Investigation of the daylighting and the thermal environment of Nigeria’s low-income housing: 
the case of Abuja

Volume one

by

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Abstract

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. At the early stage of the city’s development, the designers involved in the process were mainly focused on providing the required quantity of dwellings to accommodate those involved in the construction. There were no weather stations set up to monitor the climatic conditions of the area and no urban areas within a hundred kilometres of the city’s location. Thus, the value of the region’s unique climatic conditions received only cursory consideration during the early phases of development. More records of the climate of the region have become available since the mid-1990s. Yet, despite the availability of such data and the global interest in an energy efficient approach to building design, it is still not clear whether the concern about energy conservation has led to a different design practice in the housing sector. On the contrary, recent statistics on energy consumption in Nigerian residential buildings indicate an increase in energy use due to the growing use of mechanical air conditioning units for meeting comfort requirements. Previous studies have shown that space air conditioning and lighting have been accounting for some 80% of domestic energy consumption in Nigeria.

Given that the region is already struggling to meet its current energy demands, it is important to examine whether improvements made to the design approach for future buildings can assist in reducing overheating indoors and energy consumption. The aim of this study is to develop passive design guidelines that will help improve the thermal and daylighting conditions in residential buildings in Nigeria, thereby reducing the need for active energy sources to keep occupants comfortable. To achieve this, the study has four main parts. Firstly, the literature relating to the environment and phases of architectural development in Abuja, Nigeria is reviewed in order to identify the unique elements of the climate and socio-economic context of the city. Secondly, the literature relating to human comfort as well as the thermal and visual performance of buildings, is reviewed in order to identify the design parameters that are crucial for improving occupants’ comfort in dwellings, especially in tropical regions. Thirdly, using computer based simulations, the research investigated the performance of eight housing types in Abuja in their current state and examined the impact changing key design parameter has on occupants comfort. Finally, the findings from the investigations are used to deduce which passive design approaches are more relevant for improving the thermal and visual conditions in residential buildings in the region.

Evaluating the performance of the buildings in their existing state revealed clear overheating problems and excessive natural lighting for most of the year. However, among the key findings from the investigation, it was found that a 6-11% decrease in the frequency of thermal discomfort and a 16-54% decrease in the frequency of visual discomfort can be achieved by adjusting the orientation of the facades. The results also showed that the frequency of thermal and visual discomfort can be reduced by about 6.5% and 71% respectively, using façade and window shading components.
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Declaration

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award.

Name: Mahmood Abdulkareem

Date: 26th March, 2016

Signature

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الحمد لله
To,
My mother
and
in loving memory of my uncle Aliyu
Dissemination


CHAPTER 1 - INTRODUCTION

1.1 OVERVIEW

The interest in energy efficiency and passive design approaches in the building sector has grown significantly in recent decades. This interest is mainly justified by the rising cost of fossil fuels. It is also driven by the realisation that the conventional sources of energy for mechanical cooling, heating and artificial lighting are major contributors to the increase in greenhouse gas emissions that, in turn cause global warming\(^1\) (Intergovernmental Panel on Climate Change [IPCC], 2013). According to the Intergovernmental Panel on Climate Change (IPCC, 2014) in 2010 the building sector accounts for about 32% of the global energy consumption, 19% of energy-related CO\(_2\) emissions, and 51% of the global electricity consumption. In that same year only about 8% of the world’s energy was consumed by commercial buildings, whereas residential building were responsible for 24% of the total final energy consumption (IPCC, 2014). Most of the pollutions are indirect emissions from electricity use in buildings, thus, the actual emission values mainly depends on electricity production and varies in different regions around the world. While in Western Europe and North America, residential buildings accounted for about 67% and 56% of the end energy use in buildings, in North Africa and Sub-Saharan Africa the housing sector accounted for about 79% and 97% of the energy use in buildings (IPCC, 2014). Thus, switching to renewable energy sources or reducing the energy use in residential buildings in Africa is crucial for limiting greenhouse gas emissions in the region and mitigating global warming.

Nowadays it is very well known that, one of the most effective ways for reducing energy use in buildings, including residential buildings, is by incorporate passive design approaches at the early stages of the design process (Attia et al., 2013; Baker & Steemers, 2002; Imessad et al., 2014; Lechner, 2014; Modeste et al., 2015; Olgyay, 2015; Santamouris & Asimakopoulos, 2013). Passive design approaches or methods refer to means of improvements to thermal and visual conditions in buildings by implementing strategies that minimise or do not require mechanical heating, cooling and/or artificial lighting. These methods take

\(^1\) Global warming refers to the increase in the overall temperature of the earth's atmosphere due to the greenhouse gas effect caused by increased level of carbon dioxide (CO\(_2\)), and other pollutants.
advantage of the natural climatic conditions and physical environment to maintain comfort (Sadineni, et al., 2011).

In addition to reducing greenhouse gas emissions, improving building performance by integrating passive design approaches will become increasingly important in Africa in the future. Due to global warming, it is anticipated that the region will be more strongly influenced by climate change due to global warming than other regions. The 2014 IPCC report on climate change predicts that temperatures in Africa are projected to rise faster than the global average increase during the 21st Century. In tropical Africa, the increase in temperatures are projected to occur one to two decades earlier than the global average because the small natural climate variability in this region generates narrow temperature bounds that can easily be surpassed by small climate changes (Niang et al., 2014). Based on various possible scenarios of global greenhouse gas emissions, the temperature projections over West Africa for the end of the 21st Century range between 3°C to 6°C above the late 20th Century average annual temperatures (Niang et al., 2014). The impact of future climate change in Africa is predicted to be further exacerbated by existing vulnerabilities in the region such as, poor governance, poverty and rapid urban population growth as well as limited access to infrastructure and technology (Grist & Speranza, 2012).

In tropical regions, limiting the amount of direct solar radiation reaching indoors is one of the most effective means of improving the thermal conditions in buildings (Edmund & Greenup, 2002). Historically, traditional dwellings in Africa had very few openings for natural lighting because most of the tasks that required lighting were performed outdoors (Denyer, 1978). In contemporary residential buildings visual tasks are often performed indoors, hence, employing similar approaches for limiting solar radiation in dwellings will inevitably lead to an increase in the use of artificial lighting. Thus, the need for good daylighting in dwellings has become increasingly important in the region. In order to reduce the energy used for lighting as well as cooling in the region, it is essential to consider the opportunities to improve the thermal conditions in houses in relation to the visual conditions. Yet, several studies have indicated that, often neither the thermal nor the visual performance of buildings are adequately considered in the design of contemporary residential buildings in cities across the Africa (Adaji et al., 2015; Dabaieh et al., 2015; Ikuzwe & Sebitosi, 2015; Isa et al., 2016; Modeste et al., 2014; Ogbonna & Harris, 2008).
The problems highlighted in the above section are exemplified by the residential building development in Abuja, the capital city of Nigeria (Figure 1.1), which is the focus of this study. The sections below briefly describe problems related to Nigeria’s housing sector in general and the housing sector in Abuja, so as to place the research in context.

1.2 The housing sector in Nigeria and the issue of energy

Nigeria has the largest population in Africa with over 173 million people of which 55% lack access to grid supply of electricity (International Energy Agency [IEA], 2014, 2015). For the households that are connected to the grid, the supply of electricity is unreliable at best. As a result, the use of backup power generation to mitigate poor grid-based supply has become common in many cities in Nigeria. In a survey of over 1000 households located in eight districts in Lagos (the most populous city in Nigeria) (Otegbulu, 2011). The findings revealed that between 60-92% of the examined sample use private backup generators frequently. The electricity problem is primarily a consequence of a rapid increase in population without corresponding increase in the production and grid supply of electricity (Olugbenga et al., 2013).
Over 57% of the electrical energy consumed in Nigeria is used in housing (IEA, 2014), mainly in cooling and lighting. Previous investigations of electricity use in Northern Nigeria have revealed that air-conditioning units and artificial lighting can account for as much as 79% to 86% of the electrical energy end use in residential buildings in the region (Enaburekhan, 2007; Irimiya et al., 2013). These findings suggest that the ability to minimise the use of mechanical systems to provide the level of comfort desired by the occupants in Nigeria’s residential buildings is key for reducing the overall energy use in the region. Yet the contemporary design approaches and the global architectural practice adopted in the country have resulted or at least contributed to inefficient energy use in the building industry. This has translated over the years to increasing demand for active energy through various devices for both lighting and cooling (Akinbami, 2003). With such dependency on artificial solutions and the rapid increase in population some believe that the energy consumption in Nigeria might become too difficult to sustain in the future (Momodu et al., 2011).

The architectural trends that emerged in the mid-70s after the Nigerian oil boom persists to this day and most of the residential buildings in the cities around the country were built during this period (Ademuliyi, 2010). The oil boom boosted the economy and, in turn, the government, for the first time, participated actively in the provision of housing for all income groups (Olutuah & Bobadoye, 2009). The building industry became more involved turn-key projects built on the premise that energy is cheap and, as a result, style became more important than performance in the building design (Uduku, 2006).

Recently an increasing number of studies have examined energy use and occupants comfort in buildings in Nigeria (Ajibola, 2001; Hayatu et al., 2015; Hussaini et al., 2015; Kadiri & Okosun, 2006; Lawal & Ojo, 2011; Nimlyat et al., 2015; Odunfa et al., 2015; Olaniyi, 2012; Wahab, 2015). However, the few published studies on the housing sector were mainly focused on the thermal aspect of the housing units in the region but very little attention is given to the visual aspect of the design. Also, the symbolism of Abuja as Nigeria’s progressive capital underpins its status in the country (Kalgo & Ayileka, 2001). Hence, improving the energy profile and the efficiency of future housing schemes in Abuja should provide an important examplar for other cities to follow. Yet, none of these studies examined the environmental performance of the residential architecture of the city of Abuja.
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1.3 Abuja’s Housing Sector: An Opportunity for Improvement

Abuja, the capital city of Nigeria, was conceived in the mid-70s amidst the optimism. Envisioned as a more centrally located new seat of government, the construction of the city eventually began in 1980 (Mabogunje, 2001). As part of an extensive public housing development programme in the country, most of the residential buildings in Abuja were constructed by the government. At the early stage of the city’s development, the efforts of the planners and architects involved in the design of the city were heavily focused on cost and providing the required quantity of dwellings. This clearly reflected in the masterplan of the city stating that “the architectural and engineering aspects of housing are perhaps the least complicated or problematic aspects of housing” (Federal Capital Development Authority [FCDA], 1979). With this mindset or attitude thousands of residential buildings in Abuja were originally designed and eventually constructed without proper regard for the unique climatic context of the region (Ukoha & Beamish, 1996).

Today, only about half the area allocated for residential building construction in the city is fully developed. With the government seeking to complete the remaining phases of the city’s development, there is a great opportunity to contribute to the architectural practice in the city by examining the performance of the existing housing schemes that are still being used as prototypes for low-income groups and providing guidelines for improving future development in the city and the region in general.

This study is focused on the evaluation of the thermal and visual performance of residential buildings that have been developed in Abuja since the 1980s.

1.4 Aim

The aim of this study is to investigate the impact of building design parameters on the thermal and the visual performance of residential buildings for low-income groups in Abuja and explore whether the integration of passive design principles can assist in improving their occupants’ sensation of comfort. In order to achieve this aim the study examines the daylighting and the thermal environment of selected housing types developed for low-income groups in Abuja by the Nigerian government, many of which are still currently being used as prototypes for low-income housing development. The purpose of the
investigation is to propose a set of recommendations to improve occupants’ comfort by integrating passive design methods which were not considered in the early generation of housing schemes in the city.

1.5 Research Objectives

The main objectives of the study can be divided into three categories. The first category deals with the history of residential building development and the contemporary building design standards and norms in the studied context. The second category considers the review of the factors and parameters that influence thermal and daylighting conditions in buildings, particularly buildings in tropical regions. The final set of objectives deal with assessing the impact key building design parameters and variables have on the thermal and visual conditions in case study buildings. The three categories of objectives can be further explained as follows:

1. Objectives related to the review of residential building development in the studied context:
   a. To review the history of public housing development in Nigeria.
   b. To review the historical phases of residential building development in Abuja as well as its environmental and social context.
   c. To review the existing Nigerian building design standards that relate to the thermal and visual performance of buildings.

2. Objectives related to the development of the preliminary design evaluation framework and evaluation tool:
   a. To identify the main factors and parameters that have an influence on the thermal conditions in buildings.
   b. To identify the main factors and parameters that have an influence on the availability of daylighting in buildings.
   c. To develop a framework for building performance evaluation based on the key parameters identified in the review of the literature and the climatic context of the study.
   d. To establish a methodological approach for assessing the performance of buildings.
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3. Objectives related to the assessment of residential buildings:
   a. To assess the performance of existing public built low-income residential buildings in Abuja.
   b. To examine the impact changes to chosen design parameters and variables have on the thermal and the visual performance of selected case studies.

1.6 Research Scope Outline

The research focuses on residential buildings for low-income groups developed by the Nigerian government within the developed districts in Abuja. The residential buildings developed by the government constitute a majority of the dwellings available to low-income earners in the major cities in Nigeria. The limits of the study as it relates to building performance evaluation are established within the conceptual framework (presented in Chapter five). The case study and simulation evaluations were based solely on the design parameters adopted for the research.

1.7 Thesis Structure

The structure of the thesis is illustrated in figure 1.2. The diagram shows the five stages of the research including the identification of the research problem in the first stage. The second stage is a review of the studied context which is followed by a review of the literature related to the impact of climate and building design characteristics on occupants’ comfort in buildings. The methodology outlined in the third stage establishes the main evaluation procedure and tool used in the research. The analysis and investigation of the case studies constitute the fourth stage of the research, which is followed by the concluding remarks and recommendations in the final stage.

Chapter one presents and justifies the focus of the study. The first section of the chapter provides an overview of the importance of adopting passive design approaches in the development of residential buildings. Section 1.2 presents a review of the problems related to energy use, thermal and visual comfort in dwellings in Nigeria, which necessitate the need for the study. The justification for choosing to focus on residential buildings specifically within the city of Abuja is discussed in section 1.3. Section 1.4 and 1.5 state the aim and objectives of the research, subsequently, the structure of the thesis is described, and the contents of the chapters are summarised in the last section of the chapter.
Chapter two examines four key factors within the context of the study. Firstly, in order to gain a better understanding of the social and economic context, it provides a brief review of the policies that influenced the development of government built residential buildings in Nigeria since 1960. Secondly, the chapter presents a detailed description of the climate and geography of Abuja, Nigeria. Thirdly, the national building code, which provides the standards for building construction in Nigeria is reviewed. This is followed by a review of the impact of Nigeria’s residential building sector on energy use in the country.
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Chapter three begins by defining thermal comfort within the scope of the research. This is followed by a review of the climatic factors and the key architectural design parameters that influence the thermal conditions in a room. These parameters are classified into four different levels including the climate, the built environment, the building and the room.

Chapter four reviews the climatic factors and the key architectural design parameters that influence the availability of daylighting in buildings. Similar to the parameters reviewed in Chapter three, the parameters associated with daylighting discussed in the chapter, are also classified into four levels/categories including the climate, the built environment, the building and the room.

Chapter five describes the methodology used in the thesis. Section 5.1 reviews the general research methods used to conduct the study. Section 5.2 presents the elements of the evaluation framework including the chosen thermal and visual performance evaluation models, indicators of discomfort and the selected building design parameters that influence both the thermal and daylighting conditions in buildings. Section 5.3 presents the fieldwork and information collation process that preceded the assessment of buildings in the study, subsequently, section 5.4 provides the selection criteria for case studies and general information about the selected cases. Section 5.5 describes the modelling tool and the simulation procedure used to predict the performance of buildings in the research. The efficacy of the simulation tool, Integrated Environmental Solutions – Virtual Environment, for predicting the thermal and visual conditions in buildings in the region is examined in section 5.6.

Chapter six aims to identify the impact the design of the selected case study residential buildings has on the thermal and visual comfort in selected rooms within these buildings. The selected case study buildings assessed are classified into two phases based on the period during which they were constructed. The analysis presented in the chapter is followed by a comparison of the performance of the buildings in each phase. The output of this latter analysis is used to outline the performance of the cases and the impact of the variations in their design parameters on their performance.

Chapter seven aims to draw a more detailed understanding of how the design variables in four parametric groups at the room level, can be used to improve the thermal and daylighting conditions in selected
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rooms in the case study buildings. The findings of the analysis are used to determine which parameters are likely to have the highest positive impact on the thermal and visual conditions in the selected case studies.

Chapter eight provides a summary of the study findings. The chapter also offers recommendations and guidelines for using passive design approaches in Abuja’s residential buildings with the aim of reducing their energy consumption while improving their occupants’ comfort.
CHAPTER 2 - CONTEXT: ABUJA, NIGERIA

2.1 INTRODUCTION

The aim of this study, as stated in Chapter one, is to examine ways in which the design of a typical low-income housing in Abuja, Nigeria can be improved by using passive design approaches to create more comfortable indoor environments. Passive design can be described as the use of the sun’s energy, as well as other local climate characteristics and selected building elements to directly maintain comfortable conditions within a built environment (Morrissey et al., 2011). If the purpose of passive design is to use the climate to determine the appropriate building design characteristics needed for indoor comfort, an understanding of the three-way interaction between climate, people and buildings is required to successfully design for comfort in low-energy buildings (Nicol et al., 2012). In their book ‘Tropical Architecture in the Dry and Humid Zones’ (1964), Fry and Drew stated that the most important factors to consider for the development of appropriate architecture in the tropical and sub-tropical regions of Africa are: the climate, the needs of the people, and the means and methods available for the construction of buildings.

The primary objective of this chapter is to examine these three key factors within the context of Nigeria and more specifically in the city of Abuja. Firstly, in order to gain a better understanding of the social and economic context, section 2.2 provides a brief review of the policies that influenced the development of government built residential buildings in Nigeria since the country gained its independence in 1960. Subsequently, the issues that prompted the creation of Abuja in 1980, as well as the planning and implementation of residential building development, i.e particularly low and middle-income housing, in the city are discussed in section 2.3. Secondly, a detailed description of the climate and geography of Abuja, Nigeria, is presented in section 2.4. Thirdly, the national building code, which provides the standards for building construction in Nigeria, is reviewed in section 2.5. Finally, the impact of Nigeria’s residential building sector on energy use in the country is reviewed in section 2.6 in order to examine the means available for providing occupants with thermally and visually comfortable living environments in contemporary dwellings.
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2.2 PUBLIC HOUSING POLICIES AND PROGRAMMES IN NIGERIA

The government activities during the pre-independence era were limited to the construction of staff housing in Government Reservation Areas (GRA) in the then regional capitals, for the exclusive use of the colonial officers (Achi, 2004; Onibokun, 1990). A significant amount of the urban housing in the colonial period was provided by individual landlords and households in the private sector (Ariba, 1983). The formation of defined GRA within existing urban areas led to an existence of multiple urban forms and layouts within the same city (Achi, 2004). Figure 2.1 below illustrates the difference between the urban layouts in the GRA and the traditional city centre of Ilorin in Kwara, Nigeria.

The government has become increasingly involved in the development of residential buildings since Nigeria became an independent country in the 1960s. In many urban areas, these buildings currently dominate the architectural landscape (Bala et al., 2014; Oyadiran et al., 2014). This section reviews the
various housing development programmes established in Nigeria from 1962 to 1985 and the limitations of the various strategies adopted.

2.2.1 Post independence housing programme, 1962-1969

Housing provision for the general population by the government did not improve significantly from the colonial era to the post-independence era. The government maintained its policy of only constructing residential buildings within selected GRAs (Olutuah & Bobadoye, 2009). In the first National Development Plan (NDP), which spanned from 1962 to 1968, housing was grouped with town-planning as well as country planning, and funds for this sector were small. The development of residential buildings by the government was limited to providing staff quarters for senior government officials in cities in different regions, including Enugu, Kaduna, Ibadan and Benin-city (Ikejiofor, 1995). However, by the mid-1960s, the demand for houses in GRAs exceeded the supply because of the increase in the number of civil servants that qualified for government quarters (Olutuah & Bobadoye, 2009). As a result of the increasing demand, housing corporations were established by the regional governments. However, these corporations were not effective, because they were not well funded (Onibokun, 1990).

2.2.2 Post civil war housing programme, 1970-1974

Despite the growing housing demand, in the second NDP (1970 to 1974), the government involvement in the provision of housing was still insignificant. About 49 million Naira (1 naira = US $1.64 at that time) was allocated for housing programmes by the government (Awotona, 1990). The demand for more housing was simply regarded as a ‘social overhead’ by the plan and the second NDP did neither contain estimates of housing needs nor targets of housing production to meet the needs (Awotona, 1990).

2.2.3 The third and fourth National Development Plan, 1975-1985

The government eventually recognised the need to actively participate in the provision of housing for all income groups as part of its social responsibility in the third NDP (1975 to 1980) (Olutuah & Bobadoye, 2009). Spurred by the oil boom between 1973 and 1974 (Nigerian oil revenue increased by 350%), the government’s efforts were intensified to improve the conditions of housing in Nigeria. The development
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plan included, construction of low-cost housing units by both federal and state governments. Furthermore, there was an expansion of credit facilities to enhance private housing construction and investment in the domestic production of cement (Ademiluyi, 2010).

The key measures taken by the federal government to put into effect its policy aims during the plan period can be summarised as follows (Ikejiofor, 1995):

- The establishment of a Federal Ministry of Housing, Urban Development and Environment, as well as the Building and Road Research Institute in 1975;
- The declaration of the rent control edict in July 1976;
- The reconstitution of the Nigerian building society into the Federal mortgage bank of Nigeria in 1977;
- The declaration of the employees’ housing scheme in 1977;
- The decentralisation of the national housing programme in September 1977; under this arrangement, 202,000 dwelling units were to be built by the Federal Housing Authority (FHA), including 46,000 houses in metropolitan Lagos, 12,000 houses in Kaduna state and 8,000 houses in each of the other 18 states;

The objectives of the housing policy in the fourth NDP (1980-1985) were as follows:

- To improve the overall quantity and quality of housing for all income groups in the country by substantially increasing the rate of new housing production;
- To provide affordable housing by using realistic designs and local materials for construction; under this arrangement, the FHA was to construct 143,000 low-cost houses across the country;
- To implement a programme for providing infrastructural services in the existing residential areas;
- To implement a policy of home ownership for Nigerians.

These targets proved to be over-ambitious for the methods made available for their achievements (Ikejiofor, 1995). Between 1974 and 1980, the government planned to deliver 202,000 housing units to the public, but only 28,500 units were delivered (representing 14.1%). Also, out of 200,000 housing units planned to be delivered between 1981 and 1985, only 47,200 (23.6%) were constructed. Furthermore, under the national housing fund programme, which was initiated in 1994 to produce 121,000 housing units, it was reported that less than 5% of the proposed housing units were constructed (Ademuliyi,
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2010). In many cases, people did not want the completed houses, because they were too expensive, badly designed and/or badly constructed. Moreover, sometimes they were built on inaccessible and undesirable sites. Ogunshakin and Olayiwola (1992) indicated that the absence of institutionalised housing policy with organised stable mechanisms and implementation processes was one of the major flaws of government housing schemes. Additionally, according to Oruwari (1990), the policies were often too general, unrealistic and adapted from more technologically advanced countries. Political bias also affected the choice of project sites, allocation of completed houses and award of construction contracts. Moreover, the policies and programmes were often introduced and implemented without adequate knowledge and awareness of the complexity of the housing problems in urban and rural areas (Makinde, 2014).

Despite the shortcomings of the housing programmes, about 100,000 houses were built in many urban areas in Nigeria between 1975 and 1995 by both state and federal government (Ademiluyi, 2010; Makinde, 2014). In addition to the residential building ‘prototypes’ produced by the government, making up a sizeable amount of the urban housing stock in Nigeria (Ajayi, 2013), the codes and standards for residential building development favoured the architectural typology adopted by the government over the architectural styles of the pre-colonial and colonial period (Gbotosho, 1994).

2.2.4 Contemporary Residential Architecture in Nigeria

There is a sufficient literature examining the domestic architecture in Nigeria up until the mid-20th Century (Carroll, 1992; Denyer, 1978; Dmochowski, 1990a, 1990b, 1990c; Enaburekhan, 2007; Eneh & Ati, 2010; Ezema et al., 2015; Ikejiofor, 1998a, 1999; Ogunyemi et al., 2015; Prucnal-Ogunsote, 2001; Uduku, 2006). Some studies were focused on the characteristics of the traditional style of architecture (Carroll, 1992; Dmochowski, 1990a, 1990b, 1990c), while others traced the emergence of the European, colonial and Brazilian styles in the region during the 18th and 19th centuries (Osasona & Hyland, 2006; Prucnal-Ogunsote, 2001). These traditional types of buildings are more common in rural areas, where access to electricity is low. Studies have also been carried out on the trend of modernism in Nigeria that emerged in the 1930s, generally referred to as ‘tropical modernism’ (Uduku, 2006). The motifs of the modern movement, such as the use of concrete external walls, supplemented by concrete, steel or
aluminium sun shading are still common in contemporary building design in Nigeria; however, examples of pure tropical modernism are rare (Prucnal-Ogunsote, 2002). A subset of the modernist movement in Nigeria, characterised by simple geometric forms, became the predominant style for government built low-income housing in the 1970s. An example of such hybrid typology, which is characterised by the use of simple forms or some compositions of simple geometrical solids that explore ideas of simplicity and functionality, is shown in figure 2.2.

This type of architecture currently makes up a greater part of the landscape of Nigerian cities (Prucnal-Ogunsote, 2002). Moreover, most of the public built residential buildings in cities around the country were built in the last few decades (Ademiluyi, 2010). Thus, it is imperative to examine the residential architectural trends that emerged in the 1970s, which persist to this day.

2.3 Abuja

The city of Abuja, which is the Federal Capital City (FCC), has been selected as the case study area of this study. This decision was primarily driven by three factors. Firstly, due to the fact that the urban development in Abuja only began in 1980, the residential building stock in the city almost entirely consists of contemporary buildings. This is a unique situation to Abuja as most of the Nigerian cities have a mix of pre-colonial, colonial, post-colonial and contemporary residential architectural styles (Achi, 2004). Yet, there are very few studies which examine the residential architecture of Abuja (Abubakar, 2014; Latessa, 2014; Ukoha & Beamish, 1996, 1997; Waziri et al., 2013). Secondly, Abuja has a culturally diverse population and a relatively stable political situation, whereas the political instability in other regions in
Nigeria will make studying the housing schemes of such regions difficult, risky and almost impossible due to security issues. Lastly, because the city is still experiencing rapid infrastructural and building development, it has a sizable amount of professionals working in the construction industry with a lot of knowledge about the development of the city. This latter fact has proven to be useful when conducting the fieldwork and in collecting the data needed, as discussed in Chapter five. In general, compared to most urban areas in Nigeria, there is relatively more data available on the residential building development in Abuja, which is accessible from various sources ranging from local and federal government agencies to international organisations.

2.3.1 BACKGROUND

Abuja is a planned city that was initially conceived by the Nigerian government in the mid-1970s in their search for a new capital city for the country. Lagos was the capital city at that time, as it had been since the creation of Nigeria. Lagos remained the capital after the country gained its independence and after the civil war; however, after the war, the Nigerian government had started considering the possibility of relocating the capital city (Falola & Heaton, 2008; Take, 1984). Interest in relocating the capital city of Nigeria arose for a couple of reasons. Firstly, as Nigeria emerged from the civil war, it became evident that severe ethnic and regional disputes continued to exist. These disputes hindered the development of Nigeria as a stable, democratic state (Falola & Heaton, 2008). The government believed that the geopolitical strategy of having a more central capital city could unify the country. Thus, the policy makers decided that if a new capital was to be built, unlike Lagos, which was historically a Yoruba city, it had to be ethnically neutral and central to the three major tribe zones of Nigeria: Hausa (North), Yoruba (South-West) and Igbo (South-East) (Take, 1984).

The second and more crucial reason for seeking to relocate the capital was that Lagos was overcrowded. The increased rate of migration to Lagos had led to an overpopulation problem in the city and to environmental degradation. The lack of sufficient land for development as well as inadequate infrastructural facilities for electricity and water supply were also factors that made living in the city uncomfortable (Kalgo & Ayileka, 2001). Mabogunje stated that "the clamour for a new federal capital had
arisen because of the heightened intolerable conditions of living and working in Lagos” (2001, p. 1).

Massive traffic congestions (see Figure 2.4) also became the norm in Lagos after the oil boom in the 1970s, which led to mass importation of cars and commercial vehicles as part of the public sector spending spree (Mabugunje, 2001).

The issue of overcrowding in Lagos had emerged as far back as the early 20th Century. The former vice chancellor of the Ahmadu Bello University (Zaria, Nigeria), Ishaya Audu, stated that:

“those who think that one more road plan will master Lagos’s mushrooming growth should take to heart, that the ‘growing congestion of the island’ was put forward as an objection to Lagos’s suitability as early as the 1st of January 1914 when Nigeria first came into being as a political entity” (Audu, 1974).

Lord Frederick Lugard, the first governor-general of the colony and protectorate of Nigeria (1913- 1918), had advocated moving the capital to Kaduna in the early 1990s, not only because of overcrowding in Lagos, but also because Kaduna’s more central would have allowed the British to spread their influence further north (Immerwahr, 2007; Kirk-Greene, 1968).
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The decision to relocate the capital from Lagos to a more central location was finally made in 1975 by General Murtala Muhammed, the then head of state of Nigeria (from 1975 to 1976), and the Supreme Military Council (Mabogunje, 2001). The decision coincided with the start of the third national development plan. Initially, an 8,000 square kilometre (km²) site in the central region, which fulfilled the goal of equal access, was defined in the 1976 Federal Capital Territory (FCT) decree. Niger, Kaduna, Plateau (now Plateau and Nassarawa) and Kwara (now Kwara and Kogi) surrounded the territory (Figure 2.3) (Mabogunje, 2001). Following this decision, the first board of the FCDA was established in February 1976, to carry out an ecological survey and census of economic assets of the population of the territory.

The federal government also gave the FCDA the responsibility of handling the design, planning and construction of the FCT (FCDA, 1979; Ikejiofor, 1998b). The FCDA commissioned the International Planning Associates (IPA), a consortium of architects and planners based in the United States, to produce the master plan for Abuja and the Federal Capital Territory (FCT) in June 1977 (FCDA, 1979). The IPA used the output of the work by the FCDA in the formulation of the master plan. The government regime at the time also identified seven principles that underpin the development of the new capital city (Mabogunje, 2001). These included:

1. Providing equal access by creating a hub that was relatively easy to reach from all parts of the country;
2. Allowing equal citizenship whereby no individual from any tribe could claim special privileges as an indigene of the FCT;
3. Generating effective regional development of the central region of Nigeria, particularly, the states that bordered the FCT;
4. It was anticipated that regional development would facilitate national economic growth by providing employment and stimulating a wide range of production activities;

5. The development of the city was expected to conserve as much of the natural environment as possible;

6. To avoid the operational problems that plagued Lagos, the design of the city was expected to be ‘functional’ in terms of accommodation, movement and circulation of people and vehicles;

7. Finally, in efforts to produce a new city that was far better than Lagos and in line with the aspirations of the country, the government wanted the city of Abuja to be beautiful.

The IPA submitted the master plan for Abuja and the FCT to the FCDA in February 1979, and construction work on the capital city site commenced in 1980 (Ikejiofor, 1998a; Kalgo & Ayileka, 2001).

2.3.2 THE SITE OF THE CITY

The IPA devised a system to evaluate and rank sites within the FCT, based on nine primary criteria, in order to identify the most appropriate location for the capital city. The primary criteria included climate, buildable geology, physiography, hydrology, land use, soil, vegetation, wildlife and disease, as well as agricultural development, as illustrated in figure 2.5 (FCDA, 1979).

The IPA considered five factors to be the most important positive qualities for defining the capital city site. These included:

- Sufficient size to accommodate future growth;
- Configuration to allow maximum options of urban form;
- Minimum topographical restrictions;
- Buildable soil and geologic conditions that would not require unusual or excessive engineering means for construction;
- The most comfortable and healthy climate available.

Following the process of evaluation, three suitable sites were identified within the FCT, as shown in figure 2.6. The Gwagwa plain in the north-east quadrant was eventually chosen to be the site of the FCC. The name "Abuja", which was later adopted for the site, was derived from a rural settlement (now called Suleja) to the west of the site (Mai & Shamsuddin, 2008). According to the IPA, the site was chosen because it had the capacity to handle population growth up to the limits of approximately three million and offered satisfactory geological and soil conditions for construction and landscaping (FCDA, 1979).
2.4 THE GEOGRAPHY AND CLIMATE OF ABUJA

Nigeria is located between latitudes 4°N and 14°N and 3°E and 15°E in the sub-Saharan region of Africa (Central Intelligence Agency [CIA], 2013). The country has a total land area of about 909,890 square kilometres (National Bureau of Statistics [NBS], 2007), covering about 14% of the land area of the West
African sub-region. There are five major geographic regions in Nigeria. These include a low coastal area along the Gulf of Guinea, hills and low plateaus north of the coastal area, a broad stepped plateau stretching to the northern border with elevations exceeding 1,200 metres, and a mountainous zone along the eastern border, which includes the country’s highest point, Chappal Waddi (2,419 metres above sea level) (CIA, 2013). Even though Nigeria is located within the tropics, it has a varied climatic distribution from being equatorial in the coastal and tropical south to the arid north (Imaah, 2008). A brief description of the various climate zones in Nigeria is illustrated in table 2.1 and figure 2.7.

Table 2.1 Characteristic climatic conditions in zones and regions of Nigeria (Imaah, 2008)

<table>
<thead>
<tr>
<th>No.</th>
<th>Climate zone</th>
<th>Some locations</th>
<th>Predominant climate conditions</th>
</tr>
</thead>
</table>
| 1   | Coastal      | Lagos, Port Harcourt, Calabar | Temperature ≥ 24°C ≥ 27°C  
Relative humidity ≥ 80%  
Warm weather at 24°C – 25°C  
Predominantly hot weather at ≥ 25°C |
| 2   | Forest       | Ibadan, Oshogbo | Temperature ≥ 27°C  
Relative humidity ≥ 60% ≤ 80%  
Hot and relatively humid weather |
| 3   | Transitional | Lokoja, Enugu, Ilorin | Temperature ≥ 24°C ≥ 27°C  
Relative humidity ≥ 60% ≤ 80%  
Predominantly warm weather |
| 4   | Savannah     | Abuja, Kaduna, Bauchi | Temperature ≥ 24°C ≤ 27°C  
Relative humidity ≥ 20% ≤ 40%  
Warm and dry weather |
| 5   | Highland     | Jos plateau, Obudu plateau | Temperature ≥ 24°C ≤ 27°C  
Relative humidity ≥ 40% ≤ 60%  
Comfortable weather |
| 6   | Semi-desert  | Katsina, Nguru | Temperature ≥ 27°C  
Relative humidity ≤ 20%  
Hot and very dry weather |

Figure 2.7 Climatic zones of Nigeria (Imaah, 2008)
2.4.1 THE GEOGRAPHY OF ABUJA

The area of Abuja covers 713km², which is located in the Savannah climate zone of Nigeria. Abuja is located at latitude 8°90’-9°20’ north and longitude 7°25’-7°55’ east of the Greenwich Meridian (Abubakar, 2014). Its location in the Gwagwa plains is surrounded by hills and rock formations, including ‘Aso Hill’ in the north-east, which is a prominent part of the city’s landscape (Figure 2.8).

![Figure 2.8 Effect of topography and seasonal trade winds on Abuja site (FCDA, 1979)](image)

The micro-climatic in Abuja was considered more favourable during the site selection process because it was anticipated that Aso Hill and the other hills north of the city would provide some protection from the dust-laden winds, which originate from the Sahara desert north of Nigeria (FCDA, 1979). Moreover, the city has a higher altitude than most areas in Nigeria. Most of the area allotted for the city’s development has an altitude between 1,200 and 1,700 feet above sea level. Thus, it was anticipated that the lower air pressure in these high altitude areas would create cooler temperatures (FCDA, 1979).

2.4.2 THE CLIMATE OF ABUJA

As it is with most regions of Nigeria, the two prevalent seasons in Abuja are the dry season and the rainy season. These seasons are primarily initiated by the sun’s movement northwards across the equator and two distinct air masses known as the trade winds. The trade winds include the tropical continental air mass (cT), which originates from the Sahara desert, and the tropical maritime air mass (mT), which originates from the South Atlantic Ocean (as shown in Figure 2.9) (Ajibola, 2001).

In Abuja, the dry season typically extends from around November to April and the rainy season occurs from early May to October. There is also a short spell of ‘harmattan’ in December, often characterised by
the occurrence of dust-laden winds caused by the north-east trade wind moving south from the Sahara (Federal Capital Territory Administration [FCTA], 2013).

The midday sun is at its lowest angle in the south during the first three months of the dry season (around 57° in December, as shown in figures 2.10 and 2.11) and there is often very little cloud cover over the city (Figure 2.13). Thus, the level of direct solar radiation (Figure 2.14) reaching Abuja during this period is high. The average hourly solar radiation in Abuja in December is about 509 watts per square metre ($W/m^2$). This leads to temperatures as high as 35°C as shown in figure 2.17. As the sun moves northward across the equator in March, it causes the tropical continental air mass to withdraw back to the Sahara Desert (Figures 2.9 and 2.12). The sun also moves on a daily path that is almost directly overhead between sunrise and sunset around this period, heating up the ground and air above, while the ground is being intensely heated as less sunlight is being dissipated by the atmosphere (from February to April). The temperatures in Abuja during this period can rise to around 37°C (Nigerian Meteorological Agency [NIMET], 2010).

