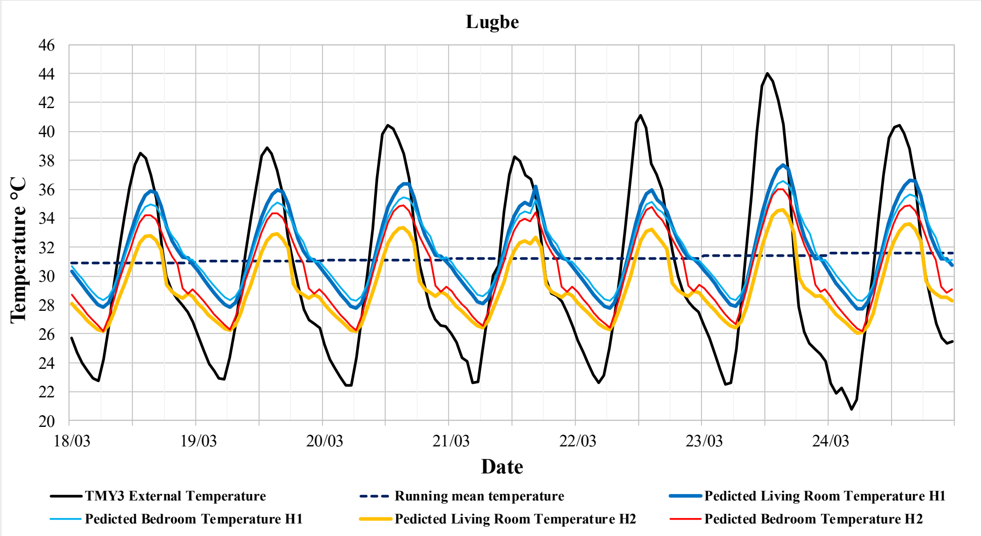


Figure 17: Predicted temperatures in the living rooms and bedrooms for the naturally ventilated (LGH1) and air-conditioned (LGH2) models at Lugbe using Abuja TMY3 external temperature.

Table 11: Maximum, minimum, and average predicted temperatures in the living rooms and bedrooms at Lugbe

	TMY3 Weather File Temp. °C	Living room PDT Temp. °C LGH1-LR	Bedroom PDT Temp. °C LGH1-BR	Living room PDT Temp. °C LGH2-LR	Bedroom PDT Temp. °C LGH2-BR
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

4.5.3 Thermal performance comparison between the naturally ventilated and air-conditioned model

The result for the naturally ventilated model between the living room and the bedroom shown in Figure 18, 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 finding 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 the external temperature exceeds 31°C for Lugbe. Even when the external temperature is predicted to rise above 40ºC, the difference between the external and internal temperature in the living room is not significant. The regression analysis shows a strong relationship exists between the outdoor and indoor temperatures in the living room (r^2 = 0.71), and bedroom (r^2 = 0.64).

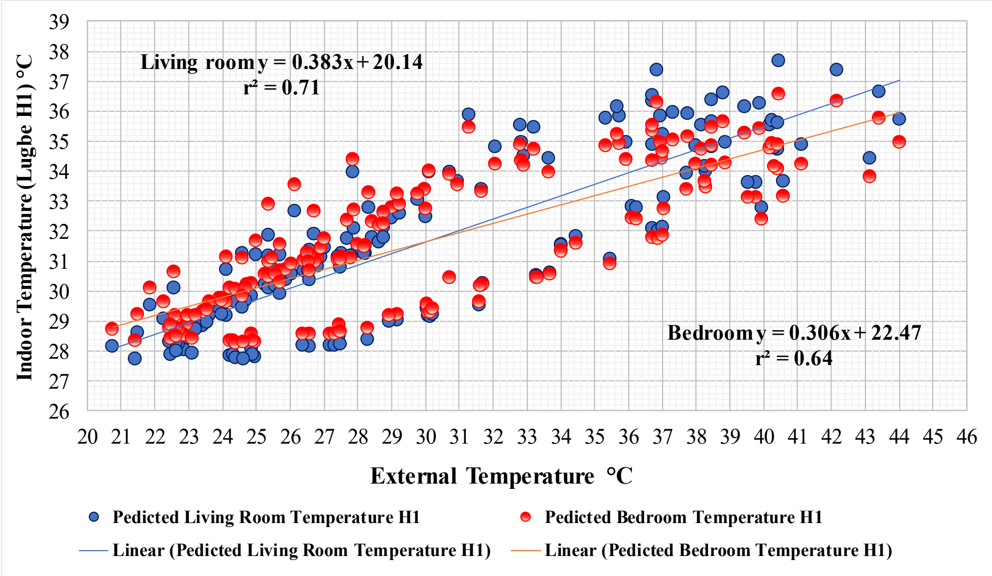


Figure 18: Relationship between the simulated internal temperature in the living room and the bedroom of the naturally ventilated model (LGH1) at Lugbe and the external temperature using Abuja TMY3.

