The Use of Passive Cooling Strategies to Improve the Thermal Comfort of Mid-rise Contemporary Residential Buildings in Abuja, Nigeria

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ABSTRACT

This research delves into the crucial issue of enhancing thermal comfort in Abuja's residential buildings, while also addressing the pressing energy crisis, need for heightened level of comfort and sustainability in architecture. The central objective of this study was to investigate the use of passive cooling strategies in improving the thermal conditions of residents in Abuja.

The research focused on mid-rise residential buildings, examining the feasibility and effectiveness of various passive cooling strategies. Through an in-depth review of existing theoretical data, the administration of questionnaires, and extensive analysis through physical observation of selected mid-rise residential buildings within Abuja.

Passive cooling strategies, such as ventilative cooling, nocturnal cooling, radiative cooling, evaporative cooling, and earth coupling were reviewed. Specifically, the strategies adopted in the case studies were: Ventilative cooling, through appropriate window sizing, building orientation, form, and courtyard utilization, evaporative cooling, by incorporating green areas and vegetation in outdoor spaces. Lastly, heat gain prevention techniques by implementing appropriate building orientation, form, distribution of indoor spaces, thermal mass, and exterior building surfaces were also implemented.

Although, these strategies were considered effective by the occupants, it remains evident that their exclusive use will not suffice to achieve the desired level of comfort in Abuja's houses. Therefore, the adoption of renewable energy sources to power active cooling strategies is recommended.

Interestingly, the satisfaction levels of residents which is relatively high, as per the questionnaire, is in contrast with the results obtained from physical observations, highlighting the subjective nature of the questionnaire and thermal comfort within diverse climatic zones and individuals.

Despite the significant number of respondents expressing their desire for further implementation of these strategies, the research recommends that professional organizations, such as the Nigerian Institute of Architects (NIA) and the Nigerian Green Building Commission (NGBC), conduct further research, develop building codes and standards, and collaborate with the Federal Housing Authority to ensure the widespread implementation of these sustainable practices, while also raising further awareness of the society on the concept of passive cooling in buildings.

Keywords: Passive Cooling, Mid-rise Buildings, Thermal Comfort, Sustainability, Residential Building

ÖZ

Bu araştırma, Abuja'nın konut binalarında termal konforun artırılması gibi önemli bir konuyu ele alırken, aynı zamanda acil enerji krizini, mimaride yüksek düzeyde konfor ve sürdürülebilirlik ihtiyacını da ele alıyor. Bu çalışmanın temel amacı, Abuja'da yaşayanların ısıl komfor koşullarının iyileştirilmesinde pasif soğutma stratejilerinin kullanımını araştırmaktır.

Araştırma, çeşitli pasif soğutma stratejilerinin fizibilitesini ve etkinliğini inceleyerek orta katlı konut binalarına odaklandı. Mevcut teorik verilerin derinlemesine incelenmesi, anketlerin uygulanması, ve Abuja içinde seçilen orta katlı konut yapıları üzerinde fiziksel gözlem sayesinde, kapsamlı bir analiz yapılmıştır.

Havalandırmalı soğutma, gece soğutma, radyatif soğutma, buharlaşmalı soğutma ve toprak kaynaklı soğutma gibi pasif soğutma stratejileri incelendi. Özellikle vaka çalışmalarında benimsenen stratejiler şunlardı: Uygun pencere boyutu, bina yönelimi, bina formu ve iç avlu kullanımı yoluyla havalandırmalı soğutma, dış mekanlarda yeşil alanlar ve bitki örtüsünün birleştirilmesi yoluyla buharlaşmalı soğutma. Son olarak, uygun bina yönelimi, bina formu, iç mekân dağılımı, ısıl kütle ve bina dış yüzeyleri uygulanarak ısı kazanımını önleme teknikleri de uygulandı.

Her ne kadar bu stratejiler sakinler tarafından etkili görülse de, bunlar özel bir şekilde uygunlansada Abuja'nın evlerinde arzu edilen konfor düzeyine ulaşması için yeterli olmayacaktır.

Bu nedenle, aktif soğutma stratejilerini harekete geçirmek için yenilenebilir enerji kaynaklarının benimsenmesi tavsiye edilmektedir.

İlginç bir şekilde, ankete göre sakinlerin nispeten yüksek olan memnuniyet düzeyleri, fiziksel gözlemlerden elde edilen sonuçlarla çelişmektedir; bu da anketin, farklı iklim bölgelerindeki ısıl konforun ve bireylerin subjektif doğasını vurgulamaktadır.

Bu stratejilerin daha fazla uygulanması yönündeki isteklerini ifade eden önemli sayıda katılımcıya rağmen, araştırma, Nijerya Mimarlar Enstitüsü (NIA) ve Nijerya Yeşil Bina Komisyonu (NGBC) gibi profesyonel kuruluşların daha fazla araştırma yapmasını, bina mevzuatı geliştirmesini önermektedir. Ayrıca standartların geliştirilmesi ve bu sürdürülebilir uygulamaların yaygın şekilde uygulanmasını sağlamak için, Federal Konut İdaresi ile işbirliği yapılması, ve aynı zamanda binalarda pasif soğutma kavramı konusunda toplumsal farkındalığının arttırılmasını önermektedir.

Anahtar Kelimeler: Pasif Soğutma, Orta Katlı Binalar, Isıl Konfor, Sürdürülebilirlik, Konut

DEDICATION

This work is dedicated to my beloved aunt whom I lost during the course of my program. Her profound influence and kindness were a constant presence during my studies. This dedication is a tribute to her immensely impactful life on me. I carry her memory in my heart as I continue to pursue my studies, knowing that she is in Allah's embrace, watching over me with love and pride. May Allah's mercy shine upon her soul. May Allah's mercy shine upon her soul and may her unwavering support and boundless love continue to be a blessing from Allah throughout my studies and future endeavours.

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INTRODUCTION

1.1 Background of Study

Thermal comfort continues to be a vital criterion to all building users. In the past, it was achieved by designing buildings to acclimatize to the climatic conditions of their location while utilizing the natural resources available, in line with the experience of their conditions. However, in recent years contemporary buildings reflect the great inclination towards the aesthetics and innovative methods of construction and functionality by the use of technology among designers and users to achieve their desired needs.

Although man has mastered the art of providing comfort over the decades, it is only logical to expect that over the years due to the increased standards of living, there is a demand for a heightened level of comfort.

Today, the energy crisis caused by high energy cost and its demand, the unending need for a comfortable environment and proclivity towards sustainable architecture aiming at lowering the energy consumption of residential buildings with a particular interest on HVAC systems which are notable contributors to the total global energy consumption, all these have led to a resurgence in the use of sustainable design strategies. These include passive solar design, passive cooling and heating techniques, net-zero energy design, and the utilization of recycled, reclaimed, and low-emission materials all of which aim to minimize adverse environmental impacts, promote resource efficiency, and create healthier and more energy-efficient living environments.

Recent indoor temperatures in residential buildings within are said to be thermally uncomfortable, this is partly due to the temperature rises and continuous climate change as a result of rapid urbanization, increased population growth and the already existing climatic condition which presents high temperature coupled with cloud cover and high humidity experienced during a significant period within the year. Hence the adoption of passive cooling within Abuja is critical in achieving the desired level of comfort.

Passive cooling uses renewable sources of energy like sun and wind to provide cooling and ventilation in a space, this revolves around gaining and maintaining just the right amount of solar energy into the indoor environment and removing the humidified air out of it through the ventilation process.

To meet the growing energy and comfort needs there needs to be a rigorous shift in how they are sourced, realized and used, it is therefore imperative to adopt solutions that can provide the desired balance between effectiveness, minimal resources and maximum benefit.

1.2 Problem Statement

Despite the great potential of passive cooling strategies in contributing to the reduced energy consumption and improved comfort in buildings, most buildings in Abuja remain poorly designed for the climate and do not incorporate passive cooling strategies rather active systems like fans and air conditioners are the most widely adopted means of cooling buildings in order to mitigate thermal discomfort among building users, which is caused by the continuous rapid urbanization, population growth and existing climatic conditions within the city as experienced in most urban dwellings in recent years, resulting to the huge amount of energy consumed by residential buildings.

With the endless power crisis in Nigeria due to the lack of constant electricity supply till date and even its absence in some parts of the country, relying on active means to achieve comfort in buildings seems to be an unsustainable one. This further contributes to environmental issues as alternative sources of electricity like diesel generators are main contributors of carbon emission to the environment.

Although various research have been carried across the country on this subject, little to no research has concentrated on the contemporary buildings being delivered by the real estate sector, Therefore this research aims at bridging this gap.

1.3 Research Aim and Objectives

The aim of the research is to understand the practice of using passive cooling strategies to improve the thermal comfort of contemporary buildings in Abuja, Nigeria.

By fulfilling the following objectives:

- To identify and review the passive cooling strategies used in contemporary buildings;
- To ascertain the thermal comfort levels of users of mid-rise residential buildings in Abuja;
- To evaluate the appropriateness and effectiveness of the passive cooling strategies used in mid-rise residential buildings in Abuja;

- To determine to what extent additional passive cooling strategies could improve the thermal comfort of mid-rise residential buildings in Abuja.

1.4 Research Questions

The research aims at providing befitting answers to the questions listed below:

- What are the passive cooling strategies used in both traditional and contemporary buildings?
- What impact does the micro-climate of Abuja have on the thermal comfort experienced in the contemporary mid-rise residential buildings located within the city?
- How appropriate are the passive cooling strategies implemented in contemporary mid-rise residential buildings in Abuja, considering the micro-climate and user preferences?
- How can alternative sustainable approaches be employed to complement passive cooling strategies, contributing to the attainment of thermal comfort in present-day mid-rise residential constructions in Abuja?

1.5 Research Methodology

The research employed both quantitative and qualitative methods. Conducting a field study involving direct observation of three contemporary mid-rise residential buildings in the study area and the distribution of questionnaires to gather comprehensive information on the subject.

The selection of case studies involved a random sampling method, with careful consideration to ensure that each case study met specific criteria.

With an estimated average of two potential respondents in each household, a total population of 74 from 32 households was deduced in which a sample size of 62 was calculated using the Yamane's formula. Therefore, questionnaires were administered to 62 individuals to ascertain the levels of comfort in some residential buildings in Abuja. Additionally, the survey assessed the perception of the users on the appropriateness and effectiveness of the passive cooling strategies implemented in the selected case studies.

In addition to the primary data collected, secondary data was gathered through a literature review, including articles, journals, papers, and published books on the subject.

The data collected from the questionnaires underwent statistical analysis using Microsoft Excel and SPSS, where charts and tables were deduced. While the data collected from physical observations and the review of theoretical information were analysed through an analytical approach and further documented in the form of written texts and photographs.

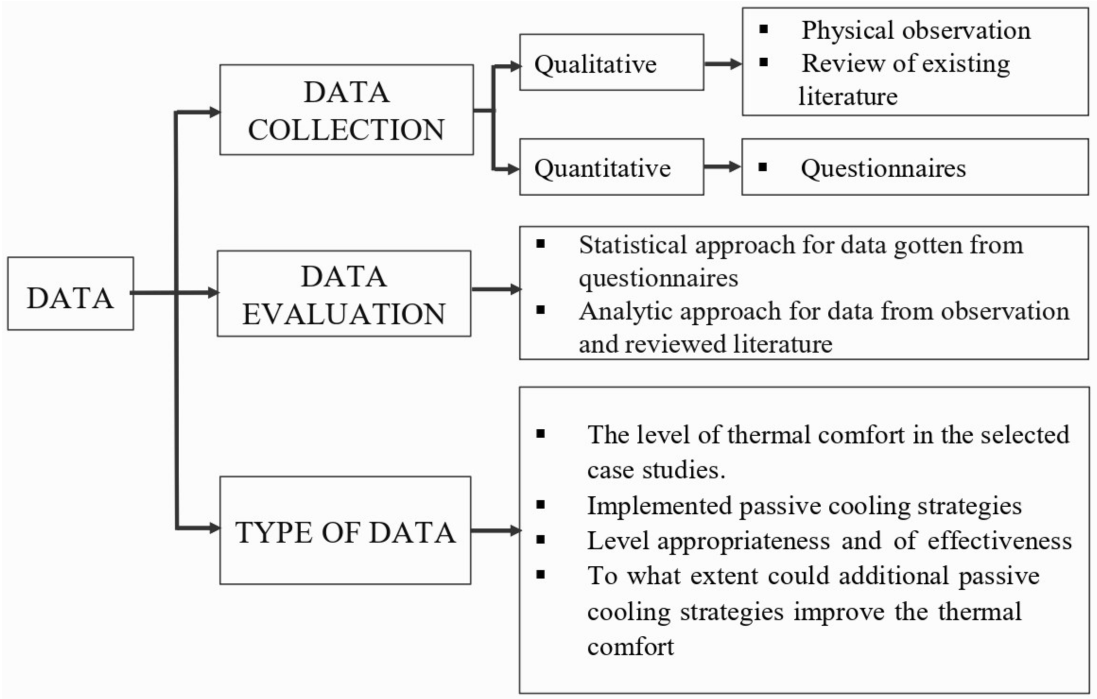


Figure 1: Summarised Research Methodology

1.6 Limitation

The city of Abuja was the selected study area as residential buildings within it characterise the challenges of thermal discomfort and high energy consumption due to high temperature, continuous population growth and urbanization. This is particularly notable as Abuja stands as the fourth most populous city in Nigeria. The emphasis was on enhancing thermal comfort conditions within residential buildings, given their heightened comfort and energy requirements in the building sector. The selection of case studies involved a random sampling method, with careful consideration to ensure that each case met specific criteria. These criteria included being contemporary and mid-rise, intended for middle or high-income earners with a high level of electricity consumption. Additionally, each case study had to feature a prototype design to provide insights from a representative sample size. Furthermore, it was a requirement that each case study represented a different building typology to facilitate the analysis of distinct features that could directly influence the required level of cooling within the buildings.

1.7 Thesis Structure

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

Chapter 1: This chapter gives an overview of the entire research establishing the context and the driving force behind the study, the intended goal and the methodology to accomplish it.

Chapter 2: This chapter examines the existing body of literature concerning passive cooling, encompassing its definition and methods of implementation. It investigates the potential of these strategies in attaining thermal comfort. Furthermore, the chapter provides insights into the concept of thermal comfort and the various comfort models and applications.

Chapter 3: This chapter introduces the study area and case studies, while giving a detailed description of the location, climate and case study selection criteria. The analysis of the passive cooling strategies adopted in the selected case studies according to: parameters affecting passive cooling within buildings, factors affecting cooling requirements in building spaces and additional means of achieving comfort within the buildings were also established.

Chapter 4: This chapter produces the deductions from the analysis completed in chapter 3 and the analysis of results gotten from the survey conducted among the residents of the selected case studies.

Chapter 5: This chapter summaries findings and provides general conclusions and recommendations for the implementation of passive cooling strategies and ways of achieving thermal comfort in buildings within Abuja. And also highlights areas of future research.

Chapter 2

LITERATURE REVIEW

2.1 The Use of Passive Cooling Strategies in Residential Buildings

Passive cooling is a building design approach that focuses on cooling by utilizing on-site energy available from the natural environment, combined with the architectural design of building components like building envelope rather than mechanical systems in a building (Niles & Kenneth, 1980), in order to improve the indoor thermal comfort with low or no energy consumption. (Santamouris & Asimakoupolos, 1996; (Leo Samuel, Shiva Nagendra, & Maiya, 2013). It encompasses all criteria and methods of transferring energy from one space to another in order to achieve a lower temperature than that of the surrounding environment and reduce the cooling demand of the building while maintaining a balance between the need for improved level of comfort, human well-being and the need to preserve natural resources and the ecosystem in general.

Some authors consider that minor and simple mechanical systems like pumps and economizers can be integrated in passive cooling techniques, as long they are used to enhance the effectiveness of the natural cooling process (Givoni, 1994).

Although passive cooling techniques are mainly strategies that expel trapped heat from the building interior space, the general concept of keeping a building cool and comfortable includes aspects of preventing buildings from overheating by the use of strategies that allow the building to gain just the right amount of solar energy needed in a space and prevent the excess and rash solar radiation from getting into the interior of a building.

2.2 Passive Cooling Strategies

The process of passive cooling operates on the principle of eliminating excess heat in a building to a natural body with lower temperature which could be air, water, the sky or ground as the case may be, all of which are referred to as heat sinks, this process depends on the availability of the natural body which serves as the skin and the thermal connection between it and building, they can act to either modulate heat gain with thermal mass or eliminate heat through natural cooling techniques which include: ventilation, nocturnal cooling, evaporative cooling, earth coupling and radiative cooling.

The bioclimatic chart, the solar diagram and the wind rose are relevant analysis tools before the application of different strategies (Brown & DeKay, 2001), furthermore the use of appropriate building layout is critical as it influences the effectiveness of some passive cooling strategies like ventilation by determining the wind that reaches the interior spaces as more compact forms tend to obstruct the free flow of air. The appropriate layout is mainly achieved through proper orientation of the building and zoning of spaces. Factors that may affect the building form/layout include: planning regulations, space availability, neighbouring site developments, architectural styles, client's preferences and cost constraints. (Santamouris & Asimakoupolos, 2013).

Buildings should therefore be located and oriented in ways that promote the flow of cold breeze from the outdoor space into the interior spaces through openings, additional features like trees could also the used to enhance this process by directing the cold breeze towards the building especially during the summer with the right placement. Human behaviours like the shutting and opening of windows and blinds is one way of improving ventilation process within a building.

According to previous research, passive cooling strategies that may be adopted in residential buildings within Abuja as they may produce favourable results in buildings within a hot-humid climate are discussed below, however further research was done within this study to ascertain the recommended strategies for the said location and their level of effectiveness.

2.2.1 Ventilation

Ventilation is the process of moving outdoor air into a building or room through purpose-built building openings like doors, windows, chimneys, wind towers etc. with the use of natural forces like wind and thermal buoyancy force, this occurs due to indoor and outdoor air density differences. The general purpose of ventilation in buildings is to provide healthy air for breathing by both diluting the pollutants originating in the building and removing the pollutants from it (Etheridge & Sandberg , 1996); (Awbi, 2003) which eventually provides occupants cooling.