The withdrawal of the tropical continental air mass causes the tropical maritime air mass to move across the country from its origin in the South Atlantic Ocean (Figure 2.12). The humid maritime air mass becomes more influential around May, as the combination of the solar radiation and the humidity of the air mass forms dense clouds and leads to the frequent occurrence of torrential rain (Barry & Chorley, 2010; Eludoyin, 2013). The amount of rainfall in the city increases from about 134mm in May to 263mm in August (Figure 2.18). The dense cloud cover creates cooler conditions by diffusing more of the sunlight (Figure 2.16). The average hourly level of direct solar radiation during this period is below 300$W/m^2$. 

![Figure 2.9 Illustration of the direction of the wind systems in relation to Abuja, including the tropical continental air mass (cT) during the dry season and the tropical maritime air mass](image)
However, daytime temperatures can still rise above 29°C. Around the summer solstice in June, the sun’s altitude angle is less than 15° north from being directly overhead (Figure 2.10) (Eludoyin et al., 2013; NIMET, 2010). Notwithstanding, the relative humidity can be as low as 30% in the afternoon during the dry season. On the other hand, the relative humidity reaches as high as 95% during the rainy season (Figure 2.19). These elevated levels of relative humidity can cause people to feel thermally uncomfortable in the city during this season.
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The diurnal temperatures are also affected by the seasonal changes. During the dry season, a significant amount of the solar radiation absorbed by the ground and structures during the daytime is emitted at night and eventually rises up beyond the earth’s atmosphere, because there is very little cloud cover over the region (Adedoja et al., 2015). Due to the nighttime heat loss, the temperatures around dawn can drop to around 18°C (about 15-17°C lower than the midday maximum temperatures). However, these environmental conditions are generally less harsh than conditions in cities further up north, like Kano (less than 350km north of Abuja), where temperatures recorded during the dry season can be as high as 38°C and as low as 13°C diurnally (Eludoyin et al., 2013). On the other hand, because of the increased cloud cover during the rainy season, a significant amount of the heat emitted by the ground and structures at night is trapped between the earth’s surface and the clouds. As a result, the fluctuation between daytime and night time temperatures during the rainy season are noticeably lower (around 10°C) (Barry & Chorley, 2010; Chiemeka, 2008). Despite the movement of the sun and other variations in the seasonal climatic patterns, there are about 12 hours between sunrise and sunset in Abuja throughout the typical annual period (from around 6:30 am to 6:30 pm) as illustrated in figure 2.21 (NIMET, 2010).

![Figure 2.11 Illustration of the sun’s altitude angle over Abuja on the winter solstice, summer solstice and equinox](image)
Figure 2.12 Wind-rose diagrams for each month illustrating the predominant wind direction and wind speed (NIMET, 2010)
Figure 2.13 Illustration of the frequency of clear sky, partly cloudy and cloudy sky conditions in Abuja over a typical year.

Figure 2.14 The average hourly global solar radiation (NIMET, 2010).

Figure 2.15 The average hourly direct solar radiation (NIMET, 2010).
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Figure 2.16 The average hourly diffuse solar radiation (NIMET, 2010)

Figure 2.17 Range between the average highs and lows of the monthly outdoor dry-bulb temperatures recorded in Abuja with comfort zone for each month, based on ASHRAE standard 55-2013 adaptive comfort model, shown in grey (NIMET, 2010)

Figure 2.18 Monthly amount of rainfall in Abuja over a typical year (Badaru et al., 2014)
Chapter two

Figure 2.19 Illustration of the frequency of low and high relative humidity levels in Abuja over a typical year

Figure 2.20 Illustration of the frequency of low and high outdoor dry-bulb temperatures in Abuja over a typical year

Figure 2.21 Daylight hours in Abuja (NIMET, 2010)
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2.5 RESIDENTIAL BUILDING DEVELOPMENT IN ABUJA

2.5.1 PLANNING

The IPA acknowledged the importance of a comfortable living environment and stated that "planning with climate should take place at all scales" (FCDA, 1979, p. 52). However, due to the on-going housing crisis in Nigeria at the time when the master plan was being developed, the residential building development plan for Abuja was mostly focused on affordability and delivering the required quantity. The IPA cited a number of problems with the delivery mechanism of the country's housing programme during the first half of the third national development plan, including:

- Lack of adequate investment in housing production by both the public and private sectors;
- Setting unrealistic standards of housing quality that did not correlate to the experience, desires and capabilities of the people;
- Inefficient land use;
- Building industry shortcomings, such as high-priced foreign contractors and imported materials;
- Preoccupation with building technology rather than delivery of affordable housing.

The residential building development programme recommended in the master plan of Abuja was considered as an opportunity to implement a strategy that could improve housing conditions in urban areas in Nigeria (FCDA, 1979). The housing programme for the master plan was built on the following principles:

- Efficient plot layout and appropriate standards of infrastructure, permitting upgrading of standards as economic capability increases;
- A range of housing options for all income groups, from detached housing to flats, to traditional multi-family compounds or rooming houses and shared-services accommodations;
- Increased reliance on local construction materials, reduced quality of architectural finish and careful management controls to assure that costs of construction are reduced and maintained at lowest possible levels;
- Sites and services approach, use of shared services and self-help/self-contracted construction to lower costs.

The IPA suggested that "the architectural and engineering aspects of housing are perhaps the least complicated or problematic aspects of housing" (FCDA, 1979, p. 52). Thus, the framework for residential
building development (Figure 2.22) in the master plan primarily focused on factors, such as plot size, house area (built space), types and cost of construction, quality of utilities (water, power, sanitary), implications of indigenous material use and subsidies. On the other hand, the framework did not comprehensively address the need to providing satisfactory or comfortable living environments. The approach adopted in the model for housing delivery in the masterplan indicates an imbalance between the need to provide the required amount of housing units and comfortable living environments in favour of the former.

The target of the master plan was for the city to be developed in phases (Table 2.2), starting with an initial construction of buildings and infrastructure for 39,050 people by the end of the first year. The master plan covered and coordinated land use, transportation, infrastructure and housing in a way that acknowledged the interrelationships of these elements of urban development. The spatial requirements were also defined in the master plan (Figure 2.23). It was anticipated that the city would eventually
accommodate 1,642,100 people in 278,000 households by 2000 (FCDA, 1979). The ultimate population anticipated for the city was set at 3,100,000.

Table 2.2 The anticipated population growth and corresponding residential development requirement for Abuja (FCDA, 1979)

<table>
<thead>
<tr>
<th>Phases</th>
<th>Year</th>
<th>Total labour force</th>
<th>Percentage of total population</th>
<th>Total population</th>
<th>Housing targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1981</td>
<td>33,700</td>
<td>85%</td>
<td>39,050</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1986</td>
<td>109,900</td>
<td>70%</td>
<td>157,750</td>
<td>25,000 dwellings</td>
</tr>
<tr>
<td>3</td>
<td>1990</td>
<td>315,680</td>
<td>65%</td>
<td>485,660</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1995</td>
<td>585,380</td>
<td>58%</td>
<td>1,005,800</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2000</td>
<td>858,350</td>
<td>52%</td>
<td>1,642,100</td>
<td>278,000 dwellings</td>
</tr>
</tbody>
</table>

The land designated for residential building development was projected to be around 124.86 km², approximately 49% of the city’s total area (Table 2.3.) (Falade, 2001). Take, who worked with Kenzo Tange on the design of Abuja’s central business district, stated that the target of constructing a city for over 1.6 million people in twenty years was "a very ambitious goal", especially when compared to the plan for Brasilia, the capital city of Brazil, where the goal was to accommodate 411,000 people in about the same amount of time (1984, p. 49).
Table 2.3 Abuja land use projections 1998-2000 (Falade, 2001)

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Total (km$^2$)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>124.86</td>
<td>48.67</td>
</tr>
<tr>
<td>Commercial business districts</td>
<td>5.61</td>
<td>2.19</td>
</tr>
<tr>
<td>Institutional</td>
<td>8.91</td>
<td>3.44</td>
</tr>
<tr>
<td>Industrial research/training</td>
<td>9.20</td>
<td>3.59</td>
</tr>
<tr>
<td>Transportation</td>
<td>17.05</td>
<td>6.65</td>
</tr>
<tr>
<td>National government</td>
<td>5.00</td>
<td>1.96</td>
</tr>
<tr>
<td>Sports and recreation</td>
<td>1.60</td>
<td>0.62</td>
</tr>
<tr>
<td>Parks, open space</td>
<td>84.35</td>
<td>32.87</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>256.58</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

2.5.2 IMPLEMENTATION

The initial implementation strategy for the master plan envisaged that workers would initially live in the "accelerated district" within the stage 1 area of the city development (Figure 2.23). The aim of the accelerated district development was to prevent construction workers from having to create shantytowns on the periphery of the city, as was the case in Brasilia. The districts were also developed to prepare the city for a population of no more than 160,000 people by 1986 (Mabogunje, 2001) and 25,000 dwelling units were projected to accommodate the inhabitants expected to reside in phase I; however, by 1986, this target was still far from being achieved (Ago, 2001). In December 1986, only 34% (8,680) of the anticipated number of dwelling units had been completed (Jibir, 1988).

The failure to develop the required amount of dwelling units was a reflection of the slow progress of the fourth NDP that only delivered 23.6% of the targeted 200,000 houses that the government was to develop between 1981 and 1985 (Ademiluyi, 2010). The major problem that hindered the housing sector development was the oil crisis in 1983, when Nigerian crude oil fell to only a third of its former price. In consequence, the initial stages of the city’s development had hardly begun, when the budgetary targets for the development were drastically reduced (Stockhausen et al., 2006).

From the outset of residential building development in Abuja, the government overlooked the recommendation to increase reliance on local construction materials and the use of self-help and self-contracted services/modes of construction (Morah, 1993). Morah (1990) indicated that some government officials believed that low-cost housing, appropriate technology, self-help construction and other similar concepts were all parts of a strategy by the Western world to make developing countries comfortable with backward conditions. In Morah’s study of government officials’ disposition on housing
development in Abuja, almost two-thirds of the decision makers interviewed agreed that any manifestation of poverty in the city should be eradicated at all cost and envisioned Abuja as an ideal world-class city “free of pity and full of pride for all Nigerians” (Morah, 1990, p. 186). These ideas influenced the governments’ decision to overlook the IPAs’ recommendations for reducing the capital cost of the housing delivery in the city. The government alternatively chose to use foreign construction companies, foreign building technology and materials for the majority of the residential buildings developed, in attempts to create the excellent city envisioned (Stockhausen et al., 2006; Ukoha & Beamish, 1996). This meant that even the range of housing types developed for lower income groups were not affordable for low-income groups under normal circumstances (Ikejiofor, 1998a).

Notwithstanding, Abuja’s unique setting as a city mainly occupied by civil servants, enabled the government to essentially undertake expensive mass housing projects to provide free housing for its employees. The FCDA also allocated completed housing units to its staff and other federal agencies in the city, who in turn assigned their staff to the units based on their ranks in civil service. The civil servants who were not allocated public housing received a monthly housing allowance (Ukoha & Beamish, 1996). The strategy was sufficient for dealing with the housing demands during the early stages, because the FCDA remained the only government organisation fully based in Abuja until 1983. However, at the time of the formal transfer of the federal capital from Lagos to Abuja in December 1991, more than 20 government ministries were already operating in Abuja with a workforce of over 100,000 officials (Ministry of the Federal Capital Territory [MFCT], 1993). The inability of the FCDA to keep up with the increased demand for housing during this period became evident (Ikejiofor, 1998b; Ukoha & Beamish, 1997). The scope of residential building development in Abuja since 1980, is discussed in section 2.5.3 and 2.5.4.

2.5.3 EARLY DEVELOPMENT PHASE (1980-1995)

In anticipation of the migration of civil servants from all states in Nigeria, the master plan proposed four broad categories of housing types. The preliminary housing programme for the city is shown in Table 2.4 and 2.5. As the tables show, the preliminary types include single family detached and semi-detached
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housing, multi-family housing (with shared facilities), flats in apartment blocks and serviced land for individualised housing development among both middle income and upper-income groups (Table 2.4). A range of building and plot sizes and standards (in terms of room sizes) for each housing type were specified for upper, medium and lower income groups (Table 2.5) (FCDA, 1979).

The development of residential buildings in Abuja began with the installation of infrastructure and high and medium density housing in Garki I and Wuse I residential districts, which flank the city centre (Figure 2.24), with the latter reaching completion in 1983 (Ajayi, 2013). The city as conceived in the master plan was to start with the smallest unit termed ‘neighbourhood’, with a cluster of neighbourhoods making up the residential districts of the city and the city centre. Each neighbourhood was to be provided with a neighbourhood centre, which would bear the brunt of providing neighbourhood facilities, including schools, corner shops, dispensaries or clinics, a post office and a community hall (Ago, 2001).

Table 2.4 Principal types of housing units (FCDA, 1979, p. 117)

<table>
<thead>
<tr>
<th>Housing type Sub-type</th>
<th>Plot area per household (m²)</th>
<th>Built space per household (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Detached/ Semi-detached</td>
<td>a. Large 1,000</td>
<td>120-160</td>
</tr>
<tr>
<td>2.</td>
<td>b. Medium 1,000-800</td>
<td>70-100</td>
</tr>
<tr>
<td>3.</td>
<td>c. Small 75-100</td>
<td>30-60</td>
</tr>
<tr>
<td>4. Flats</td>
<td>a. Large 80</td>
<td>100</td>
</tr>
<tr>
<td>5.</td>
<td>b. Medium 60-80</td>
<td>85-100</td>
</tr>
<tr>
<td>6.</td>
<td>c. Small 35-60</td>
<td>45-70</td>
</tr>
<tr>
<td>7. Multi-family</td>
<td>a. 2-3 family 120-150 tpa</td>
<td>40-75</td>
</tr>
<tr>
<td>8.</td>
<td>b. 4 family 180 tpa</td>
<td>60-80</td>
</tr>
<tr>
<td>9.</td>
<td>c. Transitional 240 tpa</td>
<td>60-80</td>
</tr>
<tr>
<td>10. Serviced Land</td>
<td>a. Large 1,000</td>
<td>2. Serviced Land</td>
</tr>
<tr>
<td>11.</td>
<td>b. Medium 400</td>
<td></td>
</tr>
</tbody>
</table>

Note: ‘tpa’ represents total plot area

Table 2.5 Housing programme options (FCDA, 1979, p. 180)

<table>
<thead>
<tr>
<th>Option</th>
<th>House types</th>
<th>Estimated % Subsidised *</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. High standard single family detached</td>
<td>L, M, S</td>
<td>T</td>
</tr>
<tr>
<td>B. Detached reduced standard</td>
<td>L, M, S</td>
<td>L</td>
</tr>
<tr>
<td>C. High density</td>
<td>S</td>
<td>L, M, S</td>
</tr>
<tr>
<td>D. Reduced density and infrastructure</td>
<td>L, M, S</td>
<td>L, M, S</td>
</tr>
<tr>
<td>E. Mixed standard</td>
<td>L, M, S</td>
<td>L, M, S</td>
</tr>
<tr>
<td>F. Mixed standard</td>
<td>L, M, S</td>
<td>L, M, S</td>
</tr>
</tbody>
</table>

Note: L= large; M= medium; S= small; T= traditional; *= percentage of the total estimated capital investment of programme not recovered through repayment by residents
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In addition to the development of the Wuse I (Figure 2.24 and 2.25) and Garki I districts, the construction of infrastructure in the central business districts, as well as the development of the Asokoro and Maitama districts, were on-going in the early 1990s. The overall development consisted of the construction of 33 neighbourhoods (Ukoha & Beamish, 1996). For the purpose of analysis, a brief description of each housing type developed in these districts is given in section 2.5.3.1 to 2.5.3.4.

![Figure 2.24 Map of Abuja, highlighting areas of on-going construction in 1983, including Wuse I and Garki I residential districts (Stockhausen et al., 2006)](image)

![Figure 2.25 Aerial photograph of a neighbourhood in Wuse I (residential district) in early 1980s, with Aso Hill visible in the background (Stockhausen et al., 2006)](image)
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2.5.3.1 SINGLE FAMILY DETACHED AND SEMI-DETACHED

At the highest standard, the effective floor space for single-family houses is more than 160m$^2$. The largest houses consist of five bedrooms, a large living room, dining room, kitchen, bathroom/toilet, guest facilities and servant’s quarters. A medium-standard size house consists of three bedrooms, a kitchen, living room, kitchen and bathroom/toilet, with an averaging floor space of 80m$^2$. The minimum standard of detached/semi-detached housing considered was 60m$^2$, consisting of two bedrooms, a living room, kitchen and bathroom/toilet.

![Image](image1.png)

Figure 2.26 Two-bedroom, four-storey block of flats, Wuse I district (Abdulkareem, 2013)

2.5.3.2 FLATS

Large three and four storey residential buildings were constructed to cater for middle and lower income groups, who are economically unable to occupy either single-family detached or semi-detached houses. The minimum assigned plot area per household in a block of flats is 45m$^2$. This area consists of one or two bedrooms, a living room, kitchen and bathroom/toilet. The typical plans for the flats feature a living/dining space with a corridor connecting the living space to a kitchen, shower room toilet and bedrooms, as shown in Figure 2.28.

![Image](image2.png)

Figure 2.27 Two-bedroom block of flats, Garki I district (Abdulkareem, 2013)
2.5.3.3 Multi-family Housing

Multi-family (rooming) houses of Lagos and other Yoruba towns, developed in the Afro-Brazilian style (Figure 2.29), became popular in the mid-19th Century and have been adopted in other major cities across the country. The typology is characterised by rooms for different families facing each other on either side of a corridor with shared facilities at the end of the corridor. These houses are commonly referred to as ‘face-me-i-face-you’ (Osasona, 2007). Contemporary versions of the multi-family housing type were proposed in the Abuja master plan (FCDA, 1979).

These types of housing units were developed to cater for low-income migrants who were expected to be attracted to the city in search of employment. Such migrant households were expected to include only a single man or man and wife. To reduce the total plot costs to individual households in these dwelling units, six migrant low-income households occupied 240m² with an effective plot area of 40m² per household consisting of two rooms, shared kitchens and sanitary facilities.
As stated previously, only 8,680 houses had been completed by December 1986, and these included developments in workers’ settlements and satellite towns within commuting distance of Abuja including, Karu, Nyanya, Abaji, Kwali, Kuje, Bwari, Gwagalada, Karshi, Rubochi and Yaba (FCDA, 1986). The houses built in the satellite towns supplemented the housing shortage in Abuja. In fact, only 2,693 houses were completed by the mid-1980s, which was far less than the target of the master plan that recommended the development of 25,000 dwellings by 1986 (FCDA, 1986). The number and type of houses developed by 1986, as well as the stages of their construction are shown in Table 2.6.

Table 2.6 Dwelling by type and stage of construction in Abuja (FCDA, 1986)

<table>
<thead>
<tr>
<th>District</th>
<th>Stage</th>
<th>1 bedroom</th>
<th>2 bedroom</th>
<th>3 bedroom</th>
<th>4 bedroom</th>
<th>5 bedroom</th>
<th>6 bedroom</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garki</td>
<td>A</td>
<td>1,086</td>
<td>1,961</td>
<td>797</td>
<td></td>
<td></td>
<td></td>
<td>4,172</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>638</td>
<td>658</td>
<td>281</td>
<td></td>
<td></td>
<td></td>
<td>1,756</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>448</td>
<td>1,303</td>
<td>516</td>
<td></td>
<td></td>
<td></td>
<td>2,416</td>
</tr>
<tr>
<td>Wuse</td>
<td>A</td>
<td>922</td>
<td>1,180</td>
<td>1,486</td>
<td></td>
<td></td>
<td></td>
<td>4,166</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>288</td>
<td>309</td>
<td>148</td>
<td></td>
<td></td>
<td></td>
<td>761</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>634</td>
<td>871</td>
<td>1,338</td>
<td></td>
<td></td>
<td></td>
<td>3,405</td>
</tr>
<tr>
<td>Asokoro</td>
<td>A</td>
<td>66</td>
<td>288</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>364</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>66</td>
<td>288</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>364</td>
</tr>
<tr>
<td>Gwarinpa</td>
<td>A</td>
<td>30</td>
<td>48</td>
<td>122</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>20</td>
<td>30</td>
<td>116</td>
<td></td>
<td></td>
<td></td>
<td>166</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>10</td>
<td>18</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>Maitama</td>
<td>A</td>
<td>60</td>
<td>28</td>
<td>28</td>
<td>116</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>60</td>
<td>18</td>
<td>28</td>
<td>106</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>A</td>
<td>2,008</td>
<td>3,237</td>
<td>2,331</td>
<td>1,376</td>
<td>38</td>
<td>28</td>
<td>9,018</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>926</td>
<td>987</td>
<td>459</td>
<td>311</td>
<td>10</td>
<td>0</td>
<td>2,693</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>1,082</td>
<td>2,250</td>
<td>1,872</td>
<td>1,065</td>
<td>28</td>
<td>28</td>
<td>6,325</td>
</tr>
</tbody>
</table>

Note: A= Awarded; C= Completed; O=On-going in 1986

Apart from the on-going work by the FCDA, a couple of ministries, including the FHA and the Federal Ministry of Works and Housing now the Federal Ministry of Land, Housing and Urban Development (FMLHUD) took up the responsibility of housing delivery in Abuja and the FCT in the early 1990s. In 1992,
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the FHA constructed 427 and 162 houses at Asokoro and Maitama district respectively, which were subsequently sold to individuals. The buildings consisted of 2, 3 and 4 bedroom block of flats (FHA, 2013). In like manner the Federal Ministry of Works and Housing constructed 86 and 55 houses at Wuse I and Gudu district respectively between 1990 and 1995, as part of the initial phase of the national prototype housing scheme (FHA, 2013).

2.5.3.4 Serviced land

Serviced land with a minimum plot area of 400m$^2$ and a maximum around 1,000m$^2$ were provided in anticipation of a demand for private residential building production. Due to a lack of private sector investment and the difficulty of acquiring serviced land, this option had limited success from the onset of the city’s development (FCDA, 1979). In 1986, the FCDA reported that over 90% of the residential plots in phase I had been allocated to individuals and government institutions for housing development. However, despite the high percentage of plot allocation, the level of private participation in terms of residential building development was less than 1% (FCDA, 1986). This was attributed to the absence of basic infrastructural services in most of the districts and a general lack of economic motivation to build houses in Abuja (Jibir, 1988).

As previously stated, there was an increase in the demand for housing in Abuja shortly after it officially became the capital city, but the increase in private sector interest in developing houses did not correspond to the level of demand for housing in the city. Ikejiofor (1997) stated that by 1995, 95% of the amount spent on construction in Abuja was borne by the federal government, even though it was anticipated that at that time the private sector would be responsible for 35% of Abuja’s building development. He cited bureaucratic constraints, the high cost of land and poor return on investment in land in Abuja as the major deterrents to the private sector residential building production activity (Ikejiofor, 1998a). Ikejiofor argued that:

“Small-scale private developers and low-income private individuals in particular, thus, face enormous difficulties in gaining access to land in Abuja. First is the excessive amount charged as official fees. The premium payable for a high-density plot (900m$^2$ or less) as of December 1994 was N175,000, while the land rent was N9,860 per annum, with a revision interval of five years.
Chapter two

"The annual take-home pay of an upper low-income civil servant is about N21,000" (Ikejiofor, 1998a, p.302).

2.5.4 PHASE II AND ONWARDS (1996-PRESENT)

Despite existing challenges of housing delivery in both the public and private sector, in 1996, the federal government instructed all its ministries to move their headquarters to Abuja (Ago, 2001). Due to this decision, efforts were made by the FCDA to complete on-going housing projects, which included:

1. 33-blocks of 66 units of three-bedroom duplexes for senior public servants in the Wuse II district;
2. 32 blocks of 198 units of two-bedroom flats allocated to intermediate staff in the Garki II district;
3. 28 houses with supporting staff quarters for ministers and permanent secretaries at the Mabushi and Asokoro districts;
4. 98 two-bedroom flats in the Garki II district;
5. 224 one-bedroom flats at the security quarters, Asokoro.

In phase II of the FMLHUD housing scheme in 1997, 23 and 668 houses were constructed at the Asokoro district and the Gwarinpa district respectively. In addition to the houses constructed by the government within the city, several other housing projects for low-income groups were carried out within the Federal Capital Territory in satellite towns by the FCDA, FMLHUD and FHA (Ago, 2001). The location and number of houses developed as part of the federal low-cost housing scheme are shown in Table 2.7. Replacement houses were built at various locations in the city to adequately accommodate the former occupants of the Gudu district, because of the government’s decision to form the legislative quarters within this district (Ago, 2001).

Table 2.7 Federal low-cost housing programme in the Federal Capital Territory (Ago, 2001)

<table>
<thead>
<tr>
<th>Satellite town</th>
<th>Type and No. of units available</th>
<th>Type and No. of units completed</th>
<th>Type and No. of units ongoing</th>
<th>Type and No. of units not started</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 bedroom</td>
<td>3 bedroom</td>
<td>1 bedroom</td>
<td>3 bedroom</td>
</tr>
<tr>
<td>Gwagalada</td>
<td>890</td>
<td>80</td>
<td>628</td>
<td>34</td>
</tr>
<tr>
<td>Abaji</td>
<td>404</td>
<td>74</td>
<td>304</td>
<td>58</td>
</tr>
<tr>
<td>Sheda</td>
<td>174</td>
<td>16</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>Kuje</td>
<td>144</td>
<td>6</td>
<td>56</td>
<td>-</td>
</tr>
<tr>
<td>Rubochei</td>
<td>50</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kwali</td>
<td>48</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Karshi</td>
<td>50</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bwari</td>
<td>40</td>
<td>8</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,800</strong></td>
<td><strong>200</strong></td>
<td><strong>1,068</strong></td>
<td><strong>92</strong></td>
</tr>
</tbody>
</table>
The master plan of Abuja projected that 278,000 dwellings would be completed by the turn of the 20th and 21st Century, yet as of 1999, less than 40% of the dwelling units required in the FCT had been provided by the government and private sector. This was attributed to inadequate private sector participation in the residential building development and the lack of development of infrastructure and transport facilities in phase II of the city, which put pressure on the facilities in phase I (Kalgo & Ayileka, 2001). Moreover, the movement of various government ministries and establishments to the FCT without adequate preparation, brought with an increased population and the emergence of squatter settlements that did not conform to the master plan (Adejuwon, 2001).

Smaller private sector firms and individuals implemented a variety of construction and financing methods, but these efforts did not provide adequate supply especially for lower income groups (Ikejiofor, 1998b). In December 1999, Suleiman (2001) reported that there were enormous deficiencies in both the quality and quantity of housing. He stated that “a vast majority of the population are tenants crowded into one and two-storey rooming houses with densities as high as 2,000 dwellings per hectare and with 50% to 70% of households occupying one room and sharing inadequate and intermittent services” (Suleiman, 2001, p. 186).
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As part of the review of the Abuja master plan in 1999, the Nigerian Institute of Architects recommended a number of strategies for improving the quality and quantity of housing in the city (Kalgo & Ayileka, 2001, p. 220). These included:

- Establishing a deliberate policy on low-income housing for involvement of both private and public sector, in solving the acute shortage of houses, which are mostly due to affordability;
- Encouraging private sector participation in housing delivery by facilitating easy access to land procurement, sites and services;
- Adopting an urban renewal approach to upgrade services, housing and neighbourhood facilities in low-income neighbourhoods without resorting to complete demolition of any existing squatter settlements in such areas;
- Prioritising the construction of more high-density residential buildings, such as blocks of flats and terraced houses;
- Prioritising the provision of infrastructure in phase II districts to facilitate more housing development projects and relieve some of the pressure on phase I;
- Allocating large plots of land for the construction of residential estates by private developers;
- Encouraging professional architects to produce practical and ideal housing designs, which can be standardised and adopted as models for people to implement, especially for low-cost housing delivery.

Following the recommendations made in the review of the city’s master plan, the concept of Private-Public Partnership (PPP) was initiated in 2000, in order to improve private sector participation in housing production in Abuja. The intention was to bridge the gap between supply and demand for housing in the city and take some of the financial burden of housing production off the government (Jibril & Garba, 2012). The programme was done in broadly three phases between 2000 and 2003, 2004 and 2007, and 2008 and 2011. On the whole, over 126,917,000m² of land across 22 districts of the city were allocated in this scheme. The districts and allocated areas are illustrated in Table 2.8.

Despite the intentions of the government, the scheme did not give room for affordable housing delivery, because private developers were more inclined to build private gated estates, designed to attract middle and high-income earners. Thus, even the smaller houses built in such estates, are too expensive for lower income groups (Jibril & Garba, 2012). Thus, while the state of private production and ownership amongst
middle and upper-income earners has improved in recent times, providing housing for low-income groups in the city remains primarily the responsibility of the government.

Table 2.8 List of mass housing allocations in Abuja by phase and district (Jibril & Garba, 2012)

<table>
<thead>
<tr>
<th>Phase</th>
<th>District</th>
<th>Area allocated (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>Kado</td>
<td>4.895</td>
</tr>
<tr>
<td></td>
<td>Duboyi</td>
<td>3.363</td>
</tr>
<tr>
<td></td>
<td>Dutse</td>
<td>5.409</td>
</tr>
<tr>
<td></td>
<td>Gaduwa</td>
<td>4.817</td>
</tr>
<tr>
<td>III</td>
<td>Galadimawa</td>
<td>6.611</td>
</tr>
<tr>
<td></td>
<td>Lokogoma</td>
<td>8.004</td>
</tr>
<tr>
<td></td>
<td>Saraji</td>
<td>5.611</td>
</tr>
<tr>
<td></td>
<td>Wumba</td>
<td>5.994</td>
</tr>
<tr>
<td></td>
<td>Bunkoro</td>
<td>8.378</td>
</tr>
<tr>
<td></td>
<td>Gwarinpa II</td>
<td>4.335</td>
</tr>
<tr>
<td></td>
<td>Nborra</td>
<td>5.371</td>
</tr>
<tr>
<td></td>
<td>Wupa</td>
<td>2.840</td>
</tr>
<tr>
<td></td>
<td>Dakwo</td>
<td>5.685</td>
</tr>
<tr>
<td></td>
<td>Kafe</td>
<td>5.986</td>
</tr>
<tr>
<td>IV</td>
<td>Karsana East</td>
<td>7.658</td>
</tr>
<tr>
<td></td>
<td>Karsana North</td>
<td>9.155</td>
</tr>
<tr>
<td></td>
<td>Karsana South</td>
<td>6.052</td>
</tr>
<tr>
<td></td>
<td>Karsana West</td>
<td>5.097</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>3.768</td>
</tr>
<tr>
<td></td>
<td>Sabo Gida</td>
<td>7.410</td>
</tr>
<tr>
<td></td>
<td>Idogwari</td>
<td>6.274</td>
</tr>
<tr>
<td></td>
<td>Idu-Sabo</td>
<td>4.289</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>126.92</strong></td>
</tr>
</tbody>
</table>

Figure 2.32 Map of Abuja showing different districts and phases (Abuja Geographic Information Systems [AGIS], 2006)
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At present, the development of residential buildings in Abuja is off the pace anticipated in the master plan. While phase I and phase II are highly developed with infrastructure in place and residential building development at an advanced stage, there is still a lack of primary infrastructure in many phase III and IV districts (Jibril & Garba, 2012). Furthermore, despite numerous efforts, there are still social and economic obstacles, negating low-income groups from accessing housing in Abuja. The current pro-market housing policies in Nigeria have placed emphasis on Public-Private Partnership (PPP) on the assumption that housing funds can be sourced from the open market. Unfortunately, the PPP orientated housing policy in Abuja is associated with over-concentration on housing the upper and middle-income groups in order to maximise profits for the developers (Abubakar & Doan, 2010). Muhammad et al. stated:

“While about 47% of Abuja residents earn ₦360,000 ($2,250) annually, the cost of a cheapest bungalow in the housing estates (under the public-private partnership programme) is ₦15 million ($94,000). This huge cost makes the housing units unaffordable” (2015, p. 29).

The high mortgage interest rates also limit the accessibility of low-income earners to housing in the city. Interest rates on mortgage loans in Nigeria are as high as 20%, excluding fees and other charges (Muhammad et al., 2015).

2.5.5 Typical residential building characteristics

2.5.5.1 Forms and layouts

Due to the increased participation of private developers, there have been aesthetic changes in the residential building architecture for the upper-income groups. Designers have also experimented with various foreign influences from North African trends, Afro-Brazilian trends and European neoclassicism, based on individual preferences (Prucnal-Ogunsote, 2001). The design manifestation of these influences includes the use of decorative columns, to create large entrance porches, wall mouldings around corners, doors and windows, and moulded eaves (Figure 2.33). The mouldings, which are typically made using Portland cement, do not appear to serve any purpose beyond the embellishment of the façade (Ezema et al., 2015).
Despite the high cost of the common construction methods and materials (which are discussed in section 2.5.5.2), the Nigerian construction industry, for the most part, remains unwilling to adopt new construction practices (Kolo et al., 2014; Makinde, 2014). On the other hand, the design of residential buildings for lower income groups, particularly those developed by the government, has not evolved either with regards to style, building technology, or layout. A number of residential building design prototypes are continuously being re-appropriated for different mass housing projects (Isah et al., 2014). For instance, the plan of a residential building consisting of two bedroom flats designed and built in 1996 by the FCDA and another developed by the FMLHUD in 2011, are shown in figures 2.34 and 2.35 respectively. While the sizes of different rooms in both plans have been altered, the general layout and façade configuration are similar.
A common characteristic of the residential buildings in the city is the use of verandas. These verandas are often positioned before the entrance to the living room and a secondary external door by the kitchen. These characteristics were likely attempts by the designers to echo the sitting terraces and the outdoor cooking area in the traditional architecture layout (Figure 2.36) and/or the verandas of the Afro-Brazilian style (Figure 2.29). However, there are no mouldings at eaves, plinths, columns and balustrades in typical contemporary residential buildings, especially those designed for low-income groups. The buildings consist of simple geometric forms with little or no decorative elements constructed, using either prefabricated concrete or cement blocks (Ukoha & Beamish, 1996). Overall, the environmental factors that influence the design of traditional dwellings only received cursory consideration in the design of the housing schemes developed in Abuja. Moreover, the references to the traditional architecture of the region in contemporary buildings seem to be mostly aesthetic. The architectural characteristics and the overall layout and geometry of a selected number of case study housing schemes are discussed in Chapter six.

![Figure 2.36 Variation of traditional dwelling compound with both sitting terrace and outdoor cooking area (Ikejiofor, 1999)](image)

2.5.5.2 Building fabric characteristics

This section provides a brief description of the common building materials used for the construction of low-income residential buildings in Abuja.

Walls: Some of the residential buildings constructed during the accelerated stages of development in Abuja in the early 1980s, were built using prefabricated concrete, but the majority of buildings in the city
in the past and at present, are constructed with sandcrete blocks. A sand cement mixture is used as mortar to join the blocks and used in plastering on both sides of the wall. There are two standard sizes of sandcrete blocks used in Nigeria, including the 225x225x450mm block, used for external and load bearing walls, and the 150x225x450mm block, used for partition walls (Figure 2.37).

![Figure 2.37 Typical hollow sandcrete block (Abdulkareem, 2013)](image)

Glazing: Some of the initial buildings constructed in Abuja have toughened glass louvers with wooden frames, but the prevalent glazing option are PVC framed units with 4mm to 6mm thick single pane, clear glass.

Roofing: The use of sandstone coated metal roofing sheets, with different profiles and finishes, have become more common in recent times, especially in private sector housing. However, corrugated iron sheet clad gable roofs still remain the most prevalent roofing type, especially in the construction of houses for low-income groups. 90.7% of the houses in the FCT have corrugated iron sheet roofing (NBS, 2013).

Ceiling: The ceilings are often made of chip wood, gypsum boards and gypsum plaster (also known as plaster of Paris).

Floor: Ground floors are often made of 150mm concrete slabs laid directly on 300mm hard-core and compacted soil; while suspended floors are made of 150mm reinforced concrete slabs cast in situ. A variety of floor finishes is used depending on preference and cost including terrazzo flooring, ceramic tiles and sand cement flooring.
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Structural frame: Columns, beams and lintels for most residential buildings are formed using a reinforced concrete and stone mix cast in situ.

As previously discussed, the masterplan included a recommendation to increase reliance on local construction material and the review of the masterplan (Kalgo & Ayileka, 2001) also included recommendations to encourage professional architects producing practical and ideal housing designs, which can be adopted as models for low-cost housing. Yet, the materials and architectural design approach in Abuja remain the same at the various phases of the city’s development. With regards to the methods and materials used in construction, the residential buildings examined in this study are exemplary cases of the common types of dwellings that exist in the city. Thus, the relevant types of construction materials and surface finishing (explained before) were used in performing the modelling and their likely impact on the thermal environment in the case study buildings are examined in Chapter six.