The comparison between the naturally ventilated living room (LGH1-LR) and the air-conditioned living room (LGH2-LR) in Figure 19, shows that LGH1-LR was warmer and has a higher temperature adaptation range than LGH2-LR. The finding also shows that when the external temperature rises above 22ºC, the predicted temperatures in LGH1-LR tend to drift towards extreme elevated temperatures. The difference in temperature between the living rooms is around 2.0ºC when the external temperature rises above is 20ºC. The result shows a strong relationship is found between the outdoor and indoor temperature where in the living room ($r^2 = 0.71$), and bedroom ($r^2 = 0.81$).

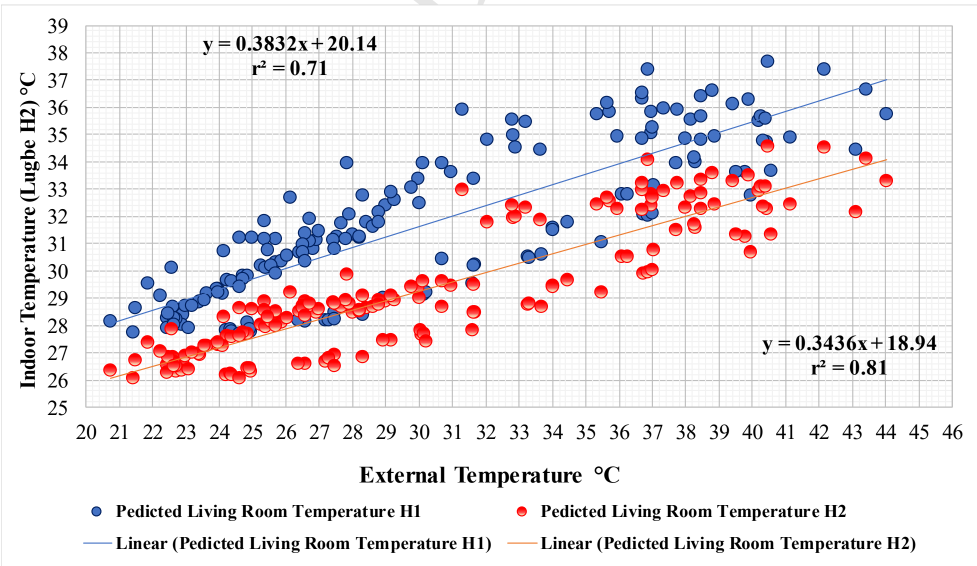


Figure 19: Relationship between the simulated temperatures in naturally ventilated living room (LGH1-LR) and air-conditioned the living room (LGH2-LR) at Lugbe and the external temperature using Abuja TMY3.

Considering the naturally ventilated (LGH1-BR) and air-conditioned (LGH2-BR) bedrooms for analysis, the result shows that LGH1-BR is predicted to be warmer than LGH2-BR throughout the simulation period (Figure 20). The study reveals that when the external temperature rises above 20ºC, all the predicted temperatures in LGH1-BR exceed 28ºC. The difference in temperature was around 2.0ºC when the external temperature was below 28ºC.

However, the difference reduces to about 0.5 ºC when the external temperature increases to 30ºC. The regression analysis shows there is a strong relationship between the outdoor and indoor temperature where in LGH1-BR (r^2 = 0.64) and, LGH2-BR (r^2 = 0.77).

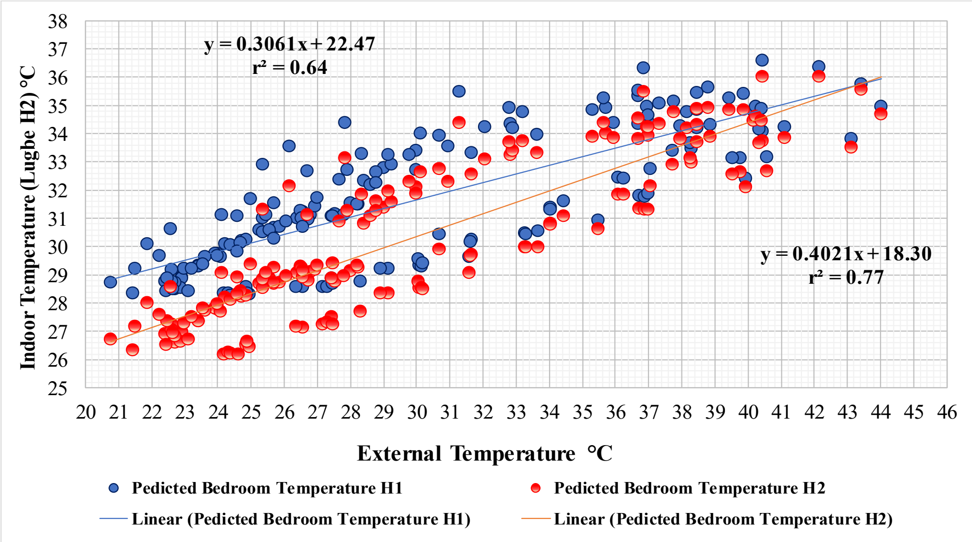


Figure 20: Relationship between the simulated temperatures in the naturally ventilated bedroom and the air-conditioned bedroom at Lugbe and the external temperature using Abuja TMY3.