A review on this strategy was done by (Aflaki, Mahyuddin, Mahmoud, & Baharum, 2015) pointing out its potential. Sahabuddin 2012 and (Priyadarsini, Hien , & David, 2008) were among the reviewed papers that made research in Singapore on cross ventilation and stack ventilation respectively as the two main ventilative strategies.

2.2.1.1 Cross Ventilation

This involves the passing of air from two sides of a space, serving as the inlet and outlet, the sizes of the two openings determines the direction and velocity of the ventilation process. Usually, an equal or greater area of outlet openings must also be provided to ensure adequate cross ventilation (Grondzik, Kwok, Stein, & Reynolds, 2010). Provision of windows in opposite directions as they align with each other is therefore recommended.

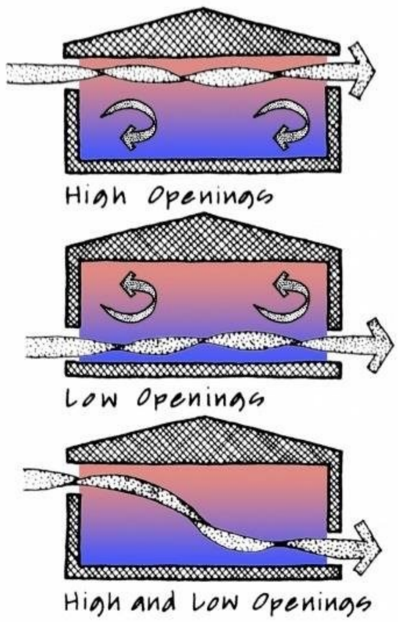


Figure 2: Cross Ventilation Illustration
Source: Brown G.Z, DeKay .M (2001)

2.2.1.2 Stack Ventilation

This is a process that relies on the buoyancy of warm dense air to rise and find an outlet through openings usually at ceiling height, while the cooler outside air coming from lower openings like normal height windows replaces it as the pressure difference due to varying air densities enables the process. Solar chimney works on this principle.

Provision of high-level windows is encouraged in order to enable the flow of cool and warm air in and out of the building.

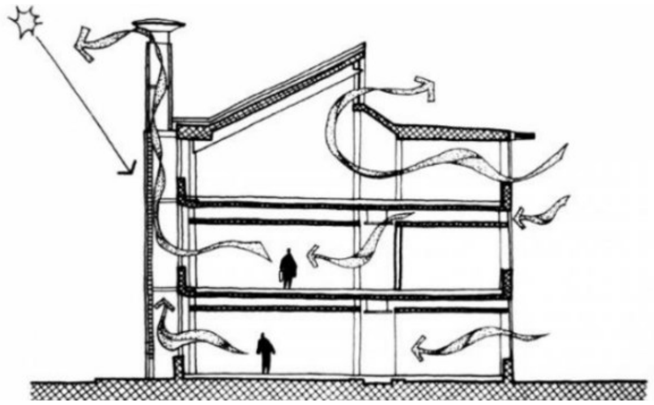


Figure 3: Stack Effect Principle in a Solar Chimney
Source: Brown .G .Z, DeKay .M (2001)

2.2.2 Nocturnal Cooling

Night cooling is a passive cooling strategy where the increased air movement at night cools a building, where the building envelope acts as a sink by storing heat gains from the environment, outdoor solar radiation and user's activities through roofs, ceilings and walls. At night, when the outside air is cooler, the envelope is opened, allowing cooler air to pass through the building so the stored heat can be expelled by convection. (Brown & DeKay, 2001). This process reduces the temperature of the indoor air and of the building's thermal mass, allowing convective, conductive, and radiant cooling to take place during the day when the building is occupied (Blondeau, Sperandio, & Allard, 1997).

Nocturnal cooling is most effective in climates with a large diurnal swing, i.e a large difference between the daily maximum and minimum outdoor temperature (Givoni, 1994). For the desired result, the night-time outdoor air temperature should fall well below the daytime comfort zone and should have little to no humidity. Thus, night cooling is more effective in sufficiently dry climate (Griffin , 2010), as the diurnal temperature swing is typically small, and the night-time humidity stays high in hot, humid climates. General limitations of this process include: the need for security, reduced indoor air quality, and poor room acoustics.

Santamouris et al 2017 suggested that it is one of the most effective strategies that could be adopted for buildings in the tropical regions. Nocturnal radiation showed that (Ezekwe, 1986) recorded a 12.2^{0}C difference between the sky and normal surface temperatures while measurements in, (Nwaigwe, 2011) recorded a temperature difference of 4.1^{0}C, this was similar to the difference recorded in (Ito & Miura, 1989)with a temperature difference of 3^{0}C this shows that the strategy is an effective one for buildings within the tropical regions.

2.2.3 Radiative Cooling

This is a process of achieving cooling through the transfer of excess heat gained during the day towards the cold atmosphere as a result of the significant difference in temperature between the outer space and earth, implementing this strategy on the roof is usually effective as it is the building structure that is most exposed to the night sky. Its effectiveness is influenced by varying climatic conditions as the desert and temperate regions have more potential of benefiting from it compared to tropical climates due to the effects of cloud cover and humidity in the regions, (Hanif , Zare , Saksahdan, & Metselaar, 2014) resolved that it could reduce energy saving of up to 25% with a temperature drop 9.55^{0}C and 10.53^{0}C under a cloudy and clear sky respectively.

Latent heat storage materials which are also known as phase change materials (PCMs) improve the thermal mass of materials as they store and release heat during the phase change process at a nearly constant temperature (Verbeke & Audenaert, 2018).

2.2.3.1 Direct Radiative Cooling

The roof surface acts as the heat sink directly absorbs solar radiation during the day. releasing at night-time. According to Al-Obaidi, Mazran & Abdul Rahman (2014) the use of reflective white paint gives the best result in terms of reflecting back solar radiation hence lowering heat gain, however the method of using reflective finishes is not long lasting as the reflectiveness gradually wears out with time due to harsh weather conditions and dust accumulation. (Tong, et al., 2014) conducted a study in Singapore on the impact of surfaces with high reflective ability, he found that a 0.1 increase in the roofs reflectivity resulted in a reduction of about 11% on the rate of heat absorption.

- **Cool Roofs**

Generally, roofs could be coated with reflective material to reduce the heat transfer and improve the rate of radiation from the surface, The first generation of materials used in cool roofs consisted of natural while the second generation was based on the development of artificial white materials designed to present very high albedo and third phase is the development of coloured high reflective materials (Santamouris, 2014).

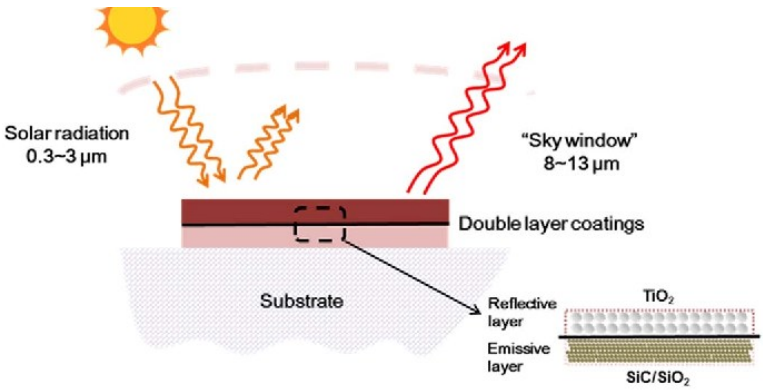


Figure 4: Direct Radiative Cooling
Source: (Bao, et al., 2017)

2.2.3.2 Indirect Radiative Cooling

The technique used to cool down the building structure indirectly involves cooling a fluid such as water or air through radiation to the sky, which is then stored in a specialized mass like rock bed, water tanks, or the building's structural mass. Alternatively, the cooled fluid can be directly flushed into the building. To implement this method, a metallic sheet can be placed over the roof, leaving a 5-10cm gap between it and the roof surface or the use of a plenum in between the roof and the radiator surface.

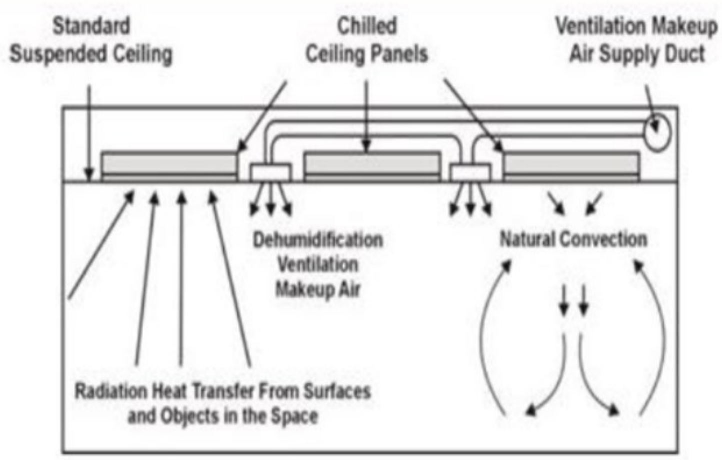


Figure 5: Indirect Radiative Cooling
Source: www.fairconditioning.org

2.2.4 Evaporative Cooling

Operates on the process of air temperature being cooled down as water passes from the liquid to gaseous state by extracting heat in the form of air, which occurs when the vapour pressure of water is lesser than the vapour in the surrounding temperature.

2.2.4.1 Directive Evaporative Cooling

This is the oldest and simplest form of cooling, done by drawing hot air from the outdoor into the building by going through an evaporative medium. Typical commercial evaporative coolers have an effectiveness of 50–70%. It can be considered a very effective solution especially for hot and arid climatic conditions. In regions where usually the outdoor temperature fluctuations are small and the humidity is considerably high throughout the whole day, direct evaporative cooling is not effective (Santamouris & Kolokotsa 2013). This technique is seen in working principle of ponds, fountains, water sprays, the use of a wet cellulose pad installed at the top of the tower which in turn cools the incoming air as the water in it evaporates.

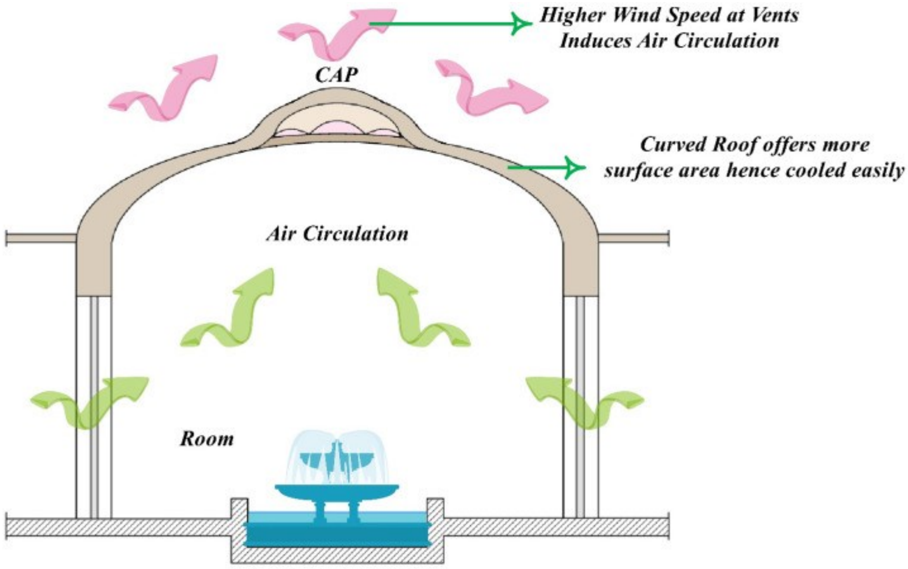


Figure 6: Pond and Fountain as Examples of Evaporative Cooling.
Source: (Yan-ling, Kamyar, Adnan, Ghaida, & Rasool, 2021)

- **Trees and Vegetation**

Adopting trees and vegetation in buildings could lower the temperature of the surround air through shading and evapotranspiration, it has been estimated that a full-size tree evaporates 1,460Kg of water on a sunny summer day which is equivalent to 870MJ of cooling capacity (Sherwood, 1991), trees could be used to provide shade to roofs, windows and other openings. Adopting trees on the southern façade was proven to lower the inside temperature of a building by 1.3^{0}C (Morakinyo , Kong , Lau, Yuan, & Edward, 2017) and the presence of a green space also resulted in the reduction of inside temperature by 2.6^{0}C (Sima, Chagolla-Aranda, Huelsz, Tovar, & Alvarez, 2015).

2.2.4.2 Indirect Evaporative Cooling

This involves the process of air-to-air heat exchange in order to expel heat from the air without adding to the moisture content in it as hot outside air is passed through a series of horizontal tubes that are wetted on the outside. A secondary air stream blows over the outside of the coils and exhausts the warm, moist air to the outdoors. The outside air is cooled without adding moisture as it passes through the tubes. Indirect evaporative cooling typically has an effectiveness of almost 75% (Santamouris & Kolokotsa 2013). Gupta (2017) studied evaporative cooling in a traditional building in India revealing that the indoor temperature can be reduced by 9.6^{0}C and a combination with a windcatcher could result in a temperature drop of 12-17^{0}C. The effectiveness of evaporative cooling is largely dependent on the humidity of the outside air as dryer air produces more cooling, although it is effective in general it may not always be suitable for all seasons in hot-humid climatic as it results in increased humidity levels.

- **Roof Pond**

A shaded water pond is installed over a non-insulated concrete roof. During the day, the roof is covered to block the absorption of solar radiation into the water body, but gets opened at night as the water body gets cooled by the cold night waves. During the day the cool water from the pond absorbs the heat from the building thereby cooling the interior space below. This technique is mainly effective in cooling just the floor directly below it, hence it is used in single storey buildings and is mostly recommended for hot climate so as to avoid heat loss during winter.

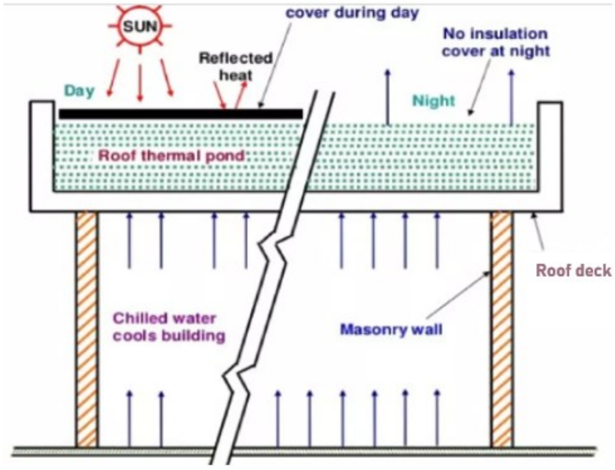


Figure 7: Indirect Evaporative Cooling Through a Roof Pond.
Source: (Gupta,2017)

- **Roof Spray**

As the surface of the roof is kept wet by spraying water on it, the sensible heat from it is converted into latent heat of vapourisation as the water evaporates, hence stopping the heat from getting into the building, causing a reduction in temperature this is generally achieved when the roof temperature is greater than that of the air.

According to Sutton (1950), covering a roof surface with a 0.05 mm or 0.15 mm water film can result in a temperature reduction of 23.4 °C and 26.2 °C respectively, which is significantly lower than that of a conventional roof. Blount (1982) states that assembling a water-spray system on large roofs of air-conditioned buildings can reduce cooling loads by 25%, while Jain and Rao (1974) also discovered that water spray can produce a greater temperature decrease than a water pond due to the more efficient evaporation of water in a mist form. The most important setback of this strategy is the attendant consumption of water, while the best climatic condition for it to work is in humid areas in terms of the availability of water, it is more effective in dry regions where water is less available.

- **Green Roofs**

This refers to the rooftop of a structure that has been partially or entirely adorned with plants and a cultivation layer, placed above a waterproofing barrier. It is categorised as either intensive or extensive. Although only a few studies have been carried out in tropical climates (Zingre, et al., 2015) to evaluate the use of green roofs. Its application leads to various advantages like: energy saving as it provides insulation thereby improving the rate of heat gain and loss through the roof, enhances the thermal comfort in hot climate by causing a significant reduction in indoor temperature of buildings while providing storm water management for buildings according to (Mentes et al, 2006; Gill et al. 2007; (Jaffal, Ouldboukhitine, & Belarbi, 2012), (Tian, Bai, Qi, & Sun , 2017); (Oberndorfer, et al., 2007). However, its initial installation cost is significantly higher than that of conventional roofs and that is one factor that inhibits its adoption in buildings.

Its effectiveness is influenced by the design, local climate and some building properties as the thickness and the thermal characteristics largely define its U-value and the corresponding transfer of heat to the building, watering is important as it determines the latent heat release and regulates the thermal balance of the roof. The impact of green roofs is more profound in non-insulated buildings. Additional cooling effect in green roofs can be obtained by increasing soil moisture through irrigation (Li, Bou-Zeid, & Oppenheimer, 2014).