2.6 BUILDING REGULATIONS AND ENERGY USE

The existing requirements for residential building development in Nigeria is set in a single source, called the National Building Code (NBC) (Federal Republic of Nigeria [FRN], 2006). The specifications that apply to residential buildings (classified as ‘use group H – residential’ in the building code) and environmental considerations include the following:

- Natural lighting,
- Natural ventilation,
- Room dimensions,
- Occupancy,
- Building materials.

2.6.1 NATURAL LIGHTING

The Nigerian building code specifies that “all habitable rooms within a dwelling unit shall be equipped with natural light by means of exterior glazed openings with an area not less than one-tenth (10%) of the floor area of such rooms with a minimum of 1m$^2$” (FRN, 2006, p.129). In the application of the provision of natural light, it is specified that the standard of natural light for all habitable rooms, shall be based on
Chapter two

2,691 lux of illumination on the vertical plane adjacent to the aperture in the enclosure of the wall and shall be adequate to provide an average illumination of 64.58 lux over the area of the room, at a height of 75cm above the floor level. The values specified in the Nigerian building codes (2006) seem to have been adapted from the International building code by the International Code Council (ICC, 2003), but it is not clear how these values relate to the quantity of daylight required for performing specific tasks in a room. Moreover, the Nigerian building codes do not include any recommendations associated with the distribution of daylight across a room.

It is also worth noting that these values differ from those recommended by the Illuminating Engineering Society of North America (IESNA) lighting handbook, which prescribes a minimum maintained illuminance of 50lux for simple orientation in spaces and 100lux for spaces where simple visual tasks are performed (IESNA, 1999). The IESNA recommendations were used in the evaluation in this study, because they provided clearer guidelines for the level of illumination required for various tasks.

2.6.2 NATURAL VENTILATION

The Nigerian building code specifies that “habitable rooms within a dwelling unit shall be provided with natural ventilation by means of exterior openings that can be opened, with an area of not less than one-twentieth (5%) of the floor area of such a room with a minimum of 0.46m$^2$” (FRN, 2006, p. 129). Where spaces without openings to the outdoors are ventilated through an adjoining room, the unobstructed opening to the adjoining rooms shall be at least 8% of the floor area of interior space, but not less than 2.4m$^2$. It is specified that the size of the ventilation to the outdoors shall be based on the total area being ventilated. It is also specified that any mechanical ventilation system used in lieu of the required exterior opening, should be able to provide two air changes per hour (ACH) in all habitable rooms and corridors, and 5 ACH in bathrooms, water closet compartments, laundry rooms and similar rooms with higher levels of humidity.

The Nigerian building code specifies that all “required exterior openings for natural light and ventilation shall open directly onto a street or public alley or a yard or court located on the same plot as the building” (FRN, 2006, p. 129). A general environmental requirement stated in the Nigerian building code is that
where more than one building is placed on a plot “the uncovered plot area should constitute an adequate source of light and ventilation for all buildings intended for human occupancy” (FRN, 2006, p. 73). This requirement is further explained in the Abuja development control manual, which specifies that “the minimum set back between two buildings shall not be less than the mean of the sum of the height of the buildings opposite or adjacent each other” (Abuja Metropolitan Management council [AMMC], 2007, p. 69). An illustration of this requirement is shown in figure 2.38.

![Figure 2.38 Illustration of setback rule recommended in the Abuja development control manual](image)

2.6.3 ROOM DIMENSIONS

Under section 7.1.4.5 in the building code, it is specified that habitable spaces should have a ceiling height of not less than 2.3m from the finished floor to the finished ceiling. Halls, bathrooms and toilets may have a ceiling height of not less than 2.1m measured to the lowest projection from the ceiling. If a room has a sloping ceiling, no portion of the room with a measured ceiling height of less than 1.5m from the finished floor to the finished ceiling shall be included in any calculation of the floor area of the room. Concerning floor areas, it is specified that every dwelling should have at least one room with a minimum floor area of 12m² and other habitable rooms, except kitchens, which should have an area of not less than 6.5m². The width of habitable rooms, except kitchens, should be no less than 3m. The minimum living space specified for efficiency dwellings, such as studio apartments and rooming units, is a floor of 20m² and an additional floor area of not less than 9.3m², which is required for each occupant of such unit in excess of two.

The specifications for the minimum dimensions of a habitable room in the Nigerian building code and the international building code (ICC, 2003, pp. 273-274) are similar. However, the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) recommends ceiling heights beyond the normal 8-10 feet (2.4-3m) for buildings that rely on natural ventilation for cooling (ASHRAE, 2009, p.
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16.13). Higher ceilings allow warm air and contaminants to rise above the occupied portions of rooms and the air is exhausted from the ceiling zones; cooler outside air comes in near the floors (ASHRAE, 2009). Minimum room dimensions for residential buildings are also specified in the Abuja development control manual’s architectural standards. The space definitions and their minimum dimensions are shown in table 2.9.

Table 2.9 Development control manual standards for space dimensions in residential buildings (AMMC, 2007)

<table>
<thead>
<tr>
<th>Space definitions</th>
<th>Basic minimum (m²)</th>
<th>Minimum side dimension (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living room</td>
<td>12.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Dining room</td>
<td>7.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>10.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Toilets (bath/WC)</td>
<td>3.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Toilet (WC only)</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Garage</td>
<td>16.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Car park</td>
<td>12.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Kitchenette</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td>6.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Stores</td>
<td>3.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Corridors (width)</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Headroom (height)</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Balcony (width)</td>
<td>1.2-1.5</td>
<td></td>
</tr>
</tbody>
</table>

Staircase:
- i. Width 1.2
- ii. Riser 0.15
- iii. Thread 0.25

Note: room sizes do not include wardrobe spaces.

2.6.4 OCCUPANCY

The standard specified in the Nigerian building code is 0.65m²/occupant with standing space of 0.28m². The maximum occupancy permitted for residential buildings is 18.6m²/occupant. Two exits are required in any building with less than 500 occupants and a minimum of 3 exits is required for buildings with more than 500 occupants.

2.6.5 BUILDING MATERIALS

The Nigerian building code specifies that “the application of all materials and components used in the construction of buildings must be such that will achieve aesthetics, durability, functionality, character and affordability” (FRN, 2006, p. 307). Specifications with regards to the durability and structural strength of a variety of building materials from glass to reinforced concrete are given. Three different sizes of sandcrete blocks including, 100x225x450mm, 150x225x450mm and 225x225x450mm are specified;
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however, no standards are set in the building code for building material thermal resistance and fabric thermal transmittance.

The climate in Nigeria is not homogeneous; a fact, well reflected in the traditional architecture of different regions. Traditional residential architecture in Nigeria is characterised by an extreme diversity in forms, techniques, knowledge and skills, dealing with materials, jointing, finishing and technology of construction (Prucnal-Ogunsote, 2001). It is evident that a purely traditional environment cannot adequately serve the needs of the present urban societies in Nigeria (Ikejiofor, 1999). However, the Nigerian codes and standards for design, planning and development control does not consider the need for region-specific climate conscious building design. Ikejiofor (1999) argued that such standards are largely dependent on inappropriate technology for their implementation.

It is not clear how compliance with the national buildings regulation and standard has influenced the environmental performance and sensation of comfort in Abuja’s residential buildings. Thus, Chapters six and seven provide a detailed examination of the performance of a range of selected housing types/schemes. With the exception of a few instances, the selected cases in this study are examples of buildings that have been constructed in accordance with the requirements for natural lighting, natural ventilation, the minimum room dimensions and maximum occupancy specified in the national building code. Moreover, all the buildings examined are constructed using the typical construction materials and methods recommended in the building code. However, the requirements for the rate of air change per hour using mechanical ventilation systems, is outside the scope of this study.

2.7 The impact of the residential building sector on electrical energy consumption in Nigeria

Since the discovery of crude oil in the Niger Delta region of Nigeria in the late 1950s, the country’s economy has been increasingly dominated by crude oil export. Nigeria is the largest oil producer in Africa and is among the world’s top five exporters of liquefied natural gas (Energy Information Administration [EIA], 2015). The Nigerian economy has continued to grow at a relatively fast rate. It was stated that the overall growth in Nigeria’s GDP was estimated at 6.61% in 2012 and was expected to rise to 6.75% in
Chapter two

2013 (NBS, 2013). Nigeria is presently the eighth most populous country in the world and the most populated country in Africa. The country’s current population is over 174 million and with an annual population growth rate of about 2.54%, this figure is likely to increase in the future adding pressure on the existing infrastructure. The rapid increase in population, economic growth, as well as the rapid urbanisation recorded in Nigeria over the last few decades, are indicative of a country in transition. Such emerging changes in the social structure, as well as in the economic profile of the country, represent different sets of opportunities as well as challenges as compared to those in more developed countries (Ogbonna, 2007). However, despite the country’s oil wealth, more than half of the country’s population does not have access to basic housing and associated facilities. At present, around 17 million housing units were required to bridge Nigeria’s housing deficit (Komolafe, 2015).

On the other hand, energy demands continue to increase for the houses that are available, without corresponding growth in supply. The country's grid-based electricity annual power consumption per capita is around 156 kilowatt-hours (kWh), which is one of the lowest in Africa and over 50% of the population are not served with electricity from the national grid (World Bank, 2015b). Most of the energy consumption is concentrated in urban areas, whereas rural and semi-urban access to electricity is estimated to be about 35% (Oseni, 2012). Thus, designing buildings that use passive solutions is important for reducing energy consumption in residential buildings in urban areas, as well as providing comfort in residential buildings with limited access to electricity. These circumstances underscore the need for detailed investigation of the visual and thermal performance of contemporary residential buildings in Nigeria.

2.7.1 Energy sources in Nigeria

Biomass fuels, consisting mainly of fuel wood, account for over 65% of the total final energy consumption in Nigeria. Biomass fuels are mainly used for cooking and heating, especially in rural areas. The sources of energy for electricity production in Nigeria over the last 50 years, include natural gas, oil, coal and hydroelectric power systems, with gas taking precedence in recent times. Figure 2.39 presents the percentage contribution of each of the sources. Oil and gas have contributed almost 65% of the primary
energy, while coal, which is often consumed locally or used for industrial heating in cement production, is neglected as an energy source for electricity (Aliyu et al., 2013; Okoro & Chikuni, 2007). This is predicated by the fact that these fuel sources are readily available. Nigeria is the ninth largest holder of natural gas in the world, with reserves of over 5,000 billion m$^3$ of natural gas. The country also has proven reserves of over 37 billion barrels of crude oil, which is the eleventh largest reserve in the world (Organization of the Petroleum Exporting Countries [OPEC], 2015).

![Percentage contribution of energy sources in Nigeria (Aliyu et al., 2013)](image)

Figure 2.39 Percentage contribution of energy sources in Nigeria (Aliyu et al., 2013)

Electricity production in Nigeria dates back to 1896, when electricity was first produced in Lagos, to serve officials of the colonial administration. The total capacity then was 60 kilowatts (kW), which were produced by two generators (Okoro & Chikuni, 2007). The electricity generation capacity grew when the first generating plant was installed in Lagos in 1898 (Olugbenga et al., 2013). In 1946, the Nigerian government started providing electricity for the public, under the jurisdiction of the public works department. The generation capacity at the time was 10 MW (Olukoju, 2004).

The government transferred control of electricity distribution to the Electricity Corporation of Nigeria (ECN) in 1950. The Niger Dam Authority (NDA) was established afterwards in 1962, to undertake the construction of dams along the Niger River and elsewhere for hydroelectric power generation (Makwe, Akinwale, & Atoyebi, 2012). A decade later, the ECN and NDA were merged to form the National Electric Power Authority (NEPA). The reason for the merger was to make both electricity production and distribution throughout the country the responsibility of one organisation (Okoro & Chikuni, 2007).
2.7.2 Challenges faced by the electricity market in Nigeria

Since its formation, the NEPA expanded its capacity in order to meet the increasing demand for electricity. Electricity generation increased from less than 1000MW per hour to a little less than 3000MW per hour in 2005 (Akinlo, 2009). Notwithstanding, the increase in population and the increase in energy-dependant technology use without corresponding in the country’s generating capacity; there has been a continual increase in the deficit between electricity supply and demand (Olugbenga et al., 2013). As of 2011, only 40% of Nigerians had access to electricity. Moreover, due to the poor transmission and distribution infrastructure, the current available capacity is about 49% of the installed capacity of the power stations (Oseni, 2012). Table 4.9 presents information on the power generation conditions in Nigeria in 2011.

The inadequate electricity supply has been reflected in the irregular power supply and frequent power outages. In the early 80s, the country entered an era of unprecedented dependence on private electricity generators (Olukoju, 2004). More than 6% of households have supported their access to electricity with power generator sets and about 3% of households rely exclusively on power generator sets for electricity (Aliyu et al., 2013)

<table>
<thead>
<tr>
<th>Power station</th>
<th>Type</th>
<th>Year of construction</th>
<th>Installed capacity (MW)</th>
<th>Available capacity in 2011 (MW)</th>
<th>% contribution to national grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kianji Hydro</td>
<td>1968</td>
<td>760</td>
<td>480</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>Jebba Hydro</td>
<td>1985</td>
<td>540</td>
<td>450</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>Shiroro Hydro</td>
<td>1989</td>
<td>600</td>
<td>450</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>Egbin Thermal</td>
<td>1986</td>
<td>1320</td>
<td>1100</td>
<td>32.8</td>
<td></td>
</tr>
<tr>
<td>Geregu Thermal</td>
<td>2007</td>
<td>414</td>
<td>276</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>Omotosho Thermal</td>
<td>2007</td>
<td>304</td>
<td>76</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Olorunsogo Thermal</td>
<td>2008</td>
<td>304</td>
<td>76</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Delta Thermal</td>
<td>1966</td>
<td>900</td>
<td>300</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>Sapele Thermal</td>
<td>1978</td>
<td>1020</td>
<td>90</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Afam Thermal</td>
<td>1963</td>
<td>726</td>
<td>60</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Calabar Thermal</td>
<td>1934</td>
<td>6.6</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Orij river Thermal</td>
<td>1950</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>6,904.6</strong></td>
<td><strong>3,358</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to Ulukoju (2004) there were three major factors that lead to the poor grid-based electrical energy supply in Nigeria. Firstly, the National Electric Power Authority (NEPA) was run as a government monopoly, which stifled productivity and fostered poor accountability. Secondly, the energy sector had been under-funded. Lastly, proposals for the private sector to inject capital and competition in the energy sector were negated by the fact that the NEPA was a social service. At the turn of the 21st Century, the
price for generating a kilowatt-hour (kWh) of electricity was ₦1.2, yet NEPA charged consumers less than 20% of that amount. Thus, incurring a 500% deficit on tariffs alone (Olukoju, 2004).

The government in 2005, adopted a holistic approach to restructuring and privatising the energy sector. Consequently, NEPA has transformed into the newly incorporated Power Holding Company of Nigeria (PHCN) plc, comprising 18 separate successor companies that took over the assets, liabilities and employees of NEPA. These included six power generation companies, one transmission company and eleven distribution companies (Olugbenga et al., 2013). Under this reform, only the transmitting company remained as a government entity, and the Nigerian Electricity Regulatory Commission (NERC) was created to regulate the price of electricity. The main reason for the reform was to ensure a gradual transition to a competitive market, which can attract private investment (Makwe, 2011). Even though the reform in 2005 lead to an increase of the electricity tariff, from approximately ₦7/kWh to about ₦10/kWh in 2009, Nigeria still has one of the lowest electricity prices in Africa (Makwe et al., 2012). In 2012, the government disbursed ₦100 billion to subsidise the cost of electricity. Although the cost of production was ₦24/kWh, the tariff scheme set up reduced the price of electricity to ₦4/kWh for low-income groups and ₦12/kWh for middle-income groups. The highest rate was set at ₦23.71/kWh for high-income groups (Onwuemenyi, Ovuakporie, & Kalejaye, 2012).

It is apparent that in order for the Nigerian power sector to become financially viable, the government has to eliminate subsidies and allow private investors to set reasonable tariffs above the cost of production for consumers. The increase in tariffs is likely to generate capital for improving the production, transmission and distribution of infrastructure in Nigeria (Makwe et al., 2012). However, it will have an unprecedented impact on the electricity consumption pattern in buildings in Nigeria (Olugbenga et al., 2013), especially in residential buildings, which typically consume more than half of the total annual electrical energy provided by the national grid (IEA, 2015).

2.7.3 IMPLICATIONS OF THE POWER SECTOR REFORM ON ELECTRICITY USE IN RESIDENTIAL BUILDINGS

There are no accurate data on Nigeria’s housing stock (Ademuliyi, 2010). However, earlier studies and observations strongly suggest quantitative and qualitative housing problems across the country
(Abumere, 1987; Adedeji & Abiodun, 2012; Akeju, 2007; Kolo et al., 2014; Nicholas & Patrick, 2015; Ogu & Ogbugbo, 2001). The problems include housing shortages, poor construction, the emergence of slums and squatter settlements, the rising cost of rent and the growing inability of the average citizen to own their own houses or procure decent accommodation (Ademuliyi, 2010).

Most government housing programmes in Nigeria have been frustrated by corruption, insufficiency of technical staff at the building site and lack of infrastructure. From the review of existing literature in section 2.2, it is apparent that the primary focus of many studies, as well as the national housing policy (FRN, 1991, 1998, 2000, 2011), has been on the effective provision of affordable housing to satisfy the requirements of the population. However, very limited consideration is given to affordability and satisfaction beyond the cost of construction and delivery of targeted quantities. The energy required in order to achieve acceptable internal conditions through artificial lighting and air conditioning in a typical urban residential building is expensive, especially for low-income earners (Odin, 2010; Community Research and Development Centre [CREDC], 2009), who constitute more than 62% of Nigeria’s population (World Bank, 2013). Moreover, as stated in the previous section, the price of electricity will have to be increased in order for the power sector to become financially viable.

A review of energy use in buildings suggests that more energy is consumed by residential buildings in developing countries situated in tropical climates like Nigeria. In sub-Saharan Africa, the residential sector consumes as much as 56.2% of the total energy in comparison to 2.2% utilised by the commercial and public buildings sector (Otegbulu et al., 2011). In 2012, the residential sector consumed 57.8% of the electrical energy supplied in Nigeria (Nigerian Energy Support Programme [NESP], 2015) and 57.3% of the electrical energy supplied in 2013 (IEA, 2015).

The electrical energy used for cooling and lighting in residential buildings can constitute as much as 80% of the total energy use (Enaburekhan, 2007). Enaburekhan (2007) carried out a study of 16 air-conditioned two bedroom flats in Gusau, Nigeria. The physical characteristics of the housing units were similar to most housing units provided by the government, particularly those located in urban areas. The study showed that the average annual electricity consumption for each of the flats was 35,808 kWh. The percentage consumption for the three major electricity end users, namely air conditioning, electrical
appliances and lighting, were 78%, 21% and 1% respectively. Given that a kilowatt-hour of electricity ranges from 4 to 24 Naira (Onwuemenyi et al., 2012), the cost of maintaining comfortable internal conditions with this level of energy consumption can be as high as 142,000 to 850,000 Naira per annum. According to the World Bank (2015a), Nigeria can be classified as a lower middle-income country with a gross national income of $2,970 (591,089 Naira as of November 2015) per capita per annum. Thus, the amount spent by households on electricity for cooling and lighting their dwellings can account for about 24% to 144% of the income of the average Nigerian citizen. Thus, any efforts to encourage practical and ideal housing designs, which can be adopted for future low-cost housing development, should not only aim to reduce the cost of building production, but also consider solutions for reducing the amount of energy needed to achieve a comfortable living environment.

2.8 CONCLUSION

The factors that have informed the residential building development trend in urban areas of Nigeria, particularly in Abuja, have been discussed in this chapter. Contemporary housing schemes in Nigeria are rightfully focused on the provision of a high quantity of affordable housing. However, not enough consideration is given to the design of houses in terms of indoor comfort and energy efficiency. The current housing trend that has been adopted and enforced by the government in Abuja is impractical for most small-scale private developers. Moreover, the climatic conditions prevalent in the region, have received little consideration in the formulation of the building regulations.

The current application of subsidy to the housing cost and electricity supply is not going to be sustainable in the future. The application of government subsidy also hides major gaps in the quality of houses provided in Abuja. Therefore, it negates any trends that could improve the efficient use of resources in the construction and habitation of residential buildings in the city. Moreover, as both the housing sector and the energy sector become more privatised, buildings developed as part of this trend will become difficult to be bought and/or maintained. Thus, adequate consideration should be given to the design of residential buildings with regards to affordability, energy efficiency and needs of the people that are intended to live in the buildings. From the review of the existing codes and standards, it is evident that
alternative techniques, materials, finishing and technology of construction, which are more appropriate
for the social and environmental context of Abuja, have to be recommended for future developments.

Ukoha and Beamish (1998) investigated the condition of residential buildings in Abuja (most of which
were provided by the government) and occupants’ satisfaction with their houses, and found that 52% of
the 1,089 respondents surveyed were dissatisfied with their houses. They also found that residents of the
room units were most dissatisfied. Jibir (1988) stated that although there are clearly several problems
with the quality of housing in Abuja, particularly for low and middle-income earners, it is worth noting
that the standards used are officially set to meet the needs of middle-class groups. He concluded that the
housing problems can be said to be essentially income problems, and even though high housing standards
are desirable, adopting and enforcing high standards might be counter-productive with regards to the
provision of affordable housing. As the existing standards set for housing in Abuja are derived from
developed countries with foreign cultures and extremely different climate from that of Abuja, the norms
and standards often place emphasis on a lifestyle that revolves around indoor living, even in the most
tropical situations (Ikejiofor, 1999). The current study is not concerned with the satisfaction of occupants
based on their aspirations, but rather with factors and parameters of residential building design that
influence the indoor visual and thermal conditions and how they can be improved using passive design
solutions.
CHAPTER 3 - FACTORS THAT INFLUENCE THERMAL COMFORT IN BUILDINGS

3.1 INTRODUCTION

The physical environment consists of several interrelated elements, including structures, sound, light, space, terrain and climate that influence an individual's physical condition and psychological perception of comfort (Thellier et al., 2009). The building envelope plays a very important role as a mechanism for providing the desired comfort conditions for the occupants in a particular environment. Olgyay (1963, p. 15) stated that "the shelter (building) is the main instrument for fulfilling the requirements of comfort by modifying elements of the natural environment to approach optimum conditions for 'liveability'". However, fulfilling the required visual and thermal comfort in a building by modifying the natural environment, is not simply achieved by providing shelter or an enclosure, rather it depends on various parameters of the building's design (Unver et al., 2004).

There are a number of design approaches that can be used to facilitate thermal comfort in buildings. Mechanical heating, ventilation and air conditioning equipment are commonly used in contemporary building designs in many regions around the world to provide thermal comfort in buildings. However, most of the electrical energy used in the process of running the equipment is produced by burning fossil fuels, which are non-renewable energy resources. Due to the progressive increase in the price and decrease in availability of non-renewable energy resources, as well as the negative impact of their use on the environment, these means of providing thermal comfort is not sustainable (IPCC, 2013). As a result, there has been an increasing interest in alternative methods, particularly passive building design strategies, as a solution for providing thermal comfort in buildings, while minimising the use of mechanical means (Arandara et al., 2010; Day & Gunderson, 2015; Dim et al., 2015; Gong et al., 2012; Kang et al., 2015; Nguyen & Reiter, 2012; Okereke & Odim, 2007; Schulze & Eicker, 2013; Stevanovic, 2013).

This chapter will focus on a number of parameters, including factors of the natural and built environment that have an influence on indoor thermal conditions and occupants' thermal comfort. One of the primary parameters of the building's design (Unver et al., 2004).

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2 The building envelope can be defined as any building element that separates a space from the external environment (Syed, 2012).
objectives of this study is to investigate the role of passive design solutions as a means of addressing the problem of inefficient use of energy in residential building development in Abuja, Nigeria. The discussion in this chapter is presented in three sections. Firstly, section 3.2 discusses the human thermoregulatory system, as well as the definitions of ‘thermal comfort’. Secondly, the benefits of integrating passive design principles for thermal comfort into building design are discussed in section 3.3. Finally, the design parameters that influence thermal conditions in buildings (particularly in warm climate regions like Abuja), which are often discussed in the literature are identified and reviewed in section 3.4. The primary objective of this chapter is to develop an appropriate framework for evaluating the thermal performance of the residential buildings in Abuja, Nigeria. Thus, there will be a particular consideration of the Nigerian urban context, throughout the chapter.

3.2 DEFINING THERMAL COMFORT

The human daily cycle comprises of various activities including physical exertion, fatigue, rest and recovery, during which the body requires energy to perform these activities. The body produces energy through a set of biochemical reactions that make up a process known as metabolism. This process is necessary to maintain the living state of the human body. However, metabolism produces heat that must be continuously released in order for the body to maintain its constant internal temperature, known as its ‘core temperature’ (36.8°C ± 0.4°C). To maintain the core temperature, the human body effectively creates heat balance through processes of heat loss and heat gain, these processes make up the human thermoregulatory system (Parsons, 2010).

There are four main processes of thermoregulation through which the body exchanges heat with the surrounding environment. These including: convection (heat transfer by the movement of heated parts of a gas or liquid), radiation (heat energy transfer by emission of heat as electromagnetic waves or as moving subatomic particles), evaporation (the conversion of liquid to vapour by heat) and conduction (heat energy transfer through a medium without movement of the medium itself) (Prek, 2005). Thus, the heat balance of the body can be expressed as an equation:

\[
M - \text{EVP} \pm \text{CND} \pm \text{CNV} \pm \text{RAD} = 0
\]
where:

\[ M = \text{Rate of metabolic energy production W/m}^2 \]
\[ \text{Evp} = \text{Evaporation} \]
\[ \text{Cnd} = \text{Conduction} \]
\[ \text{Cnv} = \text{Convection} \]
\[ \text{Rad} = \text{Radiation} \]

The thermoregulatory system is quite effective at creating a heat balance even in extreme environmental conditions (Fanger, 1972). However, most people are physically and psychologically more comfortable when the body temperatures are held within narrow ranges, skin moisture is low and minimal effort is required for the body to maintain its core temperature (ASHRAE, 2009). The primary condition necessary for human sensation of thermal comfort within a given environment is the existence of a heat balance between the body and the environment (Fanger, 1972). According to Fanger (1972), the state of 'thermal comfort' is reached when heat flow to and from the human body is balanced and skin temperature, as well as sweat rate, are within a comfort range, which depends solely on metabolism. However, this early understanding of the concept of thermal comfort has modified in recent years. A widely accepted definition of thermal comfort, used by ASHRAE, is: "Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE, 2013a, p. 8.1). This definition emphasises that the judgement of comfort is a mental process, influenced by physical as well as psychological factors. As humans can and do live in various climatic regions from low to high latitudes, the perception of thermal comfort by people and the range of thermally satisfactory conditions can vary, depending on regional climatic conditions, living conditions, culture and individual routine (Chappells et al., 2015; Martinelli et al., 2015; Nicol et al., 2012). Thus, there is no absolute standard for thermal comfort.
3.2.1 The Adaptive Thermal Comfort Model

According to current European and American standards for the analysis of thermal comfort, a methodology founded on Fanger’s model is prescribed for any typology of air-conditioned buildings. On the other hand, a methodology, based on a model of adaptive comfort, is prescribed for buildings that use natural ventilation in warm weathers (Desogus et al., 2015; Humphreys et al., 2015). Fanger’s model calculates the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) indexes through the analysis of environmental parameters (air temperature, relative humidity, mean radiant temperature and air velocity) and personal factors (metabolism and clothing insulation). In contrast, the adaptive comfort model takes into account the occupants’ ability to adapt to varying conditions on a
physiological, psychological and behavioural level (Humphreys et al., 2015). While the former model is based on the mean monthly outdoor temperature, the latter introduces the concept of adaptation based on the running mean outdoor temperature (ASHRAE, 2013b).

The adaptive model is based on studies that have used statistical analyses of the results from surveys of thermal comfort in the field. Field surveys from most of these studies suggest that in many real situations, people are more tolerant of temperature change than the laboratory studies suggest. This ability to respond to a wide range of temperatures has been given the name ‘adaptive’ since the subjects are assumed to be adapting to their environment (Nicol & Parsons, 2002). Behavioural thermoregulation, such as changing activity or performing them less or more vigorously, choice of clothing and posture, opening windows and adjusting blinds (which can also be considered to be a behavioural means of improving visual comfort), can be a way of consciously or subconsciously affecting the heat balance of the body (Nicol et al., 2012). Therefore, it is possible that thermal comfort can be achieved in a wider range of temperatures than predicted by the heat balance approach when individuals have more opportunities to adapt to their environment (Nicol, Allaudin, & Jamy, 1999). These adaptive variables are particularly important in buildings without active heating or cooling systems (Nicol et al., 1999). In order to allow a wider temperature variation for buildings that are naturally ventilated, the revision of the ASHRAE standard 55 is a clear indication of the growing consideration and importance of passive design principles and adaptive opportunities in thermal comfort science (ASHRAE, 2013b). Furthermore, adaptive comfort standards have been gaining wider acceptance and are now considered to be an integral part of thermal comfort research (Mishra & Ramgopal, 2015). The adaptive model established by ASHRAE (2013) is used to evaluate the performance of case study residential buildings under naturally ventilated conditions in Chapters six and seven.

3.3 **Benefits of Integrating Passive Design Principles into Building Design**

One of the primary functions of a building is to control the extent to which external climatic conditions affect the thermal conditions experienced by occupants (Bravo & Gonzalez, 2013). Therefore, achieving thermally comfortable conditions in buildings is an important indicator of building performance, which
can be addressed using active mechanical systems, passive strategies or principles, or a combination of various methods. Interest in passive design principles has grown significantly in the last few decades (Day & Gunderson, 2015; Dim et al., 2015; Stevanovic, 2013), as a result of the movement towards more comfortable, healthy and energy-efficient buildings. In addition to concerns about the environmental impact of using active systems, occupants’ wellbeing and satisfaction as well as sustainable energy use are the primary reasons often cited in the literature for the introduction of passive design principles in building design (Aynsley, 2014; Steemers & Steane, 2004; Yi & Peng, 2014).

3.3.1 OCCUPANTS WELLBEING AND SATISFACTION

Wellbeing is defined as "the state of being comfortable, healthy or happy" (Stevenson & Waite, 2011, p. 1639). These three aspects correlate with the fundamental requirements of architecture defined over two millennia ago by Vitruvius as “firmness, commodity and delight”. This implies a building ought to be well made or constructed (firmness), properly facilitate the function for which it was built (commodity) and evoke a positive psychological response. The fundamentals of architecture defined by Vitruvius, namely commodity and delight, are associated with the level of physical and psychological satisfaction an occupant experiences in a room. Moreover, the ability to perceive a condition as being satisfactory, can be thought of as an evolved response for maintaining physical and psychological wellbeing (Steemers & Manchanda, 2010). Generally, buildings that incorporate passive principles in their design are often perceived as more satisfactory for their occupants than those that use mechanical systems to provide comfort (Steemers & Manchanda, 2010). This is likely because they provide opportunities for contact with natural elements including daylight, views to the outdoors, good indoor air quality and some degree of sensory variability in ambient conditions across time and space, which are all important for physical and psychological wellbeing (Li & Lim, 2013).

Moreover, previous studies have shown that increasing energy use in order to maintain consistent thermal conditions, does not necessarily lead to a concurrent improvement in wellbeing. Based on a survey of 177 office buildings in the United Kingdom, it was found that their occupants perceived only 25% of the buildings as healthy and all the buildings perceived as healthy had some element of natural ventilation (Leaman & Bordass, 2007). Steemers and Manchanda (2010) investigated the relationship
between occupants’ wellbeing and the environmental performance of office and educational buildings in the UK and in India. Six buildings from each country were selected with varying thermal control systems, ranging from centrally air-conditioned to mixed mode, to naturally ventilated. After the selection process, they carried out an occupants’ survey and also recorded the energy consumption pattern for the buildings. It was found that air-conditioned buildings emit 2-3 times more CO$_2$ than naturally ventilated buildings in both the UK and in India, without any significant improvement in occupant satisfaction. They also found a very strong link between natural ventilation and overall health. In terms of reported cases of illness the naturally ventilated buildings yielded better results than the mechanically ventilated buildings.

3.3.2 Sustainability

In 2010, buildings accounted for 32% (24% for residential and 8% for commercial) of total global final energy use and 19% of energy-related greenhouse gas emissions (including electricity-related emissions). This energy use and related emissions may double by 2050 if no action is taken to improve energy efficiency in the building sector (IEA, 2013). This increase is driven by rapid growth in the number of households, residential and services floor area, higher ownership rates for existing electricity-consuming devices and increasing demand for new products. An emerging trend in developing countries (such as Nigeria) is the increased access for billions of people to adequate housing, electricity and improved cooking facilities (IPCC, 2014). The ways in which these energy-related needs will be provided in developing countries, especially those in tropical climate regions, will largely affect future building energy use and related emissions.

In tropical climates, the energy consumed by heating, ventilation and air-conditioning (HVAC) can exceed 50% of the total energy consumption of a building (Chua et al. 2013). In hot and humid regions, such as in Nigeria, the air-conditioning units commonly used for maintaining thermal comfort in indoor environments account for a major share of the energy consumption of buildings. As discussed in Chapter two, the energy used for cooling to provide thermally acceptable conditions can account for as much as 40% to 78% of the total energy used in residential buildings. (Enaburekhan, 2007; Irimiya et al., 2013). Enaburekhan’s (2007) analysis of the electricity consumption pattern in 16 air-conditioned, two bedroom houses in Gusau (North of Nigeria), Nigeria revealed that the annual electricity consumption of the houses
was 572,933 kilowatt-hours (kWh) (35,808 kWh per household). In contrast, the average electricity and gas consumption per household in the United Kingdom in 2014, was 54% lower (4,001 kWh for electricity and 12,404 kWh for gas) (Department of Energy and Climate Change [DECC], 2015). In a more recent study of energy consumption of residential buildings in Kaduna and Kano, (also North of Nigeria) the authors Irimiya et al. (2013) reported that on average 62.7% of the annual electrical energy consumed was used for lighting, while 23.65% was used to run air conditioning systems.

Batagarawa et al. (2011) conducted an energy audit of fifteen office buildings in four cities in Nigeria, including Lagos, Abuja, Kaduna and Port-Harcourt. They found that on average the cooling, lighting and appliances load accounted for approximately 40%, 12% and 48% of the electricity consumed respectively. The ambient temperature was also taken into consideration, but the findings showed that there was very little correlation between the outdoor temperatures and the level of usage of the air condition system during the course of a year. The reason could be that individuals are not responsible for paying for electricity in their offices, hence, there is a possibility of substantial savings through better cooling control systems and management.

The findings of these studies on building energy consumption in Nigeria highlight the importance of cooling in the region. The cost associated with running mechanical cooling systems in the buildings in the region and the negative environmental effects of greater CO$_2$ emission from running such systems are often cited in these studies, as the main reason why alternative solutions are required (Table. 3.1.). It is also important to consider that the use of several air conditioners in structurally dense urban areas contributes to an increase in temperatures around the area (due to increased air pollutants) as part of the phenomenon known as the 'urban heat island' (discussed in section 3.4.2.1) (Akinbode et al., 2008).
### Table 3.1 Some of the recent studies on energy consumption and production in Nigeria

<table>
<thead>
<tr>
<th>Researcher(s)</th>
<th>Year</th>
<th>Location in Nigeria</th>
<th>Energy efficiency</th>
<th>Renewable energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iyke</td>
<td>2015</td>
<td>Not specific</td>
<td>Review of energy consumption pattern</td>
<td></td>
</tr>
<tr>
<td>Chindo et al.</td>
<td>2015</td>
<td>Not specific</td>
<td>Review of energy consumption and carbon emission</td>
<td>Hydropower, wind energy, geothermal energy, solar energy and biomass</td>
</tr>
<tr>
<td>Okoro</td>
<td>2015</td>
<td>Delta state</td>
<td></td>
<td>Hydropower, wind energy, geothermal energy, solar energy and biomass</td>
</tr>
<tr>
<td>Shaaban and Petinrin</td>
<td>2014</td>
<td>Not specific</td>
<td></td>
<td>Hydropower, wind energy and solar energy</td>
</tr>
<tr>
<td>Oyedepo</td>
<td>2012</td>
<td>Not specific</td>
<td></td>
<td>Hydropower, wind energy, solar energy and biomass</td>
</tr>
<tr>
<td>Oseni</td>
<td>2012</td>
<td>Not specific</td>
<td>Review of energy consumption pattern</td>
<td></td>
</tr>
<tr>
<td>Otegbulu et al.</td>
<td>2011</td>
<td>Lagos</td>
<td>Review of energy consumption pattern in residential buildings</td>
<td></td>
</tr>
<tr>
<td>Ohunakin</td>
<td>2011</td>
<td>Bida, Minna, Makurdi, Ilorin &amp; Lokoja</td>
<td>Wind energy</td>
<td></td>
</tr>
<tr>
<td>Fagbenie et al.</td>
<td>2011</td>
<td>Maiduguri &amp; Potiskum</td>
<td>Wind energy</td>
<td></td>
</tr>
<tr>
<td>Gujba et al.</td>
<td>2011</td>
<td>Not specific</td>
<td></td>
<td>Hydropower, wind energy, solar energy and biomass</td>
</tr>
<tr>
<td>Batagarawa et al.</td>
<td>2011</td>
<td>Lagos, Port-Harcourt, Kaduna &amp; Abuja</td>
<td>Energy consumption audit</td>
<td></td>
</tr>
<tr>
<td>Momodu et al.</td>
<td>2011</td>
<td>Not specific</td>
<td>Energy consumption audit</td>
<td></td>
</tr>
</tbody>
</table>

### 3.4 Key Parameters That Influence Thermal Conditions in Buildings

Providing thermal comfort, while also conserving energy use in buildings, is dependent on determining an appropriate set of values for the design parameters of the buildings in relation to the external conditions (Oral et al., 2004). Oral et al. (2004) classified some of the main parameters that have an impact on the thermal performance of buildings into two categories, namely parameters related to the outdoor environment and design parameters related to the built environment (Table 3.2). They grouped the parameters related to the built environment into four scales or levels, including 'the settlement unit scale', 'the building scale', 'the room scale' and 'the element scale'.