In the air-conditioned model (LGH2) in Lugbe as shown in Figure 21, the study 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), and bedroom (r^2 = 0.77).

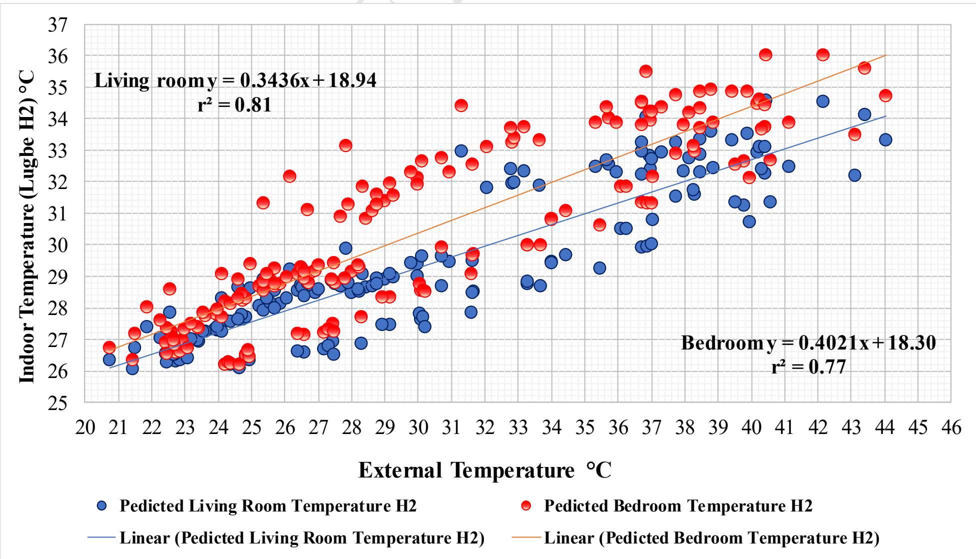


Figure 21: Relationship between the simulated temperatures in the living rooms and the bedroom in the air-conditioned dwelling at Lugbe and the external temperature using Abuja TMY3.

Across all the case study buildings at Lugbe, the average indoor temperature was within the comfort range (28-30ºC) until outdoor temperature exceeds 30.0ºC. The result reveals comfort is within a wider range at the naturally ventilated spaces than the air-conditioned spaces at Lugbe. The study also shows there is a strong correlation between the simulated internal temperature and the external temperature in the buildings at Lugbe.

4.5.4 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 mean monitored temperatures in the naturally ventilated living room (LGH1-LR) 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 15).

Table 15: Maximum, minimum and average measured and predicted temperatures in the living room and bedroom in the naturally ventilated dwellings (LGH1) 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 temperature measured in the living room (LGH2-LR) of 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 temperature in the bedroom (LGH2-BR) was 3°C more than the measured temperature (Figure 22). The maximum predicted temperatures in the living room are higher than the predicted temperatures in the bedroom by more than 1°C. However, the result shows there is no significant difference between the measured maximum and average temperatures in the living room and bedroom temperatures. The reported minimum temperature in the living room is about 2°C higher than the temperature observed in the bedroom (Table 16). The comparison between the measured and simulated internal temperatures for the naturally ventilated spaces at Lugbe shows the occupants are likely to be exposed to elevated temperatures above 28°C for several hours per day.