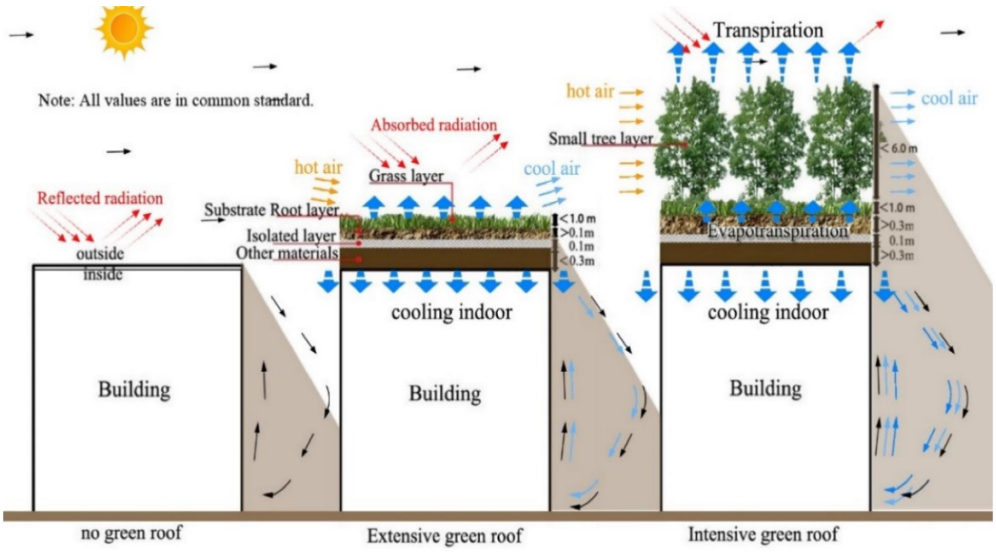


Figure 8: Cooling Through Green Roofs
Source: (Zhang, He, Zhu , & Dewancker, 2019)

2.2.5 Earth Coupling

Earth coupling is the use of the moderate and consistent soil temperature to cool a building through the process of conduction, mainly effective in hot climates, where soil temperatures are lower than the surrounding air temperatures. This could be achieved through:

2.2.5.1 Direct Coupling

When a building uses earth as a buffer for the walls. Earth sheltering improves the performance of building envelopes by reducing heat losses and also reduces heat gains by limiting infiltration (Kwok & Grondzik, 2011).

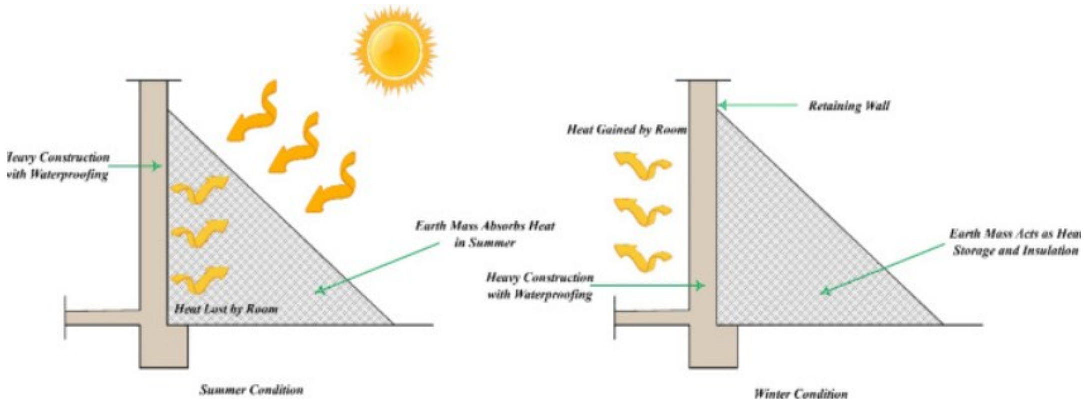


Figure 9: Direct Earth Coupling
Source: (Yan-ling, Kamyar, Adnan, Ghaida, & Rasool, 2021)

2.2.5.2 Indirect Coupling

The earth to air heat exchange (EATHE) technique is the most common method of indirect earth coupling, as a building is coupled with the earth by means of earth ducts buried beneath the ground that act as an avenue for air to travel through, with one end connected to the house and the other to the outside. The supply air drawn by a fan is cooled by conductive heat transfer between the tubes and surrounding soil. Therefore, earth ducts will not perform well as a source of cooling unless the soil temperature is lower than the desired room air temperature (Kwok & Grondzik, 2011). Earth ducts typically require long tubes to cool the supply air to an appropriate temperature before entering the building. Some of the factors that affect the performance of an earth duct are: duct length, number of bends, thickness of duct wall, depth of duct, diameter of the duct, and air velocity.

Sawhney, Buddhi & Thanu (1998) recorded a lower temperature of 27^0C at the outlet of the tunnel compared to that of 42^0C of the ambient temperature while using a 75mm long tube from a study carried out in a house in India. Ogbonnoya & Iheanyi (2019) showed the adoption of a ground pipe reduces the adoption of air conditioners by a large percentage as it aids the cooling and ventilation process.

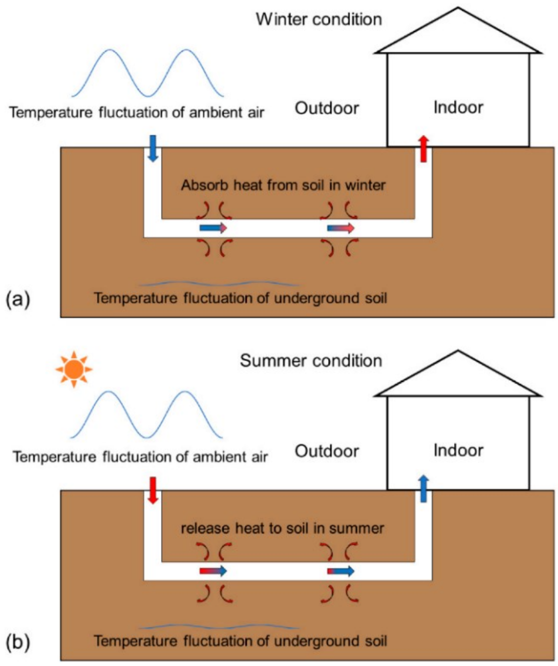


Figure 10: Earth to Air Heat Exchange
Source: (Chong, Jinbo, Liao, Feifiei, & Wenjie, 2020)

2.3 The Adaptation of Passive Cooling Strategies Used in Residential Buildings within Nigeria

Due to the high temperature within Nigeria, discomfort is mainly caused by overheating of the building envelope, this partly explains the inclination of most building approach of achieving comfort towards the measures of preventing excessive heat gain in order to avoid overheating, hence the adoption of passive solar control by the use of thermal insulation, appropriate orientation, shading in form of overhangs, awnings, louvres, glazing, trees and vegetation etc. however they do not actually produce cooling effect but rather reduce the building's cooling demand This is clearly seen from the vernacular to the contemporary architecture in the country.

In Nigeria most contemporary buildings are poorly designed for the climate and do not incorporate passive cooling strategies rather active systems like fans and air conditioners are used to cool buildings and achieve comfort as thermal discomfort continues to be a major challenge faced by the residents of Nigeria (Eziyi , Akunnaya , Albert, & Dolapo, 2013). This contributes to the challenge of energy consumption in buildings within Nigeria which is aggravated by extreme high temperature and intense solar radiation.

However, for a country where just 55% of its population have access to electricity according to World bank (2020) with a 5,500MW electricity supply out of over 13,000MW generation capacity for about 200 million people leading to erratic power supply and lack of energy in some parts of the country (Okon, 2022). The reliance on the use of active systems through the use of electricity to achieve thermal comfort in buildings seems to be an unsustainable one.

Although it can be said that building users prefer cooling by passive means according to (Chukwuma-Uchegbu, et al., 2020), the use of advanced strategies like green roofs, roof ponds are however less often, this may be due to: additional cost of installation and maintenance, limited availability of resources, low knowledge and experience concerning the strategies as they are not often implemented and also involve a high level of technicality.

Vernacular buildings in the past were more often comfortable than not with passive strategies due to the unpopularity, in-availability and even the absence of active systems to an extent, therefore building professionals were made to conduct extensive research and observations on how to be comfortable in the absence of active systems as time went on. Although Saad (1981) could not ascertain the level of awareness of thermal comfort within traditional building users and builders within northern Nigeria, it could therefore be argued that the comfort features implemented by local builders like building form and materials among others which seem to consider thermal comfort requirements were coincidental, i.e., technical and cultural requirements happen to operate in line with comfort requirement rather than thermal comfort being considered deliberately by the builders (Sa'ad, 1991).

However, this does not negate the fact that most buildings achieved comfort through the use of readily available materials like earth, thatch, timber and stones. The main source of achieving thermal comfort in buildings was through the use of mud bricks for walls and even roofs in some cases, due to its poor thermal conductivity it was slow in heat transfer thereby serving as a buffer between the indoor and outdoor space, by allowing the interior spaces to maintain moderate temperature during the day, at night when the outdoor space was cool it begins to radiate off, but this has gradually faded away as most building walls are now built with sandcrete blocks. The passive cooling strategies that have been adopted over the years in buildings within Nigeria include: ventilative and evaporative cooling by adopting building features like courtyards, water ponds, vegetation, fountains and openings.

2.3.1 The Use of Courtyards to Enhance Cooling

A courtyard is a central open space that is partially or completely bounded by the walls of a lager building, improving natural ventilation, lighting and shading to the surrounding spaces, although its adoption has been linked back to old Egyptian architecture at around 2000 B.C (Berkovic , Yeziero, & Bitan, 2012). Others believe it dates even farther back to neolithic settlements with no particular origin (Edwards, 2006). It serves as a space for social activities, leisure and provides security (Edwards, Sibley, Hakimi & Land, 2006; Agboola & Zango 2014) although its function is mainly influenced by religious and cultural customs as it was in the case of vernacular architecture.

Figure 11: Floor Plan of a Hausa Vernacular Residential Building in Kano with a Courtyard
Source: Adeyemi, 2008

Courtyards have been usually considered to act as a medium for modifying microclimate thereby improving comfort within buildings (Akande 2010; Ignacio et al 2018) due to their capacity to moderate high temperatures, direct gentle wind and regulate the amount of humidity (Taleghani et al., 2012) provided the right design parameters like depth, width, geometry and orientation are rightly implemented.

It works in different phases depending on the time of the day, at night cold surrounding air flows into the courtyard and through to the surrounding interior spaces, in the afternoon it serves as a heat sink by storing the cold air as it exchanges it with the warm air from the surrounding interior spaces while the warm air coming from the interior spaces rises up and gets expelled through the courtyard. Giovani (1994) suggests that it is one of the most suitable passive strategies to be used in buildings especially in hot-dry regions. Functions of the courtyard are usually supported by other features like trees, pools, fountains etc.

2.3.2 Evaporative Cooling Through Water Ponds and Vegetation

One would find water pools created by soil excavation, in vernacular settlements, ideally these should improve the relative humidity during the dry period but they sometimes dry up in during the dry season thereby not being so effective in traditional form (Saad,1991). These were also provided to enhance the cooling process of the courtyard as the water from the pond evaporates and escapes through the opening. Pools are however also used in contemporary buildings and the cooling effect through evaporation is achieved successfully with no adverse effects especially in dry regions, oftentimes it is used in the presence of fountains providing a repetitive process.

Trees and other vegetation of various types have always been present in the built environment and other than just providing comfort through shading, the loss of water content from the leaves which is known as evapotranspiration causes a reduction in the surrounding temperature hence causing a cooling effect.

Figure 12: The Use of Vegetation in a Residential Estate in Abuja
Source: www.nigerianproperty.com

2.3.3 Openings to Achieve Stack Effect

Ventilation in vernacular buildings through openings was not given much attention as factors like privacy, security and protection against harsh weather conditions like wind, rain and sun were given a higher priority, walls with openings were also observed to erode faster than blank walls therefore sizes of openings were minimised as doors were placed at a low level of just above a meter while windows were placed high above normal level, although these placements were done for the factors mentioned above, they also promoted natural ventilation through the stack effect. Contemporary buildings however show a better knowledge of window placements and adequate wall to window ratio as seen in buildings around us today.

Figure 13: A Façade of a Vernacular Building Showing Door and Window Placements in Kano
Source: www.pinterest.com

2.4 Factors that Affect the Passive Cooling Levels in Buildings

According to Santamouris and Asimakopoulos (2013), specific parameters directly impact the rate of passive cooling in buildings. These parameters encompass micro-climate and site design, building orientation, building form and layout, apertures, solar control and thermal mass. Additionally, the exterior surfaces of a building are considered to affect the passive cooling levels within a building according to (Hatamipour, Mahiyar, & Taheri, 2007). A summarized explanation of the influence of these parameters are given below:

2.4.1 Micro-climate and Site Design

Micro-climatic factors such as wind and sun play a crucial role in passive cooling strategies for buildings. As these strategies are designed to either prevent overheating by blocking solar radiation from entering interior spaces or to promote cooling by facilitating the ingress of comfortable wind. Consequently, the availability and influence of these factors are paramount when selecting an appropriate passive cooling strategy for a specific location. Site design features like trees and fences can be utilized to optimize these factors, further enhancing the cooling potential. Additionally, the site layout directly impacts the rate of air movement and exchange within building blocks.

2.4.2 Orientation

In hot-humid regions, the design of buildings requires meticulous planning to prevent excessive solar radiation from reaching both the exterior surfaces and interior spaces. According to Lorraine (2007), the orientation of the building is a critical factor in determining the potential solar gain and the entry of prevailing winds. Therefore, analysing the adoption of the appropriate orientation greatly influences the cooling levels within building spaces.

2.4.3 Building Form and Layout

A building's form and layout determine its form factor which in turn influences how it interacts with micro-climatic factors like sun and wind, by determining the area of the building envelope that is exposed to solar radiation, or surface that promotes heat loss. Striking a balance in the compactness level of building is critical because while a compact building is needed to avoid solar heat gain it is often disliked as it impedes air flow and exchange within blocks.

The appropriate layout of spaces is only achieved through optimal distribution of spaces. In order to achieve this, factors like the building user behaviour and occupancy patterns, and internal heat gain levels in interior spaces are what serve as guides, as spaces that are characterised with high activity and occupancy patterns as well as internal heat gains typically have higher cooling demands.

2.4.4 Apertures

These are known to be one of the most critical elements in a building envelope and are most often the source of cooling in buildings through natural ventilation. However, they can be one of the weakest points due to their ability to promote heat gain when inappropriate design features like size, glazing type or position are implemented.

2.4.5 Solar Control

Integration of solar control measures within buildings in hot-humid climate is necessary as it is one of the core means of reducing direct exposure to sunlight, furthermore, they mitigate heat absorption and transmission via the building envelope thereby preventing overheating and causing a reduction in the cooling loads within building spaces. Therefore, in order to maintain a cool indoor living environment, it is critical to implement the appropriate shading control which may vary according to the orientation and surfaces it may be applied on.

2.4.6 Thermal Mass

A building components thermal mass is its capacity to absorb, store and release thermal energy. Although its requirement level varies from one zone to another. Its adoption in hot-humid climates is mainly to even out significant temperature differences between the indoor and outdoor temperatures, enhance ventilation and allow the interior spaces to benefit from the cool outdoor temperature during night-time. During the day, it maintains a cool indoor space when shaded without the building interior being heated due to its low heat retention capacity.

2.4.7 Exterior Surfaces as Absorbers

The absorption rate of exterior surfaces in both the building envelope and outdoor surroundings directly influence the solar heat gain within interior spaces, as a result the adoption of surfaces with low absorptivity coupled with high reflectivity serves as a way of reducing the cooling loads within the interior space of a building.

2.5 Factors that Determine the Cooling Requirement Within a Building

According to Santamouris and Asimakopoulos (2013), the cooling levels required within a building is influenced by certain parameters as listed below:

- Building user behaviour
- Occupancy patterns
- Internal heat gain levels.

2.6 Thermal Comfort

According to the international standard ISO 7730, thermal comfort is that condition of mind which expresses satisfaction with the thermal environment. In simple words, it is the comfortable condition where a person with a normal clothing level is not feeling too hot or too cold in order to maintain a definite internal body temperature of 37^{0}C irrespective of the heat generated within the body and the environment as it is essential to the health and well-being of individuals.

Achieving thermal comfort across all fronts can be tedious therefore it is most often not expressed in degrees as it is not a stand-a-lone concept but rather an interrelationship of different factors and may vary between individuals. However, according to the comfort standards there is a reasonable comfort level when 80% of the occupants are satisfied.

2.6.1 Factors that Affect Thermal Comfort in Buildings

According to Fanger (1970) factors that affect the thermal comfort within individuals involve both environmental parameters: air temperature, air velocity, humidity, radiant heat and personal parameters: metabolic rates and clothing choices, he had made further investigations of some second order parameters like age difference, sex difference, geographic difference, and race difference and it appears that they have little effect on the preferred comfort temperature. These factors were grouped by Schittich (2011) under the room, occupant and climate categories as represented below.

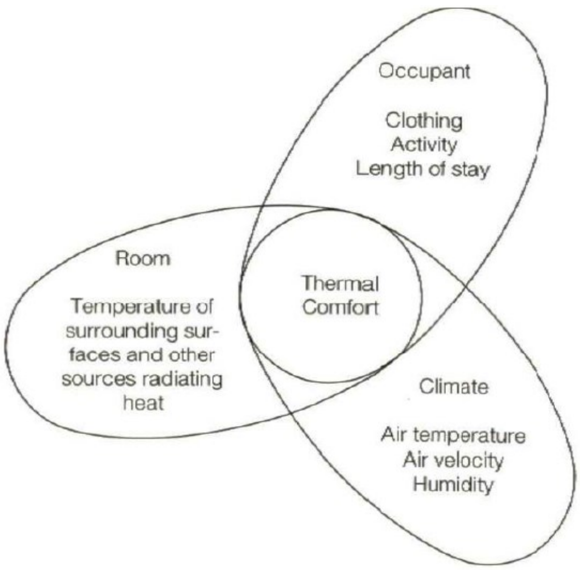


Figure 14: Factors Influencing Thermal Comfort in Buildings.
Source: (Schittich, 2011)

2.6.1.1 Air Temperature

With high air temperature in a space, the body automatically works harder to keep the body temperature within the required range, through the process of transpiration however when it is not sufficient it leads to a feeling of discomfort, when air temperature is too low to the extent that it is lower than the skin temperature it encourages heat loss from the body, making us feel cold. ASHRAE 55 standard recommends temperature values of 24.5^0C for optimum comfort with an acceptable range of 23-26^0C during summer and 22^0C with an acceptable range of 20^0C-23.5^0C during winter, although it has a low level of influence of 6% on thermal comfort.

2.6.1.2 Radiant Heat

This is the heat radiated from the surfaces within a space, when a surface has a higher temperature than the surrounding air temperature it releases some of it into the building space. Although radiant temperature cannot be measure by a basic thermometer as it may not always influence the air temperature, it can be measured by a surface thermometer.