A similar classification or framework has been adapted in this study to identify the parameters that affect the thermal performance of residential buildings in the studied context of Nigeria. In addition to the main parameters listed in the classification by Oral et al. (2004), this classification also includes the consideration of other parameters that are often analysed in studies of the influence of building envelope on thermal comfort. The parameters in this study are classified into the following levels:
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- the climate (level I),
- the built environment (level II),
- the building (level III),
- the room (level IV).

Table 3.2 Parameters with an influence on the envelope design for thermal comfort (adapted from: Oral et al., 2004)

<table>
<thead>
<tr>
<th>Researcher(s)</th>
<th>Levels</th>
<th>Parameter</th>
</tr>
</thead>
</table>
| Oral et al. 2004. | Design parameters on the settlement unit scale | • Air temperature  
• Solar radian  
• Humidity  
• Wind velocity |
| | Design parameters on the settlement unit scale | • Dimension and orientation of external obstacles  
• Solar radiation reflected off surrounding surfaces  
• Soil cover, and nature of ground cover |
| | Design parameters on the building scale | • Orientation of the building  
• Building form |
| | Design parameters on the room scale | • Position of room within the building  
• Dimensions of the room and shape factor  
• Orientation of the room  
• Absorption coefficient of the room for solar radiation entering through transparent component |
| | Design parameters on the element scale | • Thickness of materials  
• Density of materials  
• Heat conduction coefficient of materials  
• Dimensions of the transparent component  
• Number of layers of glazing  
• Heat transmission coefficient of glazing  
• Absorption, reflection and transmission coefficient of the glazing for solar radiation  
• Transmission coefficient of the glazing for diffused sunlight.  
• Transmission coefficient of the glazing for direct sunlight.  
• Type of frame used for the transparent component. |

3.4.1 The climate (Level I)

The key climatic factors that influence the thermal conditions in a region are beyond the control of building designers. Yet, these factors should be considered by designers in order to optimise the thermal performance of buildings. Based on the literature reviewed (ASHRAE, 2009; Givoni, 1998; Thellier et al., 2009), the main elements of the natural environment that influence the thermal performance of buildings, include the following:
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- Solar radiation,
- Air (dry-bulb) temperature,
- Relative humidity,
- Air movement.

3.4.1.1 Solar radiation

The movement of the sun and the energy flows from the sun are the primary factors that determine the climate in any region on the earth. The position of the sun at a given time can be determined by its altitude angle (vertical angle of the sun above the horizontal plane) and azimuth angle (the sun’s position east or west from the true north, 0°) (Szokolay, 2014). The energy flow from the sun, also known as solar radiation, is quantified by determining the amount of solar energy reaching a particular surface area; thus, it is measured in watts per square metre (W/m²). The total solar radiation reaching a given surface is the sum of three components: the direct and diffused radiation (which make up the global solar radiation), as well as the light reflected by surfaces in the natural and built environment (Augustine & Nnabuchi, 2009). Hence, microclimatic conditions, such as atmospheric water vapour content, layers and distribution of cloud cover, turbidity, natural and built structures can exert a depleting influence on solar
radiation at the earth's surface, especially in urban areas (Hodder & Parsons, 2007; Okogbue, Adedokun, & Holmgren, 2009).

The buildings in Nigeria are constantly exposed to high levels of solar radiation every day. Consequently, the possibility of achieving thermal comfort in buildings in the region depends on the amount of solar radiation excluded from the interior space (Ajibola, 2001). One of the most important considerations for passive cooling is preventing excessive solar radiation, which leads to overheating, while still providing adequate illumination. When these factors are not properly considered in the design of buildings, a lot of active energy will be required for air-conditioning, ventilation and artificial lighting in order to attain a thermal and visual comfort indoors (Lawal & Ojo, 2011).

3.4.1.2 Air (Dry-bulb) Temperature

The air temperature determines the heat transfer between the human body and the air through convection. Lower temperatures lead to greater heat loss from the body and higher temperatures result in increased heat gain to the body (ASHRAE, 2009). Thus, air temperature, $T_a$, is the primary factor that influences the thermal condition of an occupant. If the air temperature is within a range in which little effort is required to maintain the body's core temperature, the effects of other factors, such as relative humidity, are negligible (Chartered Institute of Building Services Engineers [CIBSE], 2008).

Air temperatures can be significantly altered by the urban landscape (physical, material and geometrical characteristics of an urban area) and the contrast between the urban and rural climates (discussed in section 3.4.2) is further enhanced by the input of heat, moisture and pollutants into the atmosphere from elevated levels of human activity, which are common in urban areas (Santamouris, Cartalis, Synnefa, & Kolokotsa, 2015).

In addition to the air temperature, the heat transfer between the body and surfaces, through radiation, can influence occupants' thermal comfort in buildings. An individual can perceive a space as thermally comfortable at low temperatures if the heat received by the body from the internal surfaces of the space offsets the heat loss from the body (Kuznik et al., 2011). The influence of surface temperatures on occupant comfort is measured using the 'mean radiant temperature', $T_r$, which is the uniform
temperature of an imaginary enclosure, in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure (Fanger, 1972). A thermal comfort measure, called the 'operative temperature' or 'dry resultant temperature', which combines the mean air temperature and the radiant temperature in space, is often used in studies as the primary index for assessing thermal comfort in buildings (CIBSE, 2008).

The mean annual dry-bulb temperatures across Nigeria range between 25.4°C to 25.6°C and is expected to be 3°C to 4°C higher by the end of the 21st Century (Ohunakin et al., 2015). Thus, it is evident that factors that contribute to heat gain in buildings, especially in cities in that region, will have a highly significant influence on occupants’ thermal discomfort indoors.

3.4.1.3 Relative humidity

The human body loses heat by evaporation of water vapour from the respiratory tract as well as perspiration from the skin (sweating). As sweat evaporates from the skin, releasing heat from the body, the temperature of the skin and blood vessels close to the surface of the skin become cooler. The cooled venous blood travelling through these vessels then returns to the body's core and counteracts rising core temperatures (ASHRAE, 2009). The evaporative heat loss from the skin depends on the amount of moisture on the skin and the difference between the water vapour pressure on the skin and in the surrounding air. The humidity of the environment, as a basic parameter of human thermal comfort, is commonly expressed using ‘relative humidity’, i.e. RH (often given as a percentage). Relative humidity is the ratio of the prevailing partial pressure of water in the air to the saturated water vapour pressure (Parsons, 2003).

Healthy humans cannot maintain their body temperature if the air temperature is as high as the body temperature and the air is saturated with water vapour (ASHRAE, 2009). While humidity levels between 30% and 65% do not have much of an effect on human thermal comfort, high humidity restricts evaporation from the skin and in respiration, and low humidity can lead to the drying out of the mouth, throat and skin (Szokolay, 2014).
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The level of humidity in buildings is influenced by several factors, including moisture sources, such as human presence, activities and equipment, air change rate and airflow in rooms, the release or uptake of moisture by hygroscopic surfaces of envelope and furniture, moisture flow through the building envelope, possible condensation and the moisture content of the outdoor air (Woloszyn et al., 2009). High humidity levels indoors can also lead to the growth of mould, which can cause discomfort and various respiratory related health problems (Zhang & Yoshino, 2010). Controlling humidity in buildings is important, especially in residential buildings, in which activities, such as cooking, washing and showering, can cause the internal relative humidity to rise very quickly in a short time (Mlakar & Strancar, 2013). Nicol (2004) suggests that humidity levels above 75% can reduce the range of temperature at which occupants feel comfortable. Nevertheless, a study on occupants’ comfort in Dhaka, Bangladesh (Mallick, 1996), suggests that people living in warm humid climates can adapt to very humid conditions and feel comfortable with relative humidity levels as high as 90%.

Figure 3.3 Psychometric charts for the dry and rainy season showing the predicted hours of thermal comfort
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According to calculations based on the adaptive thermal comfort model, the typical annual thermal conditions in Abuja are within an acceptable range of 31% and 39% of the hours during the dry season and rainy season respectively, as illustrated in figure 3.2. The figure also shows that in both seasons there are periods during which the thermal conditions can be comfortable, despite the level of relative humidity being above 80%.

3.4.1.4 Air Movement

Elevated air speed can offset high indoor air temperature and restore thermal comfort by easing the process of heat loss from the body through convection and evaporation (Candido, de Dear, Lamberts, & Bittencourt, 2010). The increase in air velocity perceived by an occupant depends on the air temperature as well as the difference between the air temperature and the mean radiant temperature. Increased air velocity is more effective when the mean radiant temperature is higher than the air temperature, and less effective if the mean radiant temperature is lower than the air temperature (Schiavon & Melikov, 2008). The perception of air movement is also influenced by velocity fluctuations and personal factors, such as clothing insulation and physical activity level. Air velocity fluctuations associated with turbulence can be perceived as more uncomfortable in comparison to steady airflow at the same mean air velocity (Toftum & Nielsen, 1996).

With regards to the design of naturally ventilated buildings, the air flow through an opening depends on the pressure difference at both sides of the opening, produced by wind or buoyancy forces, as well as on the resistance opposed to the air flow by the opening itself. In addition to the geometry of the openings of a building and the incidence angle of the wind, the magnitude of the wind velocity plays an important role on the air-change rate of a building, and as a result, it influences the indoor air quality and perception of thermal comfort (Nikas, Nikolopoulos, & Nikolopoulos, 2010).

The minimum monthly wind speed recorded in Nigeria was 0.78 m/s at a meteorological station in Ondo (Southwest Nigeria) in November between 1983 and 2003, while the maximum monthly wind speed was 13.10 m/s in Bauchi (Northeast Nigeria) in December. The overall annual mean wind speed measured for Nigeria was 4.62 m/s (Fadare, 2010). Thus, buildings, particularly in the warm humid south and the central
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region of Nigeria, require larger openings and narrow plans to provide sufficient cross ventilation (Fry & Drew, 1964).

3.4.2 THE BUILT ENVIRONMENT (LEVEL II)

The design of buildings within urban areas and the design of urban areas in general deal with different geometrical characteristics related to the orientation, height and width of buildings and urban blocks in relation to open spaces and pedestrian sidewalks and streets. New buildings may create a different microclimate, like changing the wind direction, daylight access and shading of existing buildings and neighbourhoods (Capeluto, 2003). The reflectivity and absorptance properties of surrounding surfaces as well as anthropogenic factors, also have an influence on the microclimate in a built environment (Oral et al., 2004; Tantasavasdi, Jareemit, Suwanchaiskul, & Naklada, 2007a).

Land-use changes, especially as a result of urbanisation, can affect the temperatures at a given location (Balogun, Balogun, & Adeyewa, 2012; Moonen, Defraeye, Dorer, Blocken, & Carmeliet, 2012). However, this study has mainly focused on evaluating the impact of the variation in the design characteristics related to the building (level III) and the room (level IV). Thus, only a short summary of the urban environment factors that can influence thermal comfort in a room is given in this section.

3.4.3 THE BUILDING (LEVEL III)

The building envelope may be defined as the totality of building elements made up of components, which separate the indoor environment of the building from the outdoor environment (Oral et al., 2004). There is a range of variables related to the physical configuration and characteristics of buildings that have an impact on the thermal conditions experienced indoors. Many of the design variables, which are often considered at the initial stages of building design, can also have an effect on energy performance of buildings in terms of cooling, heating and lighting loads (Bekkouche et al., 2013). In the initial design stages, the geometry of a building can change a number of times, as the architect deals with a multitude of design constraints and design drivers, including structure, space planning, fire, safety, cost, etc. This might also include considering the number of storeys, layout (i.e. open plan and cellular spaces) and the external visual appearance (Lomas, 2007). Considerations of the appropriate design for visual and thermal
comfort during these initial stages can help to reduce the energy consumption of buildings in an efficient way (Bekkouche et al., 2013). Building orientation, building shape and wall shading elements are among the primary design variables influencing thermal performance at the building level (Stevanovic, 2013; Oral et al., 2004; Unver et al., 2004). A short description of the influence of each of these three variables is given in the following subsections.

3.4.3.1 BUILDING ORIENTATION

Orientation is one of the key parameters and the most frequently studied parameter of passive solar design (Morrissey et al., 2011). Both the horizontal and the vertical surfaces of a building will experience different levels of solar heat gain during the course of a day, as a result of the seasonal and hourly changes in the sun's position in relation to the building. Thus, the general orientation of buildings and the orientation of their facades have an impact on the amount of heat being transferred into the internal spaces (Pacheco et al., 2012). The orientation of the facade also influences other aspects of design, such as shading and the positioning of openings (Pacheco et al., 2012). For a simple rectangular building shape, the building aspect ratio, which is the ratio of the length of a building to its width, can be adjusted to improve the thermal performance by examining the amount of solar radiation that will occur on the longer façade areas (Mehlika & Demirbilek, 2000). The proper solar-orientation of a building on site according to the prevailing climate, can also influence other variables, including placement of windows, shading elements and integration of thermal mass, which can help in providing thermal comfort to occupants (Chandel & Sarkar, 2015).

3.4.3.2 BUILDING SHAPE

Building shape influences the rate of heat loss and heat gain through the building envelope and it can be considered as one of the characteristics of a building which has a more perceivable influence on thermal performance (Granadeiro et al., 2013). The impact of the shape of a building on its thermal performance is primarily associated with two rules. Firstly, forms with different geometric shapes, which have the same contained volume, have different surface areas. This factor is commonly known as the compactness ratio
C, or shape coefficient, which is defined as the ratio between the building's envelope surface S and the inner volume of the building V (Albatici & Passerini, 2011). This ratio is often expressed as follows:

\[
C = \frac{S}{V}
\]

Secondly, a given form with a smaller size has a lower compactness ratio than the larger form with the same geometric shape. These two factors have important implications on thermal conditions in buildings, because building forms with a low compactness ratio are less susceptible to solar radiation and variations in outdoor temperature (Capozzoli et al., 2009).

In warm humid climates, such as that of the southern and central region of Nigeria, where ventilation is the most effective way to minimize the effect of the high relative humidity, an elongated building form, which allows good natural cross-ventilation by providing more wall areas than a compact form, is more desirable (Pacheco et al., 2012). The large surface area of the building envelope also permits faster cooling in the evening when the external temperatures are usually lower than the internal temperatures (Givoni, 1994). One of the common elements in traditional Nigerian residential architecture is the organisation of small compact circular or rectangular rooms within a compound or around courtyards (Dmochowski, 1990a; 1990b; 1990c). This design approach allowed the buildings to have a large external surface area to facilitate cross ventilation, while also providing partially shaded transitional, open spaces within the dwellings. Due to high cost of land in urban areas and cultural changes, the traditional courtyard house is far less common than the contemporary face-me-i-face-you residential buildings and mid-rise apartment buildings in cities across Nigeria (Jiboye, 2014).
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3.4.3.3 WALL SHADING ELEMENTS

Despite the fact that more compact building forms admit less solar radiation indoors, as discussed in the previous section, less compact forms can be more desirable for achieving thermal comfort through cross ventilation, especially in warm-humid regions. Besides optimising the orientation and shape, shading the opaque and transparent external façade areas of a building is another vital approach for mitigating heat gain indoors (Capozzoli et al., 2009). The appropriate shading design approach primarily depends on the local climatic conditions, building form and orientation, but is also related to the intended function of the building. Finding a suitable shading approach can significantly reduce the amount of electrical energy required for cooling in a building and the environmental impact of the building (Kirimtat, Koynubaba, Chatzikoustantinou, & Sariyildiz, 2016). However, external shading devices also have an impact on the internal daylight distribution. Hence, the cooling, daylighting and architectural impact of shading design must be taken into account at the same time (Manzan & Pinto, 2009).

In addition to rigid and flexible shading devices, the use of porches, verandas or courtyards, which partially or completely protect building facades from the full impact of the ambient conditions of the environment, is commonly adopted in traditional architecture in various regions (Givoni, 1994). Transitional covered space between buildings and the outside, including porches and verandas, are a feature of the traditional, colonial and Afro-Brazilian architectural styles in Nigeria (Dmochowski, 1990a; 1990b; 1990c, Osasona & Hyland, 2006). As discussed in Chapter two, these traditional elements are still being used in the contemporary design practice in Abuja.

3.4.4 THE ROOM (LEVEL IV)

A room is defined as "a part of a building separated by wall[s], floor and ceiling". It can also be defined as "space viewed in terms of its capacity to accommodate contents or allow action[s]" (Stevenson & Waite, 2011, p. 1249). At a room level, the thermal conditions experienced by occupants are primarily influenced by the way in which heat is transferred through the elements that separate the internal environment of a room from the external environment and other parts of the building (Koenigsberger et al., 1974).
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These processes of heat transfer between the room and the external environment are illustrated in figure 3.5. The heat output from human bodies, artificial lighting and other mechanical appliances, contributes to internal heat gain $Q_i$. Heat is transferred by means of conduction $Q_c$ and convection through the composite elements of the building envelope (walls, windows, roof, floor). Heat is also transferred by radiation at the surfaces of a building. Unlike conduction and convection, radiation ($Q_r$) does not depend on an intermediate material as a medium of heat transfer, but rather it is impeded by the presence of a material between two environments. The effect of solar radiation can be considered in terms of transmittance, however, the transfer of heat through transparent elements, such as windows, should be considered separately. Ventilation and infiltration also lead to the transfer of heat between spaces $Q_v$ (ASHRAE, 2009; Koenigsberger et al., 1974; Olgyay, 1963).

The rate of heat transfer through these processes and between the different components of a room depends on the following parameters:

- Building fabric and thermal transmittance,
- Orientation of walls, roofs and windows,
- Ventilation, infiltration and exfiltration,
- Window properties,
- Fenestration factor,
- Window to wall ratio,
- Window shading devices,
- Internal heat gains.

Figure 3.5 Processes of heat transfer between a room and the external environment (adapted from Baker & Steemers, 1996; Koenigsberger et al., 1974)
3.4.4.1 Building Fabric and Thermal Transmittance

The amount of radiant energy emitted by a material depends on the thermal resistance of the material and its absolute temperature (ASHRAE, 2009). Thermal resistance (the r-value) is a measure of the ability of a single material component to impede heat transfer as a result of convection, conduction and radiation. The r-value is expressed in m²K/W. The thermal transmittance, commonly known as u-value, is the rate of transfer of heat (W) through one square metre of the building fabric, divided by the difference in temperature across that element of the building fabric (CIBSE, 2015). Thermal transmittance is also known as the overall heat transfer coefficient and is expressed in W/m²K. The u-value is obtained by combining the thermal resistances of the component parts and the adjacent layer that make up the area of the building fabric (CIBSE, 2015). Thus, it is expressed by the following equation:

\[
U = \frac{1}{R_{SI} + R_1 + R_2 + \ldots + R_A + R_{SE}}
\]

where:
- \( U \) = Thermal transmittance, u-value of the building fabric (W/m²K)
- \( R_{SI} \) = Thermal resistance of the internal surface (m²K/W)
- \( R_{SE} \) = Thermal resistance of the external surface (m²K/W)
- \( R_A \) = Thermal resistance of the air spaces (m²K/W)
- \( R_1 \) and \( R_2 \) = Thermal resistance of the components (m²K/W)

With regards to thermal performance, the thermal transmittance of components of the building envelope affects the thermal conditions of the internal space and also determines the amount of energy required for cooling or heating in order to achieve thermal comfort (Munoz et al., 2013). The thermal properties of the building envelope are particularly important in residential buildings, because the energy demands in dwellings are primarily influenced by heat loss or gain through structural components and ventilation. On the other hand, internal heat gains from occupancy, lighting and electrical appliances often do not have a strong influence on the heat gain in dwellings (Al-Hamoud, 2005).

In general, the rate of heat transfer is slower when buildings are constructed with materials, which have a low u-value and high r-value (Barrios et al., 2012). Insulation materials are commonly placed within the building component to reduce the rate of heat flow through the building envelope. Insulation materials perform best when they are placed close to the area where the heat is being discharged. This means it is
better to place insulation closer to the internal surfaces for climatic regions, where heating is required more often to reduce heat loss, and closer to the external surfaces in regions, where cooling is required to reduce heat gain (Al-Hamoud, 2005). The type and thickness of the materials used in the construction of the building envelopes also affect the thermal performance of the building and its ability to delay heat transfer through the structure over a period of time. Materials that have high heat storage capacity, such as earth, rock, wood, brick or concrete, can be used to absorb and store heat energy during a warm period of the day (acting as a heat sink) and to release heat energy during a cool period later (acting as a heat source). This practises is referred to as thermal massing (Ma & Wang, 2012).

In general, insulation is more important in regions with extreme seasonal temperature variations and smaller daily variations, while thermal mass is more important in regions with large diurnal temperature ranges. Thermal massing is commonly used in traditional residential architecture in Nigeria, even in the areas with very high humidity. The walls, which are made of a mixture of earth and cut dry grass, are normally 0.5 to 1m thick at the base, depending on the height of the building, and slightly narrower at the top (Dmochowski, 1990a). There are two common types of roof construction, thatched roofs or thick mud roofs, which are either flat or vaulted. The thatched roofs consist of several layers of bamboo and raffia palm stems in situ, or guinea corn stalks (if the roof is small) tied together with bands of straw and locally woven rope made of bamboo (Dmochowski, 1990a). There are very few instances of thermal massing being used in contemporary residential building construction in Abuja.

3.4.4.2 ORIENTATION OF WALLS, ROOFS AND WINDOWS

Orientation is an important factor to consider in order to ensure that buildings in hot regions effectively minimise the impact of solar gain. The position of the sun in the sky is dynamic, changing according to time of day, time of year and the site’s latitude. These changes and the level of exposure to solar radiation determine the amount of solar energy absorbed by walls and windows, which can lead to overheating and increased thermal stress inside rooms. Under conditions of excessive solar radiation the orientation of windows and walls should minimise undesirable solar heat gain (Olgyay, 2015). Some of the methods
that can be used to limit solar radiation through opaque and transparent building components at different orientations are as follows:

**Opaque elements:** Solar heat gain through walls and roofs can be minimised through the use of reflective colour, shading, as well as adequate thermal insulation (Givoni, 1994). Thermal mass can also be used efficiently to postpone heat gain according to the time lag required for each wall orientation and roof, as the peak heat gain for each occurs at different times (Hamdani et al., 2012). Lechner (2001) outlined some general guidelines for using thermal mass for controlling heat flow through the building envelope in relation to orientation as follows:

- North facing walls have little need for time lag due to the small heat gain.
- East morning load should not be delayed to the afternoon, thus, mass with very long time lag (over 14 hours) should not be used on the east facade of buildings in warm or hot climates. A cheaper alternative is to use very short time lag or no mass on the outside of the east wall.
- South mid-day heat can be delayed until evening by using mass with medium time lag (approximately 8 hours).
- Medium time lag can also be sufficient for West orientation, as the number of hours between the peak solar exposure and sunset is very short.
- The roof requires very long time lag as it is exposed to sunlight most of the day. However, it is expensive and not always practical to place very heavy mass on the roof, thus, additional insulation is often a better solution.

These details can be modified at the microclimate level by factors, such as the topography and the overshadowing effects of neighbouring building, particularly in dense cities (Lechner, 2001).

**Transparent elements:** One of the primary factors which influences the amount of energy consumed through heating, cooling or lighting in a building is its fenestration system (Lee et al., 2013). The design and selection of a proper window system is one of the important ways for effectively conserving the energy used in buildings (Lee et al., 2013). At the design stage, the orientation of the windows should be
considered before decisions are made regarding window area, window type and shading requirements (Haglund, 2010).

Apte and Arasteh (2006) carried out a study of the impact of windows on energy consumption in residential and commercial buildings in the United States, using available information on the properties of the installed window stock. They found that windows are responsible for approximately 24% of residential heating energy use and 42% of residential cooling energy use. However, a particular distinction should be made between latitudes within about 15 degrees of the equator and higher latitudes. Most of the world's hot dry areas are located in sub-tropical latitudes, where the intensity of solar radiation is higher on the eastern and western walls around the summer solstice and on the southern wall around the winter solstice (Giovoni, 1994). In warm-humid tropical latitudes the provision of effective cross-ventilation under the local wind direction is one of the major factors that should be considered when determining the orientation of the windows (Giovoni, 1994).

Odim (2008) compared the indoor thermal conditions of two experimental model buildings in Owerri, Nigeria (warm-humid climate). The buildings had identical plans, sections and elevations and two unshaded windows of equal sizes, but the windows in the first building were located on the east and west facing wall, while the windows in the second were located on the north and south facing wall. The air temperatures and relative humidity in both buildings were recorded every two hours from 6am to 8pm every week for 24 months from January 2005 to December 2006. The study revealed that the mean air temperature in the model with the east-west window orientation was 1.3°C higher than that of the other room; however, the relative humidity in both models was around 80%. The results indicated that there is a strong relationship between window orientation and indoor thermal conditions in the region.

3.4.4.3 Ventilation, infiltration and exfiltration

As stated previously, the convective and/or evaporative heat exchange between a person and the surrounding environment is partly influenced by air movement. Air movement can be used to effectively cool a body even for temperatures above the limits that are normally considered thermally comfortable (Nguyen & Reiter, 2012). Thus, ventilation is important for cooling spaces in buildings and reducing the
possibility of overheating. Even in cold conditions, where ventilation can lead to undesired heat loss, some degree of air exchange between the external and internal environment is necessary in spaces to provide good indoor air quality for human occupancy. In general, ventilation has three functions, which require different levels of air flow through the building, including (Givoni, 1998):

1. Providing thermally comfortable conditions in a warm environment by increasing convective and/or evaporative heat loss from the body (comfort/daytime ventilation).

2. Cooling the building fabric (during the night) and using the cooled mass as a "heat sink" during the daytime in order to maintain low indoor temperatures in relation to the external temperature (nocturnal cooling).

3. Maintaining acceptable indoor air quality by replacing indoor air with fresh outdoor air. This function is of particular interest in cold climates and air-conditioned buildings in all climates.

Ventilation in not air-conditioned buildings can be divided into two types: intentionally provided natural ventilation, and air infiltration and exfiltration (CIBSE, 2008).

Natural ventilation: In all climatic regions around the world, there are times when natural ventilation can be the simplest and most effective way to provide indoor thermal comfort. The main purpose of natural ventilation as a passive cooling strategy, is to optimise the rate of air flow and provide appropriate temperature and relative humidity (Schulze & Eicker, 2013). The factors that influence the air flow in buildings include the elements of the outdoor environment (as discussed in section 3.4.1), the shape of the building and geometrical configuration (as discussed in section 3.4.3), as well as orientation of openings (covered in section 3.4.4.2). Furthermore, window size, distribution and type and subdivision of internal space also influence air flow in a room (Tantasavasdi et al., 2007b). The average interior air velocity is a function of the exterior wind velocity, the angle at which the wind strikes the opening, and the size of the opening. Figure 3.6 and table 3.3 demonstrate how the size, number and location of the openings affect the air flow (DeKay & Brown, 2013).

Different window types also have an influence on airflow, depending on the way in which they are operated. For instance, casement and projecting windows can typically be fully opened, allowing for greater ventilation. An outward-projecting sash may help to direct outdoor air into a room. Under harsh
Chapter three

wind conditions, however, inward-projecting sashes may be more feasible. Sliding windows have more limited openings of less than half of the overall window area (45%) (Bliss, 2006; DeKay & Brown, 2013). There are varying window types that are used in residential building developments in Abuja; however, sliding windows are increasingly being employed for houses in Abuja. The impact an area with limited options to be opened has on the ventilation in houses is discussed and investigated in Chapters six and seven.

Table 3.3 Average interior air velocity as a percentage of exterior wind velocity for different sizes of openings (Brown & Dekay, 2001)

<table>
<thead>
<tr>
<th>opening height as a fraction of wall height</th>
<th>opening width as a fraction of wall width</th>
</tr>
</thead>
<tbody>
<tr>
<td>single opening</td>
<td>1/3</td>
</tr>
<tr>
<td>two openings in same wall</td>
<td>2/3</td>
</tr>
<tr>
<td>two openings in adjacent walls</td>
<td>3/3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>opening height as a fraction of wall height</th>
<th>1/3</th>
<th>2/3</th>
<th>3/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>single opening</td>
<td>12-14%</td>
<td>13-17%</td>
<td>16-23%</td>
</tr>
<tr>
<td>two openings in same wall</td>
<td>—</td>
<td>22%</td>
<td>23%</td>
</tr>
<tr>
<td>two openings in adjacent walls</td>
<td>37-45%</td>
<td>37-45%</td>
<td>40-51%</td>
</tr>
<tr>
<td>two openings in opposite walls</td>
<td>35-42%</td>
<td>37-51%</td>
<td>47-65%</td>
</tr>
</tbody>
</table>

Note: range = wind 45° perpendicular to opening

Infiltration and exfiltration: Infiltration is the flow of outdoor air into a building through cracks and other unintended openings and through the opening of doors. Infiltration is simply defined as air leakage into the building (ASHRAE, 2009). Exfiltration is defined by ASHRAE (2009) as the leakage of indoor air to the outside of a building through similar types of openings. Infiltration and exfiltration are driven by natural and artificial pressure differences. The amount of air infiltration depends on tightness of windows and doors, outside wind velocity and height of building (ASHRAE, 2009). The amount of air infiltration around
windows depends on a number of factors, including type of windows used in a building, type of weather strips used in windows, location of windows in a building and location of a building, as well as weather conditions, such as wind speed and temperature difference. The total heat load due to infiltration consists of sensible heat (heat which raises the temperature of moist air) and latent heat loss associated with the evaporation or condensation of moist air (Hassouneh et al., 2012).

Air leaks into a building through various openings and cracks have a significant effect on building energy consumption. A number of experimental studies have estimated that the impact of infiltration and exfiltration can account for between 25% and -50% of the cost of energy used for cooling/heating in residential buildings in humid and dry tropical climate regions (Hassouneh et al., 2012; Nabinger & Persily, 2011; Park & Kim, 2012; Rhodes et al., 2011).

3.4.4.4 WINDOW PROPERTIES

In addition to the rate of infiltration, the solar heat gain coefficient (SHGC) and the thermal transmittance (U-value) also determine the thermal performance of the window for heating as well as for cooling in spaces. The SHGC represents the fractional amount of the solar radiation that strikes the window that ends up warming the internal space either through radiation or convection (ASHRAE, 2009). This coefficient varies according to the incident angle of the source, whether it is a direct beam, diffused or reflected component of solar radiation (ASHRAE, 2009; Oliveti et al., 2011). Table 3.4 shows the thermal properties of different types of glazing systems (Singh & Garg, 2009).

The SHGC is a function of solar transmittance and absorption of each layer and inward flowing fraction of heat (Finlayson et al., 1993). The SHGC can be calculated for each component of the window separately, using the following equation:

\[
\text{EQUATION 3.4.} \quad \text{SHGC} = T_{\text{sol}} + A_{\text{sol}} N
\]

where:

- \( T_{\text{sol}} \) = solar transmittance
- \( A_{\text{sol}} \) = solar absorptance
- \( N \) = inward flowing fraction
Chapter three

Table 3.4 lists some types of glazing and summarises their impact on solar heat gain, while table 3.5 shows the varying u-values (heat transmittance) of different double glazing types.

Table 3.4 Some commonly used glazing materials and application technologies (adapted from: Gan, 2001; Giovannetti et al., 2012; Givoni, 1998; Sbar et al., 2012)

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear glass</td>
<td>Clear glass transmits the highest amount of daylight, but also causes the highest solar heat gain into the building.</td>
</tr>
<tr>
<td>Coloured glass</td>
<td>Grey and coloured glass absorbs more visible light than infrared radiation. They are more effective at reducing glare and excessive sunlight from penetrating through large windows.</td>
</tr>
<tr>
<td>Heat reflecting/tinted glass</td>
<td>This glazing system is produced by placing a very fine semi-transparent metallic coating on the glass surface, which selectively reflects a larger proportion of the infrared radiation. Thus, it reduces the solar heat gain. However, the level of daylight entering the room is also lowered.</td>
</tr>
<tr>
<td>Multiple-glazed unit</td>
<td>Multiple-glazed units are used to increase the resistance of a window to the transfer of heat by using two or three separate glass panes with air spaces between them. In a double glazing unit for example, a second pane of glass is separated from the first pane by an air space. Thereby it increases the thermal resistance due to the low thermal conductivity of air and the extra barrier to long wave radiation exchange provided by the second pane.</td>
</tr>
<tr>
<td>Low emissivity glass</td>
<td>These types of glazing are produced by depositing specially designed coating on the surface of the glass, which reduces the rate of heat transfer through the glazing.</td>
</tr>
<tr>
<td>Heat absorbing glass</td>
<td>This type of glass selectively absorbs a higher fraction of the infrared (heat) part of the solar radiation compared with its absorption of visible light. Thus, the light to heat ratio of such glazing systems is higher than that of clear glass. The temperature of the glass itself rises as a result of the absorbed infrared radiation. This can lead to increased convective heat flow in buildings.</td>
</tr>
<tr>
<td>Electrochromic glazing</td>
<td>These types of glazing use electrochromic materials that modulate light in the visible and near infrared by application of an applied voltage. A typical design for window applications consists of five thin film layers on a single glass substrate or sandwiched between two glass substrates. Electrochromic glazing provides glare control that improves occupant comfort and tints, while still permitting a view to the outdoors.</td>
</tr>
</tbody>
</table>

Table 3.5 Different glazing systems and thermo-optical properties (Sing & Garg, 2009)

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single, 6 mm, clear</td>
<td>5.65</td>
</tr>
<tr>
<td>Double, 6 mm, 12 mm air gap, clear</td>
<td>2.95</td>
</tr>
<tr>
<td>Double, 6 mm, low-e coated, 12 mm air gap, clear</td>
<td>1.80</td>
</tr>
<tr>
<td>Double, 6 mm, low-e coated, 12 mm air gap, clear</td>
<td>1.74</td>
</tr>
<tr>
<td>Double, 6 mm, low-e coated, 12 mm air gap, clear</td>
<td>1.63</td>
</tr>
<tr>
<td>Double, 6 mm, green, 12 mm air gap, clear</td>
<td>2.95</td>
</tr>
<tr>
<td>Double, 6 mm, grey, 12 mm air gap, clear</td>
<td>2.95</td>
</tr>
<tr>
<td>Double, 6 mm, absorbing film coated, 12 mm air, clear</td>
<td>2.90</td>
</tr>
<tr>
<td>Double, 6 mm, absorbing film coated, 12 mm air, clear</td>
<td>2.80</td>
</tr>
<tr>
<td>Double, 6 mm, reflective film coated, 12 mm air, clear</td>
<td>1.95</td>
</tr>
</tbody>
</table>

Operable wooden shutters were commonly used in window openings in traditional residential buildings and colonial architecture in Nigeria (Dmochowski, 1990a; Denyer, 1978). The use of clear glass became more prominent during the emergence of the tropical modernist movement in West Africa in the fifties (Uduku, 2006), and it has remained the most common glazing type in Nigeria. However, the use of tinted glass is becoming increasingly popular, particularly in commercial buildings (Batagarawa, 2011; Lawal & Ojo; 2011).
3.4.4.5 Fenestration factor

There are a number of variables that are associated with windows, which influence the thermal conditions in a room. As previously discussed, these include the orientation, size and position of multiple windows in a room, as well as the thermal properties of the window materials. That said, the appropriate size of the total window area in a room can also be related to the size and function of the room. A window-to-floor ratio, also known as the fenestration factor, provides a guide for designers to determine the optimum areas for windows in relation to the floor area of a room (Catalina et al., 2008). The fenestration factor can be calculated by dividing the size of the total window area by the size of the total floor area in a room and multiplying the value derived by one hundred to derive a percentage. The percentage value for the fenestration factor is one of the few environmental design factors specified in the Nigerian building codes (FRN, 2006). As previously stated in section 2.6, the Nigerian building code recommends a minimum window to floor area ratio and a minimum openable window area to floor area ratio. While the total window area determines the level of solar heat gain in the room and airflow through cracks between the wall and window components, the openable window area is the main determinant of the air movement in naturally ventilated buildings (Tantasavasdi et al., 2007b).