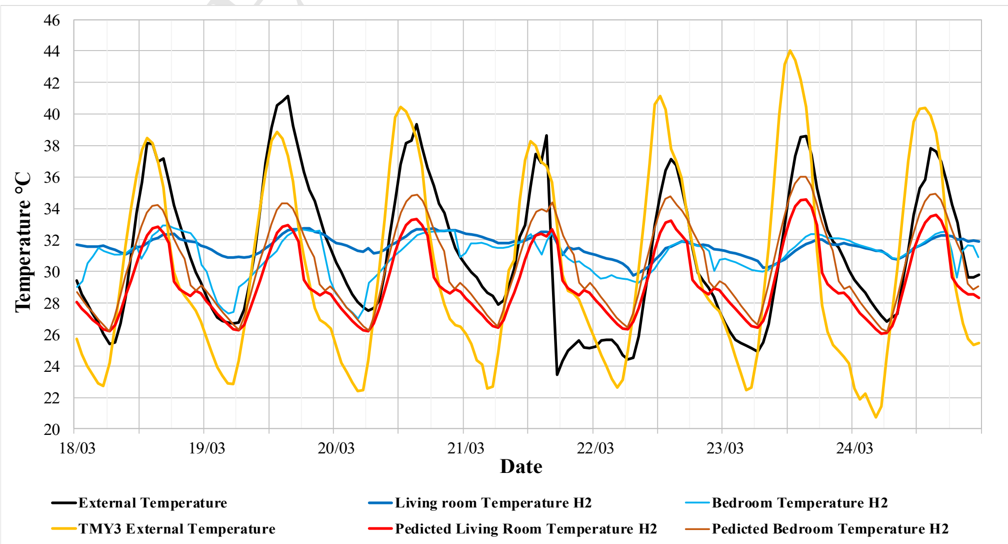


Figure 22: Measured and Predicted temperatures in the living room and bedroom of the air-conditioned dwelling at Lugbe.

Table 16: Maximum, minimum, average measured and predicted temperatures in the living room and bedroom of the air-conditioned dwelling (LGH2) 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

The mean measured living room temperatures in the naturally ventilated dwelling (BWH1-LR) 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 about 34°C in the model. Figure 23 shows that the monitored temperatures in the living room and bedroom were warmer than the simulated results obtained in the corresponding spaces Table 17.

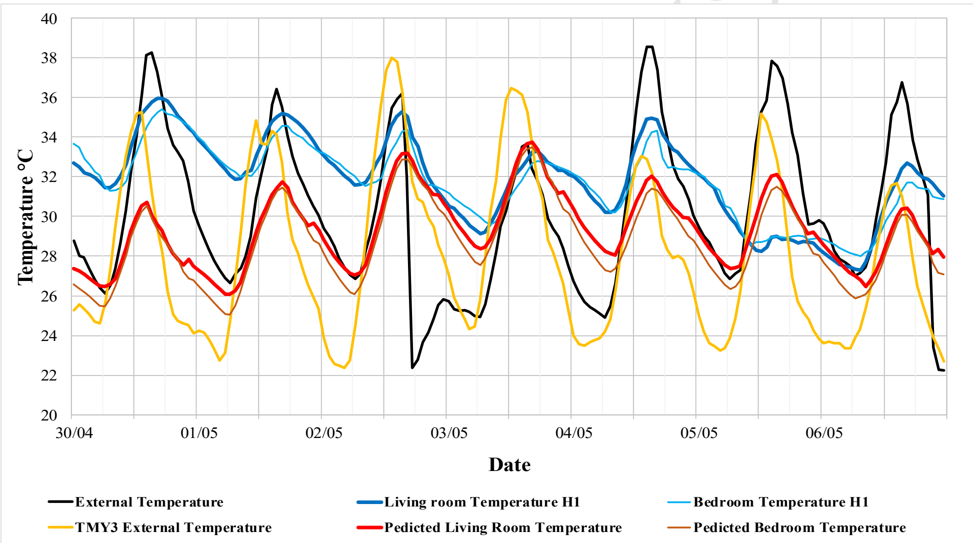


Figure 13: Measured and predicted living room and bedroom temperatures at the naturally ventilated dwelling at Bwari.

Table 17: 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 (BWH2-LR) in Bwari had temperatures around 29°C for the monitored air-conditioned dwelling which agrees with the predicted temperature of 28.6°C in 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 24). The maximum predicted bedroom temperature was almost 1°C higher than the monitored bedroom temperatures (BWH2-BR), though the difference between the monitored and simulated temperatures was not more than 1°C (Table 18).

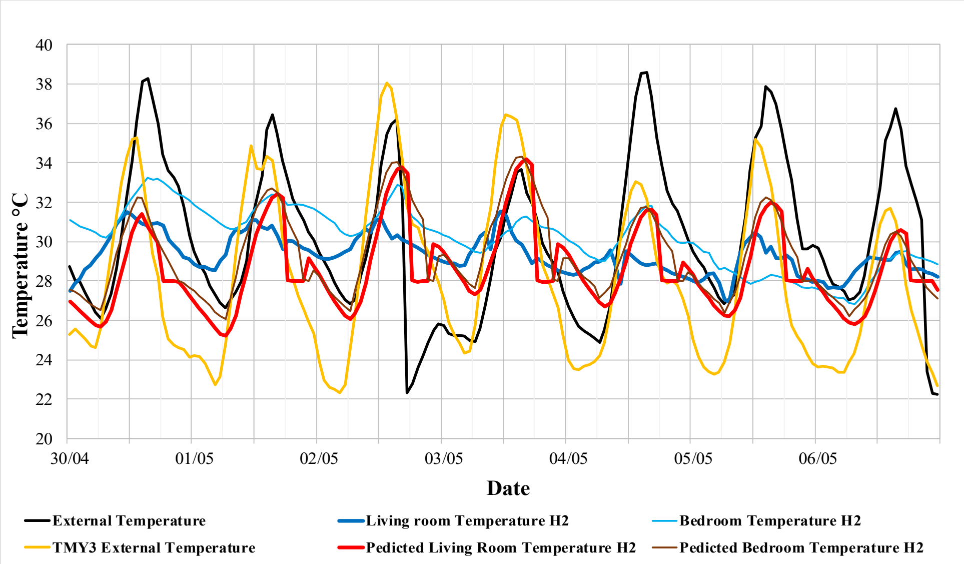


Figure 24: Measured and predicted living room and bedroom temperatures at the air-conditioned dwelling at Bwari.