The temperature of surfaces like walls can however be improved during the winter by the adoption of radiant heating units and heated facades in a bid to control the temperature drops and improve the comfort of the space by 50%.

2.6.1.3 Air Velocity

This is known as the rate of air movement within a space. Low air velocity leads to a place feeling stuffy and uncomfortable while high velocity aids in the process of cooling through convection. The air velocity within a space is recommended to be less than 0.15 m/s as shown in Figure 14, by an operative temperature between 20^0C to 22.5^0C, although it can be increased to 0.8m/s when the operative temperature is within 22.5^0C to 24.5^0C and can be improved by cold surfaces and ventilation systems. Kai-An (1985) carried out a study on college students and found that there was a higher level of comfort with the introduction of a fan which increased the air velocity in the space and the increase in air velocity also offsets the temperature of the surrounding.

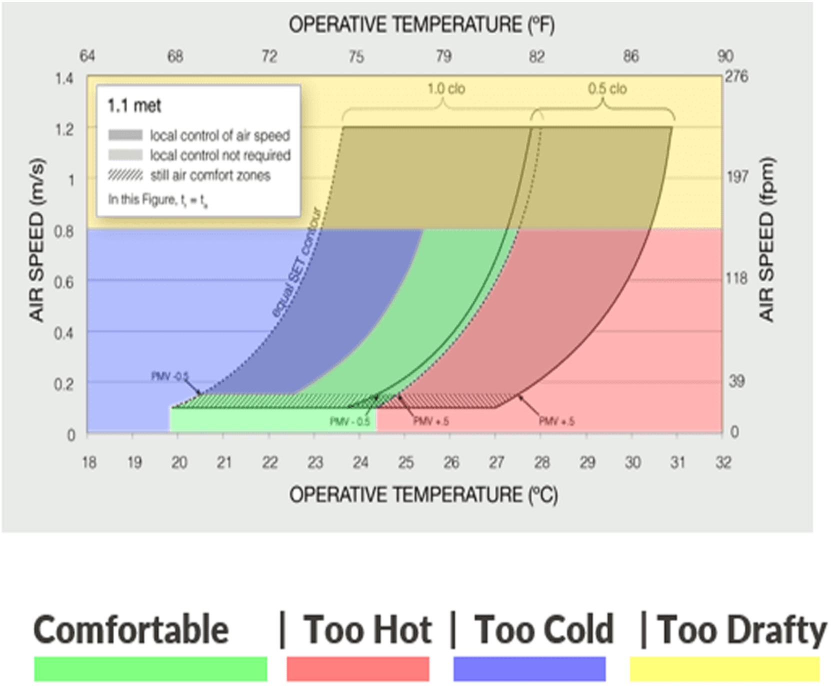


Figure 15: Air Speed and Operative Temperature Comfort Chart.
Source: (Jenkins, 2022)

2.6.1.4 Humidity

This is the amount of water vapour in the air. The fact that the human skin relies on air to get rid of the moisture from it when we perspire in the form of sweat makes humans sensitive to humidity, as regulating the body through precipitation is the body's main method of maintaining its desired temperature, because when sweat evaporates off the skin the core body temperature cools down causing a feel of relief, however, if there is too much moisture in the air, this process is inhibited causing individuals get drenched in the sweat, leading to discomfort which usually occurs when humidity is above 70%. Low relative humidity of below 20% can lead to dry surrounding air causing: irritations, drying of skin, eyes and mucous glands while also making sweat to evaporative at a faster rate causing the body to feel cold (Canadian Centre for Occupational Health and Safety, 2018). A humidity level of within 30-60% is recommended by the ASHRAE 55 standard.

2.6.1.5 Activity Levels/ Metabolic Rates

The metabolic rate in humans is responsible for the level of heat production within the body as energy is released from digested food to the body organs. The heat released from the body is directly related to the active cells within the body and the different parts of the body parts involved, therefore it differs from one activity to the other, hence, metabolic activities result in heat that must be continuously dissipated and regulated to maintain the appropriate body temperature which is at 37^0C.

2.4.1.6 Clothing

ASHRAE (2010) considers clothing as a form of thermal insulation to the body which has the ability to influence the heat transfer within the body thereby affecting the heat balance process, this eventually determines the level of thermal comfort experienced by an individual. It influences the rate at which the body produces and evaporates sweat. Newsham (1997) suggested that clothing adjustment may be the most influential of all thermal comfort factors available to occupants in the office building.

2.7 Development of the Concept of Human Thermal Comfort

The concept of thermal comfort involves different aspect of building physics, mechanical engineering, physiology and even psychology with its importance revolving around the need to: provide a satisfactory condition for people, control energy consumption and to suggest and set standard according to (Nicol, 1993).

The first development concept began by a British physician in 1774. Afterwards, engineers and physiologists developed different indices relating temperature to comfort, and now, building physicists use different thermal comfort standards. A literature review of the current knowledge on thermal comfort shows two different approaches for thermal comfort, each one with its potentialities and limits: the heat-balance model and the adaptive model (Doherty & Arens, 1988).

2.7.1 The Heat Balance Approach

It is based on the principle of heat flow and transfer in and around the body which resulted in a model on the basis of physiology and physics while being supported by data acquired from climate chamber studies which is a method of achieving steady-state thermal comfort models by conducting the research in an environmental test chamber that can have different climatic parameters. The personal variables (clothing insulation and metabolic rate) are determined by the task, and are normally assumed to be fixed. The most important reason to use such a steady-state situation is the ability to produce the desired environmental conditions (air temperature, radiant temperature, air velocity, humidity) while controlling unwanted variables, which might influence the results (Taleghani, Tenpierik, Kurvers, & Dobbelsteen, 2013).

The best well-known heat-balance models are the predicted mean vote (PMV) (Fanger, 1970) and the standard effective temperature (SET) (Gagge, Fobelets, & Berglund, 1986). The PMV model is particularly important because it forms the basis for most national and international comfort standards.

2.7.1.1 Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD)

The PMV index is a tool that forecasts the average response of a large group of individuals based on the seven-point ASHRAE thermal sensation scale, which ranges from -3 (cold) to +3 (hot), as illustrated in table 1, To assess the proportion of the group who might be unhappy with the surroundings in terms of PPD, PMV has been expanded. PPD determines the percentage of individuals who voted outside the neutral three-point range on the ASHRAE scale (votes -3, -2, +2, +3), which were considered dissatisfied. The PPD value is derived from the PMV value. It is a characteristic of the PPD index that its value does not in practice fall below 5% for any value of the PMV. The reason for this fact is the difference in thermal sensation between individuals; the thermal neutrality for different people is achieved at environmental parameters, which are not identical (Markov, 2002).

Table 1: Seven-point Scales Usually Used in Thermal Comfort Assessment
Source: Nicol et al 2012

ASHRAE Scale	
Descriptor	Number
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

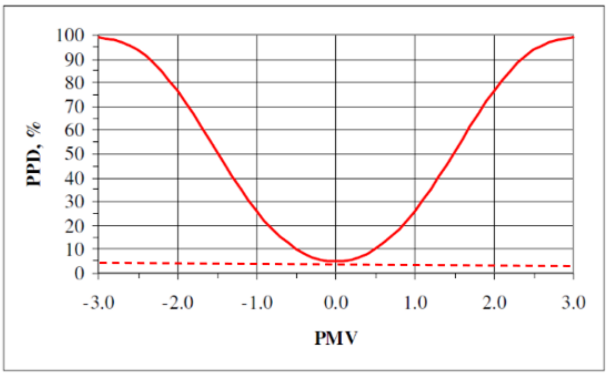


Figure 16: PPD as a Result of PMV
Source: (Markov, 2002)

Although this model has been used to assess thermal comfort worldwide for more than 40 years. It showed that it was largely accepted while others showed inconsistencies (Howell & Kennedy, 1979; Humphreys & Nicol, 2002) due to its limited application range as it was derived from the climate chambers studies and its validity. A review of thermal comfort among occupants of naturally ventilated spaces found that the indoor temperature that is regarded as most comfortable its prediction increased significantly in warmer climatic contexts, and decreased in colder climate zones (De Dear, 2004) showing that it is not possible to control passive buildings to the extent in which mechanically run buildings are within a single temperature. This was supported by (Nicol F. , 2004) as he pointed out that due to the lack of consideration for adaptive behaviour of humans, the prediction of the PMV model in a naturally ventilated building will overestimate the thermal sensations of subjects in high-temperature environments, yet underestimate thermal sensations of subjects in low-temperature environments. Other studies also found that there were differences between the actual and predicted values of the PMV model.

Therefore, the model based on heat balance approach is appropriate for mechanical heating or cooling buildings but not for free running passive buildings (Nicol & Roaf, 2007).

2.7.1.2 SET Model

The SET thermal comfort model was developed based on the two-node model of human temperature regulation (Gagge, 1986). This model continued to get gradual acceptance within studies as it was suitable for dynamic conditions and could also predict the body’s skin temperature and skin moisture unlike the PMV model which does not predict the psychological response of the body.

(Omrani, Garcia-Hansen, Capra, & Drogemuller, 2017) and (Nguyen, Singh, & Reiter, 2012) among other studies suggest that considering the mode of operation while adopting the SET method is not necessary.

2.7.2 The Adaptive Approach

The adaptive approach employs field surveys based on the fundamental assumption of that if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort (Nicol et al., 2012), this could be done through physiological adaptation, psychological adaptation or behavioural adaptation (Roaf, Nicol, Humphreys, Tuohy, & Boerstra, 2010). It is influenced by the local climate, cultural and social environment. Adaption through a change in behaviour is the most significant way of achieving comfort, this could be done by changing: clothing choices, activity levels, individual location within a building, drawing of blinds and even the use of mechanical systems. This model is adopted in the ANSI/ ASHRAE and the European standard EN 15251.

2.7.2.1 Field Survey

A thermal comfort field survey is an on-site vote of comfort within a defined population by implementing the 7-point ASHRAE scale of thermal sensation accompanied by measurements of the environmental condition of the area. It is the best instrument of adaptive approach.

It is aimed at studying thermal comfort in the existing context as research are conducted while subjects go about normally with their activities with no attempt of their environment being controlled which may have varying factors. In many surveys metabolic rates, clothing choices, temperature among others are documented. Additionally indirect factors like psychological and cultural factors affect the results of a field study.

2.8 International Comfort Standards for Indoor Environment

Comfort standards are a set of recommendations deduced from extensive research to serve as guide in providing buildings that will be comfortable and not frustrate the vast majority of the users.

Although many standards do exist the most widely adopted ones are: ASHRAE-55 standard, ISO 7730 standard and CEN EN 15251 standard.

2.8.1 ASHRAE-55 Standard

It is a comfort standard sponsored and controlled by the American Society of Heating Refrigerating and Air conditioning Engineers which aims at giving the right combination between indoor thermal environment and personal parameters in order to achieve comfort. The standard is globally accepted and implemented even though it is an American standard as data was gotten from field studies spread across numerous regions and the global market is being dominated by US air-conditioning industry.

It was developed after a rigorous string of research by deDear & Brager (1997) from different studies within Austrlia, U.K, U.S.A, Canada, Greece, Pakistan, Singapore, the results of the study implied that the thermal responses of occupants is influenced by the outdoor temperature and may be different for mechanically run buildings. Thus, it further incorporated the six factors that have an influence on the thermal comfort of buildings as proposed by Fanger (1970), becoming the first standard to implement the adaptive approach after originally being developed and used based on the PMV and PPD models of approach which adopts the use of the ASHRAE 7-point scale consisting of seven ratings in form of: cold, cool, slightly cool, neutral, slightly warm, warm equally represented with the use of numbers from -3 to +3.

The standard defines acceptable zones using the relationship between indoor comfort temperature and outdoor temperature as shown in Figure 16. These zones are expected to be accepted by 80% of users for typical applications and by 90% when a higher standard is desired, deduced from the equation:

$$T_{accept} = 0.31T_0 +/- T_{lim} \quad (1)$$

Where T_{accept} represents the acceptable zones limits, T_{lim} is the range of acceptable temperature which was earlier defined as the mean outdoor temperature.

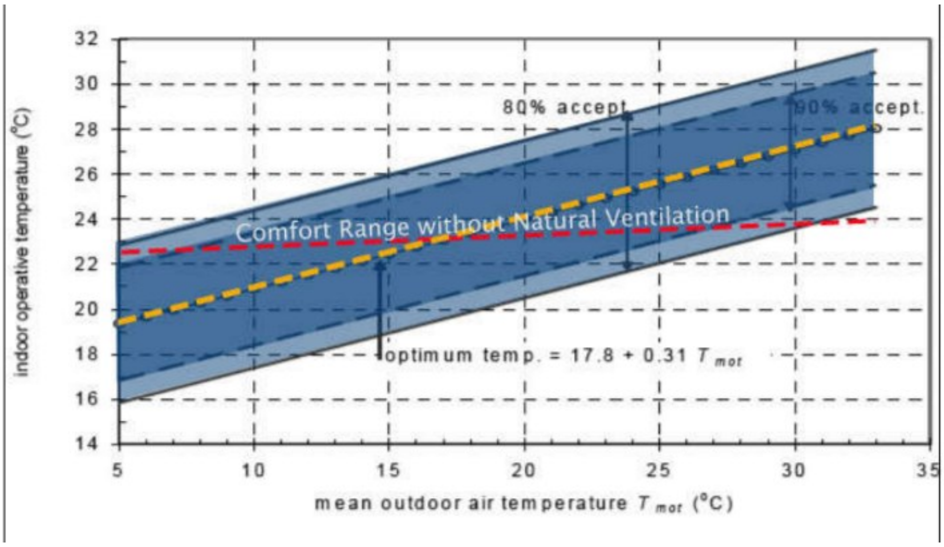


Figure 17: Adoptive Comfort Range Recreated from ASHRAE Standard 55
Source: (Raychoudhury, 1994)

2.8.2 ISO 7730 Standard

The standard is sponsored by the International Organization for Standardization. It presents methods of predicting thermal conditions that will be considered acceptable and thermal dissatisfaction i.e degree of discomfort using the PMV and PPD models through analytical determination and interpretation within moderate environments. Adopting the operative temperature within the range of 24.5^{0}C and 22.0^{0}C in the summer and winter respectively, these aligns with the recommendation of the ASHRAE standard as it was developed in line with the revised ASHRAE 55 standard.

According to Kontes et al 2017 the standard operates on 3 different comfort categories based on the PPD percentage range the categories are as follows:

i. Category A: For buildings whose occupants have special comfort needs e.g children and elderly;
ii. Category B: Normal comfort needs used for new and renovated buildings;
iii. Category C: Already built, less energy-efficient buildings.

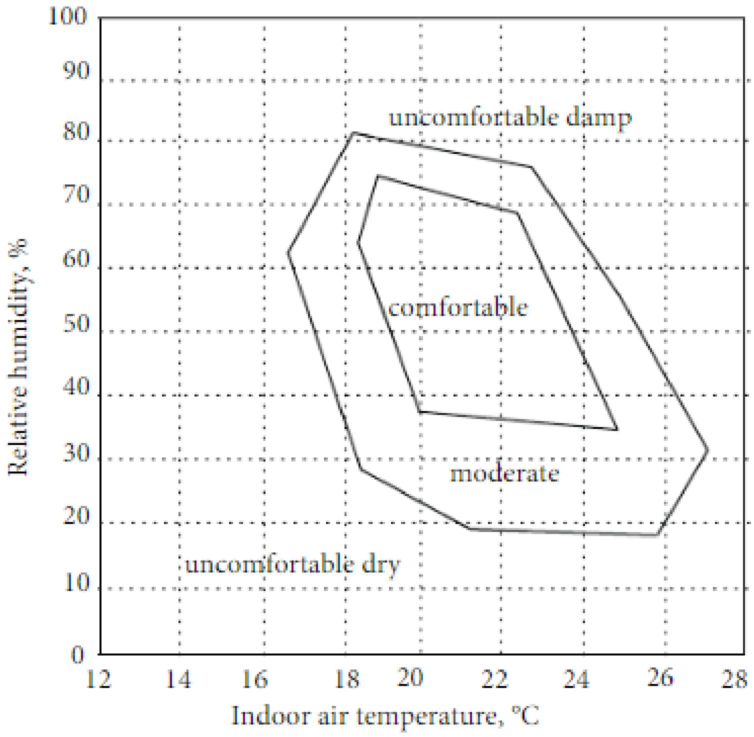


Figure 18: Comfort Range According to ISO 7730
Source: Kontes et al, 2017

2.8.3 CEN EN 15251 Standard

This is the European standard developed by the Comité Européen de Normalisation in a bid to support the Energy Performance of Building Directives (EPBD). Adopting the basis of building comfort assessment through the use of PMV models and also the adaptive approach.

It specifies how to establish indoor environmental input parameters for building system and energy performance calculations, methods for long term evaluation of the indoor environment obtained as a result of calculations or measurements and gives parameters to be used for monitoring the indoor environment in existing buildings. Mainly applicable to non-industrial buildings where the criteria for indoor environment are set by human occupancy and where the production or process does not have a major impact on indoor environment. The standard is thus applicable to the following building types: single family houses, apartment buildings, offices, educational buildings, hospitals, hotels and restaurants, sports facilities, wholesale and retail trade service buildings (EN 15251:2005).

It adopts building categories based on the nature of the building rather than the factors of indoor air quality as it was used in the ISO 7730 standard to avoid giving advantage to the high energy building. In this standard both naturally ventilated and mechanically cooled buildings in one category.

Data was collected from the Smart Controls and Thermal Comfort (SCATs) project with a standard set of instruments over the same period. In this project, 26 European buildings in France, Greece, Portugal, Sweden and the UK were surveyed for three years covering free-running, conditioned and mixed-mode buildings (McCartney & Nicol , 2002).