3.4.4.6 Window to wall ratio

The ratio of the total external window area to external wall area also affects the thermal conditions in a room, because glazed areas transmit more and absorb less heat through radiation and convection than walls. The window to wall ratio can be calculated by dividing the size of the total window area by the size of the total external wall area of a room and multiplying the value derived by one hundred to derive a percentage (Chou, 2004). A high window to wall ratio can increase the level of solar heat gain in a space (Lee et al., 2013). While this can sometimes be beneficial for thermal comfort in cold climates, in warm or hot conditions, a high window to wall ratio can lead to overheating indoors, especially if the window is not properly shaded. However, a high openable window to wall ratio is advantageous, particularly in warm-humid regions where air movement and ventilation have a very high influence on the perception of comfort (Dahlan et al., 2009; Jamaludin et al., 2013).
3.4.4.7 WINDOW SHADING DEVICES

As with wall shading elements, window shading devices provide a form of thermal control by limiting the level of solar radiation reaching the room through the windows. Thus, the application of shading devices, internally or externally, can have a significant impact on the level of solar heat gain in a room. Interior shading devices, such as curtains, totally or partially obstruct daylight; however, the radiation reaches the interior before it is obstructed. Thus, these types of devices do not effectively limit solar heat gain. On the other hand, external shading devices are able to effectively reduce the amount of solar radiation reaching the window surface. Hence, they are more effective at controlling the level of solar heat gain and reducing the overheating period in a space (Kim et al., 2012). Shading devices can also hinder or enhance natural ventilation in spaces by modifying the pattern of air movement through an opening, depending on the type, orientation, position and size of the shading device being applied (Hien & Istitiadi, 2003).

3.4.4.8 INTERNAL HEAT GAINS

The occupancy rate and activities of occupants in buildings can lead to an increase in the level of heat and humidity (Szokolay, 2014). The sources of internal heat gains include:

1. Sensible and latent heat gain from people,
2. Sensible heat gain from artificial lighting, and
3. Sensible heat gain from equipment, such as electrical plugs and devices, as well as sensible and latent heat gain from processes, such as cooking (Koenigsberger et al., 1974).

Occupancy: Each human being emits heat and pollutants, such as water vapour, carbon dioxide and odour. Therefore, his/her presence directly modifies the indoor environment (Kwok & Lee, 2011). The processes through which the body transfers heat to the surrounding environment have been described in section 3.2, including, latent heat transfer through evaporation of moisture from the skin (sweating) and sensible heat loss through radiation. The effects of building occupancy are often analysed, based on fixed profiles of their occupancy presence and associated implications of their presence (Page et al., 2008). The heat output rate is dependent on the schedule of occupancy (determined by observing the
number of persons in a space over a period of time) and their level of activity, which determines the rate of heat production based on metabolism. The rate of heat in watts (W) for various activities is shown in table 3.6. Thus, the internal heat gain from occupants can be determined by multiplying the appropriate rate by the number of occupants (Koenigsberger et al., 1974). However, in order to accurately determine the contribution of human occupancy to the total internal heat gains, the behaviour of occupants with regards to their use of artificial lighting and other household appliances should be assessed as well (Dibra, Mahdavi, & Koranteng, 2011).

Table 3.6 Average heat output rate of human bodies for different levels of activity (Koenigsberger, 1974, p.42).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Watts (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeping</td>
<td>minimum 70</td>
</tr>
<tr>
<td>Sitting, moderate movement</td>
<td>130-160</td>
</tr>
<tr>
<td>Standing, light work at machine</td>
<td>160-190</td>
</tr>
<tr>
<td>Sitting, heavy leg and arm movements</td>
<td>190-230</td>
</tr>
<tr>
<td>Standing, moderate work, some walking</td>
<td>220-290</td>
</tr>
<tr>
<td>Walking, moderate lifting or pushing</td>
<td>290-410</td>
</tr>
<tr>
<td>Intermittent heavy lifting</td>
<td>440-580</td>
</tr>
<tr>
<td>Hardest sustained work</td>
<td>580-700</td>
</tr>
<tr>
<td>Maximum heavy work for 30 minutes duration</td>
<td>maximum 1,100</td>
</tr>
</tbody>
</table>

Given the way occupants inhabit their dwellings, establishing a precise pattern of use in housing is relatively more difficult than determining the pattern of use for an office or classroom where the level of activity and number of occupants are often specific (Kim et al., 2012).

**Artificial lighting:** All the electrical energy used by electric lamps is ultimately released as heat and can be a major component of the building’s cooling load, particularly in commercial buildings. Moreover, a substantial proportion of the energy from electric lamps is emitted as radiant heat, which can be a source of discomfort to the occupants (CIBSE, 2008). Table 3.7 illustrates the approximate ratio of radiant to conductive/convective heat transfer for a number of lamp types.

A survey of residential and public buildings in three cities in Nigeria, including Abuja, Lagos and Benin, revealed that 65% of the people use incandescent lamps (CRDC, 2009). A similar survey of 66 residential buildings in Ilorin, Nigeria, revealed that 90% of the lamps used in the buildings were incandescent lamps, 6% were fluorescent lamps, 1% were halogen lamps and 3% were compact fluorescent lamps (Sule et al., 2011). Incandescent bulbs are the most popular lamp type in Nigeria, because they are a lot cheaper than
other lamp types and about ten times cheaper than the low energy lamps readily available in Nigeria (CRDC, 2009).

Table 3.7 Typical energy dissipation for different types of lamps (CIBSE, 2006)

<table>
<thead>
<tr>
<th>Lamp types</th>
<th>Heat output (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radiant</td>
</tr>
<tr>
<td>Incandescent/filament (tungsten)</td>
<td>85</td>
</tr>
<tr>
<td>High pressure mercury/sodium, metal halide</td>
<td>50</td>
</tr>
<tr>
<td>Low pressure sodium</td>
<td>43</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>30</td>
</tr>
</tbody>
</table>

Appliances: Operations of domestic appliances, including cooking appliances, televisions, personal computers and refrigerators as well as activities, such as washing up dishes and taking a bath or a shower, consume energy in the form of electricity, gas or oil, while also generating heat in residences (Papakostas & Sotiropoulos, 1997). The heat generated by appliances is subjective due to the variety of appliances, applications, duration of use and type of installation. In estimating the internal heat gain from appliances, the probability of simultaneous use and operation for different appliances within the same space should be considered (CIBSE, 2008). However, the current study is focused on low-income housing with limited and erratic electricity supply. Thus, in most of the households that are being considered, the heat from electrical appliances is often very low. Thus, for the simulations used in carrying out the building performance assessment in Chapters six and seven of this study, only the sensible and latent heat gain from occupants is taken into account.

3.5 CONCLUSION

To produce a thermally comfortable and healthy environment for building occupants as well as to ensure buildings are more energy efficient, a number of environmental parameters and building design parameters must be adjusted to improve the internal thermal conditions. The thermal performance of indoor spaces in relation to these parameters are, therefore, a fundamental part of passive building design and can also be the underpinning of a framework for evaluating their thermal performance.

Such an evaluation is important with respect to the determination of the optimal values for the design parameters. The parametric evaluation process gives designers the opportunity to consider thermal
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performance as part of the design process before the actual construction process is initiated or as a post-construction performance analysis tool for improving the performance of existing buildings.

In this chapter, the benefits of passive building design and the main parameters discussed in literature that affect the thermal performance of buildings are explained with reference to the region of the study. Using a framework similar to that used by Oral et al., (2004), the framework adapted in this study is structured into four levels, including climatic factors (level I), parameters of the urban environment (level II), design parameters of the building (level III) and design parameters of the room (level IV). The natural or climatic parameters include temperature, solar radiation, relative humidity and air movement. The elements of the local environment that can have an impact on the external temperatures, particularly in densely populated urban centres, are briefly discussed at the urban environment level. The parameters related to the physical characteristics of buildings (level II) that have an impact on the thermal conditions indoors are building shape, building orientation and wall shading elements. The design parameters discussed at the room level are associated with the thermal conditions experienced inside rooms in buildings separated by elements, such as walls or other partitions from the external environment and other parts of the building. Based on the review carried out in this chapter, the parameters related to thermal performance of buildings and their variables that are considered within the framework of the study are listed below in table 3.8.
Table 3.8 List of parameters and variables that influence the thermal performance of buildings

<table>
<thead>
<tr>
<th>Level</th>
<th>Parameters and factors</th>
<th>Variables</th>
<th>Nomenclature</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Climate</strong></td>
<td>Solar radiation</td>
<td>Global irradiance</td>
<td>G</td>
<td>W/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Direct (beam) irradiance</td>
<td>Gₜ</td>
<td>W/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diffused irradiance</td>
<td>Gₐ</td>
<td>W/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar altitude angle</td>
<td>α</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar azimuth angle</td>
<td>ψ</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar zenith angle</td>
<td>ϕ</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air (dry-bulb) temperature</td>
<td>Tₑ₀</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Relative humidity</td>
<td>&lt;30%, 30-75%, &gt;75%</td>
<td>RH</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Air velocity</td>
<td>V</td>
<td>m/s</td>
<td></td>
</tr>
<tr>
<td><strong>The built environment</strong></td>
<td>Size and orientation of external obstructions</td>
<td>Reflectance</td>
<td>ρ</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Properties of external surfaces</td>
<td>Transmittance</td>
<td>τ</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Absorptance</td>
<td>α</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emittance</td>
<td>ϵ</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific heat capacity</td>
<td>c</td>
<td>j/kgK</td>
<td></td>
</tr>
<tr>
<td><strong>The building</strong></td>
<td>Orientation</td>
<td>North, south, east, west, others</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compactness ratio</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wall shading elements</td>
<td>Porticos, verandah, overhangs, fins</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wall shading element proportions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>The room</strong></td>
<td>Façade orientation</td>
<td>North, south, east, west, others</td>
<td>θ</td>
<td>°</td>
</tr>
<tr>
<td></td>
<td>Room dimensions</td>
<td>Width, depth, height</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>External surface area</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Internal volume</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Window orientation</td>
<td>North, south, east, west, others</td>
<td>θ</td>
<td>°</td>
</tr>
<tr>
<td></td>
<td>Window dimensions</td>
<td>Width, height</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Window layout and location</td>
<td>Unilateral, bilateral, multilateral,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Window shading elements</td>
<td>Shutters, overhangs, fins, egg-crates, sills, awnings, louvers, brise-soleil</td>
<td></td>
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<td></td>
<td>Window shading element proportions</td>
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<td></td>
<td>Fenestration factor</td>
<td>FF</td>
<td>%</td>
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<td></td>
<td>Window to wall ratio</td>
<td>WWR</td>
<td>%</td>
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<td></td>
<td>Reflectance of external surfaces</td>
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<tr>
<td></td>
<td>Thermal transmittance of components of building envelope</td>
<td>Specific heat capacity</td>
<td>U-value</td>
<td>W/m²K</td>
</tr>
</tbody>
</table>
CHAPTER 4 - FACTORS THAT INFLUENCE VISUAL COMFORT IN BUILDINGS

4.1 INTRODUCTION

Daylight, which is a combination of direct sunlight and diffused skylight, has always been a crucial factor in the design of buildings (The Society of Light and Lighting [SLL], 2014). Before the advent of artificial light, it was necessary to design buildings so that their occupants could make maximum use of available daylight. Some of the design constraints, such as narrow plans and windows large enough to allow for an adequate amount of natural light indoors, which were a product of the need for daylighting, have been removed by the opportunity to use artificial lighting. This discounts the benefits of daylight contributing to human comfort and satisfaction in indoor environments (SLL, 2014).

Windows in all their forms and sizes are a fundamental element of most buildings and have been for many years (SLL, 2014). In Nigeria, traditional dwellings were mainly made of mud walls and lit by various sizes of openings. The main design obstacle that prevented or at least contributed to the lack of adequately sized windows is the limitations imposed by the structure. Sizeable windows require horizontal beams and lintels to transfer loads on openings to walls; however, such structural components were not common in Nigerian traditional earth dwellings. Thus, in traditional dwellings, tasks that required more visual attention were normally performed outdoors (Denyer, 1978). As a result, many visual tasks in the traditional setting were performed outside or in courtyard spaces within the dwellings (Agboola & Zango, 2014; Carroll, 1992). Unlike the traditional dwellings of the region, daylighting design has become very important for residents of contemporary dwellings who tend to spend most of their lives indoors. That said, daylighting is not only an important issue in modern architecture affecting the functional organisation of spaces and occupant’s visual comfort, but it also affects energy use in buildings (Li et al., 2010). Hence, in contemporary Nigerian buildings, good daylighting requires a balancing act between the need for sufficient access to daylight in order to reduce the need for artificial lighting and the need to limit solar heat gain to reduce the energy needed for cooling.
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This chapter focuses on a number of key parameters, including factors of the natural and built environment, that have an influence on indoor visual conditions and occupant’s comfort. Similar to the previous chapter (Chapter three), the primary objective of this chapter is to develop an appropriate framework for evaluating the visual performance of residential buildings in Abuja, Nigeria. With this objective in mind, the review in this chapter is presented in three sections. Firstly, the concept of daylighting and the main drivers for improving daylighting design of buildings are discussed in section 4.2. Secondly, climatic factors that relate to daylighting design of buildings and people’s preferences of a certain quality of daylight in the tropical and sub-tropical regions are briefly discussed in section 4.3. Finally, the design parameters, which influence visual conditions in buildings and which have often been discussed in the literature, are reviewed in section 4.4.

4.2 Benefits of Daylighting

4.2.1 Defining Good Daylighting

Daylight is generally taken to be the sum of visible radiation originating from the sky and the sun (when visible) during the hours of daytime (SLL, 2014). Daylight or natural light also refers to all indirect sources of light (such as light reflected from surfaces that are originally illuminated by primary or other secondary sources). The radiation from the sun can be harnessed or controlled within the built form to contribute to both the visual and thermal comfort of occupants (Major et al., 2005). The term ‘daylighting’ on the other hand, can be defined as the act, art, science or practice of using daylight as a primary source of daytime illumination in a space or building (Ternoey, 1999).

As a practice, daylighting can be considered from a variety of perspectives. From the architects’ point of view, daylight is often seen to provide a visually stimulating, healthy and productive environment, whereas engineers might be more concerned with the environmental aspect of daylighting design, energy requirements and/or the reduction of lighting loads (Reinhart & Wienold, 2011). Daylight, as a design element, has always captured the architects’ attention, but in recent decades there has been an increase in the level of interest in research on the topic of daylighting in the built environment. Much of the literature has identified the maximising of the effectiveness of daylighting in buildings for two main
reasons, firstly, the consideration of the use of natural light as an effective energy saving strategy and, secondly, the physical and psychological impact of daylight on human comfort (Aries et al., 2015; Kollmann & Schulz, 2006; Koshiba et al., 2015; Phillips, 2004; Tregenza, 2003; Tregenza & Wilson, 2011).

4.2.2 SUSTAINABILITY AND ILLUMINATION

Technological advancements in artificial lighting have increased the availability of safer, cleaner and more efficient sources of artificial lighting, thus, encouraging the widespread use of lighting for the performance of tasks, rather than using the natural resource of daylight. Daylight from both direct sunlight and diffused skylight can be used more effectively in the design of buildings replacing the need for artificial light during the daytime (Baker & Steemers, 2002; Major et al., 2005). Daylighting in sustainable building development is linked with the benefits of energy conservation and savings achieved by reducing the use of artificial lighting (Dubois et al., 2007). A number of simulation-based and field monitoring studies from various regions with different climates have reported that proper daylighting design approaches can result in energy savings ranging from 30% to 77% (Cantin & Dubois, 2011; Ihm et al., 2009; Li et al., 2006). In addition, lighting control systems used during the operational phase of a building’s life cycle can also lead to energy savings (SLL, 2009). Thus, determining the daylighting strategy required at the preliminary stages of building design plays a significant role in reducing the energy consumed through artificial lighting (Ihm et al., 2009). In tropical climatic conditions, like in the Nigerian context, where there is an annual average of 12 sunshine hours, daylighting can be an important factor in reducing the energy consumption of residential buildings. However, daylighting design strategies are not commonly incorporated in housing in Nigeria. Oyedepo (2012) suggests that daylighting design solutions can be used to effectively reduce the energy consumed by artificial lighting in Nigeria, if buildings are designed to take advantage of the natural light that is available.

Although the potential for reducing energy consumption through daylighting is substantial, the impact of daylighting on occupants is equally important. Kollmann and Schulz (2006, p. 16) stated that "today's dream home should be first and foremost bright and sunny. Nothing is as unappealing as a gloomy room to live or work in". The human eye has the ability to adapt to a large range of lighting conditions, however, there are certain optimum conditions, in which the eye works better depending on the task or activity
being performed (Hopkinson et al., 1966). Adequate lighting makes it easier to see visual tasks and it leads to improvements in the performance of tasks. Furthermore, daylight allows spaces to be lit at higher levels than with electric lighting alone (Leslie, 2003). An illuminance of 500lux in an internal space is sometimes perceived as too bright, whereas outdoors 5,000lux is sometimes perceived as gloomy; this is an example of the deficit between artificially lit spaces and daylit spaces. Outdoor illuminance can vary between 100,000lux in sunny, clear sky conditions to below 5,000lux on cloudy days (Kollmann & Schulz, 2006). This difference in the way we perceive daylight and artificial light might work well in Abuja, where high illuminance of the clear sky prevails for most parts of the year. During the fieldwork, (which is discussed further in Chapter five) the highest sky illuminance level recorded for a location was in Gadowa, Abuja, which was 209,000lux.

4.2.3 Health and wellbeing

Making good use of daylighting is a promising approach for improving visual health, which is one of the components of a healthy environment. Both the amount of illuminance and the quality of light are important factors for the health and wellbeing of buildings’ occupants (Kim & Kim, 2010). Human beings depend on the natural cycle of day and night (light and dark) for the body to regulate the daily sequences of sleep, hunger, body temperature and alertness, as well as to regulate almost all hormones (Tregenza & Wilson, 2011). A number of studies has shown that people living in houses that lack daylight have a relatively low mental health status (Lawrence, 2011). It is also evident that poor indoor lighting causes health problems and artificial light cannot substitute for the quality of daylight. A health problem often associated with a lack of daylighting is Seasonal Affective Disorder (SAD), a condition in which sufferers experience symptoms of depression. People who work in situations or inhabit buildings, which have access to natural light, are likely to be less affected by SAD (Kim & Kim, 2010; Phillips, 2000). Over-exposure to electromagnetic radiation can have harmful effects on the body and eyes; however, controlled exposure to direct sunlight boosts the body’s production of vitamin D. In addition to promoting the synthesis of vitamin C, other reported benefits include initiating defences against microbes and stimulating the immune system. It also increases the oxygen carrying capacity of the blood circulating in the capillaries close to the skin’s surface. This reduces the work required by the heart and lungs and
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normalises both cholesterol levels and blood pressure, as well as it reduces the possibility of coronary heart disease (Baker & Steemers, 2002). Successful daylighting design can help improve both the psychological and physical health of building occupants by providing adequate levels of daylight, while also reducing discomfort problems caused by glare.

4.2.4 Views and Appearance of Space

People like to have the pleasure of a view through a window, which enables them to stay connected with external events and to remain consciously or subconsciously aware of their surrounding social context. A number of studies has indicated that the access to a view is important for occupants’ physical and psychological health and wellbeing (Aries et al., 2015; Baker & Steemers, 2002; Lim & Kim, 2012; Raanaas et al., 2012). The perception of the outside environment in a room with a view is an experience associated with changes in daylight from dawn till dusk and throughout seasonal change. The perception of a view has an influence on the way the body responds to daylight (Tregenza & Wilson, 2011). Occupants prefer rooms with daylit appearance during daytime hours as opposed to rooms without windows. There are few buildings that can be described as windowless, yet a significant amount of buildings uses electrical lighting during the daytime. An appropriate visual environment can be achieved, even in rooms that are artificially lit during the daytime, by ensuring that the changes in the external daylit environment is clearly noticeable within the internal environment (CIBSE, 2008).

Cheung and Chung (2008) used a survey data analysis to determine how people value different attributes in daylit residential apartments in Hong Kong. They investigated user preferences and their satisfaction with the attributes related to general brightness, desktop brightness, perceived glare, quality of view, sunlight penetration, shading control and impact on energy consumption. The results showed that participants in the study considered the quality of the view the most important attribute when evaluating a daylit space; its importance level was 24%. The attribute with the second highest importance was general brightness, which was only 1% less important to the occupants in their evaluation of the space. Interestingly, they found that quality of view and general brightness accounted for almost 50% of the total influence of attributes in a daylit space.
4.3 Daylighting in the Tropics

Daylight normally enters buildings through different openings, such as windows, roof lights, atria and light ducts in roofs. However, the amount of natural light that is received indoors depends on the latitudinal location of the building, as well as the climate of the region. The regions between the Tropic of Cancer (approximately 23° north of the equator) and the Tropic of Capricorn (approximately 23° south of the equator) receive a high amount of solar radiation throughout the year (Obaidi et al., 2012). Edmund and Greenup (2002) observed that in these regions, the compromise between natural lighting and thermal comfort has traditionally favoured thermal comfort, thus, older buildings in such regions have relatively small window areas with a correspondingly low ratio of internal illuminance. In tropical climates with frequent instances of clear sky conditions and high levels of direct solar radiation, both the physical and psychological effects of increased exposure to natural light and passive heat gain would be disadvantageous (Edmund & Greenup, 2002). Due to the accompanying thermal radiation, over-lighting would lead to overheating, which would cause much greater discomfort than under-lighting. A slightly under-lit room could also be psychologically more acceptable, as light is mentally associated with warmth and reduced lighting is associated with coolness (Koenigsberger et al., 1974).

In general, the use of daylight in buildings located in tropical and sub-tropical regions where intense solar radiation prevails for most of the year can only be an effective passive design element for improving overall energy efficiency if it simultaneously negates solar heat gain. Yet, there are only a few studies on daylighting in Nigeria (Amasuomo & Alio, 2013; Atolagbe, 2013). Thus, in this study, the visual and thermal performance of selected residential building prototypes in Abuja are simultaneously examined to assess the possibility of naturally illuminating the buildings without increasing the risk of overheating.

4.4 Parameters with an Influence on Visual Conditions in Buildings

Baker, Fanchiotti and Steemers (1993) classified the design parameters and variables that have an impact on daylighting on three levels, from the level of the room (level I), to the building (level II) and to the urban context (level III). The framework, which they developed as a means to help designers generate new combinations of existing concepts used in daylighting, is similar to the framework adopted for
examining the parameters that influence the thermal performance of buildings discussed in Chapter three. However, it is notable that with regards to daylighting, the level of visible solar radiation is the main parameter related to the outdoor environment. On the other hand, the characteristics of the transparent apertures, through which light enters the building, are the main design variables associated with daylighting. Hence, the opaque components of the building envelope have a limited influence on the visual performance of the building. The variables of each level, as listed below, are explained in the following sections of this chapter. Each level presents a number of design elements that ought to be considered in the selection and analysis of case studies. However, the section on the urban context will be brief, as the impact of urban planning on the daylight conditions in buildings is not the main aim of this study. The parameters in this study are classified into the following levels:

- the climate (level I),
- the built environment (level II),
- the building (level III),
- the room (level IV).

4.4.1 THE CLIMATE (LEVEL I)

4.4.1.1 SOLAR RADIATION

As stated before, the amount of daylight received indoors is directly related to the climatic conditions of a location/region and the sun’s position in relation to a site. The latitude, longitude, date and time of day can be used to calculate the exact position of the sun in the sky for a given location (Littlefair, 2011). Given that the solar radiation reaches the surface of the earth under different atmospheric conditions, the amount of solar gain and the daylight available vary greatly during the course of the day. Conditions, such as turbidity, transparency, air-mass, atmospheric water vapour content and distribution of cloud cover can all reduce the solar radiation received at the earth’s surface (Okogbue et al., 2009). At the local level, certain conditions, such as gaseous and particulate pollution, reflected light from the ground and buildings, as well as obstruction by terrain formations also have an impact on the quantity and quality of available daylight at a location (Baker & Steemers, 2002). Sky conditions are often classified using the clearness index (given as a fraction), $H/H_0$ where $H$ is the average global radiation and $H_0$ is the extra-
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terrestrial solar radiation (solar radiation directly outside the earth’s atmosphere) (Augustine & Nnabuchi, 2009). Therefore, the clearness index represents the difference between the light from the sun and the amount that reaches a given location after the light is obstructed or diffused by elements within the atmosphere.

Figure 4.1 Average hourly global horizontal solar radiation (W/h/m²) for each month in Abuja (NIMET, 2010)

Figure 4.2 Average hourly direct normal solar radiation (W/h/m²) for each month in Abuja (NIMET, 2010)

Figures 4.1 and 4.2 respectively show the direct and diffused solar radiation incident on the horizontal surface during a typical annual period in Abuja. The data illustrated indicates that the level of direct solar radiation is reduced by changes in atmospheric sky conditions and the precipitation during the rainy season (May to October).
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4.4.1.2 SKY CONDITIONS

The prediction of sky luminance is very important for estimating the amount of natural light available at a location at a specific time. The available light is determined by the sky conditions, which are difficult to model accurately. Nevertheless, for daylighting purposes, the International Commission on Illumination (CIE) recommends the use of sky models, which include a wide range of conditions that are partly defined by functions associated with the solar altitude, even when most of the light from the sun is diffused (2003). Of the various sky types, clear skies, partly cloudy skies and cloudy skies are often defined as the main sky conditions commonly used for modelling purposes (Szokolay, 2014). Under a clear sky condition, direct sunlight can provide an illuminance of about 100klux, but if the sunlight is excluded, the illuminance level is between 40klux and 50klux. A partly cloudy or intermediate sky condition is a cloudier variant of the clear skies, which can be modelled with or without direct sunlight. Under a cloudy sky condition, the diffused component of light is much greater than the direct component. Thus, a fully overcast sky usually acts as a diffuse light source (Szokolay, 2014). For lighting design simulations, the sky conditions can be broadly delineated by determining the level of cloud cover. Clear skies have less than 30% cloud cover, partly cloudy skies have between 30% and 70% cloud cover, and cloudy skies have more than 70% cloud cover, with complete cloud cover (100%) under overcast skies (Larson, 1998; Mischler, 2004). These four main sky conditions can be classified further into fifteen types using four parameters, including the horizontal sky-diffuse illuminance ($D_z$), the extraterrestrial illuminance ($E_z$) (illuminance at the outer edge of the atmosphere), the zenith luminance ($L_z$) (a function of atmospheric turbidity and solar altitude), and the luminous turbidity (Janjai & Plaon, 2011; Li et al., 2014).

The cloud cover data presented in figure 2.13 in Chapter two indicates that clear sky conditions are prevalent in Abuja for 61% of the typical year, partly cloudy sky conditions occur for about 23% of the year and cloudy skies only occur for about 16% of the year. These facts are considered when conducting the daylight simulation modelling presented in Chapter six.
4.4.2 The built environment (Level II)

4.4.2.1 Urban space layout

As stated before, the daylight that reaches the interior of a building through its aperture often consists of a combination of direct illumination from the solar disk, the sky dome and reflected illumination from the ground, as well as other naturally illuminated external surfaces (Baker et al., 1993). The spacing and arrangement of buildings and open areas have an influence on the level of natural illuminance available in buildings. Thus, the influence of overshadowing and mutual obstruction caused by buildings can be particularly critical in high-density urban areas, reducing the amount of daylight received indoors. Hence, in order to provide adequate daylight in buildings, urban design has to be considered with the aim of optimising the configuration or manipulating the urban fabric to admit the natural illuminance needed to satisfy the requirements of the building (Morello et al., 2009).

In the European reference book “Daylighting in Architecture”, published in 1993, Baker et al. classified urban space layout configuration of European cities into seven types, based on the size and orientation of urban blocks, as well as the size of open spaces (Figure 4.3). The typologies presented included large urban blocks, small urban blocks, solar orientated blocks, North-South slabs, East-West slabs, open blocks and towers. In a more recent study of urban spaces in Brazil, Amorim (2009) identified two additional types, taking into consideration construction and building elements existent in the urban centres of Brazil. The two additional urban forms included superquadras and intermediary slabs. The urban form determines the level of obstruction created by other structures at a location, thus, it influences the quality and quantity of light reaching a room regardless of the prevalent sky conditions. Cheng et al. (2006) carried out a study on the relationship between urban built form, density and daylighting potential. They analysed daylight performance of eighteen generic urban layout models with equal usable floor area and a range of built forms and densities within a site of 10,000m². They found that those arrangements with higher buildings, smaller building footprints and more open area performed better than arrangements with lower buildings and wider site coverage. The spaces between higher detached open urban blocks permitted greater penetration of daylight, while the facades of lower small urban blocks with less open space around them had less exposure to daylight. The study also revealed that a variation of building
heights and dispersed layout of buildings to maximise open space was better for daylighting performance than a grid or uniform grouping of buildings.

![Urban block layout classification](image)

A study of the master plan of Abuja suggests that buildings and settlements were planned to satisfy the number of housing units needed, but no attention was given to the impact of the overall planning on the microclimatic conditions at the city/urban level (FCDA, 1979). However, based on the data collected during the field study, most of the mass housing schemes developed for low-income groups in Abuja include a mixture of north-south or east-west slabs and small urban blocks. Figure 4.4 shows the juxtaposition of these urban forms in a residential estate developed by the government in Gaduwa, Abuja.

![Residential area in Gaduwa, Abuja](image)

4.4.2.2 Reflectance of Facades

The surface of a building can be considered a source of light. The building surface can either scatter light (such as with a white painted wall) to provide a soft and diffused light or reflect light more precisely (like...
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a mirror or sheet of polished stainless steel) and act as a secondary point of illumination (Major et al., 2005). Hence, it is important for designers to consider the urban environment (including building surfaces and ground surfaces) as a highly structured three-dimensional luminance field made up of reflecting and transmitting structures acting as lighted and lighting mediums.

The reflected light from neighbouring structures, particularly under clear or partly cloudy sky conditions, can represent an important source of illumination within a building. The light reflected by building facades and other external surfaces can be considered as illumination generated by inter-reflected light between facades (Li et al., 2010).

The width of the streets, the height of the buildings and the reflectance of the opposing façade are factors, which determine the level of daylight that can be redistributed to a space within a building. Changes to façade design can significantly affect daylight distribution in an urban canyon. Baker et al. (1993) categorised the reflectance of buildings into three groups, including buildings with high reflectance ($\rho > 85\%$), medium reflectance ($60\% < \rho < 85\%$) and low reflectance ($\rho < 60\%$), based on the configuration of a building's facade and the nature of it surfaces.

4.4.2.3 Overshadowing

The quantity and quality of daylight inside a space can be diminished if obstructing buildings are large in relation to their distance from the facade. The shading effect due to the obstruction by surrounding building is more pronounced in cities with dense urban blocks separated by relatively narrow streets. The level of shading created by buildings on the opposite side of the street is an important factor that determines the level of natural illuminance in a room, as well as the area of the sky that is visible to the occupants inside the room (Littlefair, 2011; Li et al., 2006). The amount of daylight that enters a space with a substantial obstruction opposite, when there is no light reaching the space from around the side of the obstruction, is proportional to the angle of sky visible ($\theta_{\text{sky}}$), measured from the centre of the window (Figure 4.5). The angle between the top of the window and the top of the obstruction from the centre of the window determines the visible area of the sky. Hence, the taller and nearer the obstruction, the less light is received in the room through the window. If $\theta_{\text{sky}}$ is greater than 65° then there is usually
adequate amount of daylight reaching the room and if the maximum angle of $\theta_{\text{sky}}$ is 90°, it means there are no obstructions in front of the façade (Littlefair, 2011). Due to overshadowing by neighbouring structures, especially in an urban area, in some instances shading is not necessary to provide protection from direct sunlight radiation, because neighbouring buildings can shade parts of the facade (Knaack et al., 2007).

It is important to consider the obstructions from the surroundings, especially in hot climates, to ensure not only adequate reception of daylight, but also to avoid overheating of interior spaces. In cities in hot climatic regions, buildings are often constructed close to each other. The obstructions of urban surroundings suppress the direct solar component during some or all hours of the day. Thus, the shading effect from nearby buildings can be significant and reflectance of the surrounding facades can be a substantial source of interior lighting in a building (Munoz, Esquivias, Moreno, Acosta, & Navarro, 2014). However, as discussed in Chapter two, the building regulations in Abuja state that for natural light and ventilation “the minimum set back between two buildings shall not be less than the mean of the sum of the height of the buildings opposite or adjacent each other” (AMMC, 2007, p. 69). The implementation of these regulations creates many open spaces between residential buildings in Abuja, thus, limiting the possibility of overshadowing in favour of natural light and ventilation.

4.4.3 THE BUILDING (LEVEL III)

The internal spaces and planning of a building is interrelated to the form of the building. The possible depth of daylight penetration indoors is related to the depth of the building plan, the floor height and the
size of the external façade area. Thus, the dimensions of the building, in both plan and section, have fundamental implications for the degree to which the building can be daylit (Baker & Steemers, 2002). The following sets of variables are often given in the literature as the main variables that influence the available daylight at the building level:

- Building shape,
- Facade orientation,
- Wall shading devices,
- Roof apertures.

4.4.3.1 BUILDING SHAPE

Daylight design and building design can merge to certain degrees, when consideration of daylighting becomes more of a generating factor for the overall design and the daylighting design becomes part of the architecture. Subsequently, different organisations of building floor spaces can be developed in response to different daylighting needs (IEA, 2000). A key parameter of daylighting is the shape of the building. The building shape determines the amount of surface exposed to the external environment. As discussed previously in section 3.4.3.2, the form of a building can be determined by using the compactness ratio. Compact building forms provide material and energy savings, as well as limit heat gain or loss (Gratia & De Herde, 2003). However, deep plan buildings are characterized by a smaller surface-to-volume ratio, which may result in a large portion of the floor area being far from perimeter daylighting. An elongated building form, with more areas close to the perimeter, can optimise daylighting and ventilation. While this may compromise the thermal performance of the building, the savings achieved by daylighting in a building with less depth can offset the factor of heat gain/loss (Lechner, 2014).

Figure 4.6 illustrates the pattern of daylight penetration, for a space with a 100% window to wall ratio on the south facade, with a 3m ceiling height and 80% interior reflectance. The simulation was created for a location in Abuja, Nigeria, at 12 noon, on August 15th, using uniformly cloudy sky conditions prevalent during the rainy season. The figure shows that a building with a narrow depth generally has a greater percentage of daylit area than a building with a deeper perimeter to core distance. Beyond the
requirements of illuminance on a working plane or general brightness, the depth of a space has a significant influence on visual comfort.

![Pattern of daylight penetration for spaces with different plan depths](image)

**Figure 4.6. Pattern of daylight penetration for spaces with different plan depths**

The relationship between the brightness at the window and the opposite wall is particularly important. The human eye can only adjust to the brightest surfaces in its visual field; thus, a space that is bright at the perimeter and substantially darker at the back can feel like a cave, even when electrically illuminated at common interior light levels. This psychological effect of the extreme contrast is common in deep buildings that are over-glazed at the perimeter (Fontoynont, 2002).
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There is a number of building plan arrangements that are used by designers to improve the daylighting conditions for buildings with deep floor plans. Spaces in buildings can either be daylit through windows or by a combination of both sidelighting and toplighting. A number of design solutions, including courtyards, galleria, atria and lightwells, which are common architectural devices, can be used to provide daylight from above to deep-plan buildings (Baker & Steemers, 2002). These interior light spaces take advantage of the sky component and the reflected light to illuminate spaces within the building (Du & Sharples, 2011). Courtyard spaces are enclosed by the walls of one or several buildings and are open at the top, sometimes in one direction to the external environment. Atria are spaces enclosed by the walls of a building and covered at the top by a translucent or transparent material. Lightwells are toplit spaces, similar to atria; however, the space is not enclosed by walls from the surrounding spaces. In lightwells, the open spaces between the floors means there are virtually no reflecting walls. Gallerias are spaces covered by a translucent or transparent material at the top that are open on two sides to the exterior (Baker et al., 1993). In all four approaches described, the parameters which determine the daylight contribution from within the internal lit space to the adjacent spaces are:

- The reflectance of the glazed top area (if any is applied),
- The volume of the space, particularly the height (above the room being considered) to width ratio,
- The average reflectance of the enclosing walls and/or floor, and
- The obstruction of light by other objects within the space.

In addition to the advantages interior light spaces provide for daylighting schemes, they can also help to improve the thermal performance of a building (as discussed in Chapter three). In traditional dwellings in several parts of Nigeria, courtyards were a common part of the dwellings’ design. These internal spaces where not only used to illuminate adjacent rooms, but also used as living spaces, in which daily visual tasks could be performed. The deep verandas around the courtyards were also used as living spaces (Dmochowski, 1990b). The inclusion of courtyard spaces in the design of contemporary buildings, especially in urban areas, is not common.
4.4.3.2 Facade Orientation

The level of direct light received by a building facade depends on the orientation angle of the building (Fang et al., 2011). The orientation of a building is usually determined by identifying the direction of the main facade or facades. The majority of the windows are usually positioned in the main facades. Therefore, the orientation of the main facades is as important for daylighting as it is for thermal comfort (Baker & Steemers, 2002). The orientation of facades also influences other parameters, such as shading. Thus, it is important to optimise the orientation of a building for various shape factors with the objective of optimising the available daylight and controlling solar gain (Pacheco et al., 2012). Daylight availability strongly depends not only on the latitude, but also on a building's facade orientation, because each orientation will require a different design emphasis. Regardless of the climate, it is more advantageous for the main facades to be orientated north and south, rather than east or west, because the sun is at a low angle in the sky in the east and west around sunrise and sunset. While orientating facades east and west might lead to greater daylight penetration in the building around early morning and late afternoon, it is difficult to shade and almost impossible if a view is to be maintained. On the other hand, south-facing facades can be shaded using overhangs, because of the typically high altitude angle of the sun in the southern sky (Baker & Steemers, 2002), especially in tropical regions like Nigeria. In Abuja, north-facing windows will only receive direct sunlight during the rainy season, when the intensity of solar radiation is reduced due to the increased cloud cover (as discussed and illustrated in Chapter two).