Table 18: 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, NV = Air Conditioned

Comparing the average predicted and measured temperatures in Table 15 to 18, the results showed that measured temperatures were higher than the predicted temperatures by about 0.5°C to 1°C for both the naturally ventilated and air-conditioned houses in Lugbe and Bwari. The results revealed that the houses in Lugbe were warmer than the houses in Bwari.

4.5.5 The Static CIBSE comfort model for monitored and simulated data

Considering the CIBSE comfort model, extreme overheating occurs during the dry season in 100% of the spaces (living rooms and bedrooms) during the monitoring period at Lugbe and Bwari. A similar result was obtained for the simulation as overheating also occurs in 100% of the spaces (Figures 25 and 26).

Figures 25 and 26 below show analysis of the risk of overheating at Lugbe and Bwari. The figures explain the percentage of hours above 28ºC for the living rooms during the daytime and evening period. Figure 26 illustrates the percentage of hours over 28ºC in the spaces at Bwari. 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 28ºC above 1% of the time for Lugbe and Bwari.

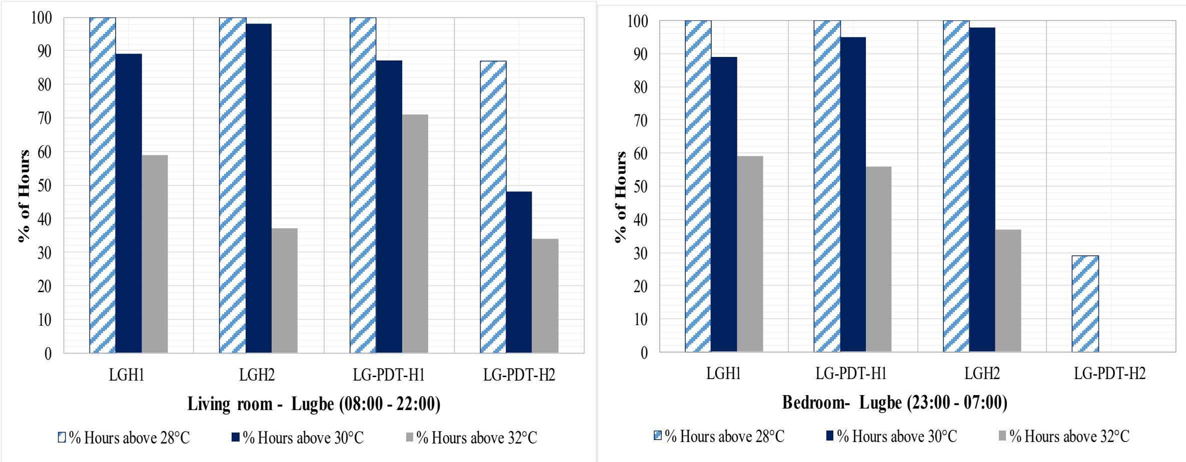


Figure 25: The static CIBSE comfort model - comparison between monitored and predicted temperatures in the living rooms and bedrooms at Lugbe.

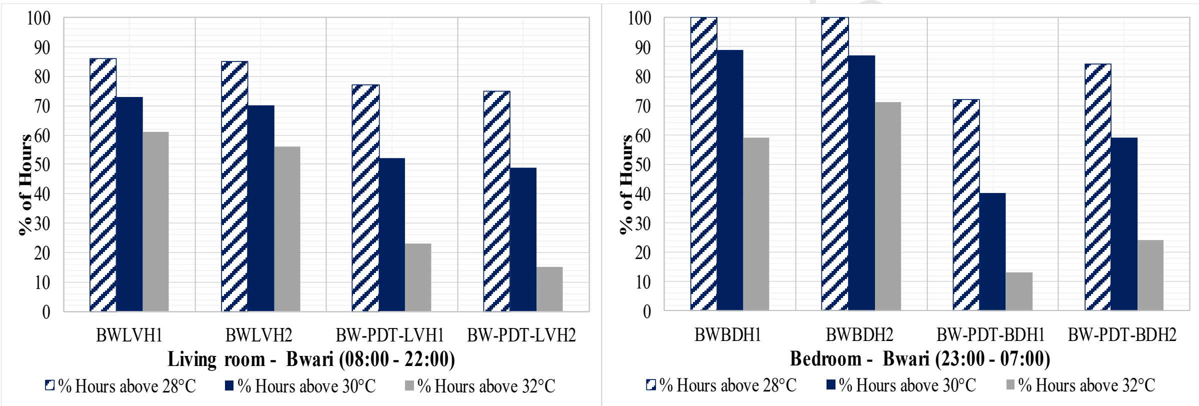


Figure 26: The static CIBSE comfort model - comparison between monitored and predicted temperatures in the living rooms and bedrooms at Bwari.