The categories based on EN-15251 standard, the categories are:

i. Category I: High-level expectation for persons with fragility like the sick, disable and elderly with a 90% acceptance level;

ii. Category II: Normal comfort level. It is the most adopted category with an 80% acceptance level;

iii. Category III: Moderate level of comfort, might just be less than the normal requirement with a 65% acceptance level;

iv. Category IV: This is the least used category as it covers conditions that may have not been covered in the other categories, with an acceptance level of below 65%.

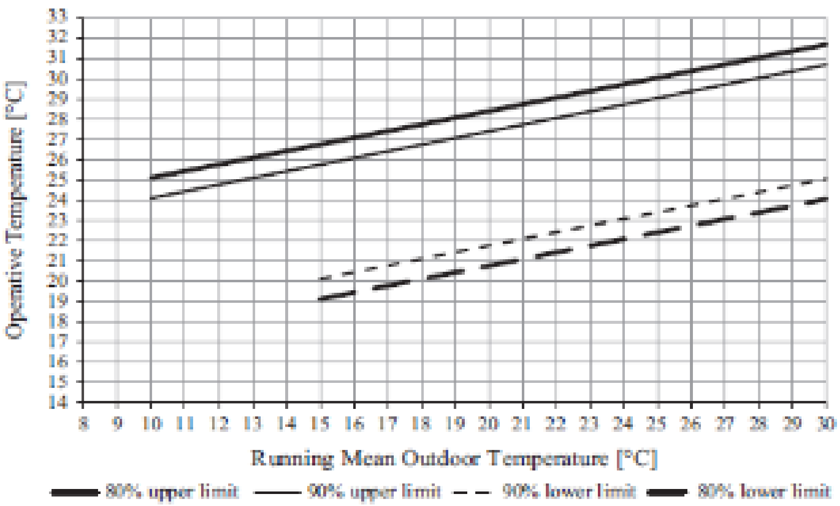


Figure 19: Thermal Comfort Range according to EN 15251
Source: (Taleghani, Tenpierik, Kurvers, & Dobbelsteen, 2013)

Although it suggests different categories of criteria for indoor environment, it does not necessitate its use in every condition as it leaves it open to different project specifications or national bodies.

The acceptable comfort levels are calculated by the equation:

$$T_{comf} = 0.337T_m + 18.8 \quad (2)$$

Where T_m is the outdoor temperature.

2.9 Thermal Comfort in Residential Buildings in Nigeria

In Nigeria, no particular local standard is being adopted, however research carried out in this field have closely considered the ASHRAE and ISO standard and some recent studies have recorded similar comfort range to those deduced from the standards like as Ojosu et al (1988) recorded lower comfort temperature range of 21^0C-26^0C within four different climatic zone; Adunola A.O (2018) recorded a neutral temperature of 24.6^0C and a comfort range of 22.6^0C-25.6^0C in a warm-humid climatic zone, this resulted in 10.6% of the users feeling hot and uncomfortable; Ogbonna and Haris (2008) recorded a neutral temperature of just above 26^0C and comfort range of 24.88 °C and 27.66 °C, where users respondents were generally comfortable while others showed comfort temperatures go well above the higher comfort rage of 26^0C according to the standards as; Adaji et al (2019) in low and middle income houses in Abuja recorded neutral temperatures between 28°C–30.4 °C compared to the preferred temperature range of 27.5°C–29.4 °C, where 70% of users were not thermally satisfied; Komolafe L.K & Akingbade F.O.A (2002) with a comfort range between 26^0C to 28^0C, where 0% to 63% of the votes experienced warm discomfort due to high temperature at some point of the day during the study; Akande & Adebamowo (2010) in Bauchi a hot-dry climate recorded a neutral temperature of 28.4^0C in dry season and 25.04^0C in rainy season and a discomfort percentage of 68% and 51% respectively and a comfort range of 25.5^0C-29.5^0C. However, the findings have not been widely accepted although they have proven to be useful as they serve as a guide for subsequent research in the field within Nigeria. The wide comfort range noticed across the studies could be as a result of the varying climatic zones, methodology, study duration, measurements accuracy and different experiences and expectations amongst users.

Chapter 3

ANALYSIS

The analysis of passive cooling strategies adopted within the case studies was carried out. In addition to that, a survey was prepared for the users of the case study buildings in order to further understand their thermal comfort conditions with the main aim of gathering the required data that will suffice in achieving the objectives of this research as stated in Chapter 1.

3.1 Location

Nigeria, formally referred to as Federal Republic of Nigeria, is a country located in sub-Saharan Africa, in the west African region. It lies between latitudes 4^0 and 14^0N and longitude 3^0 and 14^0E of the Greenwich meridian. Bounded by Niger, Chad, Cameroon, and Benin in the north, north-east, east and west accordingly, with a distance of 1400km from the north to south and 1100km from east to west of the country with a total area of 923,770km^2.

It comprises of 36 states and its Federal Capital Territory, Abuja with a population of 206 million making it the most populous country in Africa (Worldometer, 2023). With English being its official language, it consists of over 250 ethnic groups with about 525 distinct languages with numerous varieties of cultures, however it is predominated by three main tribes that make up the 60% of the total population (CIA-World factbook, 2019): the Hausas from the northern part of the country, the Yorubas from the southern part and the Igbos from the western part of the country.

Characterized by three main climatic zones: a tropical monsoon climate in the south, a tropical savannah climate in most part of the central regions and a Sahelian hot and semi-arid climate in the northern region of the country. The northern part is mostly hot and dry as it experiences high temperatures through-out the year with an average rainfall of about 500-750mm, the southern part is hot and humid with an average rainfall of over 2000mm lasting for a large part of the year (World bank, 2019).

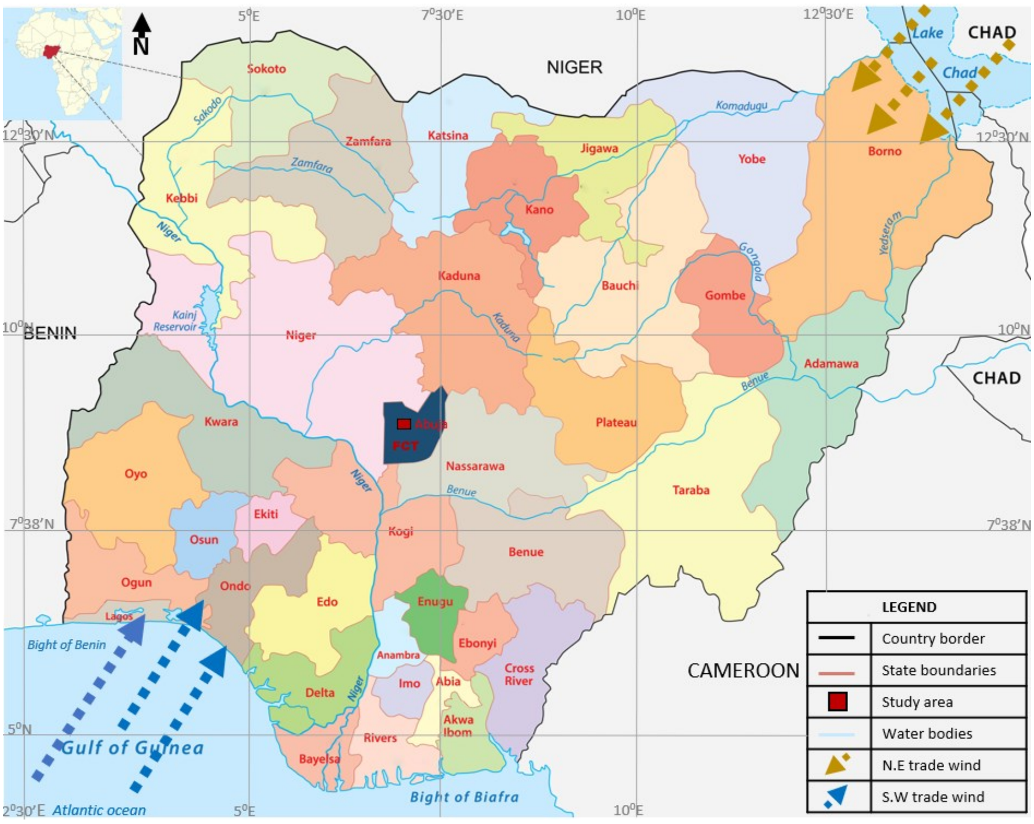


Figure 20: Map of Nigeria
Source: www.atlas.com (2023). Edited by Author

The federal capital territory of Nigeria, Abuja is located in the central part of the country, it lies on latitude 9^0 4'N and longitude 7^0 29'. It is north of the confluence of the Niger and Benue Rivers. Bordering the FCT are the states of Kaduna to the northeast, Plateau to the east and south, Kogi to the southwest, and Niger to the west and northwest, slightly west of the center of the country (New World Encyclopedia, 2022) .

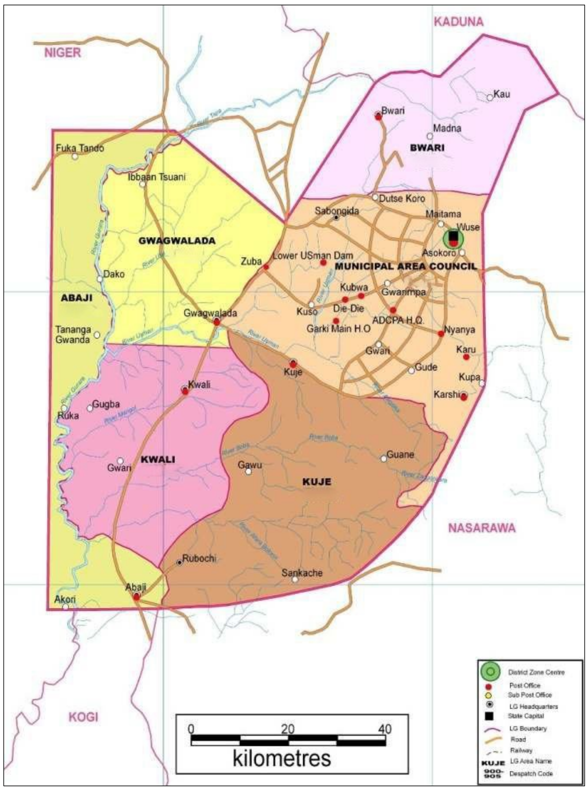


Figure 21: Map of Federal Capital Territory, Abuja
Source: Geograhic Information System, 2010.

It consists of six different area councils namely: Abuja municipal area council, Abaji, Bwari, Gwagwalada, Kuje and Kwali with an estimated population of 3.8 million in the urban dwelling with a growth of 5.15% from 2022-2023 making it the 4th most populated city in the country, and the fastest growing city in Africa (United Nations, 2023). Furthermore, due to the rapid urbanization and population growth, the high influx of residents from rural areas in search of better economic opportunities and standards of living has resulted in the creation of satellite towns like Karu, Kubwa, Mpape, Zuba, Nyanya among others, around the territory resulting in an estimated metropolitan population of 6 million (Jaiyeola Andrews). Housing different ethnicities ranging from the Afo,Fulani, Bassa, Hausa, Gangana, Gwandara (New World Encyclopedia, 2022).

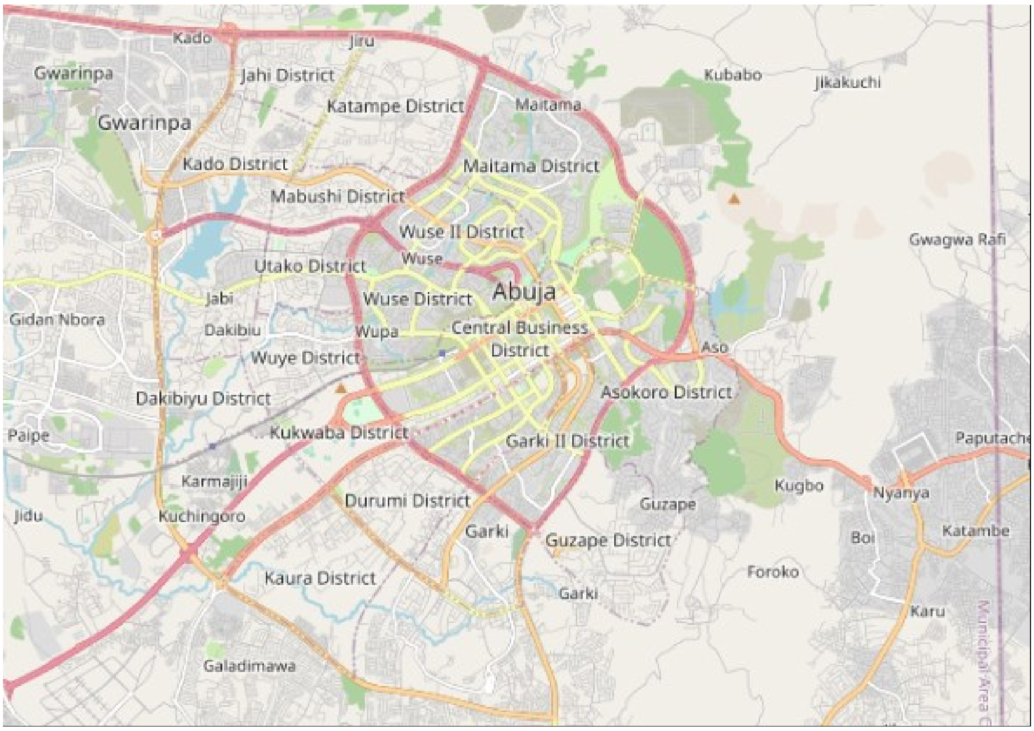


Figure 22: A Section of Map of Abuja City Showing Different Districts and Surrounding Settlements
Source: www.openstreetmap.org

3.1.1 History

The area which was earlier the south-western part of the Hausa Kingdom of Zaria was occupied by British colonial army as of 1902, it was known as Suleja a neighbouring town which was developed to become the first planned city in the country (Editors of Encyclopaedia, 2023), from three different mother states with Niger making most of it (Abdulazeez, 2009). The name Abuja was coined from the name of the Fulani king who was known as “Abu-ja” meaning Abu the red while others say “Ja” was gotten from the first syllable of his father’s name “Jatau”.

Its development which started in 1976 according to a master plan by International Planning Associates (IPA), it was not completed until 1980s due to economic and political instability (FCDA, 1988) and later became the capital in 1991 as it was created to be, as a result of the: ethnic and religious growth and development, existing plans to relocate the capital from Lagos to a more central location within the country and a place of neutrality to all tribes and religion, this led to the designation of the selected area as the new Federal capital territory as it signified neutrality and unity (Editors of Encyclopaedia, 2023) accompanied with the fact that Lagos was starting to get overcrowded as a result of economic growth as it became the most populous state in the country. Therefore, it was chosen due its central location, easy accessibility, pleasant climate, low population density and the availability of land for future expansion (New World Encyclopedia, 2022). It is for the said reasons that it is referred to as the Centre of Unity.

3.1.1.1 Climate of Abuja

Based on the Koppen-Geiger's climate classification, Abuja is characterized with a typical tropical wet and humid climate influenced by its medium altitude and undulating terrain, also referred to as the Aw category. The climate results in: a long rainy season that is mostly warm, humid, and sometimes cold, a hot and dry season, and a transitory period of harmattan, causing dryness, haze, and cold temperatures (Tripreport, n.d.).

- **Temperature**

The average high daily temperatures vary from 28.5^0C to 36^0C while the average low daily temperatures vary from 20^0C to 25^0C, temperature levels usually do not go higher than 39^0C or lower than 16^0C as shown in Figure 22. Due to the location of the city, there is a significant temperature variation within the course of the day. The hot season lasts for about 3 months from February to April while the cold season lasts for about 4 months from June to September (Weather spark, n.d.), with March being the hottest month, with a high average temperature of 36^{0}C and an average low temperature of 25.2^{0}C, while August being the coldest month with a high average temperature of 28^{0}C and a low average temperature of 20.5^{0}C. Most temperature levels being above the recommended temperature range by the ASHRAE 55 standard as shown in Figure 22.

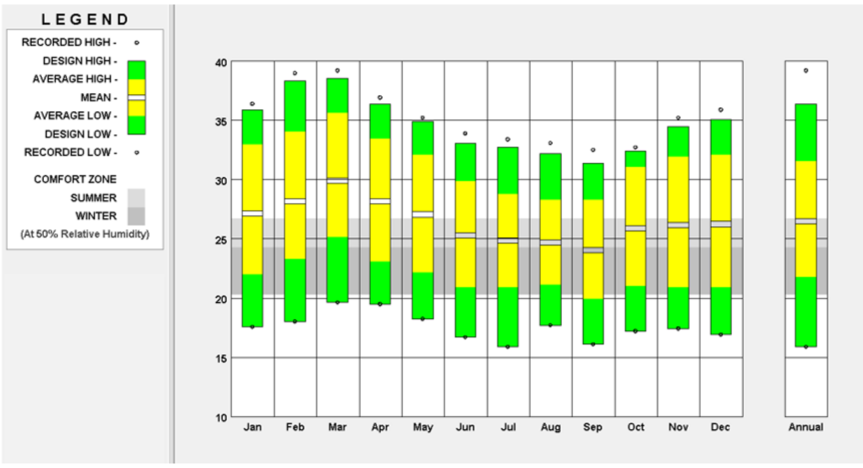


Figure 23: Temperature Range of Abuja within the Year
Source: Climatic consultant 6.0

- **Rainfall**

The region experiences an extended period of rainy season that lasts for about eight months from March to November. During this time, it receives at least 1mm of rainfall with August being the wettest month, recording as much as 194mm of rain. The dry season lasts for about four months, starting from November to March, with December and January being the driest months receiving no rainfall (Weather Atlas, n.d.) as shown in Figure 23.

Figure 24: Average Monthly Rainfall in Abuja
Source: www.weatheratlas.com

This corresponds with the significant variation of the cloud cover within the city. The clearer part of the year is within November to January lasting for about 3 months with December being the clearest month. The cloudier part of the year is within February to October lasting for about 9 months with August being the cloudiest month as shown in Figure 24.