It is well known that well-orientated buildings maximize daylighting through building facades and reduce the need for artificial lighting. In passive solar architectural concepts, solar gains are controlled by the orientation and the application of shading systems as a function of the sun's position (IEA, 2000).

4.4.3.3 Wall Shading Devices

The design decisions that affect daylighting in a building are not only determined by the characteristics of the apertures, but also by the design of the building itself. In addition to elements of the building form, such as atria and courtyards, architectural elements, including verandas, porticos, porches, balconies and overhangs are common environmental controls that have a significant impact on the form and aesthetics of a building and its internal daylighting quality (Lechner, 2014). Buildings can be constructed with roofs
that are extended outwards to act as overhangs over windows and walls. The overhangs can be extended further to create intermediate/transitional light spaces, which can also act or serve as living spaces in certain buildings (Singh et al., 2011). These extensions of the building’s form can be classified, based on the design and materials used in construction and dimensions. The dimensions of an intermediate light space created can determine the way it is used, either as a transitional space (corridors, overhangs, walkways) or as an intermediate living space (verandas, porches, balconies). Using these components as a part of building facade configuration can have a significant effect on the amount of natural light available in the internal spaces (Baker et al., 1993; Maragno & Roura, 2010).

The use of large roof overhangs and verandas is a common part of the vernacular architecture in various tropical and sub-tropical regions around the world (Kim et al., 2012; Singh et al., 2011; Maragno & Roara, 2010). In Nigerian traditional architecture, particularly in southern regions of the country, verandas were used as intermediate living spaces within traditional courtyard houses that separated the external courtyard from the internal rooms. The use of verandas as a part of the external facade configuration became more common around the time of colonisation in the 19th century (Osasona & Hyland, 2006; Prucnal-Ogunsote, 2001). As discussed in Chapter two, verandas and balconies are still part of the contemporary architectural design practice in Nigeria.

4.4.3.4 Roof Apertures

The top floors of multi-storey buildings and single-storey buildings have no constraint on plan depth, because they can be daylit through the surface area of the roof. This is usually referred to as zenithal daylighting. Although the toplight glazed openings are normally distributed over a horizontal surface of the building envelope, glazed apertures are not always horizontal and may be inclined or vertical, with specific orientation to encourage or avoid solar gain (Baker & Steemers, 2002). There are various configurations of zenithal daylighting components, including monitor roof, north-light roof or saw-tooth roof, skylight and dome (Baker et al., 1993). Zenithal daylighting components often improve the level of natural illuminance in a space and also allow ventilation, but do not necessarily provide a view. The roof of a building is usually heated by solar radiation from sunrise to sunset, and with lack of proper shading, this can lead to excessive solar gain and glare problems (Perez-Garcia & De Luis, 2004).
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Roof apertures are not a common architectural feature in traditional or contemporary Nigerian residential buildings; however, they can be found in some public buildings in the country (Figure 4.7). Historically roof-lighting concepts for rooms have been used in high latitude regions with predominantly cloudy skies. However, they are often excluded from the design of residential buildings in tropical climates, because direct sunlight and the associated high sky luminance will most likely lead to solar gain and visual discomfort (glare problems) (IEA, 2000).

**Figure 4.7** Left: Ceiling of the central mosque, Abuja, Nigeria. Right: Shehu Musa Yar’adua centre features a screened glass dome (Abdulkareem, 2013)

4.4.4 The room (level IV)

The physical and geometrical properties of the room and the apertures influence the amount of daylight entering the room and the pattern of its distribution (IEA, 2000). Once the natural light enters the room, the surfaces inside the room act as secondary sources of illumination by reflecting light. The following sets of variables are often given or described in the literature as the main variables that influence the quantity and quality of daylight at the room level:

- Room window-plan/layout,
- Orientation of windows,
- Window proportions,
- Fenestration factor,
- Window to wall ratio,
- Reflectance of room surfaces,
- Shading strategies and glare control.
4.4.4.1 ROOM WINDOW-PLAN/LAYOUT

In general, any space can be daylit using side-lighting (vertical apertures), top-lighting (horizontal apertures) or angled lighting (inclined apertures). However, the use of vertical openings in the wall (side-lighting) is the most common way of introducing daylighting into a room (Baker & Steemers, 2002). Although roof lights are effective sources of daylight that are exposed to high incidents of sunlight, the opportunities to use roof-lighting are limited, because it can only be introduced directly through the roof on the top floor in buildings. Moreover, for dwellings and other buildings with relatively less visual requirements, the application of complex and advanced daylighting systems is usually not appropriate. The proper use of a window as a side-lighting aperture for a room has a strong influence on the distribution and level of daylight. Hence, it can greatly improve the visual aspect of the internal environment (IEA, 2000).

Windows can be used unilaterally, bilaterally, multilaterally or a completely glazed facade can be applied to provide daylighting in a room. In a unilaterally daylit room, the daylight distribution is not uniform and declines the further away one moves from the position of the window (Baker & Steemers, 2002). In high latitude regions, it is a commonly accepted theory that a sufficient amount of daylight can penetrate a room to a distance about twice the height of the window head from the floor in that room (Figure 4.8) (Kollmann & Schulz, 2006).

![Figure 4.8 Illustration of daylight penetration rule for spaces in northern hemisphere](image)

The ability of a window in a single facade to distribute daylight to deep spaces is limited (especially under overcast sky conditions). Thus, bilateral and multilateral lighting can be applied for rooms with greater depths. The use of bilateral and multilateral lighting is dependent on the building’s form and the location of the room within the building (IEA, 2010). In a bilateral daylighting scheme, the windows are located on
opposite walls of a room to create two primary lighting zones. A common design strategy involving bilateral daylighting is the combination of a window that fulfils multiple functions (such as, external view, illumination and ventilation) for a large area of the floor space with a secondary window facing an atrium or courtyard. In a multilateral daylighting scheme, the windows are located on non-opposing walls of a room that create three or more primary lighting zones. A multilaterally daylit room is often located at the corners of buildings. Daylight entering a room from more than one direction produces less glare than daylight from a single source. Furthermore, a more even distribution of light results in less contrast in the room and reduces the impression of dark corners. A completely glazed wall area can also be applied as a daylighting design solution to create a larger zone of high illuminance than is usually possible using the other schemes. In this instance, two primary lighting zones are created (IEA, 2010). Although windows are often the only type of apertures in residential buildings in Nigeria, there are no recommendations or standards about the depth of rooms in the Nigerian building codes.

The location of a window in a wall can also be described based on its position along the height or width of a wall. Along the height of the wall, the window position can be described as a high (window sill height more than 1.6m above the room floor level), intermediate (window sill height between 0.75m and 1.6m) or low window (window sill height less than 0.75m above the room floor). Alternatively, windows can also be classified as central, lateral or as corner windows, depending on the position along the wall width (Baker & Steemers, 2002; Baker et al., 1993). Raising the window head height can improve both the amount of daylight entering a room and its distribution pattern.

In tropical regions, a number of design options can be adopted to limit solar gain and optimise the availability of daylight for performance of tasks. One suitable arrangement is to place the window high, with a sill that is above eye level. Thereby, admitting reflected light to the ceiling. If the ceiling colour is bright, this approach can admit an adequate amount of diffused light to the interior space through a relatively smaller window. Vertical strip windows at the corner of the room can also be used to allow diffused light penetrate into a space by being reflected off an internal wall (Koenigsberger et al., 1974). However, this approach can limit the view out.
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4.4.4.2 ORIENTATION OF WINDOWS

The orientation of windows has an impact on the amount of sunlight and skylight that penetrates a space. The sun’s path at a location can have great influence on natural illumination, and the orientation of windows can have an effect on the visual, as well as the thermal comfort of occupants inside a space. In general, a south-facing window will receive more sunlight than a north-facing window. East-facing and west-facing windows will receive sunlight only at certain times of the day (Littlefair, 2011). Based on these characteristics, it is possible to categorise window orientation as follows:

- East and West facing windows,
- North facing windows,
- South facing windows.

In temperate regions, dwellings without a main window wall within 90° of due south is likely to be perceived as insufficiently daylit (especially during the winter months), whereas the orientation of main windows due south in tropical climates will likely lead to visual problems, such as glare and thermal discomfort (Littlefair, 2011; Koenigsberger et al., 1974).

![Figure 4.9 Illustration of the sun’s path over Abuja near the winter solstice (15th December), equinox (March 15th) and summer (June 15th)]

4.4.4.3 WINDOW PROPORTION

Shape: as a design variable, the shape of the window can be described based on the relationship between the width and the height. Thus, the window shape could be classified as a vertical window, a horizontal window or an intermediate window. Window shape has a direct impact on the distribution of daylight within an interior. In general, a vertical window on a wall with a higher window head height will provide better distribution of daylight to the back of a room than a horizontal window of the same size (Figure 4.10). This is due to the fact that the height of the window from the finished floor determines the depth
of daylight penetration (Baker & Steemers, 2002), as described in section 3.5.4.1. A horizontal window could be placed at a higher position on a wall to allow greater penetration of daylight, however, this would diminish the aspect of a view.

![Illustration of the daylight penetration rule for vertical and horizontal windows](image)

Figure 4.10 Illustration of the daylight penetration rule for vertical and horizontal windows

Size: for an efficient visual performance of tasks, the size of the aperture should be determined by the level of internal illumination required in the space and in relation to the sky conditions prevalent in the region. Design methods for adequate daylighting in regions with typically clear and partly cloudy sky conditions differ substantially from those applicable for regions with predominantly overcast sky conditions (IEA, 2010). Kollmann and Shulz (2006) suggest a window area that is equal to around 30% of the floor area, as the minimum size required for residential spaces in temperate regions.

Lukman, Ibrahim, and Hayman (2010) observed that rules for adequate daylighting based on the relationship between the window area and the floor area were well established in Europe and North America. They also found that these rules were inappropriate for tropical regions and that there were less well established rules for tropical regions. A study by Santiago (2011) investigated the suitability of using guidelines recommended for achieving adequate illumination in the United Kingdom for the tropical climate of Santa Cruz de la Sierra, Bolivia. A comparative analysis was carried out using computer
simulations to model sidelit rooms with varying window sizes. The study findings suggested that the
guidelines for a minimum window area in the United Kingdom were of greater proportion than required
for daylighting in the tropical region.

Traditional residential buildings in Nigeria have had relatively small rectangular openings for the
penetration of daylight into rooms. As stated before, most of the tasks, which required higher levels of
illuminance and tasks usually associated with indoor rooms today, including kitchens and living rooms,
were carried out outdoors or in open shaded areas (Dmochowski, 1990a; 1990b; 1990c). The idea of
outdoor living spaces is no longer common in contemporary Nigerian residential architecture, particularly
in urban areas. Yet, there are no standards concerning window design for maximising the use of natural
light when eliminating the risk of overheating. A key objective of this study is to provide guidelines that
can assist designers in maximising the role of daylight inside residential buildings in Abuja. The findings of
this research can also be beneficial to residential buildings situated in similar tropical regions.

4.4.4.4 Fenestration Factor

As previously mentioned, the size of the window plays an important role regarding the quantity of natural
light reaching a room. The ratio of total window area to the room floor area, which is commonly referred
to as the fenestration factor or window to floor ratio, is a useful parameter for determining the
appropriate window size for an internal volume of space in order to achieve visual comfort. For
daylighting purposes, the fenestration factor should be considered in relation to the planes on which
lighting is required and the tasks that are carried out in the room (Baker & Steemers, 1996).

For all window types and all geographic locations, increasing the fenestration factor increases the level
of illuminance indoors, thereby reducing the need for artificial lighting (Kraftie et al., 2005). According to
Baker et al. (1993), the level of illuminance provided by varying fenestration factors can be classified as
follows:

- Fenestration factor lower than 1% - illumination is very low,
- Fenestration factor lower than 4% - illumination is low,
- Fenestration factor between 4% and 10% - illumination is medium,
Fenestration factor between 10% an 25% - illumination is high,

Fenestration factor above 25% - illumination is very high.

It is worth noting that this classification was developed for countries in Europe that experience relatively lower levels of solar radiation than a tropical country like Nigeria, yet, the building standards for Nigeria recommend a 10% minimum fenestration factor (FRN, 2006). The recommendation suggests that a high level of illumination is required in Nigerian buildings. However, having higher fenestration factors in buildings located under Abuja’s clear sky conditions will likely have a negative impact on thermal conditions indoors. Accordingly, the optimisation of the fenestration factor in residential buildings in the studied context is investigated further in Chapters six and seven.

4.4.4.5 WINDOW TO WALL RATIO

Although larger windows will lead to higher levels of daylighting illuminance, the larger window to wall ratio does not substantially improve daylight distribution. As the size of the window area increases, the daylight illuminance in a space is improved, but the effect diminishes disproportionately at distances further away from the window. A room’s depth has a stronger influence on the penetration of daylight than the window area (Chou, 2004). As shown in figure 4.5, even with a 100% window to wall ratio, large parts of a room with a deep plan can still have low light levels. Besides simple horizontal illuminance on a working plane, the relationship between the brightness in areas around the windows and the areas furthest from the windows is vital (Fontoyont, 2002). As mentioned before, the human eye tends to adjust to the brightest surfaces in its visual field, thus, a space that is bright at the perimeter and darker towards the interior can feel like a cave. This ‘cave effect’ is common in buildings with deep floor plans, especially when they are over-glazed at the perimeter (Meek & Van Den Wymelenberg, 2015). Therefore, in order to improve the visual conditions in a sidelit space using daylighting, the window to wall ratio should be considered in association with other parameters, including the depth of the plan and the fenestration factor.
4.4.4.6 Reflectance of room surfaces

The reflectance of surfaces in a room (walls, floor, ceiling, furniture, etc.) has an influence on how occupants perceive and experience the space. Beyond the architectural and aesthetic value of influencing the appearance of a space, surface reflectance determines the level of illumination in a room (Hagenlocher, 2009). The average daylight factor of a room changes approximately linearly with changes in mean reflectance. When light falls on a surface, it can be reflected, transmitted and/or absorbed. The ratio of light reflected to light absorbed is called the reflectance ($\rho$) and is often expressed as a percentage or fraction. The ratio of light transmitted to incident energy is called transmittance, $T$. In both cases, a part of the energy from the light is absorbed. The ratio of the energy absorbed by the surface to the incident energy is called absorptance, $\alpha$.

The internal surface might be illuminated either by light reflected from external surfaces or by direct skylight. In addition to the external reflected component, light reflected by surfaces within the room also contributes to the overall illumination value. An important characteristic of internally reflected components is that it is often fairly uniform in all areas of the room (Baker & Steemers, 2002).

The way in which light reflected by opaque surfaces illuminates a room depends on the reflectance and texture of the finished surface, as well as the angle of incidence of light on the surface.

**Surface reflectance:** The ratio of light absorbed by a surface to the light reflected by the surface determines the intensity of the reflected light. In a room with a single window, the wall opposite the window contributes to the amount of daylight in the room depending on its reflectance ($\rho$). Interreflection between surfaces usually occurs in a room and contributes to the overall illuminance of the space. According to Tregenza and Wilson (2011, p. 48), when there is inter-reflection between surfaces, the final illuminance becomes greater as the reflection values of the surfaces increase and the distribution of light becomes more uniform within a space.

**Surface texture:** The way a surface diffuses light influences the distribution of light in a room. A smooth mirror-like finish merely redirects the beam of light. A mat finish (such as matte paint) with a more
diffusing surface scatters the light. Therefore, the properties of a surface with regards to its effects on the distribution of natural light are important.

Three parameters can be used to describe most common surfaces:

- Diffused reflectance allows light to be reflected at many angles;
- Specular reflectance allows light to be reflected at a single angle, thus, the exact image of the source can be seen;
- Dispersed or scatter reflectance (narrow or wide), with a narrow scatter (low dispersion) creating the perception of a bright spot corresponding to the proportions of the light source, and a wide scatter (high dispersion) reflecting light in a non-uniform manner and with the bright spot not being seen.

Surfaces commonly used in buildings exhibit these characteristics to a varying degree under different daylighting conditions (Baker et al., 1993).

**Angle of incidence of light:** The appearance of smooth finishes becomes glossier as the angle of incidence increases and the beam of light becomes nearly parallel with the surface plane. The opposite effect occurs with a mat surface; light falling at a larger angle enhances the textured appearance of the material on the surface plane and the effect becomes greater when the angle between the light beam and the line of view is increased (Tregenza & Wilson, 2011).
In tropical regions, such as Nigeria, which often have intense solar radiation, due to the prevailing sky conditions, it is crucial in daylighting design to exclude the penetration of direct sunlight, as it would most likely lead to excessive heat gain. The skylight is bright enough to provide sufficient illumination, but could also create glare problems (Koenigberger et al., 1974). Therefore, it is important that daylighting design in such regions maximises the use of reflectance of surfaces to reduce visual discomfort and improve visual performance. Moreover, more evenly distributed levels of illuminance, as a result of optimisation of the reflectance, diminishes the contrast in brightness between the areas of the window and the walls, which reduces glare problems (Wong & Istiadij, 2004).

4.4.4.7 Shading strategies and glare control

Optimising daylight is not merely achieved by increasing illumination. In designing a good visual environment, the way internal areas are illuminated is usually more important than the level of lighting (Baker et al., 1993). The principal aim of daylighting design is to maximise daylight illuminance while avoiding glare. To achieve this aim, a system of control is usually required. Daylighting design without shading strategy or sunlight control strategies is impractical, particularly for tropical regions where solar gain is a major concern (Chou, 2004).

There are several types of shading devices that can be used to control daylighting in a space, ranging from venetian blinds to sophisticated light guiding systems and laser cut panels. Generally, shading devices can be classified as being either fixed or operable. Fixed shading devices cannot be adjusted by users, but they usually require less management and maintenance. Operable shading devices can be more effective, as potentially greater control can be applied either by the users or automatically to respond to the transmission of both sunlight and excessive daylight (Lim & Kim, 2010; Edmonds & Greenup, 2002).

Shading devices can also be applied externally or internally around the apertures or be integrated within the glazing (for example, laser cut panels) (Hirning et al., 2010; Laar, 2001). In tropical regions, fixed external shading devices (either attached to the building facade or as part of the skin itself) can be one of the most effective passive design choices, as they can block the solar radiation before it reaches the indoor environment (Wong & Istiadij, 2004). Besides the consideration of daylighting and shading,
number of other factors, such as maintenance, running cost and available workmanship, have to be considered by designers, before attempting to use more sophisticated daylighting control systems (Laar & Grimme, 2002).

Using computer simulation analysis, Wong and Istiadji (2004) have investigated the effects of seven different shading devices on the internal illuminance in spaces in a residential building in Singapore (tropical region). They found that most of the shading devices admitted illuminance levels higher than 300 lux, even when the shading device obstructed most of the direct light. On the other hand, Dahlan et al. (2008), as well as Koranteng and Simons (2012) concluded in their respective studies of student hostels in Malaysia and Ghana that the use of deep set balconies in the design of the hostel accommodation for both tropical regions resulted in insufficient lighting levels.

According to Fry and Drew (1964), the design of deep set verandas on all sides of houses was often adopted to exclude the sun's heat, glare and rain from penetrating internal spaces in Nigeria and other west African countries during the colonial regime. However, the system resulted in such gloomy indoor conditions that occupants preferred to carry out their daily task on the verandas.

Baker et al. (1993, pp. 5.18-5.26) categorised the various devices that can be used to control and/or admit daylight into a building into five groups including, solar obstructors, separator surfaces, rigid screens, flexible screens and solar filters (see Figure 4.12). A brief description of their characteristics with a reference to their use in Nigeria’s contemporary architecture is given in appendix 4.
4.5 CONCLUSION

From the literature, it is evident that good daylighting can have a positive impact on the way occupants perceive a space and reduce the energy use in buildings. A number of design parameters, mainly associated with the transparent façade areas of a building, have to be considered in relation to the prevalent climatic conditions in a region in order to improve the visual performance of a building. As regarding the parameters discussed in the previous chapter, these parameters are fundamental to
passive building design and can also be the underpinning of a framework for evaluating the visual performance of the buildings. Likewise, the parameters for visual performance, which were discussed in this chapter, have been structured into four levels, using a framework similar to that used in the previous chapter, but also includes elements and parameters adapted from Baker et al. (1993).

The parameters related to the natural environment level include consideration of the solar radiation and the sky conditions at a location. While the existing urban environment can have a significant impact on the natural light available in a building, it is clear that the current residential building development standards and approaches in Abuja limit the importance of these parameters. Also, the Nigerian building regulations do not provide satisfactory guidelines concerning the daylighting design of buildings. The fenestration factor is one of the few design parameters stated in the Nigerian codes and the recommended percentage value for the fenestration factor appears to be vague. Thus, the main parameters that influence the quantity and quality of daylighting in rooms have been covered in more detail in this chapter.

Due to the heat energy that accompanies light from the sun, designing for adequate daylighting should be examined in relation to the requirements for improving occupants’ thermal comfort. Following the review carried out in this chapter, the parameters related to visual performance of buildings and the variables that are considered within the framework of the study are listed below in Table 4.1. Furthermore, Table 4.2 illustrates the connections between the main thermal performance parameters and the main visual performance parameters. Both parameters related to the visual performance and those concerned with the thermal performance of buildings listed in the table and highlighted in grey are then used as a basis for assessing the variation in daylight conditions and the thermal environment of eight selected housing types, representing Abuja’s current residential architecture.
Table 4.1 List of parameters and variables that influence the visual performance of buildings

<table>
<thead>
<tr>
<th>Level</th>
<th>Parameters and factors</th>
<th>Variables</th>
<th>Nomenclature</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Climate</strong></td>
<td>Solar radiation</td>
<td>Global horizontal illumination</td>
<td>I</td>
<td>Lux</td>
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<td></td>
<td>Direct normal illumination</td>
<td>I&lt;sub&gt;b&lt;/sub&gt;</td>
<td>Lux</td>
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<td></td>
<td>Solar altitude angle</td>
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<td></td>
<td>Solar azimuth angle</td>
<td>ψ</td>
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<td></td>
<td>Solar zenith angle</td>
<td>ϕ</td>
<td>°</td>
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<tr>
<td></td>
<td>Sky condition (cloud cover)</td>
<td>&lt;30%, 30-70%, &gt;70%</td>
<td>K&lt;sub&gt;d&lt;/sub&gt;</td>
<td>%</td>
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<tr>
<td><strong>The built environment</strong></td>
<td>Size and orientation of external obstructions</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>Reflectance of external surfaces</td>
<td>&lt;60%, 60-85%, &gt;85%</td>
<td>ρ</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Angle of sky visible</td>
<td>θ&lt;sub&gt;sky&lt;/sub&gt;</td>
<td>°</td>
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<tr>
<td><strong>The building</strong></td>
<td>Orientation</td>
<td>North, south, east, west, others</td>
<td>θ</td>
<td>°</td>
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<td></td>
<td>Compactness ratio</td>
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<td></td>
<td>Wall shading elements</td>
<td>Porticos, verandah, overhangs, fins</td>
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<td></td>
<td>Wall shading element proportions</td>
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<tr>
<td><strong>The room</strong></td>
<td>Façade orientation</td>
<td>North, south, east, west, others</td>
<td>θ</td>
<td>°</td>
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<td></td>
<td>Room dimensions</td>
<td>Width, depth, height</td>
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<tr>
<td></td>
<td>Window position in wall</td>
<td>Central, corner, high, low</td>
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<td></td>
<td>Window shape</td>
<td>Horizontal, vertical, intermediate</td>
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<td></td>
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<td>North, south, east, west, others</td>
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<td>Window dimensions</td>
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<td>Window layout and location</td>
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<td>Shutters, overhangs, fins, egg-</td>
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<td></td>
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<td>crates, sills, awnings, louvers,</td>
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<td>Window shading element proportions</td>
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<td></td>
<td>Fenestration factor</td>
<td>FF</td>
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<td></td>
<td>Window to wall ratio</td>
<td>WWR</td>
<td>%</td>
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<tr>
<td></td>
<td>Reflectance of internal surfaces</td>
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<td></td>
<td>Texture of internal surfaces</td>
<td>Diffused, specular, and dispersed</td>
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<td>Glazing visible transmittance</td>
<td>Transmittance</td>
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<td>Reflectance</td>
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<td>Absorptance</td>
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<td></td>
<td></td>
<td>Translucent glass, coloured glass, glass with thermocromatic film</td>
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</tbody>
</table>
Table 4.2 List of parameters and variables that influence the thermal and visual performance of buildings

<table>
<thead>
<tr>
<th>Level</th>
<th>Thermal/Visual performance parameters and factors</th>
<th>Parameters and factors</th>
<th>Variables</th>
<th>Parameters and factors</th>
<th>Variables</th>
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<td>Direct (beam) irradiance</td>
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<td>Direct normal illumination</td>
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<td>Diffused irradiance</td>
<td>Solar altitude angle</td>
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<td>Solar altitude angle</td>
<td>Solar azimuth angle</td>
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<td>Solar azimuth angle</td>
<td>Solar zenith angle</td>
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<tr>
<td></td>
<td>Air temperature</td>
<td>Sky condition (cloud cover)</td>
<td>&lt;30%, 30-70%, &gt;70%</td>
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<tr>
<td></td>
<td>Relative humidity</td>
<td>Reflectance</td>
<td>&lt;60%, 60-85%, &gt;85%</td>
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<tr>
<td></td>
<td>Air velocity</td>
<td>Angle of sky visible</td>
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<td>The built environment</td>
<td><img src="https://via.placeholder.com/150" alt="Table" /></td>
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<td>Reflectance</td>
<td>Properties of external surfaces</td>
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<td></td>
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<td>Absorptance</td>
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<td>Emittance</td>
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<td></td>
<td></td>
<td>Specific heat capacity</td>
<td></td>
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<tr>
<td>The building</td>
<td>Orientation</td>
<td>Orientation</td>
<td>North, south, east, west, others</td>
<td>North, south, east, west, others</td>
<td></td>
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<tr>
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<td>Compactness ratio</td>
<td>Compactness ratio</td>
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<td></td>
<td>Wall shading elements</td>
<td>Porticos, verandah, overhangs, fins</td>
<td>Wall shading elements</td>
<td>Porticos, verandah, overhangs, fins</td>
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<tr>
<td></td>
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<td>Width, depth, height</td>
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<td>Width, depth, height</td>
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<tr>
<td></td>
<td>External surface area</td>
<td>Window position in wall</td>
<td>Central, corner, high, low</td>
<td></td>
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<tr>
<td></td>
<td>Internal volume</td>
<td>Window shape</td>
<td>Horizontal, vertical, intermediate</td>
<td></td>
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<tr>
<td></td>
<td>Window orientation</td>
<td>Window orientation</td>
<td>North, south, east, west, others</td>
<td>North, south, east, west, others</td>
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<tr>
<td></td>
<td>Window dimensions</td>
<td>Window dimensions</td>
<td>Width, height</td>
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<tr>
<td></td>
<td>Window layout and location</td>
<td>Window layout and location</td>
<td>Unilateral, bilateral, multilateral</td>
<td></td>
<td></td>
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<td></td>
<td>Window shading elements</td>
<td>Shutters, overhangs, fins, egg-crates, sills, awnings, louvers, brise-soleil</td>
<td>Window shading elements</td>
<td>Shutters, overhangs, fins, egg-crates, sills, awnings, louvers, brise-soleil</td>
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<td>Window shading element proportions</td>
<td>Window shading element proportions</td>
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<td></td>
<td>Fenestration factor</td>
<td>Fenestration factor</td>
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<td></td>
<td>Window to wall ratio</td>
<td>Window to wall ratio</td>
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<tr>
<td>The room</td>
<td>Reflectance of external surfaces</td>
<td>Reflectance of internal surfaces</td>
<td></td>
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<td></td>
<td>Thermal transmittance of components of building envelope</td>
<td>Specific heat capacity</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Transmittance</td>
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<td></td>
<td>Absorptance</td>
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<td></td>
<td>Emittance</td>
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<td></td>
<td>Density</td>
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<td></td>
<td>Thickness</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Glazing type</td>
<td>Translucent glass, coloured glass, glass with thermochromatic film</td>
<td></td>
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</tr>
</tbody>
</table>
CHAPTER 5 - METHODOLOGY

5.1 INTRODUCTION

The design parameters discussed in Chapter three in relation to the influence of the climate, the built environment and the building envelope are presented as modifiers of the thermal conditions indoors. Likewise, the parameters influencing the daylighting conditions and visual comfort indoors are discussed in Chapter four. Nevertheless, the optimisation of thermal and visual conditions in residential buildings situated in tropical regions as Abuja’s require different design approaches to buildings located in temperate and cold climate regions (Batagarawa, 2011). Due the advent of its development in the 1980s and the governmental initiatives behind its creation, most of the current residential buildings developed for low and middle income groups in Abuja over the last three decades were part of government mass housing projects. The majority of these projects were primarily designed to conform to certain international aesthetic standards, which were easily and quickly produced and reproduced. Concerns about energy use and motivations for improving the energy efficiency of such dwellings were not common at the time of the development of the city housing sector, and thus basic passive design techniques were not actually considered in the design of such dwellings. This study investigates the thermal and visual performance of the housing types developed in Abuja since the 1980s many of which are still in use today as prototypes for low-income housing developments. The purpose of the investigation is to propose guidelines that can assist in improving indoor comfort conditions by integrating passive design principles which were not considered in the existing schemes.

The objectives of this chapter is to provide a framework for the investigation carried out in this study and validate the method and tools used for the investigation. The main content in the chapter is split into five sections. Firstly, section 5.2 presents a review of the conceptual framework of the research. The framework has been developed based on the literature on the studied context (Chapter two) and the review of the factors and parameters that effect building performance (as presented in the two previous chapters). Secondly, the information gathered from the fieldwork preceded the investigation of the performance of buildings in the study is presented in section 5.3. Thirdly, the criteria for the selection of
case study residential buildings established after the first phase of the fieldwork is discussed in section 5.4. General information about the selected case studies is also presented in this section. Fourthly, the simulation tool and procedure used to predict and analyse the performance of the case studies are discussed in section 5.5. Lastly, the output from the exercise used to validate the simulation tool is discussed in section 5.6.

5.2 CONCEPTUAL FRAMEWORK

The investigation is carried out using a quasi-experimental approach to examine selected parameters using simulations in a virtual environment as the primary evaluation tool. The primary difference between experimental and quasi-experimental research is the lack of random assignment in the latter. There are many natural settings in which researchers can introduce quasi-experimental design into data collection procedures even though full control over the assignment of experimental stimuli which makes a true experiment possible, is not conceivable. Quasi-experimental research designs typically allow researchers to control the assignment using some criteria instead of random assignment (DiNardo, 2008). This involves developing a framework based on the researcher’s knowledge of the research context, the available literature or data, and evidence from the study itself (Marshall, 1996).

The investigation in this study can be carried out solely as a quantitative research, assessing the impact of a several parameters on the thermal and visual performance of selected buildings, in order to derive a number of effective passive design parameters. However, the social and economic context of Nigeria are taking into account to derive practical and implementable design approaches based on the reviewed literature on passive design approaches for improving thermal and visual comfort.

5.2.1 PERFORMANCE EVALUATION MODELS

As stated previously, there are two widely accepted standard models for assessing the thermal comfortable conditions in a room: the Predictive Mean Vote – Predicted Percentage Dissatisfied model (PMV-PPD) and the Adaptive model.

The PMV-PPD approach (Fanger, 1972) is based on a steady-state energy balance of the human body. It can be used to predict occupants’ thermal sensation and comfort satisfaction as a function of parameters
related to the indoor environment including, internal air temperature, air velocity, relative humidity, and mean radiant temperature as well as the occupants’ activity (metabolic rate) and clothing. This approach can be used without any correlation with the external environmental conditions. However, it is less suitable for evaluating occupants comfort in naturally ventilated buildings, without mechanical cooling or heating systems and where occupants have the freedom to vary their behaviour and activity (Sicurella et al., 2012).

On the other hand, the adaptive model (Nicol & Humphreys, 1973) considers people’s interaction with the external and internal environment and allows a range of thermal comfort conditions which is wider than that deduced through the PMV-PPD steady-state model. The adaptive model is based on the rationale that the outdoor climate in a region has a significant influence on occupant’s indoor comfort because humans can adapt to different temperatures during different times of the year (Turner, 2011; de Dear & Brager, 2002). The adaptive hypothesis predicts that contextual factors, such as having access to environmental controls (like opening and closing window or adjusting shading devices), and past thermal history influence building occupants' thermal expectations and preferences (de Dear & Brager, 2002). Previous studies using this model have shown that occupants of naturally ventilated buildings accept and sometimes prefer a wider range of temperatures than occupants of air-conditioned buildings (Nicol et al., 2012). The adaptive model is primarily based on the correlation between the operative temperature and the running mean outdoor dry-bulb temperature measured over previous days. Therefore, the thermal comfort in free-running buildings can be assessed just as a function of the indoor operative temperature, neglecting all the other parameters accounted for in the PMV-PPD model. Notwithstanding, the adaptive model also takes the effect of metabolic rates and occupants freedom to adapt their clothing to the indoor and/or outdoor thermal conditions into account (Hoyt et al., 2013).

From the review of the problems in the power sector of Nigeria, and consideration of the rising cost of electrical energy the country (as discussed in Chapter two), it is evident that any model used for assessing thermal comfort in residential buildings in Abuja cannot be based on expectations that will be more appropriate for buildings with air-conditioning systems. Thus, the model used to define the thermal
comfort boundary in this study is the ASHRAE standard 55-2013 adaptive model for thermal comfort in naturally ventilated buildings (ASHRAE, 2013b).

The models for evaluating visual comfort are less standardised than that of thermal comfort. The EN Standard 15193 (2007) introduced an indicator (daylight dependent artificial lighting control) for evaluating energy consumption for lighting, which also includes the contribution of daylight (Tian & Su, 2014). This approach can be used to evaluate lighting control systems in connection with daylight, for energy savings. However, the daylight availability is still assessed through the calculation of the daylight factor which is a static approach that cannot be used to analyse the potential of daylighting dynamically (Sicurella et al., 2012). Many evaluations of daylight performance are made using greatly simplified ‘snap-shot’ or single-point-in-time methods that do not account for all the influences on daylight illumination levels nor the variation over time. Indeed, the most common method, the daylight factor calculation does not even include the contribution from direct sunlight, only skylight under the Commission Internationale de l’Eclairage (CIE) standard overcast sky distribution (Mardaljevic et al., 2011).

In this study, the Frequency of Visual Comfort (FVC) approach proposed by Sicurella et al. (2012) is used for evaluating visual comfort. The concept is similar to the ‘Useful Daylight Illuminance’ (UDI) indicator introduced by Mardaljevic and Nabil (2005). UDI is defined as the annual occurrence of illuminances that are within a range considered ‘useful’ by occupants (Mardaljevic et al., 2011). The main difference between the approaches is that Mardaljevic and Nabil (2005) model is based on spatial rendering of useful daylight illuminance which is fulfilled in every point of the calculation grid. On the other hand, Sicurella et al. (2012) work on an average daylight illuminance.

Daylight illuminance in the range 100 to 300 lux is considered effective either as the sole source of illumination or in conjunction with artificial lighting. Daylight illuminance in the range 300 to around 3,000 lux is often perceived either as desirable or at least tolerable. However, it is worth noting that these values are based on studies of non-residential buildings where glare on visual display devices can be a problem (Mardaljevic, 2006). In contrast tasks in the domestic setting are not limited to desks and display screens. Thus, it should be noted that there is considerable uncertainty regarding preferred upper limits for residential buildings (Mardaljevic et al., 2011). Moreover, based on the average daylight illuminance, the
compliance to 3000lux upper limit is not suitable since it would not avoid daylight illuminance levels that are too high in some parts of the room being evaluated.

The traditional architecture of the central region of Nigeria where Abuja is located favoured limiting solar heat gain through windows over allowing higher levels illuminance indoors. Even in urban areas people might be inclined to use outdoor spaces for visual tasks that require more light rather than creating larger apertures to enable them perform such tasks indoors. Thus, the upper limit and lower limit for preferred daylight illuminance used for this research are 500 lux (for performance of visual tasks of high contrast and small size) and 100 lux (for space where simple visual tasks are performed), as prescribed by the Illuminating Engineering Society of North America (IESNA, 2000) (Table 5.1). Although it is important to note that the upper limits of acceptability can be adjusted to a higher value depending on the actual use and type of activities taken place in a particular room; in this research visual comfort is achieved when the average daylight illuminance across the working plane in the room (0.75m above the finished floor) between 100lux and 500lux.