4.5.6 The EN15251 dynamic adaptive comfort model for monitored and predicted temperatures

The predicted temperatures during the daytime and evening period in the naturally ventilated living room at Lugbe exceed the Cat. II upper threshold and exceed the Cat. III upper threshold for similar percentage of the time when compared with the results obtained from the monitored data (Figure 27). The result aligns with the findings on the assessment of the risk of overheating over the same period when monitored temperatures were evaluated. The results also showed the monitored spaces are warmer than predicted and occupants are prone to warm discomfort for longer hours during dry season. The findings also revealed extreme indoor thermal conditions during the daytime and evening period in Lugbe (Figure 27a). The night-time adaptive overheating analysis in Lugbe showed temperatures exceed the Cat. II upper threshold for more than 5% of the time. The results also agree with the assessment of the measured data when the Cat. II upper threshold and the Cat. III upper limit were considered (Figure 27b).

In comparison to the predicted indoor temperatures for Lugbe, the findings revealed extreme indoor thermal conditions during the daytime and evening period. The night-time adaptive overheating analysis in Lugbe showed temperatures exceed the Cat. II upper threshold for more than 5% of the time. The results also agree with the assessment of the measured data when the Cat. II upper threshold and the Cat. III upper limit were considered. The results also suggest warm discomfort in the bedroom which agrees with the results obtained during the monitored temperatures in the bedroom.

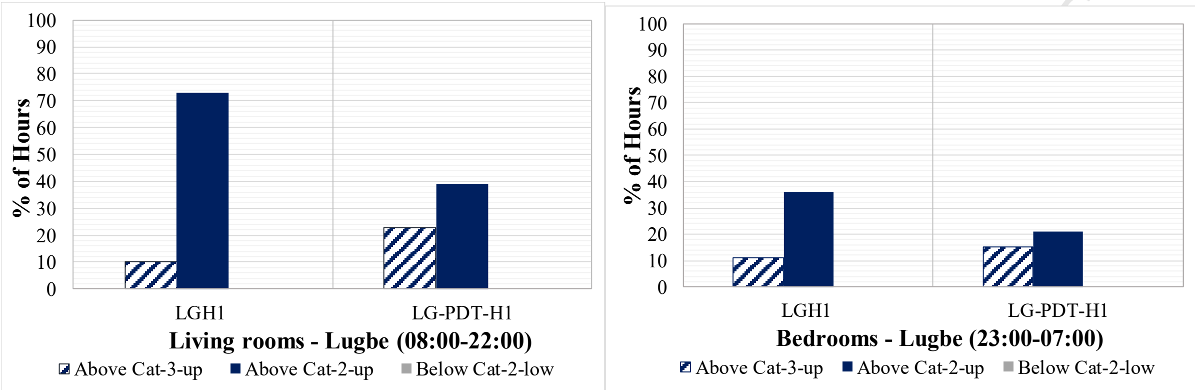


Figure 27: Comparison between monitored and predicted temperatures in the living rooms and bedrooms at Lugbe using the dynamic EN15251 adaptive comfort model.

The naturally ventilated living room in Bwari showed predicted temperatures rose above the 5% of hours over the Cat. II upper threshold for more than 5% of the time and was above the 1% of hours over the Cat. III marker for more than 1% of the time (Figure 28a). The predicted naturally ventilated living room temperature during the daytime and evening periods in Bwari, exceeded 5% of hours above the Cat. II upper threshold which agrees with the monitored temperatures during the same period (Figure 28a). Although the monitored temperatures showed more hours above the Cat. II upper and Cat. III upper thresholds compared to the predicted temperatures indicating warm discomfort occurs in the naturally ventilated living room space in Bwari. In the bedroom, the temperature rose above the Cat. II upper threshold for more than 5% of the time indicating warm discomfort at night. The results agree with the assessment of the measured data when the Cat. II upper threshold limit was considered (Figures 28b). The results also suggest warm discomfort in the bedroom which agrees with the results obtained during the monitored temperatures in the bedroom at Bwari.