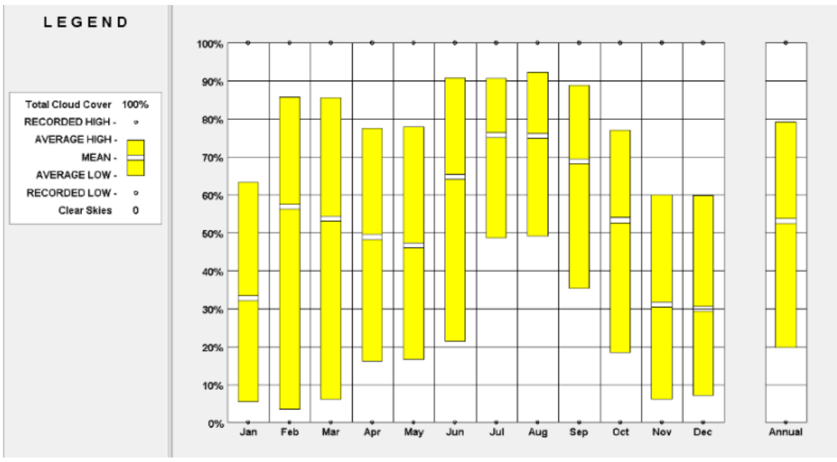


Figure 25: Cloud Cover Range within the Year in Abuja
Source: Climatic consultant 6.0

- **Humidity**

The humidity levels vary according to different seasons in the city, as muggier days with high humidity levels last for about 7 months in which most part of it coincides with the rainy season, it lasts from February to November with January and August have the lowest and highest humidity levels respectively (Weather spark, n.d.) as shown in Figure 25.

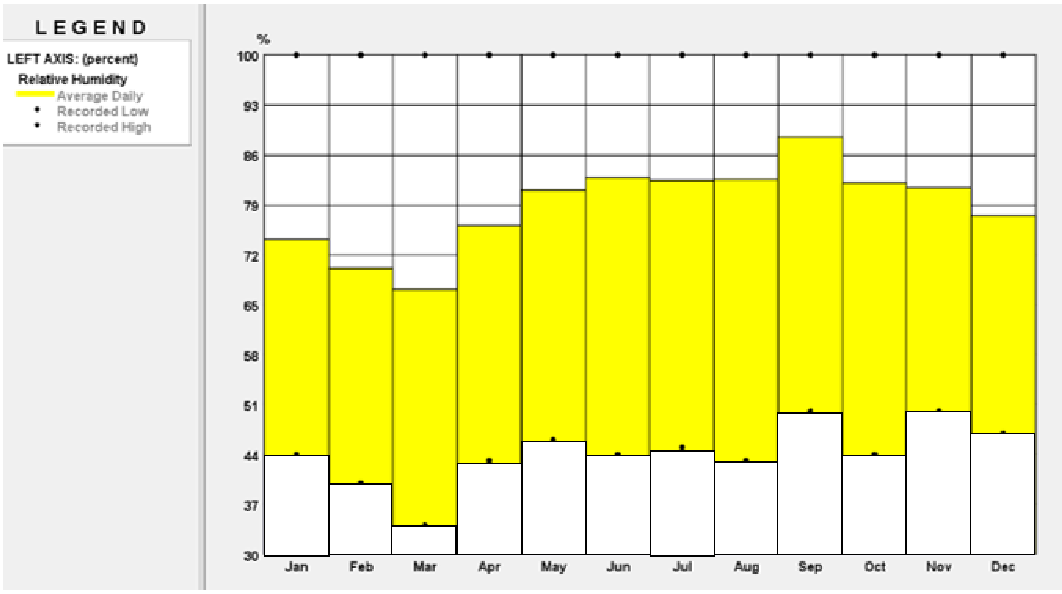


Figure 26: Average Daily Humidity within the Year in Abuja
Source: Climatic consultant 6.0

- **Solar Radiation**

In Abuja seasonal variations have no significant effect on the length of the day as the difference between the longest and shortest day in 2023 is just 1hour 3 minutes with a difference of 42 minutes between the earliest and latest sunrise and a difference of 48 minutes between the earliest and latest sunset (Weather spark, n.d.) as shown in Figure 26.

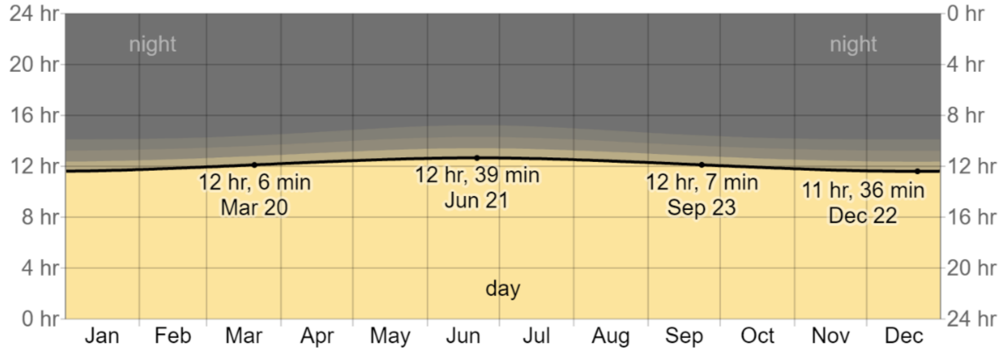


Figure 27: Average Hours of Daylight within the Year in Abuja
Source: www.weatherspark.com

The radiation from the sun that reaches the earth surface is influenced by the elevation of the sun, cloud cover, atmospheric condition and the length of the day, thus the intensity of radiations are felt differently at different times, seasons and orientations, during winter the solar radiations are uncomfortable for over 1506 hours, comfortable for 532 hours and indoor spaces remain cold due to in adequate solar exposure of just 36 hours as shown in Figure 27. During summer it causes discomfort for 1171 hours, is comfortable for 855 hours and indoor spaces remain cold due to in adequate solar exposure of just 61 hours as shown in Figure 28.

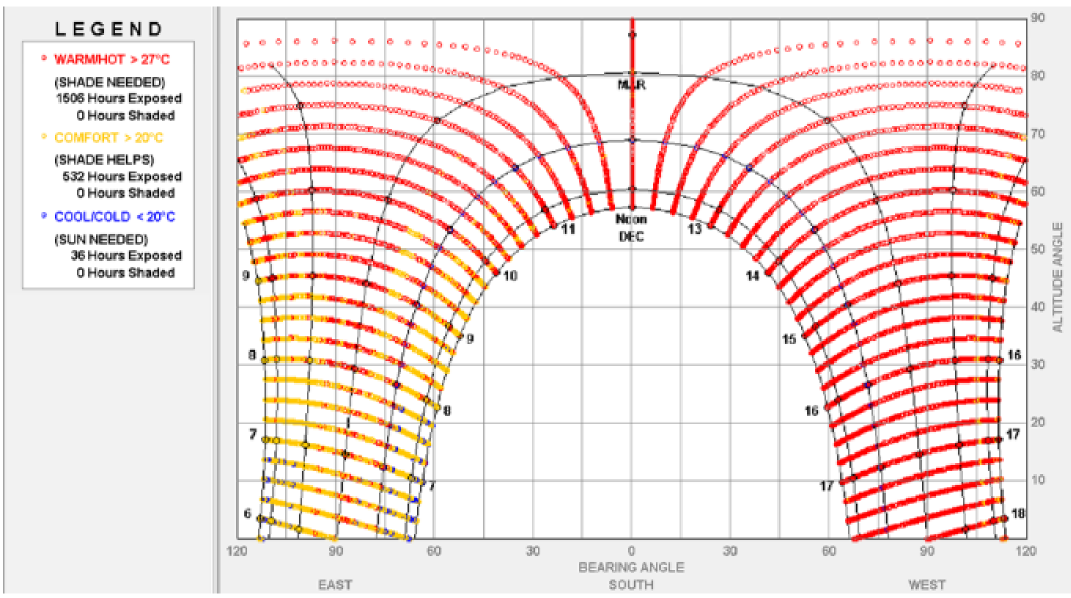


Figure 28: Sun Chart Diagram During Winter in Abuja
Source: Climatic consultant 6.0

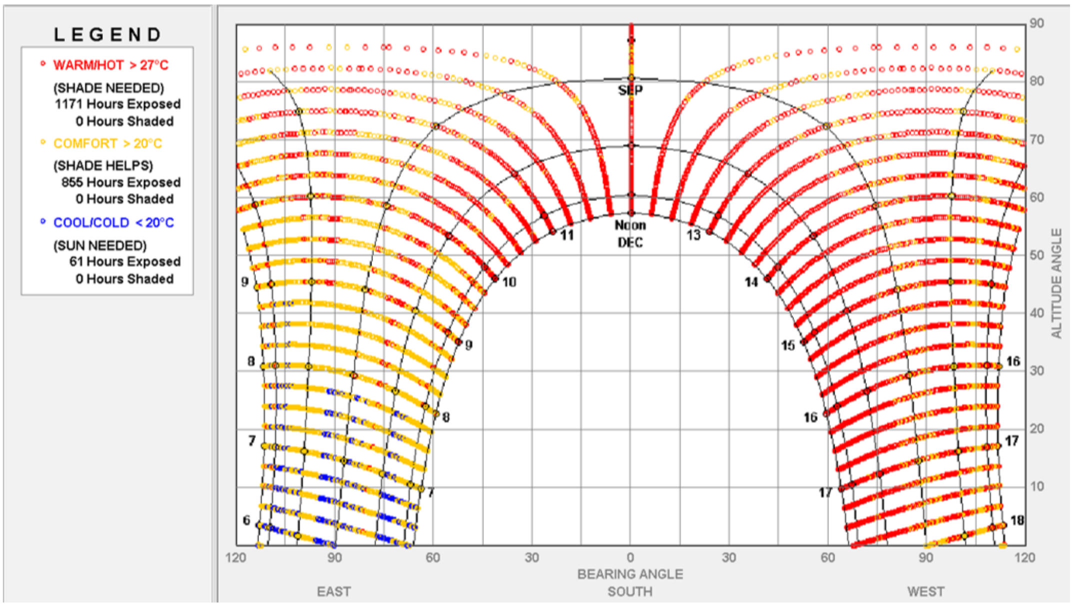


Figure 29: Sun Chart During Summer in Abuja.
Source: Climatic consultant 6.0

- **Wind**

The predominant winds in Abuja are the harmattan winds also known as tropical continental airmass, blowing through the northeast and originating from the Sahara Desert, reaching the area from late November to mid-March. During this period, the winds are typically dry and dusty, resulting in unclear visibility and hazy atmosphere. Conversely, the south-westerly monsoon winds also known as the tropical maritime airmass are the prevailing winds within the rest of the year, originating from the Atlantic Ocean bringing in moisture and precipitation to the area from April to October causing the raining season in the region (Pioneer education centre tutorial upper branch, 2020) as shown in Figure 29. Thus, the south-west trade wind is considered the comfort wind as it cools down the indoor spaces of buildings through convection while circulating through them. In contrast, the north-east wind produces a cooling effect by reducing the outdoor temperature, which then transfers to indoor spaces through conduction, as its direct flow into interior spaces is restricted due to the presence of dust and particles it comes with.

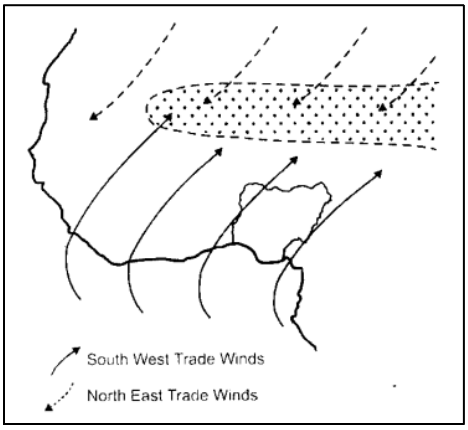


Figure 30: West African Map Showing Nigeria and its Prevailing Winds
Source: Ologe, O.K 2023

The wind direction however slightly varies over the course of the day and year, it is felt mainly from the south direction for 4.4 months from February to June, August to October with a peak percentage of 52% in May, from the west for 2.3 months and some parts of June to August with peak percentage of 60% in July and from the east for 3.5 months from October to February with a peak percentage of 44% in January (Weather spark, n.d.).Throughout the year, there is a small variation in the wind speed, with march experiencing the highest wind velocity of slightly above 2m/s and October having the lowest wind speed of below 2 m/s. It can however go as high as 17m/s and as low as 0 m/s as shown in Figure 30.

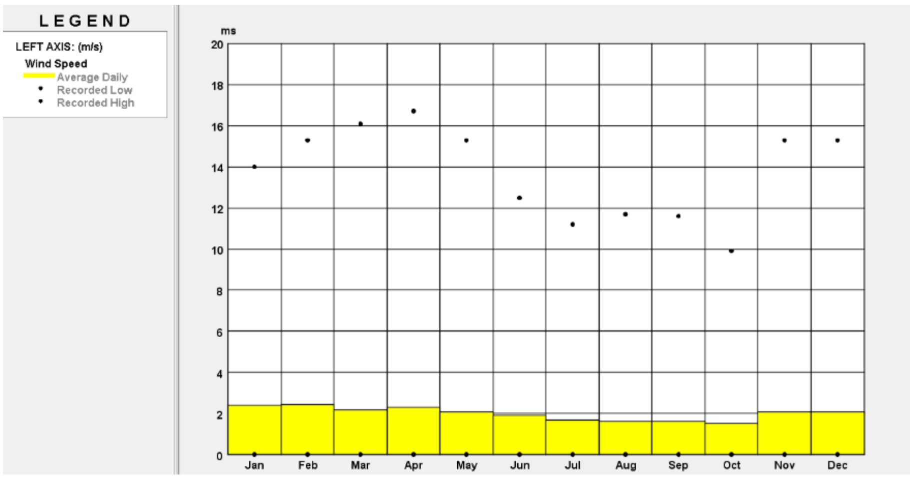


Figure 31: Average Wind Speeds within the Year in Abuja
Source: Climatic consultant 6.0

- **Psychometric Chart**

The psychometric charts below depict the comfort levels experienced in Abuja throughout the year, based on the climatic factors previously discussed. Figure 31 shows that in the absence of any passive design strategy, only 0.3% of the year, that is 27 out of 8760 hours are considered comfortable. However, when passive solar design strategies as sun shading on windows, internal heat gain, and passive solar direct gain high mass methods are adopted, the comfort level increases to 5%, with 441 out of 8760 hours being considered comfortable as shown in Figure 32. This level of comfort is typical of buildings in Abuja in the absence of active cooling systems, as most contemporary residential buildings implement these passive solar strategies. Thus, the remaining 8319 hours of the year are dependent on active or other forms of cooling or changes in occupants behaviour to achieve comfort.

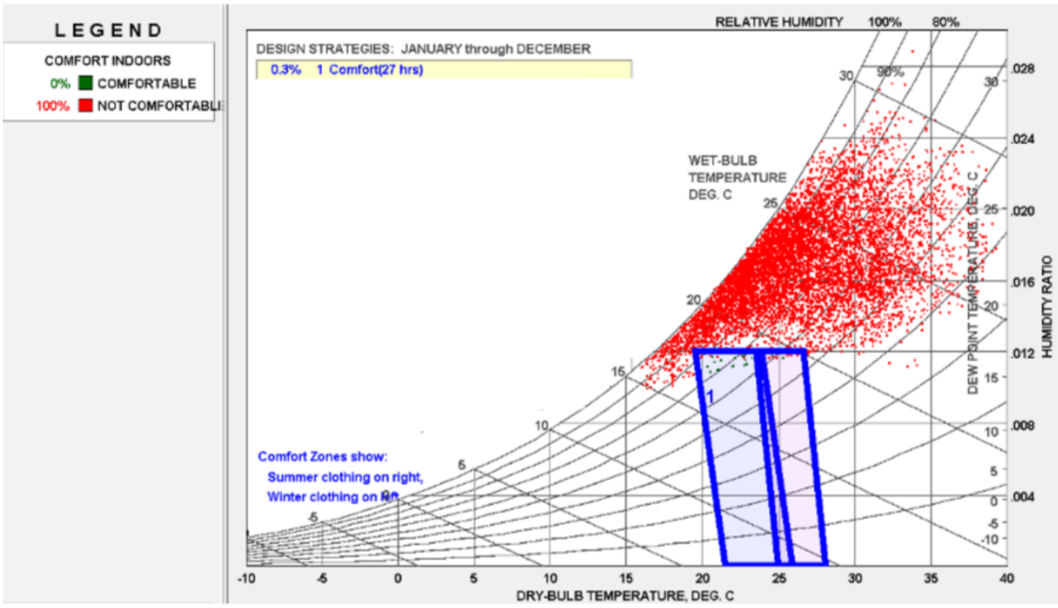


Figure 32: Psychometric Chart of Abuja Showing Indoor Comfort Levels in the Absence of Any Passive Design Strategy within the Year
Source: Climatic consultant, 6.0.

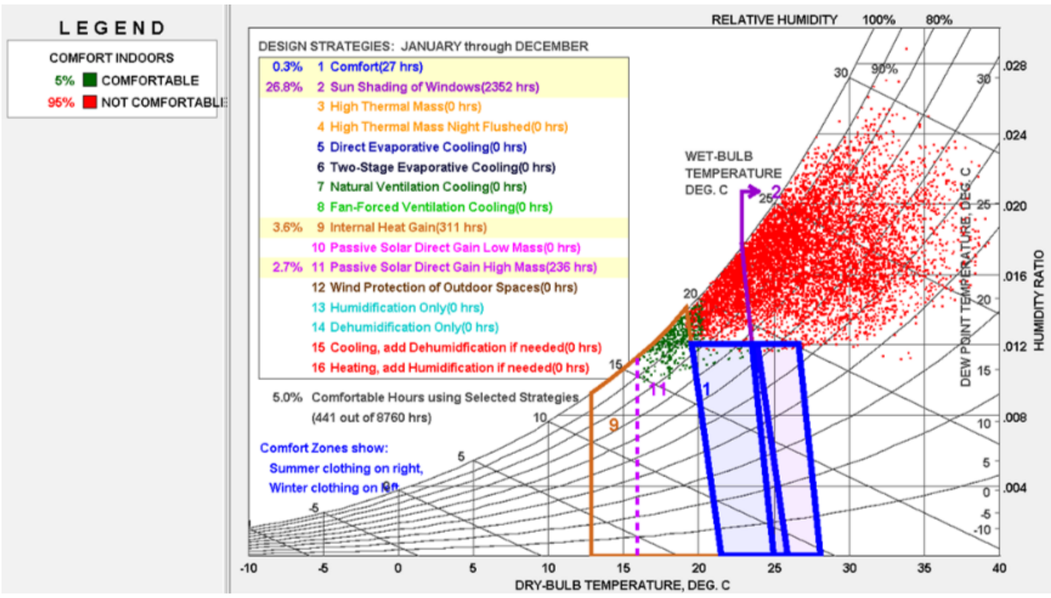


Figure 33: Psychometric Chart of Abuja Showing Indoor Comfort Levels when Passive Solar Design Strategies are Adopted
Source: Climatic consultant, 6.0.