<table>
<thead>
<tr>
<th>Type of Activity</th>
<th>Illuminance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public spaces</td>
<td>30 lux</td>
</tr>
<tr>
<td>Simple orientation for short visits</td>
<td>50 lux</td>
</tr>
<tr>
<td>Working spaces where simple visual tasks are performed</td>
<td>100 lux</td>
</tr>
<tr>
<td>Performance of visual tasks of high contrast and large size</td>
<td>300 lux</td>
</tr>
<tr>
<td>Performance of visual tasks of high contrast and small size</td>
<td>500 lux</td>
</tr>
<tr>
<td>Performance of visual tasks of low contrast and small size</td>
<td>1000 lux</td>
</tr>
</tbody>
</table>

5.2.2 INDICATORS

The standards of comfort which are used in this study to evaluate the performance of residential buildings in Abuja are defined in the previous section. Additionally, an approach based on simple indicators calculated using a statistical method is adapted from Sicurella et al. (2012). The indicators selected are used for the simultaneous evaluation of the indoor thermal and visual comfort. The building environmental characteristics being investigated in this study are primarily related to the availability of natural light and the effects of different levels of heat. The indicators used to analyse the performance of buildings based on the key parameters for thermal and visual comfort are namely the operative
temperature and the level of illuminance. Thus, the statistical indicators used to measure and analyse the
frequency as well as the magnitude of discomfort (in accordance with the selected comfort models) are
based on the predicted operative temperatures and the levels of illuminance in the case study buildings.
These indicators include:

- The Hours of Thermal Discomfort (HTD)
- The Frequency of Thermal Discomfort (FTD)
- The Area Under Curve (AUC) for thermal discomfort (Intensity)
- The Hours of Visual discomfort (HVD)
- The Frequency of Visual Discomfort (FTD)
- The Area Under Curve (AUC) for visual discomfort (Intensity)

5.2.2.1 **Hours of Thermal Discomfort (HTD) and Frequency of Thermal Discomfort (FTD)**

Hours of thermal discomfort is a measure of hours within a given time period during which the indoor
thermal comfort conditions are not accomplished. Frequency of Thermal Discomfort (FTD) is the
percentage of time within a given period during which the indoor thermal comfort conditions are not
accomplished. The values for HTD and FTD can be delineated by defining the upper and lower limits of
the acceptable temperature range, $T_{\text{over}}$ and $T_{\text{under}}$ to determine $\text{HTD}_{\text{over}}$ or $\text{FTD}_{\text{over}}$ and $\text{HTD}_{\text{under}}$ or $\text{FTD}_{\text{under}}$
respectively. It can be assumed that thermal comfort is achieved when the operative temperature in a
room is greater than $T_{\text{under}}$ and less than $T_{\text{over}}$. If the operative temperature $T_o$ in a room is greater than
$T_{\text{over}}$ the occupants might suffer from hot sensation and if the operative temperature $T_o$ in a room is less
than $T_{\text{under}}$ the occupants might suffer from cold sensation.

The values for $T_{\text{over}}$ and $T_{\text{under}}$ is calculated in compliance with the adaptive thermal comfort criterion
specified in section 5.4 of the ASHRAE standard-55 (2013b). The upper and lower limits of the
temperature range acceptable for 80% of occupants in the buildings are determined using the following
equation (ASHRAE, 2013b, p. 12):

\[
\begin{align*}
\text{EQUATION 5.1 UPPER 80% ACCEPTABILITY LIMIT } (^\circ\text{C}) &= 0.31 \times T_{\text{PMA}} + 21.3 \\
\text{EQUATION 5.2 LOWER 80% ACCEPTABILITY LIMIT } (^\circ\text{C}) &= 0.31 \times T_{\text{PMA}} + 14.3
\end{align*}
\]

Where:
T_{pma} is the prevailing mean outdoor air temperature which is the arithmetic mean of all the mean daily outdoor air temperatures for no fewer than 7 and no more than 30 sequential days prior to the day in question.

Upper 80% acceptability limit = T_{over}

Lower 80% acceptability limit = T_{under}

It is worth noting that even though the standards also include a calculation for 90% acceptability for higher standards of thermal comfort, the 80% acceptability limits is the most appropriate one to use for typical applications (ASHRAE, 2013b, p. 34). In the present study the 80% acceptability limits calculated for each day is derived from the prevailing mean outdoor air temperature for 14 days prior to the day in question.

5.2.2.2 THE AREA UNDER THE CURVE (AUC) FOR THERMAL DISCOMFORT

The area under the curve for thermal discomfort or the intensity of thermal discomfort, is the time integral of the difference between the current operative temperature and the upper limit of comfort (T_{over}) or the lower limit of comfort (T_{under}) (Sicurella et al., 2013). The AUC can be calculated by estimating the area between the curve of the operative temperatures over a given time period and the upper limit of comfort (T_{over}) or the lower limit of comfort (T_{under}) as shown in figure 5.1.

5.2.2.3 HOURS OF VISUAL DISCOMFORT (HVD) AND FREQUENCY OF VISUAL DISCOMFORT (FVD)

Hours of visual discomfort is a measure of hours within a given time period during which the levels of illuminance in a space is considered excessive or insufficient. On the other hand, frequency of visual
discomfort (FTD) is the percentage of time within a given period during which the levels of illuminance in a space is considered excessive or insufficient. The values for HVD and FVD can be delineated by defining the upper and lower limits of the acceptable illuminance, \(E_{\text{over}}\) and \(E_{\text{under}}\) to determine \(\text{HVD}_{\text{over}}\) or \(\text{FVD}_{\text{over}}\) and \(\text{HVD}_{\text{under}}\) or \(\text{FVD}_{\text{under}}\) respectively.

In the present study only the period during the day when external daylight is sufficient to provide visual comfort will be considered (approximately 12 hours from 7 am till 6 pm in Abuja throughout the year).

A range for indoor visual comfort can be defined by delineating two values of daylight illuminance: the upper limit of acceptable illuminance (\(E_{\text{over}}\)) and the lower limit of acceptable illuminance (\(E_{\text{under}}\)). As previously stated the upper and lower limits defined in this study are 500 lux and 100 lux respectively. The concept behind the definition of the FVD is similar to the useful daylight illuminance model introduced by Mardaljevic and Nabil (2005). The main difference is that useful daylight illuminance criterion is based on spatial rendering of useful daylight illuminance and it should be fulfilled in every point of the calculation grid. On the other hand, the model adopted from Sicurella et al. (2012) uses average daylight illuminance. Thus, \(E_{\text{over}}\) is used to calculate \(\text{FVD}_{\text{over}}\) for the period of time during which the average illuminance in a room is above 500 lux and \(E_{\text{under}}\) is used to calculate \(\text{FVD}_{\text{under}}\) for the period of time during which the average illuminance in a room is below 100 lux. It can be assumed that visual comfort is achieved when the illuminance in a room is greater than \(E_{\text{under}}\) and less than \(E_{\text{over}}\).

5.2.2.4 The Area Under the Curve (AUC) for Visual Discomfort

The intensity of visual discomfort is used to deduce the magnitude of discomfort, it is defined as the time integral of the difference between the spatial average of the current daylight illuminance and the upper limit of visual comfort (\(E_{\text{over}}\)) or the lower limit of visual comfort (\(E_{\text{under}}\)). The intensity of visual discomfort is calculated by estimating the area between the curve of the changing daylight illuminance levels over a given time period and the upper limit of comfort (\(E_{\text{over}}\)) or the lower limit of comfort (\(E_{\text{under}}\)) plotted on a graph as shown in figure 5.2.

The rationale for adopting these indicators is the optimisation of building design parameters to provide appropriate balance between providing adequate levels of natural lighting and passive cooling.
5.2.3 ADDITIONAL MEASURES

In addition to the indicators of thermal and visual discomfort that are based on the predicted operative temperatures and illuminance levels, the hourly level of solar gain and the uniformity ratio of illuminance are used to further examine the thermal and visual conditions in the dwellings assessed in this study.

5.2.3.1 SOLAR GAIN

Solar gain, which is also known as passive solar gain or solar heat gain, refers to the increase in the temperature in a space, object or structure due to solar radiation. In buildings that often require significant levels of cooling, solar gain is especially troublesome because it is the largest and most variable source of heat gain the building will experience (Kotsy et al., 2009). While solar radiation can be transmitted through opaque objects as well as transparent objects, windows and other openings are generally the greatest direct source of solar radiation (ASHRAE, 2013a). In the study only the solar radiation transmitted by the glazing into the rooms is taken into account in the solar gain values calculated.

Solar gain through windows consists of two components including the directly transmitted solar radiation and the visible transmittance, which is the solar radiation weighted with respect to the response of the human eye to light (ASHRAE, 2013a). Thus, solar gain can also be useful for assessing the visual conditions in a room and the determinants of visual discomfort.
5.2.3.2 Uniformity Ratio
Although the average illuminance levels might be appropriate, an occupant’s satisfaction with the visual condition in a room can still be compromised if the lighting is not uniformly distributed across the room. As previously stated in Chapter four, the human eye can only adjust to the brightest surfaces in its visual field, thus a space that is bright at the perimeter and substantially darker at the back can feel like a cave, even when electrically illuminated at common interior light levels. The ‘uniformity ratio’, UR, is a variable that can be used to investigate the daylight distribution in a space. It is the ratio of the minimum internal illuminance, $E_{\text{min}}$, to the average internal illuminance, $E_{\text{in}}$ (Lim, & Kim, 2012). It can be expressed as shown in the equation below:

$$\text{Equation 5.3 } UR = \frac{E_{\text{min}}}{E_{\text{in}}}$$

Higher uniformity ratios indicate that the light levels across the room are more even. Notwithstanding, with regards to the distribution of daylight in a room, the Chartered Institute of Building Services Engineers (CIBSE, 2006) recommend that the uniformity ratio of day-lighting should be in the range of 0.3 to 0.4 for side-lit rooms.

5.2.4 Selected Building Design Parameters
This section identifies the building design parameters that have an impact on both the thermal and visual performance (summarised in table 4.2) of residential buildings in Abuja based on the review of literature and investigation (including fieldwork) in this study.

5.2.4.1 Room Orientation
The orientation of a room’s external facade is determined by the layout design of the building. However, in Abuja prototype buildings are often arranged in different configurations based on street access and the nature of the site rather than consideration of the best orientation for providing comfort. Thus, often buildings which have appropriate orientation are constructed opposite identical buildings with inappropriate orientation.
5.2.4.2 Fenestration Factor

The national building code for Nigeria specifies the minimum exterior glazed façade area and openable aperture area based on the total floor area being served (FRN, 2006). The ratio of the window area to floor area is known as the fenestration factor. As the purpose of this study is to provide additional recommendations with regards to the existing standards, the evaluation of the impact of different values for the fenestration factor is appropriate for the study.

5.2.4.3 Building Fabric Thermal Transmittance

The fabric transmittance of building envelope components has a major influence on indoor thermal comfort conditions and also determines the amount of energy required for cooling to achieve thermal comfort (Munoz et al., 2013). The thermal transmittance is particularly important in residential buildings because, the energy demands in residential buildings are primarily imposed by heat loss or gain through structural components and by air leakage or ventilation as opposed to internal heat gains from occupancy, lighting and electrical appliances (Al-Homoud, 2005). The prevalent wall construction material in Nigeria is the sandcrete block, however interest in finding new wall construction materials is rising due to the cost of sand stone and concrete. Hence there is an opportunity to proffer new materials and methods that are more effective in reducing heat gain, especially in residential buildings.

5.2.4.4 Wall Shading Devices

As stated previously, wall shading, particularly verandas and balconies are a common characteristic of the traditional and contemporary residential architecture in Nigeria. The use of verandas as part of the external façade configuration in buildings has adopted for many buildings in Abuja, however, the
effectiveness of these components for improving the thermal and visual conditions in dwellings in the city is unclear.

5.2.3.5 WINDOW SHADING DEVICES

The basic function of shading devices is to limit the amount of solar radiation that reaches the building interior. Thus, the application of shading devices internally or externally can have a significant impact on the level of solar heat gain in a room as well as daylighting (Kim et al., 2012). One of the most effective and simple ways to improve thermal conditions in a room is to have larger openable area to increase the air movement through the space, provided the open façade area is adequately shaded (Koengsberger et al., 1974; Frey & Drew, 1964). Thus, the balance between window sizes and shading projections can be an important factor to consider.

Table 5.2. Illustrates the connection between the building design parameters that have an effect on comfort and the external environmental factors. The first step in data collection is deciding how to measure what you are interested in studying (VanderStoep & Johnson 2009). In this study, comfort is assessed primarily by measuring the most important physical parameters associated with the visual and thermal conditions, namely illuminance and operative temperature. The design parameters at the building and room level highlighted in the table are selected from table 4.2. The indicators, which can be used to evaluate how the differences in the characteristics or changes made to different design parameters affect the frequency and magnitude of discomfort, are also shown in the table. The table also contains a number of factors of the urban environment which often have an influence on comfort conditions in buildings that can be considered.
Table 5.2 Framework showing the relationship between environmental factors, building design parameters, the measures of comfort and the indicators used in this study

<table>
<thead>
<tr>
<th>Study framework</th>
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<tbody>
<tr>
<td><strong>Thermal</strong></td>
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<tr>
<td><strong>Visual</strong></td>
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<tr>
<td>** Measures **</td>
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<tr>
<td><strong>Operative temperature</strong></td>
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<tr>
<td><strong>Base performance model</strong></td>
</tr>
<tr>
<td><strong>Indicators</strong></td>
</tr>
<tr>
<td><strong>Hours of Thermal Discomfort (HTD)</strong></td>
</tr>
<tr>
<td><strong>Frequency of Thermal Discomfort (FTD)</strong></td>
</tr>
<tr>
<td><strong>Area Under the Curve (AUC)</strong></td>
</tr>
<tr>
<td><strong>Additional measures</strong></td>
</tr>
<tr>
<td><strong>Solar gain</strong></td>
</tr>
<tr>
<td><strong>Level</strong></td>
</tr>
<tr>
<td><strong>Parameters and factors</strong></td>
</tr>
<tr>
<td><strong>Climate</strong></td>
</tr>
<tr>
<td><strong>Solar radiation</strong></td>
</tr>
<tr>
<td><strong>Air temperature</strong></td>
</tr>
<tr>
<td><strong>Relative humidity</strong></td>
</tr>
<tr>
<td><strong>Air velocity</strong></td>
</tr>
<tr>
<td><strong>The built environment</strong></td>
</tr>
<tr>
<td><strong>Size and orientation of external obstructions</strong></td>
</tr>
<tr>
<td><strong>Properties of external surfaces</strong></td>
</tr>
<tr>
<td><strong>The building</strong></td>
</tr>
<tr>
<td><strong>Orientation</strong></td>
</tr>
<tr>
<td><strong>Compactness ratio</strong></td>
</tr>
<tr>
<td><strong>Wall shading elements</strong></td>
</tr>
<tr>
<td><strong>Wall shading element proportions</strong></td>
</tr>
<tr>
<td><strong>The room</strong></td>
</tr>
<tr>
<td><strong>Façade orientation</strong></td>
</tr>
<tr>
<td><strong>Room dimensions</strong></td>
</tr>
<tr>
<td><strong>External wall area</strong></td>
</tr>
<tr>
<td><strong>Internal volume</strong></td>
</tr>
<tr>
<td><strong>Window orientation</strong></td>
</tr>
<tr>
<td><strong>Window area</strong></td>
</tr>
<tr>
<td><strong>Window layout and location</strong></td>
</tr>
<tr>
<td><strong>Window shading elements</strong></td>
</tr>
<tr>
<td><strong>Window shading element proportions</strong></td>
</tr>
<tr>
<td><strong>Fenestration factor</strong></td>
</tr>
<tr>
<td><strong>Window to wall ratio</strong></td>
</tr>
<tr>
<td><strong>Reflectance of external surfaces</strong></td>
</tr>
<tr>
<td><strong>Texture of internal surfaces</strong></td>
</tr>
<tr>
<td><strong>Thermal transmittance Of components of building envelope</strong></td>
</tr>
<tr>
<td><strong>Glazing type</strong></td>
</tr>
</tbody>
</table>

Note: Parameters assessed in base cases | Parameters assessed in base cases and modified cases

The adaptive model and frequency of visual comfort model have both been selected because of their suitability for the context of the study. Similarly, from the parameters that are discussed in Chapters three and four, only the parameters that can meet the purpose of this study and can be applied in the context of low-income housing design in Abuja have been chosen. It is worth noting that simple, low cost, sustainable design measures are particularly well-suited for this demographic. Thus, even though the possibility of using some complex shading devices and glazing systems to improve indoor comfort is covered in Chapters three and four, such elements are not likely to be employed for low income residential building development. Table 5.2 illustrates the connection between the evaluation models,
Chapter five

indicators and key parameters that influence thermal and visual conditions in a room and provides the framework for the investigation in this study.

5.3 FIELDWORK AND DATA COLLECTION

5.3.1 DATA COLLECTION

The types of data collected during the fieldwork in Abuja, included pictures, architectural drawings of residential buildings and associated materials including, maps, site plans, documentation on public sector building production. A formal request to obtain architectural drawings associated information on residential buildings for low income groups required was submitted to the director of the public buildings department of the FCDA, the director of development control for the AMMC, and the managing director of the FHA. The researcher also requested for drawings from the chief architect for the FMLHUD and a couple of private developers.

Some of the drawings obtained from the public buildings department were produced in the 1980s and early 1990s on sulphur based tracing paper. Many of the drawings were not properly preserved and have deteriorated (Figure 5.4.). Thus, only some of the drawings could be copied without being completely damaged. In total 71 drawings (including 19 hard copies and 52 soft copies) of residential buildings constructed between 1981 and 2006 were collected from various sources.

A number of maps and historical data were also acquired from FCDA and the Abuja Geographic Information Systems (AGIS) agency. These maps and data provided an overview of the existing as well as the anticipated residential building development in each district in the city. It was discovered that while most of the residential districts in phase I of the city were fully developed there were only a few districts in phase II and III that had a high level of infrastructural and housing development. Overall, as shown in figure 5.5 only around half of the total area in the city allocated for residential development has been fully developed in terms of infrastructure, housing and supporting services.
5.3.2 Weather Data

In order to simulate the effects of the typical annual climate of Abuja on buildings in the city, accurate weather data is required. It is also essential that the type of weather data used is appropriate for assessing visual as well as thermal performance in relation to the dynamic climatic context of the city. Thus hourly climate information for dry bulb temperature, relative humidity, solar irradiation, wind direction, wind speed and cloud cover were required. However, from the search and inquiry carried out to obtain such data it was discovered that weather data for Abuja is rather sparse. The Nigerian Meteorological Agency data resource services did not have complete records for all years over the past decade and in instances...
where records for a year were available, some of the climate parameters required were not consistently recorded at the weather stations in Abuja.

In order to simulate accurate climatic conditions, three options were considered. The first option was to use a weather data file for another city with a similar climate, preferably within the same region. However, the difference in latitudes and physical environment would affect output data such as the effects of atmospheric pressure, humidity, wind speed and solar shading performance. The second option was to set up a mini weather station in Abuja. The equipment required to successfully implement this option is expensive and the processes involved would require a long period of extensive observation. The third option, which was eventually used in this study, was the generation of a representative database for a typical annual duration, known as a Design Reference Year (DRY) or Test Reference Year (TRY). It is also known as a Typical Meteorological Year (TMY). TMY consists of individual months of meteorological data sets selected from different years over the available data period which is called long-term measured data series. Several methods for generating typical data have been developed. TMY methodologies have been proposed by various researchers in different regions of the world (Miguel & Bilbao, 2005; Kalogirou, 2003; Petrakis et al., 1998; Lam et al., 1996), including researchers undertaking studies in Nigeria (Ohunakin et al., 2015; Fadare, 2009; Skeiker & Ghani, 2009; Fagbenle, 1995). The primary objective of these methods is to select single year or single month from the multi-year database to create a weather file composed of months from different years which were selected as the most representative for that month’s typical weather.

The sparseness and the quality of data is one of the main limitations that might affect the creation of a typical weather file. Generally, 240 records per month can be regarded as good raw data for creating a TMY weather file. The data available from the meteorological station in Izom (less than 100km away from Abuja) consisted of records from 2005 to 2013. However, there are on average 133 records per month on dry-bulb temperature, cloud cover, and wind speed, 109 records per month on dew point temperature, dropping down to 28 in January (the worst month). That means on average, there are just four records per day, and as low as 1.5 records per day in January. The values for the other hours are all interpolated. That means the daily profiles, especially for the worst months (January and May), can be
unreliable. The sparsity of data can affect the hourly profiles of temperatures, and illuminance levels as well as other factors that can be simulated in a virtual environment.

On the other hand, the Abuja weather data available from the station at Nnamdi Azikiwe airport has significantly more records and there are no months with less than 150 records per month. However, the records were only available for 2008 to 2011. Nevertheless, the TMY weather file for Abuja was eventually produced using the 2008 to 2011, records from the meteorological station at the airport, because the raw data available was more reliable and the location is closer the centre of the city. Even so it is worth noting that a substantial amount of the data, especially the values for solar radiation, needed to be interpolated by White Box Technologies (a company that processes weather data for use in building energy simulations), from the existing records to formulate the weather file for the simulations.

5.4 SELECTION CRITERIA FOR EXEMPLARY CASES AND SELECTED CASES

5.4.1 SELECTION CRITERIA

The case study buildings were selected based on criteria presented in sections 5.4.1.1-3. Furthermore, the case studies were selected to provide an adequate representation of the majority of the types and sizes of houses developed for low and middle income groups in Abuja.

5.4.1.1 LOCATION

Although a vast majority of residential buildings developed for low income groups working in Abuja have been constructed in satellite towns these areas are outside the scope of this study, the selection of buildings in this study is limited to developed districts of the city in phase I, II and III.

As previously stated in Chapter two, over the past decade the government has encouraged joint venture developments with the private sector in districts outside the phase I area. Nevertheless, due to the high cost of building production in Abuja, a large amount of the housing for low-income groups in the city, are constructed by the government and subsequently procured by citizens at a subsidised price. Therefore, the buildings that are considered are located in residential neighbourhoods developed by government agencies.
5.4.1.2 LAND USE

Due to the high cost of land in Abuja, few residential buildings developed for low-income groups are located in areas designated for low-density developments. Thus, the selected buildings are located in medium and high density residential areas, as defined in the map below (Figure 5.6).

5.4.1.3 HOUSING TYPES

The selection of the housing types is based on the date of construction of the building as well as the materials and technology used to construct the buildings. The selection attempts to reflect the contemporary trends of architecture for low income groups in Abuja and Nigeria in general. Primarily, the focus and the aim of the study affects the selection of case studies. As stated previously, the selection process is likely to favour residential buildings developed by the government, because the majority of affordable houses available in Abuja are part of public residential building projects. Most of the housing developed by large-scale private companies is usually in form of gated communities, for upper-middle and upper income groups, whereas those developed by the government are for the public encompassing a larger area selected for the purpose of housing. Some low-income housing is produced by the small-
scale private sector, however most of these houses are constructed without official approval under land, planning and building regulation (Ikejiofor, 1999). Hence, most of the chosen government built houses were constructed using the material, methods and standards detailed in section 2.6 of Chapter two.

5.4.2 SELECTED RESIDENTIAL BUILDINGS

Eight case study buildings are chosen from four neighbourhoods in four districts in Abuja. Four of the selected buildings were designed and constructed during the first 15 years of the city’s development (1981-1996), while the other four buildings were designed and constructed during the subsequent 15 years (1997-2012). The location of the districts and neighbourhoods are shown in the satellite photograph of Abuja in figure 5.7, while table 5.3 shows the general location of the buildings selected as case studies for this research and provides a general view of the urban area in which the buildings are located. It also illustrates how often the prototypes are replicated in the same neighbourhood. A detailed description and architectural drawing of each of the selected case study residential building is also presented in Appendix 2. All except two of the case study buildings are prototypes that have been reproduced multiple times as part of government housing schemes. As a result collectively the selected dwellings and spaces from the case study buildings have envelope forms and material characteristics that are comparable to over 800 other dwellings in the chosen neighbourhoods. Moreover, as stated previously in Chapter two, over the past three decades some of these prototype designs have been reused in other government residential development schemes either with the same exact characteristics or a few modifications.

Figure 5.7. Satellite photograph of Abuja, with selected neighbourhoods outlined in red and districts outlined in orange
5.5 SIMULATION AND MODELLING PROCEDURE

Simulation research comes out of the general human fascination with creating representations of the real world. However, as opposed to simply attempting to replicate some elements of the real world, simulation research is characterised by the generation of data, in a form that can be used to make suggestions or recommendations that might be beneficial to the real world context (Groat & Wang, 2002).

Table 5.3 General building description and location aerial photograph

<table>
<thead>
<tr>
<th>Phase</th>
<th>District</th>
<th>Location</th>
<th>Aerial photo</th>
<th>Building ID /D.O.C</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wuse I</td>
<td>Mombasa street, Zone 5</td>
<td></td>
<td>Case study building 1 (RB1) /1983</td>
<td>Block of flats. 24, 1-bedroom units.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Case study building 1 (RB2) /1983</td>
<td>Block of flats. 24, 2-bedroom units.</td>
</tr>
<tr>
<td>1</td>
<td>Garki II</td>
<td>FCDA quarters and Samuel Ladoke Akintola boulevard</td>
<td></td>
<td>Case study building 1 (RB3) /1995</td>
<td>Multi-family dwelling 4, 1-bedroom units and 2 studio units.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Case study building 4 (RB4) /1996</td>
<td>Block of flats. 6, 2-bedroom units.</td>
</tr>
<tr>
<td>3</td>
<td>Gwarinpa II</td>
<td>FMWH quarters</td>
<td></td>
<td>Case study building 5 (RB5) /2003</td>
<td>2, 1-bedroom units. Semi-detached bungalow.</td>
</tr>
<tr>
<td>2</td>
<td>Gaduwa</td>
<td>FMWH quarters</td>
<td></td>
<td>Case study building 1 (RB6) /2005</td>
<td>Block of flats. 6, 2-bedroom units.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Case study building 7 (RB7) /2005</td>
<td>Block of flats. 6, 3-bedroom units.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Case study building 8 (RB8) /2005</td>
<td>Multi-family dwelling. 4, 1-bedroom units and 2 studio units.</td>
</tr>
</tbody>
</table>
Simulation occurs with a replication of a real-world context (or a hypothesised real-world context) containing within it dynamic interactions that are the results of manipulated factors. These interactions are reflective of interactions actually occurring in the real world (or expected to occur in future), and a simulation research design is one that is able to collect data on these interactions for application into the real-world context (Aksamija, 2013).

Computer modelling and simulation is used in this study to deduce the possible conditions occupants in residential buildings would likely to experience without the intervention of mechanical cooling and/or artificial lighting. A parametric study of selected examples of existing buildings in Abuja is adopted to assess the extent of the impact of the parameters listed in the framework on building occupants sense of visual and thermal comfort.

The buildings are selected according to their location, land use allocation, housing type, house design as discussed in section 5.4 of the previous chapter. Most of the residential buildings in the city of Abuja that have the attributes suitable to be selected as case studies in the research, are prototypes that have been replicated in districts across the city. In some instances 3 to 5 prototypes were replicated to form entire neighbourhoods. In total 25 residential building prototypes are identified from the initial stages of data collection and fieldwork. Out of these typical prototypes, 8 building types are selected for the analysis in this study and this is due to the data availability. However, although this figure or sample is around 1/3 of the overall building prototypes, the selected prototypes are mainly occupied by low-income groups.

As previously stated, simulation can provide real world information in ways that yield measurable and useful data, however the obvious limitations of simulation research are that replicated contexts are simply not the same as real contexts. Law states “If it is possible to (and cost effective) to alter the system physically and then let it operate under the new conditions, it is probably desirable to do so, for in this case there is no question about whether what we study is valid. However, it is rarely feasible to do this, because such an experiment would often be too costly or too disruptive to the system” (2007, p. 4). Simulation research can also circumvent ethical impossibilities because the replicated context is one that
can assess issues of human interaction and behaviour without placing the actors into compromising positions (Law, 2007).

5.5.1 SIMULATION SOFTWARE TOOL

In order to investigate the thermal and visual performance for each house in the study, a software tool which could be used to simulate the performance of buildings was required. There is a wide range of building simulation software available which can be used to analyse thermal and visual performance as well as energy consumption in buildings. These include, EnergyPlus, DesignBuilder, DOE.2-IE, TRNSYS, Ecotect, and Integrated Environmental Solutions-Virtual Environment (IES-VE) (Schwartz & Raslan, 2013, Crawley et al., 2008; Maile et al., 2007).

IES-VE was chosen for the purpose of this study based on its established building performance assessment capability and interoperability of the platform with other common Computer-aided Design (CAD) software including, AutoCAD and Revit (Aldossary et al., 2014; Al-Tamimi & Fadzil, 2011). IES-VE is an integrated collection of applications linked by a common user interface and a single integrated data model (Kim et al., 2012, p.106). This means that the 3 dimensional (3D) model and data input for on one application can be used by the others. The version (IES-VE 2014) used for this study consist of over 20 different applications. Only six modules of the package were used to carry out the investigation, these include:

- **ModellIT**: a 3D model design and construction tool.
- **Suncast**: sun path and solar shading calculation tool.
- **Macro-flo**: a simulation program used to create nodal airflow model and appraise naturally ventilated and mixed mode buildings.
- **Apache**: dynamic thermal simulation tool.
- **Vista**: used for collating and analysing the results from one or more simulations carried out using the different applications.
- **RadianceIES**: a backwards ray-tracing program used to predict and evaluate daylighting design in buildings.

The simulation procedures which were set-up to yield hourly data for a typical year are summarised in figure.5.8.
5.5.2 MODELLING PROCEDURE

In the present research, the approach adopted required the translation of three real building-related conditions into a format that the computer program can understand. These include the physical built environment, behaviour of occupants (i.e. pattern of occupancy) and the climate. Information on all 3 are programmed into the simulation in a way that brings them together in dynamic interactions and yields measurable data on the indoor conditions that are predictive of real conditions. The IES-VE modelling of the selected buildings involved two stages. Firstly, a model of each building in its existing state under the prevailing climatic conditions of Abuja, Nigeria was developed in order to investigate and establish the performance of the selected rooms. Secondly, re-modelled versions of each case study building was developed with changes to the chosen parameters that are investigated within the framework of the study (as identified in section 5.2.) in order to assess their impact on the thermal and visual comfort conditions in typical dwellings in Abuja.

A 3D model was constructed for each case study building using ModellIT, based on the actual design specification and construction material used. The drawings and information gathered during the...
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fieldwork process provided a detailed account of; the architectural design characteristics of the buildings, the types and area of each room, the size of the windows and other openings, the type of materials used in construction, as well as the orientation of each building. This data was inputted into IES-VE to simulate the thermal and visual conditions in selected rooms in each case study building. In order to properly evaluate the effect of solar insolation on the roof as well as the facades of the case study buildings, the rooms that were selected from each building are located in units on the top floor (Figure 5.9).

![Figure 5.9 IES-VE models of case study buildings with units selected for evaluation highlighted in red](image)

With regards to simulating the behaviour of occupants, establishing a pattern of use for the selected housing units would be difficult and probably imprecise, because there are a variety of living patterns for
each household and its individual occupants. Instead the simulation is set-up for full-time occupancy with the maximum dwelling occupancy rate specified by the Nigerian government, as shown in table 5.4 (FRN, 2006). Moreover, with regards to window opening modulation, the simulation was prepared based on the assumption that the occupants would make the best possible decision in an attempt to achieve thermal comfort as required for occupant controlled naturally ventilated rooms. In terms of degree of modulation, the set-up involves conditions under which the occupants would open windows if the indoor operative temperature is outside the range considered acceptable and if the outdoor dry-bulb temperature is below the indoor operative temperature or if the CO2 concentration in the room is above 1000 parts per million (ppm). The maximum acceptable level of CO2 concentration (1000ppm) was adapted from ASHRAE standard 6.21 (2013a), while the occupant’s thermal load is adapted from the standards suggested by the CIBSE (2015).

### Table 5.4 Simulation reflectance, occupancy, and opening modulation set-up

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal surface reflectance (ρ)</td>
<td>Windows (4mm clear glass)</td>
<td>0.080</td>
<td>Reflectance values from Baker and Steemers (2002, pp. 225-227).</td>
</tr>
<tr>
<td></td>
<td>Doors (dark oak)</td>
<td>0.100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Walls (222,212,187)</td>
<td>0.650</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling (white emulsion on plain plaster)</td>
<td>0.800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Floors (cement screed)</td>
<td>0.450</td>
<td></td>
</tr>
<tr>
<td>External surface reflectance (ρ)</td>
<td>Roof (corrugated aluminium)</td>
<td>0.700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Walls (cream paint)</td>
<td>0.650</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Floor (vegetation)</td>
<td>0.250</td>
<td></td>
</tr>
<tr>
<td>Occupancy schedule</td>
<td>Time of occupancy (hrs)</td>
<td>24</td>
<td>Full time occupancy assumed for residential building</td>
</tr>
<tr>
<td></td>
<td>Rate of occupancy (person/m²)</td>
<td>18.6</td>
<td>Value obtained from table 10.7 of the national building code (FRN, 2006, p. 170), this value also accounts for all other spaces that discharge through the space in order to gain access to an exit.</td>
</tr>
<tr>
<td>Occupant’s thermal load</td>
<td>Sensible gain (Watt/person)</td>
<td>70</td>
<td>Values of heat gain for seated occupants doing light work obtained from CIBSE guide A (2006, table 6.3)</td>
</tr>
<tr>
<td></td>
<td>Latent gain (Watt/person)</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Opening schedule formula</td>
<td>(T_{op}&gt;T_{over}) &amp; (T_{op}&gt;T_{a}) or (CO_{2}&gt;1000ppm)</td>
<td></td>
<td>It is assumed that occupants will open windows: if the indoor operative temperature (T_{op}) is greater than the upper limit of acceptable temperature (T_{over}) and the outdoor dry bulb air temperature (T_{a}), or the indoor carbon dioxide (CO_{2}) levels are above 1000 parts per million (ppm) (ASHRAE standard 6.21, 2013a)</td>
</tr>
<tr>
<td>Ventilation opening area</td>
<td>Lounge (sliding window)</td>
<td>45</td>
<td>The percentage of the opening area designed to allow air flow is derived from Bliss, (2006, table. 3.1), a standard double panel sliding window type is used for all window opening</td>
</tr>
<tr>
<td>(percentage of window area)</td>
<td>Bedroom (sliding window)</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

The results from the simulations for each of the selected rooms were used to calculate the monthly mean, maximum and minimum predicted operative temperatures as well as the frequency of thermal
discomfort for each month. On the other hand, a daily profile of the thermal and visual conditions in the rooms on the 15th day of each month was used to calculate the mean, maximum, minimum operative temperatures and average illuminance levels as well as the frequency of thermal and visual discomfort (as described in table 5.5). In addition, the levels of solar gain were also observed in order to appraise the effects of solar radiation on the comfort conditions indoors while the uniformity ratios of the illuminance across the working plane were used to appraise the quality of daylight distribution in the rooms.

A further phase of analysis involved a parametric evaluation of some of the rooms selected in the study to determine the influence of employing certain passive design solutions on the comfort conditions in the rooms. With consideration of the social context of the study the façade characteristics of the selected rooms were re-modelled with varying degree of changes to the parameters identified in the framework of this study (Table 5.2). This process included varying extent of changes to the orientation, fenestration factor of the selected rooms as well as changes to the thermal transmittance of roof and walls of the selected buildings. Furthermore, varying types and sizes of shading elements were also applied to the model of the buildings to assess the impact of shading on the performance of the buildings. The simulations results from both phases of analysis were compared to determine the impact of each change on the thermal and visual conditions indoors and also to identify the approaches that are appropriate for improving the performance of the houses.

Table 5.5 Framework for room simulation result analysis

<table>
<thead>
<tr>
<th>Measures</th>
<th>Thermal</th>
<th>Visual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>24 hours</td>
<td>12 hours (from 7 am to 6 pm)</td>
</tr>
<tr>
<td>Indicators and means of measurement</td>
<td>24 hours</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Maximum, mean and minimum operative temperature in room</td>
<td>Day (15th of each month)</td>
</tr>
<tr>
<td></td>
<td>Frequency of thermal discomfort</td>
<td>Maximum, mean and minimum average illuminance levels, using set points 0.5m apart and across working plane 0.75m above finished floor in room.</td>
</tr>
<tr>
<td></td>
<td>Frequency of thermal discomfort</td>
<td>Frequency of visual discomfort</td>
</tr>
</tbody>
</table>
5.6 Validation Process

The computer modelling procedure consists of two parts including model setting and model validation. The model setting as described in section 5.5.2 is creating three dimensional models of the case study buildings and establishing a framework for occupancy rate and occupants behaviour (Table 5.4). That said, validation experiments were conducted in order to determine the efficacy of the modelling and simulation tool (IES-VE) in predicting thermal and daylighting conditions in Abuja, Nigeria. The modelling and simulation validation was carried out by measuring the air temperature and illuminance levels in unoccupied test rooms and statistically comparing the values recorded with the values predicted from simulations of the same scenarios in models of the test rooms.

The validation consisted of two phases of on-site measurements in two separate case study buildings over two different time periods. The first phase (experiment one) was carried out in case study building 5 between May 1st and July 31st, 2014 (92 days), while the second phase (experiment two) was carried out in case study building 8 between December 1st and December 21st, 2014 (21 days). The procedure undertaken and the analysis of the results from the validations are presented in the subsequent sections.

5.6.1 Experiment One

5.6.1.1 Description of Tested Room in Case Study Building 5

The test room chosen in case study building 5 was the living room in one of the two flats. It is at the ground floor level and only the south and east façade are external walls. It is also worth noting that the south façade is shaded by a 1m deep balcony. The room has a square shape, 3.95m long, 3.95m wide and a height of 2.75m from finished floor to ceiling (Figure 5.10). Thus, the room has a total volume of about 43m$^3$.