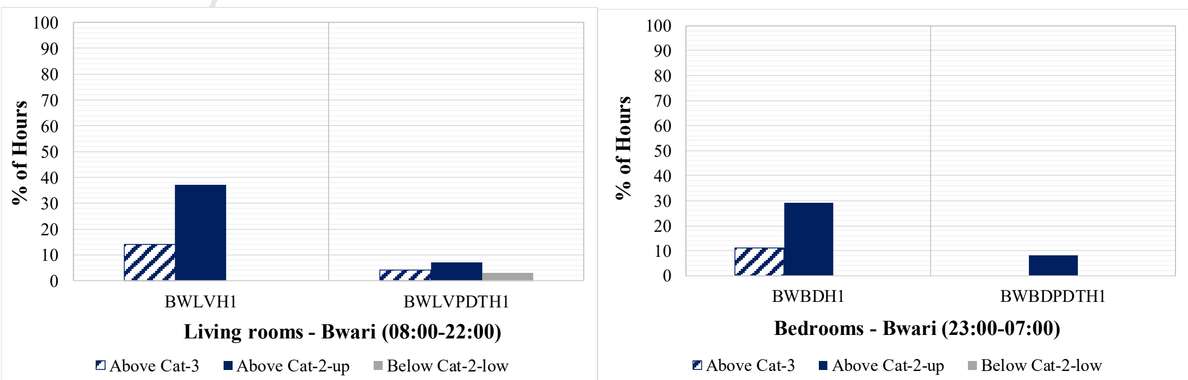


Figure 28: Comparison between monitored and predicted temperatures in the living rooms and bedrooms at Bwari using the dynamic EN15251 adaptive comfort model.

4.5.7 Comparison of the results from this study with existing studies

Comparing the results obtained from the current study with the existing studies on indoor thermal comfort in temperate region and Nigeria (Table 19), higher mean, neutral, and preferred temperatures are reported in this study than most of the existing studies in the region and temperate region. The results showed occupants in the hot and humid climate have the ability to feel 'neutral' at a higher temperature and prefer 'no change' to the thermal environment at a higher temperature than those in other regions. The study also revealed the possibility of occupants being exposed to the risk of elevated temperatures in the region while further research will be considered to identify possible passive cooling strategies to improve the thermal environment of the buildings in the case study buildings. The study also shows that the use of air-conditioning in the hot and humid climate may not improve overall thermal comfort of occupants. Therefore, adaptive measures and design strategies would be helpful in reducing the frequency of elevated temperatures within the thermal environment of buildings in the region.

Table 19: Summary of thermal comfort research in temperate region and Nigeria with reported neutral and acceptable comfort range for comparison

Year	Study	Location (Climatic zone)	Type of Building/Space	Season	Key findings
Current study	Current study	Abuja (Hot Humid)	Residential (NV and AC)	Dry Season	1. Neutral temp. = 28.0°C - 30.4°C 2. Combined preferred temp. = 27.5°C – 29.4°C 3. Overall mean temp = 31.7°C
2016	Adekunle and Nikolopoulou	UK (Temperate)	Residential (NV)	Summer	1. Combined neutral temp. = 20.8°C 2. Combined preferred temp. = 21.1°C 3. Overall mean temp = 23.3°C
2016	Efeoma and Uduku	Enugu (Hot Humid)	Office (AC)		1. Neutral temp. = 28°C
2013	Lomas and Kane	UK (Temperate)	Residential (NV)	Summer	1. Mean temp = 22.3°C
2012	Adunola A. O.	Ibadan (Hot Humid)	Residential (NV)	April	1. Regression equation: Y = 0.483*X – 15.59(TSENS with respect to TOP*) 2. Neutral temp. = 32.3°C TOP*
2012	N. Djongyang et al	Ouagadougou Dry-tropical sub-Saharan Africa region.	Bedrooms (AC)		1. Neutral temp. range = 29°C – 32°C
2010	N. Djongyang, & R. Tchinda	Ngaoundere & Kousseri, (Cameroon) Harmattan season	Residential	November 2008 to January 2009.	1. Neutral temp. (Ngaoundere) = 24.69°C 2. Neutral temp. (Kousseri) = 27.32°C
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 (N.V.)	July & August (Rainy Season)	1. Regression equation: Y = 0.3589*X – 9.4285 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

Year	Study	Location (Climatic zone)	Type of Building/Space	Season	Key findings
Current study	Current study	Abuja (Hot Humid)	Residential (NV and AC)	Dry Season	1. Neutral temp. = 28.0°C - 30.4°C 2. Combined preferred temp. = 27.5°C – 29.4°C 3. Overall mean temp = 31.7°C
2016	Adekunle and Nikolopoulou	UK (Temperate)	Residential (NV)	Summer	1. Combined neutral temp. = 20.8°C 2. Combined preferred temp. = 21.1°C 3. Overall mean temp = 23.3°C
2007	Adebamowo	Lagos (Warm Humid)	Residential (N.V.)		1. Neutral temp. = 29.09°C
1988	Ojosu et al	Hot Dry			1. Acceptable comfort zone = 21 – 26°C
		Temperate Dry			2. Acceptable comfort zone = 18 – 24°C
		Hot Humid			3. Acceptable comfort zone = 21 – 26°C
		Warm Humid			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)