Figure 33 shows that although passive cooling could be a way of reducing energy consumption and improving comfort generally, it is not closely enough to achieve the desired level of comfort. As further cooling and dehumidification strategies have the most significant influence on the indoor comfort of buildings in Abuja as they both improve the comfort levels with 51.3% and 44.8% respectively.

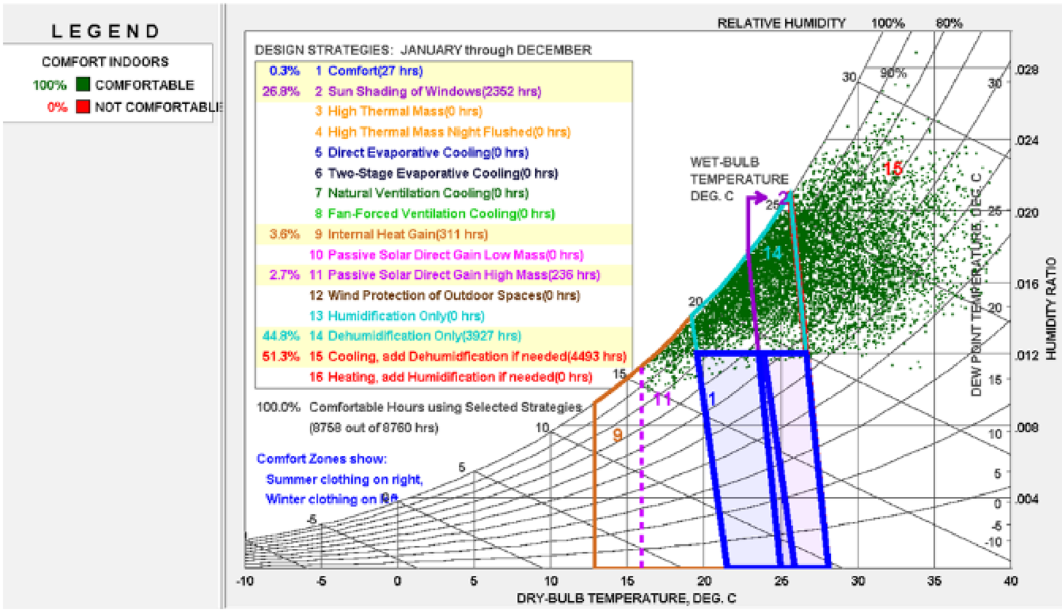


Figure 34: Psychometric of Abuja Showing Comfort Levels with the Adoption of Further Cooling and Dehumidification Strategies.
Source: Climatic consultant, 6.0.

3.2 Data Collection: The Analysis of the Selected Case Studies in Abuja

Data collection was done by employing both qualitative research method through physical observation of three selected case studies representing different residential building types within Abuja and quantitative research methods through the use of questionnaires which were distributed to the occupants of the buildings used as case studies.

3.2.1 Physical Observation

The physical observation of selected case studies is an effective way of gathering a detailed and accurate data by studying the existing condition of the of the selected buildings. In this research it was done in order to identify the passive cooling strategies as well as building features that have been implemented in order to promote or inhibit the process of passive cooling in the buildings, this was achieved based on some selected parameters.

The data gotten from this method was analyzed through an analytic and descriptive approach as they were documented and presented in form of writing, photographs and CAD drawings. Observed features were further likened and contrasted with existing literature and standards to find out the level of effective implementation of passive cooling strategies in the buildings.

3.2.1.1 Criteria for Selecting Case Studies

The criteria below were used in selecting the appropriate residential buildings to serve as the case studies for this research, therefore it was ensured that the residential buildings should:

1. Represent mid-rise buildings;
2. Represent contemporary buildings;
3. Be for middle or high-income earners as they have a higher level of electricity consumption for cooling due to its availability in their areas and their economic status;
4. Have a prototype design so as to have a view from a reasonable sample size and draw a conclusion about the views of the residents on the asked questions especially the thermal conditions of the selected buildings as opposed to having the opinions of few persons;
5. Each case study should represent a different building typology in order to analyze the distinct features in each case that may have direct effect on the level of passive cooling required in each case study like floor numbers and exposed building surfaces.

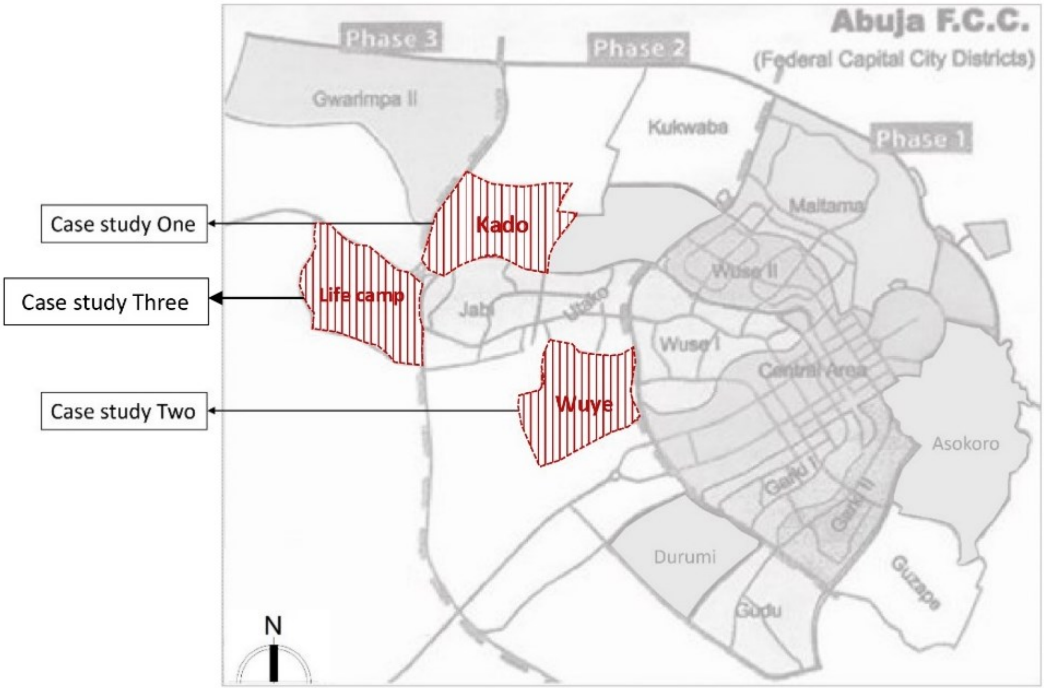


Figure 35: Site Location of Case Studies
Source: www.linkedin.com (2017)

3.2.1.2 Case Study One: Ivy Homes by Zavati E-build

Ivy Homes by Zavati E-build is a residential development for high-income earners. It is located in Kado, which is a developed area in phase two of Abuja, offering both residential and commercial facilities such as schools, healthcare centers, eateries, with recreational spaces having a great boost due to the presence of Jabi lake, places of worship, and even markets. The neighbourhood is home to a diverse range of residents, including traders who operate in the nearby market, civil servants, and middle to high-income earners.(Propertypro, 2023).

The case study comprises of 6 units of six-bedroom (6) detached duplexes and 11 units of four (4) bedroom terraces as shown in Figure 35. The buildings are multistorey with two floors and a pent-floor.

Figure 36: Site Plan of Case Study One (Ivy Homes)
Source: Company's Archive

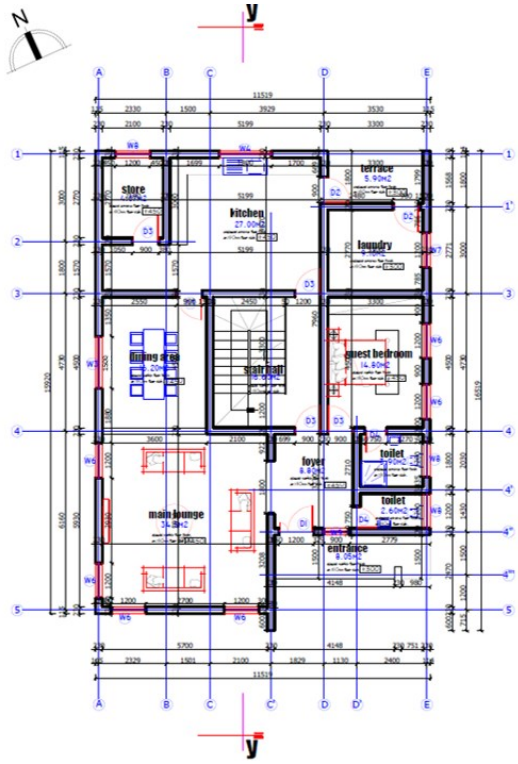


Figure 37: Ground Floor Plan Of A Single Duplex Unit (Block 1) in Case Study One (Ivy Homes)
Source: Company's Archive

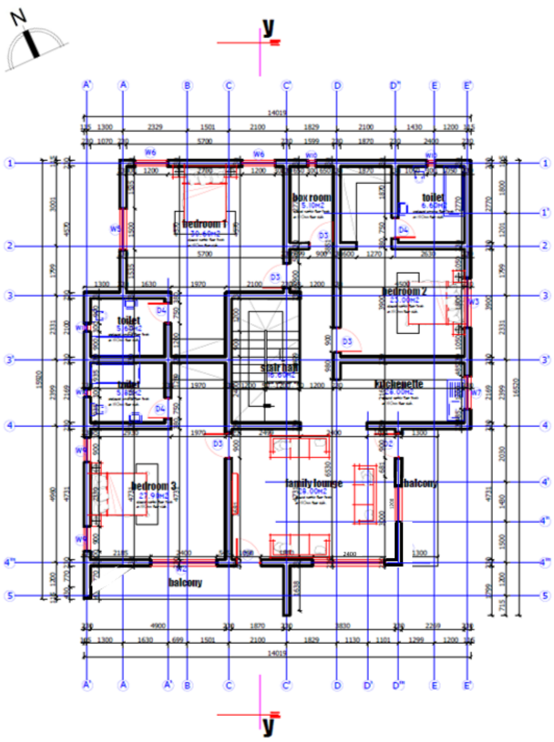


Figure 38: First Floor Plan of a Single Duplex Unit (Block 1) in Case Study One (Ivy Homes)
Source: Company's Archive

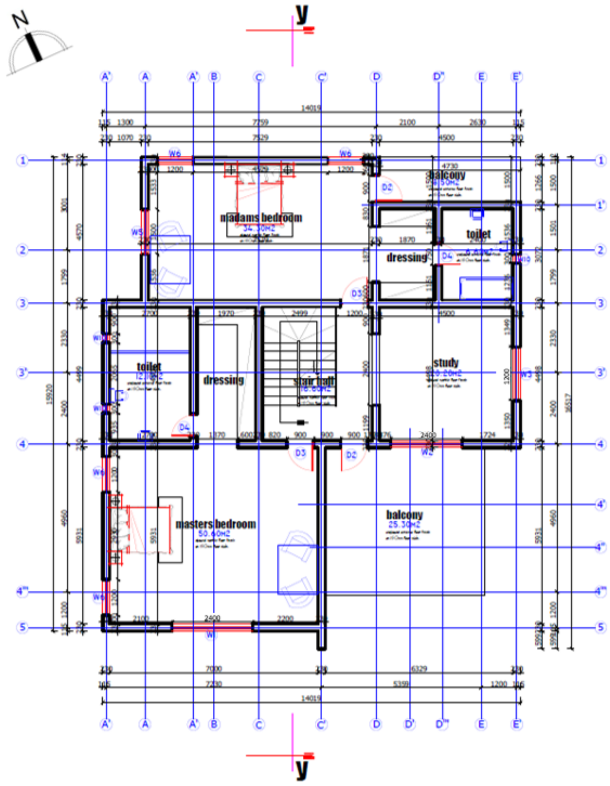


Figure 39: Second Floor Plan of a Single Duplex Unit (Block 1) in Case Study One (Ivy Homes)
Source: Company's Archive

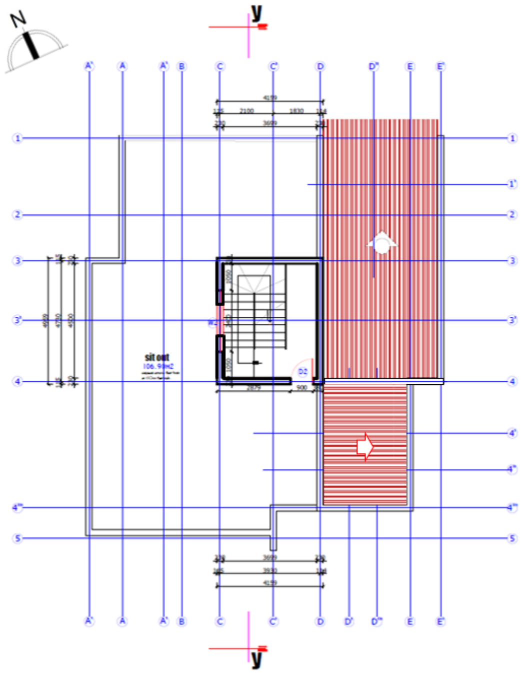


Figure 40: Roof Plan of a Single Duplex Unit (Block 1) in Case Study One (Ivy Homes)
Source: Company's Archive

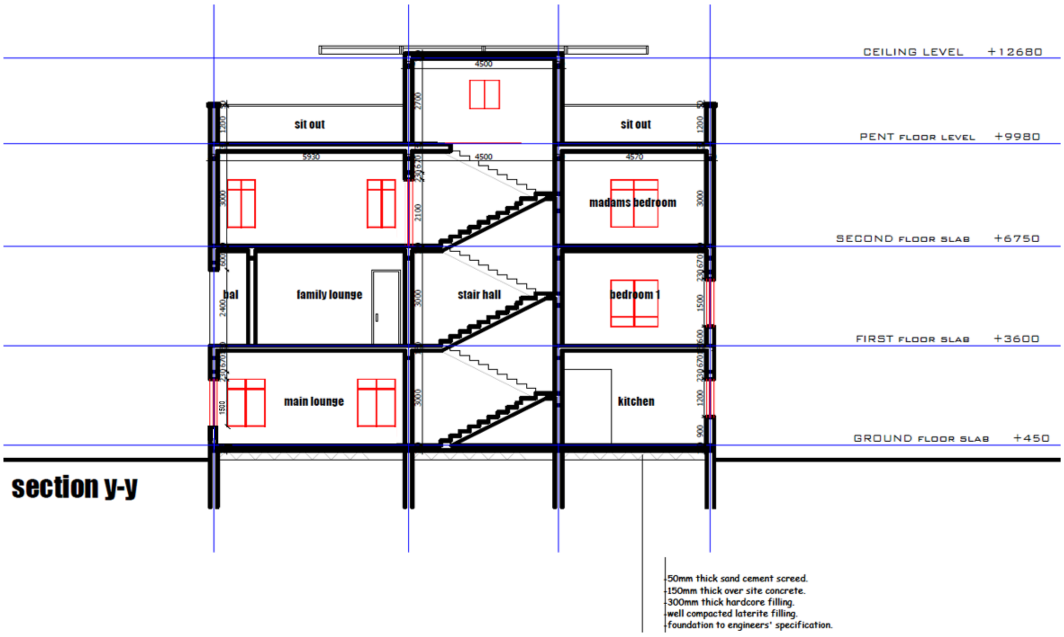


Figure 41: Section Y-Y of a Single Duplex Unit in Case Study One (Ivy Homes)
Source: Company's Archive

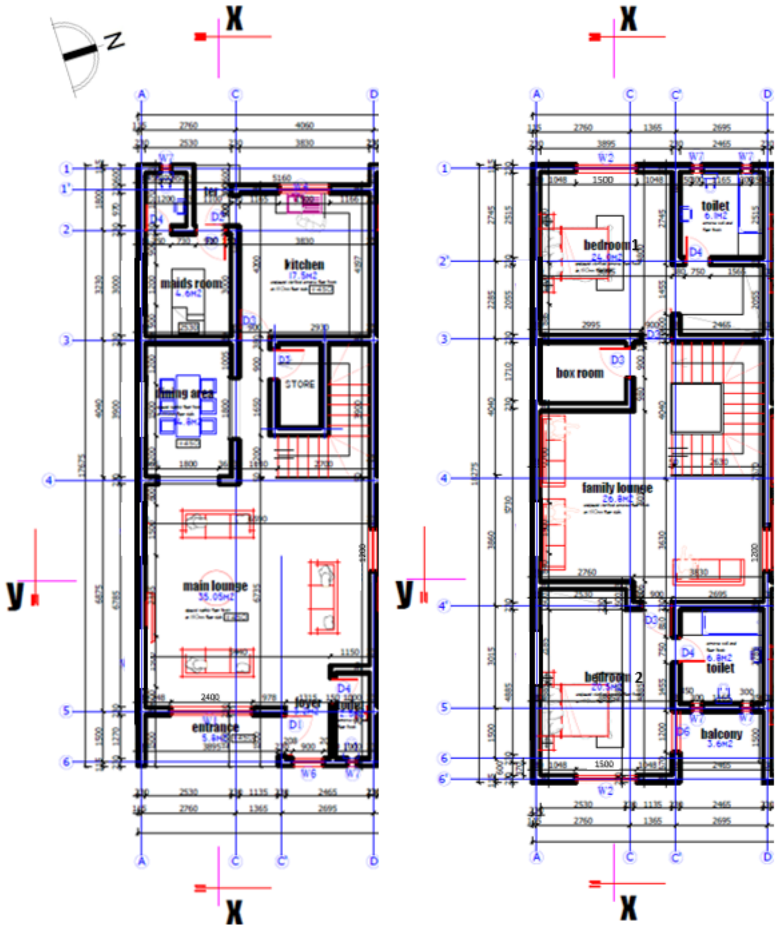


Figure 42: Ground Floor Plan (to the left) And First Floor Plan (to the right) of a Terrace Unit in Case Study One (Ivy Homes)
Source: Company's Archive