There are three opening present in the room including a window in the east façade and in the south façade that each have a total area of about 1.3m$^2$, and a door in the south façade with a total area of about 1.8m$^2$. Both windows have a single glazing system (glass layer 4mm), with a thermal transmittance (u-value) of approximately 5.224W/m$^2$K, while the estimated u-value of the walls and roof are around
2.148W/m²K and 3.788W/m²K respectively. The ground floor which is cast in place on a layer of hardcore and compacted laterite has an estimated u-value of about 0.936W/m²K.

![Figure 5.10 Monitored house floor plan](image)

5.6.1.2 Field measurement

The Indoor air temperature and illuminance measurements were carried out in the test room for 24 hours over 92 days from midnight on the May 1st (during the rainy season). The instruments used to record the air temperature and illuminance levels both inside and outside the test room included a Hobo pendant temperature data logger (UA-001-xx) and temperature/light data logger (UA-002-xx) (Figure 5.11). The data loggers were chosen because of their accuracy, storage and battery capacity logging data for long periods of time. The specifications for both data loggers are shown in table 5.6.

![Figure 5.11 Instruments used for indoor and outdoor thermal and daylighting condition measurements](image)
Chapter five

### Table 5.6 Objective measurement instrument specifications

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Hobo pendant temperature data logger</th>
<th>Hobo pendant temperature/light data logger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement range</td>
<td>Temperature: -20°C to 70°C</td>
<td>Temperature: -20°C to 70°C</td>
</tr>
<tr>
<td></td>
<td>Light: 0 to 320,000 lux</td>
<td>Light: designed for measurement of relative light levels</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Temperature: ± 0.47°C at 25°C</td>
<td>Temperature: ± 0.47°C at 25°C</td>
</tr>
<tr>
<td>Resolution</td>
<td>Temperature: 0.10°C at 25°C</td>
<td>Temperature: 0.10°C at 25°C</td>
</tr>
<tr>
<td>Drift</td>
<td>Less than 0.1°C/year</td>
<td>Less than 0.1°C/year</td>
</tr>
<tr>
<td>Response time</td>
<td>Airflow of 2m/s: 10 minutes typical to 90%</td>
<td>Airflow of 2m/s: 10 minutes typical to 90%</td>
</tr>
<tr>
<td>Water depth rating</td>
<td>30m from -20°C to 20°C</td>
<td>30m from -20°C to 20°C</td>
</tr>
<tr>
<td>Battery life</td>
<td>1 year typical use</td>
<td>1 year typical use</td>
</tr>
<tr>
<td>Memory</td>
<td>8 kilobytes (approximately 6500 sample and event readings)</td>
<td>8 kilobytes (approximately 3500 sample and event readings)</td>
</tr>
</tbody>
</table>

The Hobo optic USB base station (Figure 5.11) was used together with hoboware-pro software to specify the operating parameters for the pendant data loggers and also to retrieve the data stored on the pendant loggers. After the measurement period the data recorded on the data loggers was transferred to Microsoft excel spreadsheets excel with an optic USB base station with coupler (Base-U-1) and the hoboware-pro windows software.

The specific procedure and layout for recording both the air temperature and illuminance level are described below.

The procedure for measuring the internal and external air temperature measurements are as:

1. Fans or air-conditioning systems were not switched on during the measurement period to assess the room in its passive mode.
2. Windows were left open throughout the measurement period.
3. Temperature readings were logged every hour using the pendant temperature data logger.
4. The logger was positioned 2.0m from the window walls (Figure 5.12) in order to collect air temperature readings at the centre of the room, and was elevated to a height of 1.6m above the finished floor.
5. A temperature data logger was also placed outside the room in the shaded porch area to record the external air temperature.
The procedures for internal and external daylight illuminance levels measurement are as follows:

1. All electric lamps in the room were switched off during the measurement period.
2. The curtains around the windows were removed throughout the measurement period. This was made possible to the researcher as flat was already set up to be renovated by its new owner.
3. Illuminance readings were logged every hour using the pendant temperature and light data loggers.
4. The loggers were positioned at 3 points 1.5m and 1.5m away from the window walls (Figure 5.13) in order to collect illuminance readings at the different depths inside the room. The loggers were elevated to a height of 0.75m above the finished floor level.
5. An additional data logger was also used to record the external illuminance levels at a high point near the building with minimal physical obstructions.

5.6.1.3 Model validation

In order to validate the model the simulated air temperatures and illuminance levels were compared to the monitored air temperatures and illuminance levels using Pearson’s product moment correlation.
Chapter five

coefficient, \( R \). This coefficient is the standard measure of the linear relationship between two variables and has the following properties (Cohen, Manion, & Morrison, 2013):

1. It is a pure number that does not have a specific unit of measurement.

2. \( R \) can take a range of values from +1 to -1. A value of 0 indicates that there is no association between the two variables. A value greater than 0 indicates a positive association; that is, as the value of one variable increases, so does the value of the other variable. A value less than 0 indicates a negative association; that is, as the value of one variable increases, the value of the other variable decreases.

3. The stronger the association of the two variables, the closer \( R \) will be to either +1 or -1 depending on whether the relationship is positive or negative, respectively.

The significance of the correlation can be determined by calculating the probability, \( p \), that the value of \( R \) is so far away from 0 that it was not likely to have occurred by chance. The smaller the value of \( p \), the larger the significance, most studies assume a value is statistically significant when \( p < 0.05 \) and statistically highly significant when \( p < 0.01 \) (Bobko, 2001). The chosen significance level in this study is 0.05.

The Relative Error (RE) between the measured and simulated results was also calculated using the following equation (Ng, Poh, & Nagakura, 2001):

\[
\text{Equation 5.4 } \text{RE} = \frac{(M_v - S_v)}{m_v}
\]

where,
\( M_v \) is the measured value
\( S_v \) is the corresponding simulated value

Table 5.7 present the results for the correlation between the measured and simulated air temperature in the test room and outside the room, while figures 5.14 and 5.15 illustrates the difference between the measured and simulated air temperature in the test room and outside the room. On the other hand, tables 5.8-5.10 present the results for the correlation between the measured and simulated illuminance levels in the test room and outside the room, while figures 5.16-5.21 illustrates the difference between the measured and simulated illuminance levels in the test room and outside the room.
Table 5.7 Comparison of measured and simulated internal and external temperatures in the test room in case study building 5

<table>
<thead>
<tr>
<th>Month</th>
<th>Week</th>
<th>Internal (T)</th>
<th>External</th>
<th>( R )</th>
<th>( p = 0.05 )</th>
<th>( p = 0.01 )</th>
<th>( \text{RE}_{\text{avg}} )</th>
<th>( R )</th>
<th>( p = 0.05 )</th>
<th>( p = 0.01 )</th>
<th>( \text{RE}_{\text{avg}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>1</td>
<td>0.4956</td>
<td>&lt;0.00001</td>
<td>0.05</td>
<td>0.5541</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.08</td>
<td>0.5541</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.4651</td>
<td>&lt;0.00001</td>
<td>0.05</td>
<td>0.5193</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.07</td>
<td>0.5193</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.6212</td>
<td>&lt;0.00001</td>
<td>0.06</td>
<td>0.6069</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.08</td>
<td>0.6069</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.5776</td>
<td>&lt;0.00001</td>
<td>0.05</td>
<td>0.6346</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.07</td>
<td>0.6346</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td>June</td>
<td>1</td>
<td>0.7316</td>
<td>&lt;0.00001</td>
<td>0.05</td>
<td>0.6484</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.07</td>
<td>0.6484</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
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<tr>
<td></td>
<td>2</td>
<td>0.4967</td>
<td>&lt;0.00001</td>
<td>0.06</td>
<td>0.5649</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.08</td>
<td>0.5649</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.3749</td>
<td>0.00044</td>
<td>0.00044</td>
<td>0.06</td>
<td>0.4854</td>
<td>&lt;0.00001</td>
<td>0.00044</td>
<td>0.08</td>
<td>0.4854</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.6759</td>
<td>&lt;0.00001</td>
<td>0.06</td>
<td>0.7217</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.07</td>
<td>0.7217</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td>July</td>
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<td>0.5249</td>
<td>&lt;0.00001</td>
<td>0.05</td>
<td>0.6090</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.06</td>
<td>0.6090</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
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<tr>
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<td>0.7587</td>
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<td>0.8135</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.05</td>
<td>0.8135</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.4796</td>
<td>&lt;0.00001</td>
<td>0.08</td>
<td>0.4899</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.09</td>
<td>0.4899</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.6560</td>
<td>&lt;0.00001</td>
<td>0.04</td>
<td>0.6511</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.06</td>
<td>0.6511</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
</tbody>
</table>

Note: "\( R \)" denotes Pearson’s correlation value, "\( \text{RE}_{\text{avg}} \)" denotes the average relative error

Table 5.8 Comparison of measured and simulated internal illuminance levels at point 1 and 2 in the test room in case study building 5

<table>
<thead>
<tr>
<th>Month</th>
<th>Week</th>
<th>Point</th>
<th>( R )</th>
<th>( p = 0.05 )</th>
<th>( p = 0.01 )</th>
<th>( \text{RE}_{\text{avg}} )</th>
<th>( R )</th>
<th>( p = 0.05 )</th>
<th>( p = 0.01 )</th>
<th>( \text{RE}_{\text{avg}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>1</td>
<td>0.4155</td>
<td>0.00009</td>
<td>0.00009</td>
<td>0.41</td>
<td>0.2995</td>
<td>0.00565</td>
<td>0.00565</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.4422</td>
<td>0.00003</td>
<td>0.00003</td>
<td>0.42</td>
<td>0.5772</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.3940</td>
<td>0.00021</td>
<td>0.00021</td>
<td>0.45</td>
<td>0.3815</td>
<td>0.00034</td>
<td>0.00034</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.2561</td>
<td>0.01870</td>
<td>0.01870</td>
<td>0.48</td>
<td>-0.0653</td>
<td>0.55509</td>
<td>0.55509</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>1</td>
<td>0.2680</td>
<td>0.01371</td>
<td>0.01371</td>
<td>0.36</td>
<td>0.0390</td>
<td>0.72467</td>
<td>0.72467</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.2498</td>
<td>0.02193</td>
<td>0.02193</td>
<td>0.45</td>
<td>-0.0091</td>
<td>0.93452</td>
<td>0.93452</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.3203</td>
<td>0.00298</td>
<td>0.00298</td>
<td>0.36</td>
<td>0.4553</td>
<td>0.00001</td>
<td>0.00001</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.4344</td>
<td>0.00004</td>
<td>0.00004</td>
<td>0.43</td>
<td>-0.1707</td>
<td>0.12055</td>
<td>0.12055</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>1</td>
<td>0.1913</td>
<td>0.00004</td>
<td>0.00004</td>
<td>0.45</td>
<td>0.6151</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.6150</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.66</td>
<td>0.1375</td>
<td>0.21230</td>
<td>0.21230</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.3389</td>
<td>0.00161</td>
<td>0.00161</td>
<td>0.63</td>
<td>0.2872</td>
<td>0.00808</td>
<td>0.00808</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.4027</td>
<td>0.00015</td>
<td>0.00015</td>
<td>0.42</td>
<td>0.3368</td>
<td>0.00173</td>
<td>0.00173</td>
<td>0.30</td>
<td></td>
</tr>
</tbody>
</table>

Note: "\( R \)" denotes Pearson’s correlation value, "\( \text{RE}_{\text{avg}} \)" denotes the average relative error
Table 5.9 Comparison of measured and simulated internal illuminance levels at point 3 in the test room in case study building 5

<table>
<thead>
<tr>
<th>Month</th>
<th>Week</th>
<th>Point</th>
<th>Illuminance</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>R</td>
<td>p=0.05</td>
<td>p=0.01</td>
<td>RE&lt;sub&gt;avg&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>1</td>
<td></td>
<td>0.2555</td>
<td>0.01899</td>
<td>0.01899</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>0.6317</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>0.4983</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>0.2022</td>
<td>0.06511</td>
<td>0.06511</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>1</td>
<td></td>
<td>0.6149</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>0.4266</td>
<td>0.00005</td>
<td>0.00005</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>0.5255</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>0.2239</td>
<td>0.04062</td>
<td>0.04062</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>1</td>
<td></td>
<td>0.3739</td>
<td>0.00046</td>
<td>0.00046</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
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<td>&lt;0.00001</td>
<td>0.58</td>
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<td></td>
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<td>&lt;0.00001</td>
<td>0.52</td>
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</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
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<td>0.00008</td>
<td>0.00008</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

Note: "R" denotes Pearson’s correlation value, "RE<sub>avg</sub>" denotes the average relative error.

Table 5.10 Comparison of measured and simulated internal and external illuminance levels in the test room in case study building 5

<table>
<thead>
<tr>
<th>Month</th>
<th>Week</th>
<th>Average internal</th>
<th></th>
<th></th>
<th></th>
<th>External</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Point</td>
<td>R</td>
<td>p=0.05</td>
<td>p=0.01</td>
<td>RE&lt;sub&gt;avg&lt;/sub&gt;</td>
<td>R</td>
<td>p=0.05</td>
<td>p=0.01</td>
<td>RE&lt;sub&gt;avg&lt;/sub&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>1</td>
<td></td>
<td>0.4243</td>
<td>0.00006</td>
<td>0.00006</td>
<td>0.38</td>
<td>0.7313</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.46</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>0.6093</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.39</td>
<td>0.6363</td>
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<td>&lt;0.00001</td>
<td>0.37</td>
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<td></td>
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<td>0.7996</td>
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<td>0.35</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
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<td>0.1623</td>
<td>0.14021</td>
<td>0.14021</td>
<td>0.40</td>
<td>0.6598</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.40</td>
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</tr>
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<td>0.00660</td>
<td>0.00660</td>
<td>0.28</td>
<td>0.6995</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
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<td>0.02265</td>
<td>0.02265</td>
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<td>0.6735</td>
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<td>&lt;0.00001</td>
<td>0.42</td>
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<td>0.3914</td>
<td>0.00023</td>
<td>0.00023</td>
<td>0.35</td>
<td>0.6969</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>0.1695</td>
<td>0.12322</td>
<td>0.12322</td>
<td>0.45</td>
<td>0.6275</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>1</td>
<td></td>
<td>0.4224</td>
<td>0.00006</td>
<td>0.00006</td>
<td>0.41</td>
<td>0.6785</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>0.5184</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.60</td>
<td>0.6479</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
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<td>0.4056</td>
<td>0.00013</td>
<td>0.00013</td>
<td>0.56</td>
<td>0.6548</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>0.4918</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.25</td>
<td>0.6504</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.51</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: "R" denotes Pearson’s correlation value, "RE<sub>avg</sub>" denotes the average relative error.
Figure 5.14 Measured and simulated internal/external air temperature in the test room in case study building 5

Figure 5.15 Scatter graph of the measured and simulated internal/external air temperature in the test room in case study building 5
Figure 5.16 Measured and simulated internal illuminance levels at point 1 and point 2 in the test room in case study building 5

Figure 5.17 Scatter graph of the measured and simulated internal illuminance levels at point 1 and point 2 in the test room in case study building 5
Chapter five

Figure 5.18 Measured and simulated internal illuminance levels at point 3 in the test room in case study building 5

Figure 5.19 Scatter graph of the measured and simulated internal illuminance levels at point 3 in the test room in case study building 5
In general, the data illustrated in the previous tables and figures show that there are significant discrepancies between the measured and simulated values especially the illuminance levels. The errors in the comparison of the measurement values in the test room and the simulations were anticipated for the following reasons:

1. There were differences between the external weather on the site and the weather simulated in the virtual environment, which was derived from past records of the weather conditions.
measured at a station that is about 35km away from the site (as previously mentioned in section 5.3.2).

2. The sky conditions in RadianceIES, were selected based on the cloud cover data given in the typical weather data file for Abuja. However, Radiance simulations results under CIE luminance distributions can show notable differences from real sky conditions, especially when the exterior environment has great variation in weather (Kim & Chung, 2011). The range of sky conditions during the rainy season in Abuja, varies from clear sunny skies to overcast skies, thus, it is harder to predict the cloud cover present at any given hour using past weather data.

3. It is difficult to accurately model the external obstructions near the building. It is also difficult to accurately model the burglar proof metal bars and mosquito net mesh around the windows. Thus, most of these details were omitted from the simulations.

4. The reflectance values for the internal and external surfaces were estimated using the guidelines from Baker and Steemers (2002, pp. 225-227).

5. There were a number of erroneous measurements records by the light data loggers used, particularly in July, which had to be omitted from the evaluation of the results.

Despite the limitations of the simulation procedure, when the predicted values were compared to the values from the field study measurements it was found that there was a notable positive correlation between the values for air temperature. The data shows that over the 12 week validation period the correlation between the measured and simulated internal air temperature ranges between 0.7587 ($p <0.00001$) and 0.3749 ($p = 0.00044$). Furthermore, the average relative error range for the weeks examined is between 0.04 (4%) and 0.08 (8%). The correlation between the measured and simulated external air temperature ranges between 0.8155 ($p <0.00001$) and 0.4854 ($p <0.00001$). The average relative error range for the weeks examined is between 0.05 (5%) and 0.09 (9%) (Table 5.7). The lowest correlation values for the measured and simulated external air temperatures occur during the third week of June, while the lowest correlation values for the measured and simulated internal air temperatures occur during the same week. On the other hand, the highest correlation values for the measured and simulated external air temperatures as well as the highest correlation values for the measured and
simulated internal air temperatures occur during the second week in July. The data suggests that the differences between the measured and simulated values in the room are mainly associated with the differences between the external values measured from, May-July 2014 and the values simulated using the available weather data from 2008-2011 (Figures 5.16-5.17).

Unlike the temperature, the correlation between the measured and simulated internal illuminance levels is not particularly strong. The data shows that over the 12 week validation period the correlation between the measured and simulated internal illuminance at point one, varies between 0.6150 (\(p < 0.00001\)) and 0.1913 (not significant). The correlation for the values at point two varies between 0.6151 (\(p < 0.00001\)) and -0.0091 (not significant), while at point three correlation for the values varies between 0.6317 (\(p < 0.00001\)) and 0.2022 (not significant). The highest average relative error during the weeks examined is about 0.66 at point one during the second week of July, whereas the lowest value is about 0.30 at point two during the last week of July. Figures 5.16, 5.18 and 5.20 show a significant number of hourly values had to be omitted from the validation calculations because erroneous values were recorded on the illuminance data loggers placed inside the room. The high variability in the values during July are partly due to the increase in the amount of erroneous data that was recorded by the illuminance data loggers in the room during the latter half of the measurement period. The problem is reflected in the range of relative errors for the average values from all three points, which exceeds 0.45 (45%) during the weeks in July (Table 5.10).

On the other hand, the correlation between the measured and simulated external illuminance levels ranges between 0.7996 (\(p < 0.00001\)) and 0.6275 (\(p < 0.00001\)) (Table 5.9). Notwithstanding, there are notable differences between the values for the measured and simulated external illuminance. Table 5.10 shows that the average relative error range is between 0.28 (28%) and 0.60 (60%). The data indicates that the differences between the measured and simulated values for the test room might also be partly associated with the differences between the measured and simulated external illuminance levels.

Because of the variation presented above between the two sets of data, another validation experiment was designed and implemented where a more refined procedure considered aiming at avoiding some of the mistakes occurred in the first experiment.
5.6.2 EXPERIMENT TWO

The second phase of the validation was carried out in a bedroom in case study building 8 for 21 days, from the 1st to the 21st of December 2014. In order to minimise the discrepancy between the measured and simulated values adjustments were made to the initial measurement and simulation procedures. These adjustments include the following:

1. Due to the fact that it is difficult to accurately model the external obstructions near the building, the room selected was chosen because the area round its external façades had very few obstructions. The only notable obstruction, which is a neighbouring building opposite the north-east façade of the test room was modelled as an opaque block.

2. The glazing and window frames were removed from the external openings in the room. Once again this was made possible as the building was being renovated.

3. There walls and ceiling of the test room were painted matte white and the reflectance values of walls, ceiling and floor were calculated as described in section 5.6.2.2.

In addition to these adjustments it was anticipated that the limited variation in the weather and sky conditions during the dry season in Abuja, which is typically characterised by consistent clear sunny skies, would minimise the relative errors between the measured and simulated values.

5.6.2.1 DESCRIPTION OF TESTED ROOM IN CASE STUDY BUILDING 8

The test room chosen in case study building 8 was the bedroom on the first floor and only the north-east and south-east façade are external walls. The room has a square shape, 5.3m long, 5.1m wide and a height of 2.75m from finished floor to ceiling (Figure 5.22). Thus, the room has a total volume of about 74m$^3$. 

![Figure 5.22 Monitored house floor plan](image-url)
There are three opening present in the room including a window in the east façade and in the south façade that both have a total area of about 1.8m$^2$, and a door in the south façade with a total area of about 1.8m$^2$. As with case study building 5 the estimated u-value of the walls and roof in case study building 8 are around 2.148W/m$^2$K and 3.788W/m$^2$K respectively. The suspended floor made of reinforced concrete cast in place, with plastering underneath and ceramic tile finish on the floor, thus, the estimated u-value of about 2.380W/m$^2$K. The glazing and the frame were removed from both windows to negate errors in the validation process that could occur because inaccurate modelling of the fenestration area (Figure 5.23).

Figure 5.23 Position of temperature and light data loggers

5.6.2.2 Field measurement

The indoor air temperature and illuminance measurements were carried out in the test room for 24 hours over 21 days from midnight on the December 1st (during the dry season), using the instruments described in section 5.6.1.2. The specific procedure and layout for recording both the air temperature and illuminance level are described below.

Similar to experiment one, the procedure for monitoring the internal and external air temperature measurements are as follows:

1. Fans or air-conditioning systems were not switched on during the measurement.
2. Temperature readings were logged every hour using the pendant temperature data loggers.
3. The loggers were positioned 2.0m from the window walls (Figure 5.24) in order to collect air temperature readings at the centre of the room, and were elevated to a height of 1.6m above the finished floor.
4. A temperature data logger was also placed outside the room in the shaded porch area to record the external air temperature.

The procedures for measuring the internal and external daylight illuminance levels measurement are as follows:

1. All artificial lighting was switched off during this measurement.
2. Illuminance readings were logged every hour using the pendant temperature and light data loggers.
3. The loggers were positioned at 4 points 1.5m and 1.5m away from the window walls (Figure 5.25) in order to collect illuminance readings at the different depths of the room. The loggers were elevated to a height of 0.75m above the finished floor level.
4. Readings were also recorded outside at a point with minimal physical obstructions.

In addition to these procedures, the area of the wall, floor and ceiling surfaces were divided into different zones as illustrated in figure 5.26. A luminance meter and illuminance meter (Figure 5.27) were then used to measure the luminance (L) and illuminance (E) of a point within each zone. The
reflectance of these points on each surface were subsequently used to calculate the reflectance of these areas using the following equation (Hiscocks, 2011):

\[
\rho = \left( \frac{L}{E} \right) \times \pi
\]

Where:
- \( \rho \) = Reflectance
- \( L \) = Luminance
- \( E \) = Illuminance
- \( \pi \) = Pi (3.14159)

The reflectance values calculated are shown in table 5.11. The average reflectance values for the internal walls, floor and ceiling in the test room were applied to the reflectance values in RadianceIES for the simulation of the illuminance levels in the room.

Figure 5.26 Illustration of the different zones on the walls and floor

Figure 5.27 Luminance and illuminance meters
Table 5.11 Calculated reflectance values for the walls, ceiling and floor in the test room in case study building 8

<table>
<thead>
<tr>
<th>Zone</th>
<th>L (cd/m²)</th>
<th>E (lux)</th>
<th>ρ</th>
<th>Zone</th>
<th>L (cd/m²)</th>
<th>E (lux)</th>
<th>ρ</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>269.6</td>
<td>865</td>
<td>98</td>
<td>21</td>
<td>207.9</td>
<td>736</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>466</td>
<td>1454</td>
<td>101</td>
<td>22</td>
<td>184.5</td>
<td>578</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>23</td>
<td>213.6</td>
<td>778</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>433.4</td>
<td>1685</td>
<td>81</td>
<td>24</td>
<td>302</td>
<td>1135</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>208.2</td>
<td>616</td>
<td>106</td>
<td>25</td>
<td>186</td>
<td>668</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>247.4</td>
<td>1069</td>
<td>73</td>
<td>26</td>
<td>162.7</td>
<td>522</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>199.3</td>
<td>774</td>
<td>81</td>
<td>27</td>
<td>207.1</td>
<td>811</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>265.8</td>
<td>1087</td>
<td>77</td>
<td>28</td>
<td>228.8</td>
<td>984</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>188.3</td>
<td>669</td>
<td>88</td>
<td>29</td>
<td>167.9</td>
<td>782</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>195.4</td>
<td>683</td>
<td>90</td>
<td>30</td>
<td>209.9</td>
<td>850</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>171.4</td>
<td>607</td>
<td>89</td>
<td>31</td>
<td>204.9</td>
<td>779</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>142.6</td>
<td>479</td>
<td>94</td>
<td>32</td>
<td>291.1</td>
<td>1069</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>230.6</td>
<td>728</td>
<td>100</td>
<td>33</td>
<td>287.3</td>
<td>1033</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>175</td>
<td>714</td>
<td>77</td>
<td>34</td>
<td>459.3</td>
<td>1747</td>
<td>83</td>
<td></td>
</tr>
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<td>15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>35</td>
<td>382.9</td>
<td>1307</td>
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</tr>
<tr>
<td>16</td>
<td>215.4</td>
<td>641</td>
<td>106</td>
<td>36</td>
<td>610.6</td>
<td>2142</td>
<td>90</td>
<td></td>
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<tr>
<td>17</td>
<td>221.7</td>
<td>576</td>
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<td>37</td>
<td>336.1</td>
<td>1374</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>211.4</td>
<td>524</td>
<td>127</td>
<td>38</td>
<td>714.9</td>
<td>2592</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>195.6</td>
<td>562</td>
<td>109</td>
<td>39</td>
<td>438.5</td>
<td>1754</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>172</td>
<td>396</td>
<td>137</td>
<td>40</td>
<td>862.7</td>
<td>3570</td>
<td>76</td>
<td></td>
</tr>
</tbody>
</table>

5.6.2.3 Model validation

As previously done, the simulated air temperatures and illuminance levels were compared to the measured air temperatures and illuminance levels using Pearson’s product moment correlation coefficient. Table 5.12 present the results for the correlation between the measured and simulated air temperature in the test room and outside the room, while figures 5.28 and 5.29 illustrates the difference between the measured and simulated air temperature in the test room and outside the room. On the other hand, tables 5.13-5.15 present the results for the correlation between the measured and simulated illuminance levels in the test room and outside the room, while figures 5.30-5.35 illustrates the difference between the measured and simulated illuminance levels in the test room and outside the room.

Table 5.12 Comparison of measured and simulated internal and external temperatures in the test room in case study building 8

<table>
<thead>
<tr>
<th>Air temperature</th>
<th>Internal (T)</th>
<th>External</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>p=0.05</td>
</tr>
<tr>
<td>December</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.9625</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td>2</td>
<td>0.9588</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td>3</td>
<td>0.9521</td>
<td>&lt;0.00001</td>
</tr>
</tbody>
</table>

Note: “R” denotes Pearson’s correlation value, “RE_avg” denotes the average relative error.
Table 5.13 Comparison of measured and simulated internal illuminance levels at point 1 and 2 in the test room in case study building 8

<table>
<thead>
<tr>
<th>December</th>
<th>Week</th>
<th>Point</th>
<th>$R$</th>
<th>$p=0.05$</th>
<th>$p=0.01$</th>
<th>REavg</th>
<th>$R$</th>
<th>$p=0.05$</th>
<th>$p=0.01$</th>
<th>REavg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9783</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.32</td>
<td>0.9025</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.9981</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.28</td>
<td>0.9825</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.9641</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.31</td>
<td>0.9029</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: "R" denotes Pearson's correlation value, "REavg" denotes the average relative error.

Table 5.14 Comparison of measured and simulated internal illuminance levels at point 3 and 4 in the test room in case study building 8

<table>
<thead>
<tr>
<th>December</th>
<th>Week</th>
<th>Point</th>
<th>$R$</th>
<th>$p=0.05$</th>
<th>$p=0.01$</th>
<th>REavg</th>
<th>$R$</th>
<th>$p=0.05$</th>
<th>$p=0.01$</th>
<th>REavg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9219</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.32</td>
<td>0.9058</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.9843</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.28</td>
<td>0.9756</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.9197</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.32</td>
<td>0.9111</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: "R" denotes Pearson's correlation value, "REavg" denotes the average relative error.

Table 5.15 Comparison of measured and simulated internal illuminance levels in the test room in case study building 8

<table>
<thead>
<tr>
<th>December</th>
<th>Week</th>
<th>Point</th>
<th>Average</th>
<th>$R$</th>
<th>$p=0.05$</th>
<th>$p=0.01$</th>
<th>REavg</th>
<th>External</th>
<th>$R$</th>
<th>$p=0.05$</th>
<th>$p=0.01$</th>
<th>REavg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9556</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.32</td>
<td>0.9486</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.9949</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.28</td>
<td>0.9903</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.9634</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.29</td>
<td>0.9512</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
<td>0.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: "R" denotes Pearson's correlation value, "REavg" denotes the average relative error.
Chapter five

Figure 5.28 Measured and simulated internal/external air temperature in the test room in case study building 8

Figure 5.29 Scatter graph of the measured and simulated internal/external air temperature in the test room in case study building 8

Figure 5.30 Measured and simulated internal illuminance levels at point 1 and point 2 in the test room in case study building 8

Figure 5.31 Measured and simulated internal illuminance levels at point 3 and point 4 in the test room in case study building 8

Figure 5.32 Scatter graph of the measured and simulated internal illuminance levels at point 1 and point 2 in the test room in case study building 8
The data illustrated in figures 5.28-5.35 show that compared to the previous phase, there are significantly less discrepancies between the measured and simulated values of the air temperature and the illuminance levels. It was found that there was a significant positive correlation between the values for air temperature. The data shows that over the three weeks examined the correlation between the measured and simulated internal air temperature ranges between 0.9625 ($p < 0.00001$) and 0.9521 ($p < 0.00001$). The average relative error range for the weeks examined is between 0.05 (5%) and 0.06 (6%). Likewise, the correlation between the measured and simulated external air temperature ranges between 0.9557 ($p < 0.00001$) and 0.9316 ($p < 0.00001$), while the average relative error range for the weeks examined is between 0.05 (5%) and 0.09 (9%). The data presented in figures 5.28 and 5.29 suggests that the differences between the measured and simulated values in the room are mainly associated with the
Chapter five

differences between the external values measured from, the 1st to the 21st of December 2014 and the
values simulated using the available TMY weather data from 2008-2011.

With regards to the natural lighting in the room, the data shows that during the days examined the
correlation between the measured and simulated internal illuminance levels at point one, varies between
0.9981 \( (p < 0.00001) \) and 0.9641 \( (p < 0.00001) \), while the correlation for the values at point two varies
between 0.9825 \( (p < 0.00001) \) and 0.9025 \( (p < 0.00001) \) (Table 5.13). Likewise, at point three correlation
for the values varies between 0.9843 \( (p < 0.00001) \) and 0.9197 \( (p < 0.00001) \), while the correlation for the
values at point four varies between 0.9756 \( (p < 0.00001) \) and 0.9058 \( (p < 0.00001) \) (Table 5.14). Similarly,
the relationship between the average values from these four points during the days examined, varies
between 0.9949 \( (p < 0.00001) \) and 0.9556 \( (p < 0.00001) \). The highest average relative error during the
weeks examined is about 0.32 (32%) during the first week of December, whereas the lowest value is about
0.28 (28%) during the second week of December. As shown in figures 5.30-5.35 there are consistent
similarities in the pattern of daylighting in the room, however, the maximum levels of illuminance
measured are about 1000lux above the simulated illuminance levels about 20% of the time over the days
examined. Moreover, the levels of illuminance measured externally are also consistently higher than the
values simulated around midday. Nevertheless, the correlation between the measured and simulated
external illuminance levels ranges between 0.9903 \( (p < 0.00001) \) and 0.9486 \( (p < 0.00001) \), while the
average relative error range is between 0.20 (20%) and 0.30 (30%) (Table 5.15).

It was observed that sky conditions in Abuja remained constantly clear and sunny throughout the
measurement period in December, yet there are notable differences between the maximum values for
the measured and simulated illuminance levels. The external illuminance level and sky luminance were
measured on the site at 1 pm on December 15th, using the illuminance and luminance meters illustrated
in figure 5.27. It was found that the illuminance level and sky luminance at this time were around 82klux
and 250900cd/m^2. By contrast, the maximum external illuminance levels predicted in RadianceIES was
around 73klux on each day during the examined period.

In general, the results demonstrated that IES-VE is reasonably accurate in simulating the temperature
and lighting environment, particularly during the dry season when there is typically less variation in the
sky conditions. However, the accuracy of the predictions is dependent on the accuracy of the weather file available for the location. In some instances the weather file for Abuja does not accurately represent the conditions observed during the field work. Nevertheless, it is the most suitable choice available for predicting the thermal and visual conditions in buildings in Abuja because it provides data on the climatic conditions of the city over a number of years, whereas the data recorded during the field work only accounts for air temperatures and illuminance levels for 21 days during the dry season and 92 days during the rainy season. Whereas a relative error of up to 25% between measured and simulated data is considered acceptable as reported by some researchers (Acosta, Munoz, Esquivias, Moreno, & Navarro, 2015; de Hoyo-Meléndeza, Mecklenburga, & Doménech-Carbó, 2011; Mardaljevic, 1999), a 30% error is fairly high and could be misleading thus a correction factor was used to provide the researcher with more confidence in the simulated illuminance values.

In order to correct the simulated results, the average relative error was used to recalculate the average illuminance levels in the test room in case study building 8 during the 1st and 15th of December as well as the test room in case study building 5 during the 1st and 15th of June. The corrected values were calculated using an equation adapted from a previous validation study carried out by (Kim & Chung, 2011):

\[
\text{Equation 5.6} \quad CS = (S_v \times CF) + S_v
\]

Where;

- \(CS\) is the corrected simulation
- \(S_v\) is the simulated value
- \(CF\) is the average value of the relative error

![Figure 5.36 Measured, simulated and corrected results for test rooms](image)
The results of the corrected simulations were then compared with the measurement results. This comparison showed that the minimum relative error was 0.11 (11%) and the maximum relative error was 0.15 (15%) (Table 5.16). These values are in agreement with those reported by Al-Maiyah and Elkadi (2012), and Mantzouratos et al., (2004). These values are also much lower than the average errors reported by Kim and Chung (2011).

Table 5.16 Results of measurements and corrected simulations

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Note: “CF” denotes the correction factor, “REavg” denotes the average relative error.
Chapter five

5.7 CONCLUSION

The concept of investigating the thermal and visual performance of residential buildings in a city can be broad because of the complexity of the physical context and the multitude of approaches that can be used to evaluate building performance. Thus, the discussion in this chapter has been focused on specifying the approach used for the investigation in this particular study. The main elements of the approach used to conduct the analysis in this study include (a) a framework for defining the boundaries of the analysis, (b) a tool for predicting the conditions that are likely to occur in the selected cases under varying scenarios and (c) the review of the validity of the study tool as a means of partially achieving the aim of the study.

The framework established in order to carry out the analysis of the performance of residential buildings in Abuja in this study was discussed in section 5.2. The framework includes a set of performance models, including the adaptive model thermal comfort model and average illuminance model, for assessing thermal and visual comfort in buildings as well as relevant indicators for examining the impact of the climatic conditions and building design on the frequency and intensity of discomfort. Based on the literature review and the assessment of the studied context the key parameters that can be practically altered through design to improve the internal conditions in the housing sector in the examined context were also considered in the framework of the study.

The information gathered during a number of field visits over the course of the study was discussed in section 5.3. The field work subsequently informed the selection criteria for case study buildings analysed in the research. These buildings were selected because they represent the common residential building types available for low-income earners within the developed districts of Abuja.

The simulation and modelling tools are described in section 5.5. In order to establish consistency between the varying case study buildings the modelling and simulation procedures were set up to represent similar characteristics for each building. The IES-Virtual environment platform used in this study has been used to examine the thermal and visual performance of buildings in several studies in various climatic conditions. However, there does not seem to be any previous example of the software being used to examine the performance of residential buildings in Nigeria. Thus, in order to validate the
software an initial experiment was conducted in section 5.6 to compare the actual temperature and lighting conditions in selected test rooms with the corresponding conditions predicted using the software. Although it was found that there were notable differences between the measured and simulated air temperatures in the test rooms examined, the relative error between the two sets of values was consistently less than 10%. On the other hand, the range of relative error values measured and simulated illuminance levels in the test rooms varied between 20% and 66%. The high relative errors can be attributed to a number of factors, including discrepancies between the actual rooms and the models, the real and predicted sky types, as well as errors during the measurement process. Thus, in order to correct the simulated results a correction factor was used to recalculate the values predicted on December 1st and 15th (during the dry season and around the winter solstice), as well as June 1st and 15th (during the rainy season and around the summer solstice). The results from the correction reduced the relative errors significantly to a range between 11% and 15%.

The approach and findings discussed in this chapter were implemented in the ensuing analysis of the selected cases in Chapters six and seven. Hence, the correction factor calculated for the different times were used to correct the predicted values simulated during the dry and rainy season in the selected case study buildings.