5. Conclusion

This study examined occupants' adaptation and comfort during the dry season in 171 low-income to middle-income residential buildings in four locations (Lugbe, Mpape, Dutse Alhaji and Bwari) in Abuja, Nigeria. The study provided empirical data on thermal comfort of occupants in the study location within the tropical region. The research methodology included post-occupancy evaluation (POE) surveys, thermal comfort surveys enhanced by environmental monitoring, and dynamic thermal simulations. The POE results revealed high dissatisfaction rates during the dry season, where the findings showed that at least 70% of the occupants are dissatisfied with their thermal environment. The results showed that the occupants' in Dutse Alhaji had the highest 'dissatisfied' responses. Over 90% of the occupants' in Dutse Alhaji highlighted they were either 'very dissatisfied', 'dissatisfied' or slightly dissatisfied' compared to the lowest dissatisfaction rate of 39.5% reported at Lugbe. The finding is further complimented with the fact that more than 76% of the occupants feel 'warm' or 'hot' during the survey period. The occupants in Dutse Alhaji had the highest levels of warm or hot sensation responses with over 86% and a highest mean thermal sensation value of 6.0. Over 70% of the respondents in other case studies indicated to be warm or hot.

The comfort surveys reported similar results for a distribution clustered above the central categories with more than 65% of the responses reporting they were 'uncomfortably warm' with a moderately even distribution of votes varying between 'neutral' and 'warm'. The comfort surveys further revealed that more than 50% of the occupants in the naturally ventilated case study buildings in Lugbe, Mpape and Dutse Alhaji felt warm or hot. However, this was significantly lower for Bwari with 38%, although internal temperatures were higher at Lugbe, Mpape and Dutse during the monitoring period. The findings contrast with the air-conditioned case study buildings where the results showed 25% of the respondents in Lugbe and Dutse Alhaji feel warm compared to 15% warm votes recorded in Bwari.

Regarding indoor temperatures, the study revealed an overall mean temperature of all the measured case study dwellings was 31.7°C which was similar to the predicted temperature (30.7°C). The result showed occupants for one week in all case studies were prone to persistent warm temperatures. Comparing the houses in Lugbe and Bwari, the monitored and simulated results showed that the houses in Lugbe are warmer than the houses in Bwari. The comparison between the measured and simulated internal temperatures for the naturally ventilated and air-conditioned spaces at Lugbe and Bwari revealed the occupants are likely to be exposed to elevated temperatures above 28°C for several hours per day continuously during the dry season.

The study showed the neutral temperatures were in a range of 28°C to 30.4°C compared to the preferred temperature range of 27.5°C to 29.4°C. The result revealed a higher adaptation potential for the residents in the region supported by the higher neutral and lower preferred temperatures reported from the surveys. The findings also showed that the residents in the region interacted more with controls during the dry season period, in particular, use of windows, doors, fans for ventilation, as well as curtains for shading. Other design related parameters found to contribute to elevated temperatures within the case study buildings include use of sliding windows where after opening, the windows allow only 50% of the air through the openings. Additionally, lack of high-level windows to encourage stack effect ventilation to reduce the overall indoor temperatures might also influence the occurrence of high internal temperatures within the buildings. The prevalence of thermal discomfort highlights the need to explore the possibilities of reducing internal temperatures, particularly by passive means (fabric, shading, insulation etc.) given the need to avoid or reduce the need for air conditioning to make the buildings energy-efficient at low cost.

It is therefore crucial to provide special consideration to the design of low-income to middle-income residential buildings, especially those built with sandcrete blocks (because of its poor insulating qualities) with appropriate strategies for effective indoor heat dissipated without much financial burden on the occupants. In addition, there is a possibility that increasing occupants' adaptive capacity can be achieved by reducing warm discomfort, therefore there is a need to provide indoor controls carefully fused into future design of buildings especially where increasing temperatures can be assessed and predicted.

Finally, this study also recommends that future research should include investigations into the relationship between warm indoor temperatures, thermal comfort and adaptive comfort models, with a further look into the relationship between indoor overheating and heat stress in residential buildings in sub-Saharan Africa.

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mbols

Indoor comfort and adaptation in low-income and middle-income residential buildings in a Nigerian city during a dry season

Highlights

- The POE results revealed over 70% of the occupants are dissatisfied with their thermal environment.
- The comfort surveys reported similar results with over 65% of the responses revealing 'uncomfortably warm'.
- The neutral temperatures were in a range of 28°C-30.4°C compared to the preferred temperature range of 27.5°C-29.4°C.
- Comparing the monitored and simulated results, the houses in Lugbe were warmer than the houses in Bwari.
- The study also recommends that future research should examine the possibility of occupants that are subject to elevated temperatures in sub-Saharan Africa.