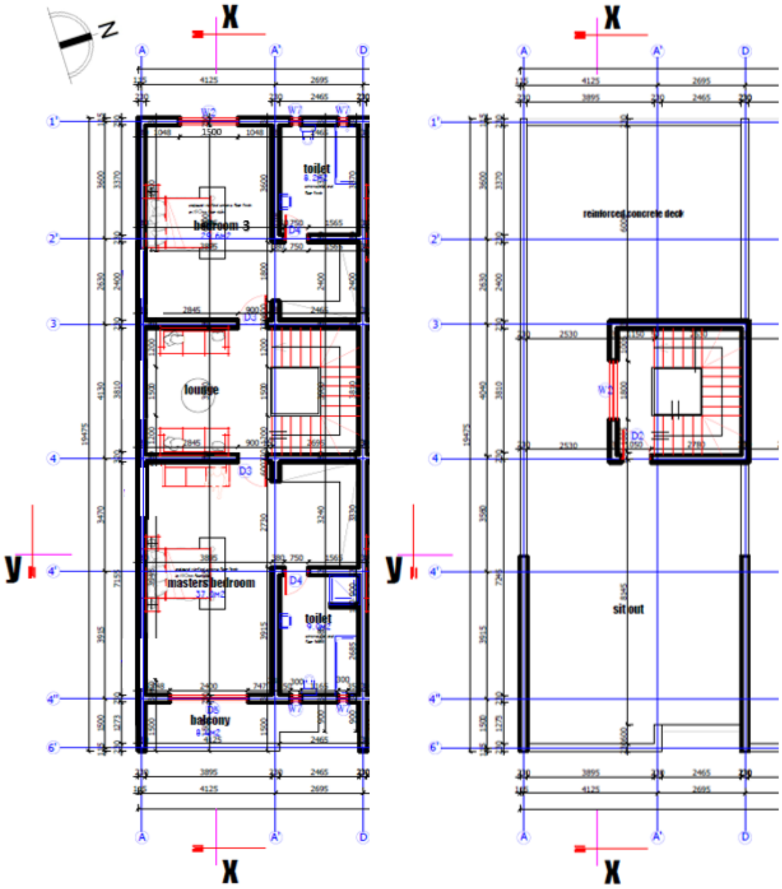


Figure 43: Second Floor Plan (to the left) and Pent Floor Plan (to the right) of a Terrace Unit in Case Study One
Source: Company's Archive

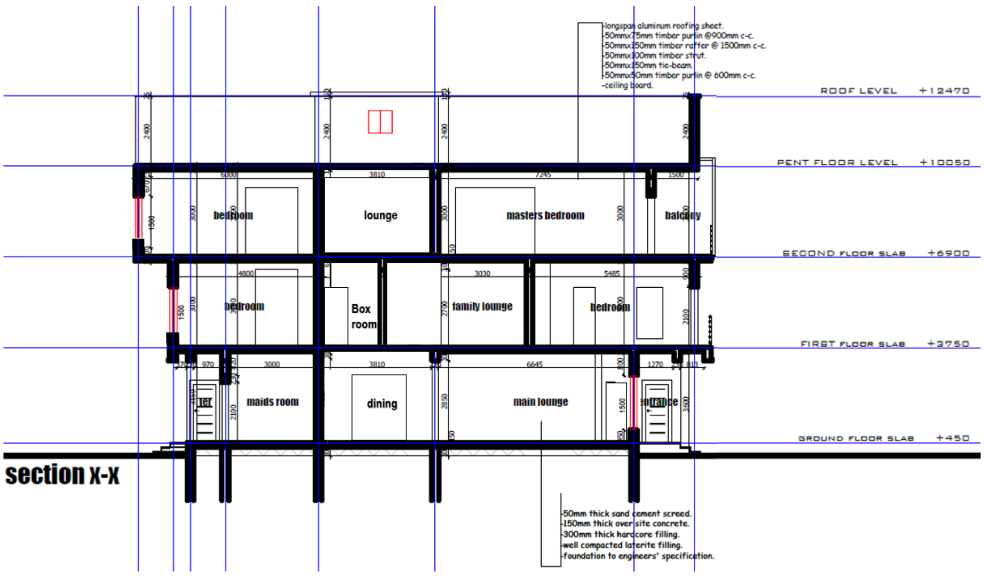


Figure 44: Section x-x of a Terrace Unit in Case Study One (Ivy homes)
Source: Company's Archive

Case study one facilitates the analysis of building features that are distinct to duplexes and terraces, while being the only case study with 3 floors, the duplexes have all four building facades with openings exposed to solar radiation as such they have the highest potential of solar heat gain. Furthermore, terraces have the least exposed sides as only 4 units have 3 sides being exposed to solar radiation, while other 7 units only have 2 exposed surfaces to solar radiation and wind, hence they have the lowest potential for passive cooling by wind although they have the lowest solar gain potential.

3.2.1.3 Case Study Two: Ivy Apartments

This is a four-bedroom middle-income housing unit among a residential development located in Wuye, which is also a phase two neighbourhood located directly to the west of Abuja city center, with close proximity to the central area and the international airport road, making it a highly sought-after central location. The significant amount of public and private investment in Wuye has transformed it into a real estate hotspot, resulting in numerous ongoing property development projects, including the construction of many housing estates. As a result, Wuye is attracting residents from different social classes, including high-class individuals, artisans, and commercial workers. (Villa Afrika Realty, 2023).

The case is situated with other five blocks of four-bedroom housing units, two blocks of two-bedroom households and four blocks of three-bedroom households.as shown in Figure 44.

Figure 45: Site Plan of Case Study Two (Ivy Apartments) and other Surrounding Housing Blocks
Source: Company's archive

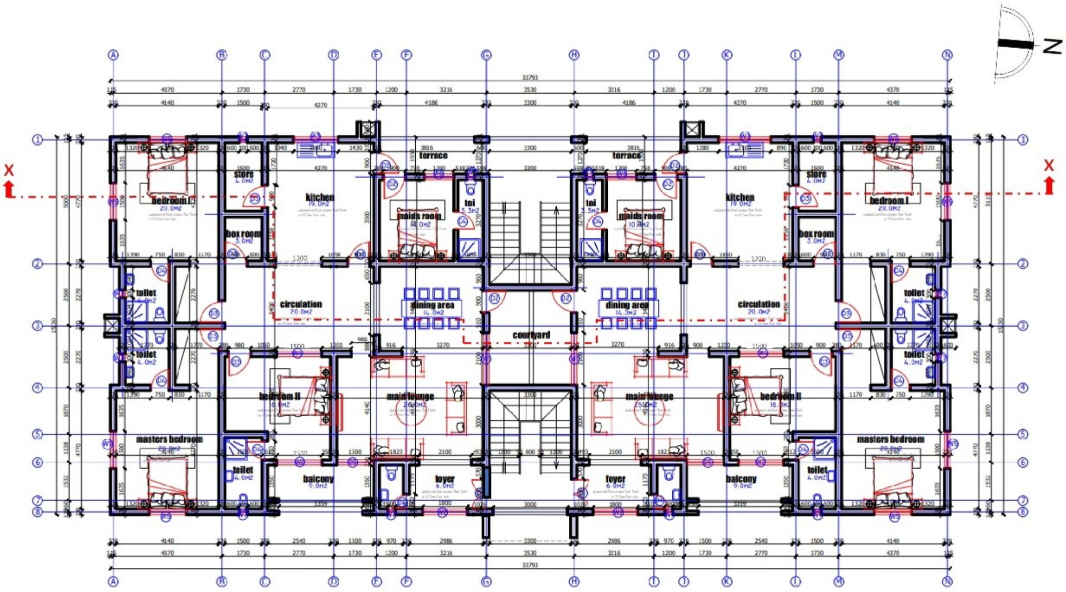


Figure 46: Typical Ground, First, Second and Third Floor Plan of Case Study Two (Ivy Apartments)
Source: Company's Archive

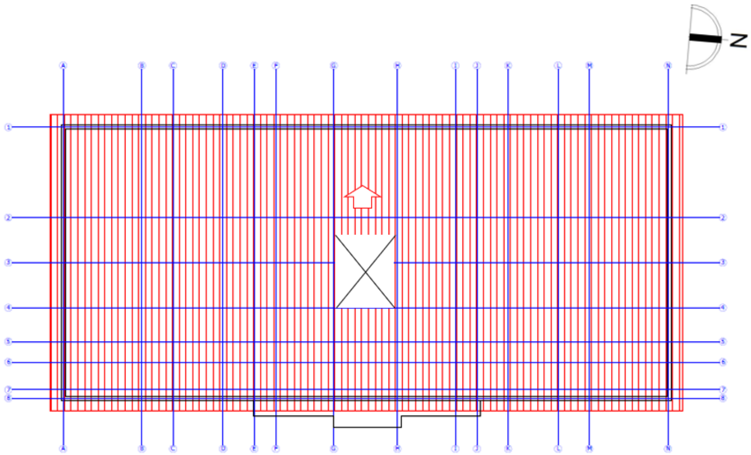


Figure 47: Roof Plan of Case Study Two (Ivy Apartments)
Source: Company's Archive

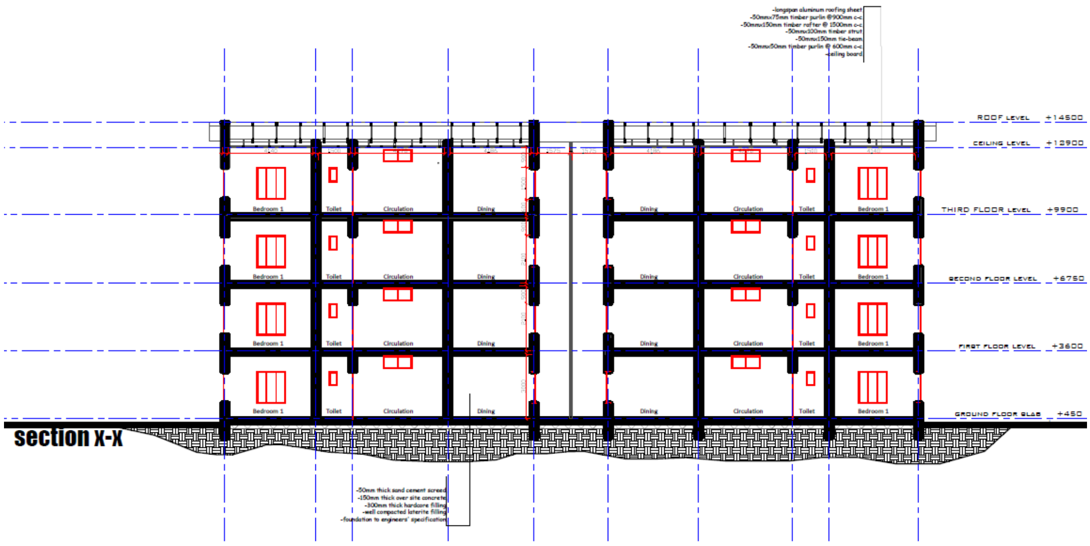


Figure 48: Section x-x of Case Study Two (Ivy Apartments)
Source: Author's Field Study

Case study two (Ivy apartments) being a four-storey block of flats has the highest cooling demand among other studies, it is also the only study with a central open space that aims at improving the ventilation level in indoor spaces, therefore this allows for the level of effectiveness of this future to be analyzed.

3.2.1.4 Case Study Three: Leptons Planet Five

Planet five is a middle-income earners housing estate located in Life camp. Life camp is a tranquil residential zone situated in phase three of Abuja, that boasts of adequate security and considerable development. This district offers some of the finest views of the city and features several parks and restaurants in close proximity. Additionally, the area is well-connected with a good network of roads and is bordered by various well-developed districts that connect it to Abuja's central area. The locality has numerous large housing estates signifying contemporary and striking architecture. Being an exclusive, leafy neighbourhood that provides a peaceful atmosphere, it is a pricey residential area. (Villa Afrika Realty, 2022).

The case study comprises of 12 units of five-bedroom (5) semi-detached houses as shown in Figure 48. The buildings are multistorey with two storeys.

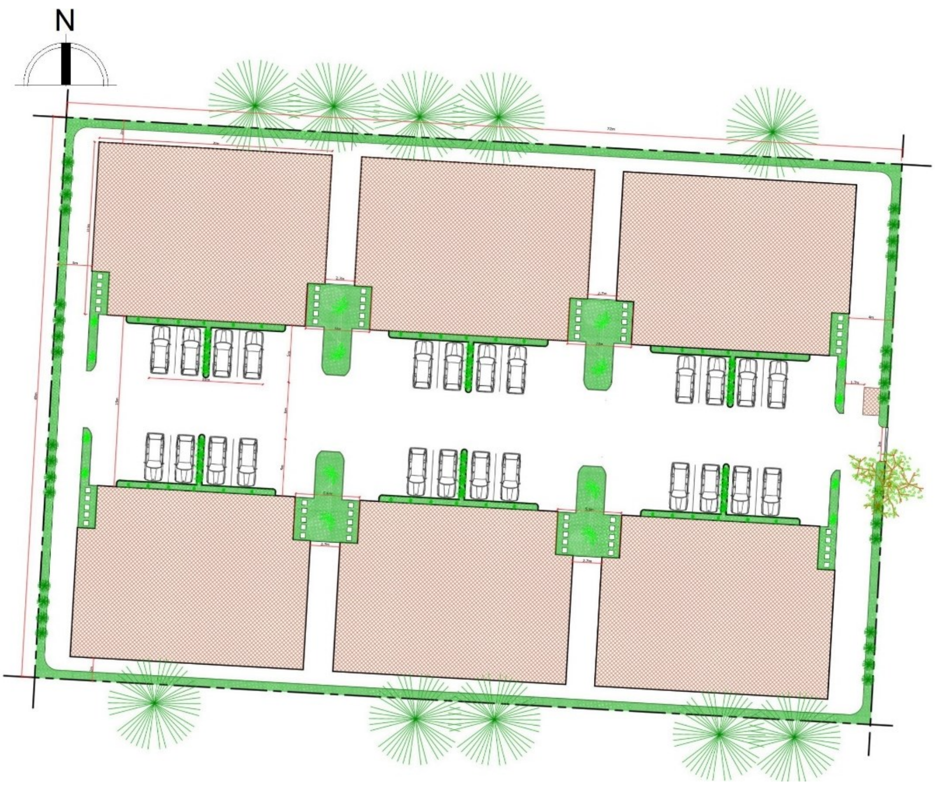


Figure 49: Site Plan of Case Study Three (Leptons Planet Five)
Source: Author’s field study

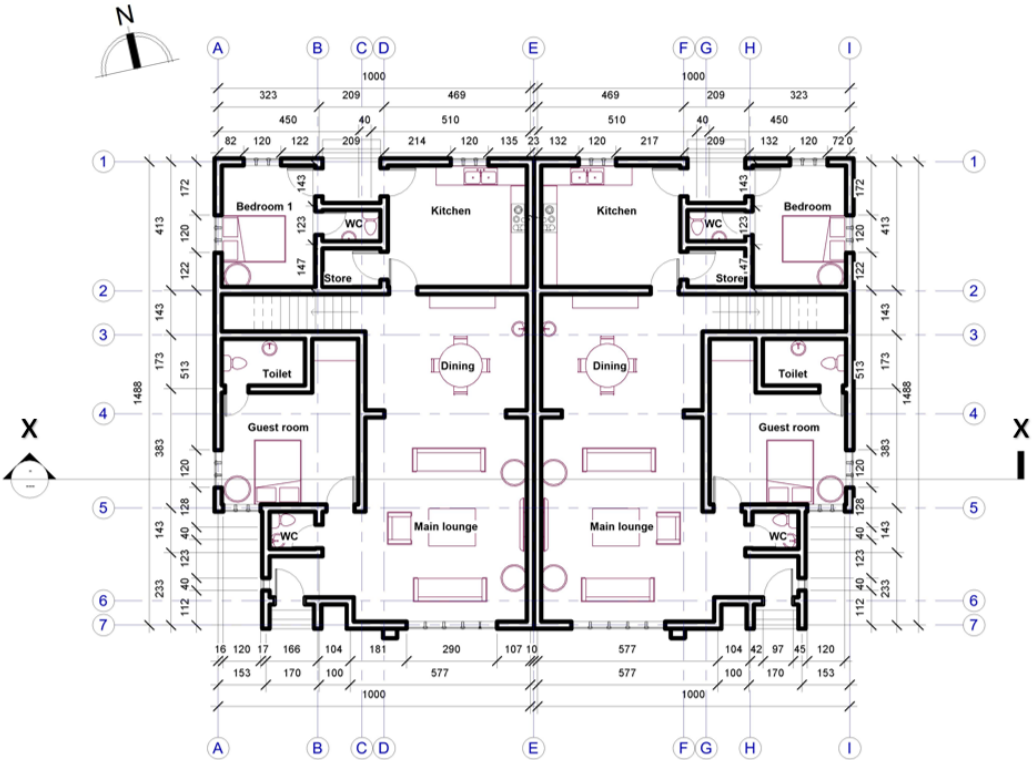


Figure 50: Ground Floor Plan of Case Study Three (Leptons Planet Five)
Source: Author’s Field Study

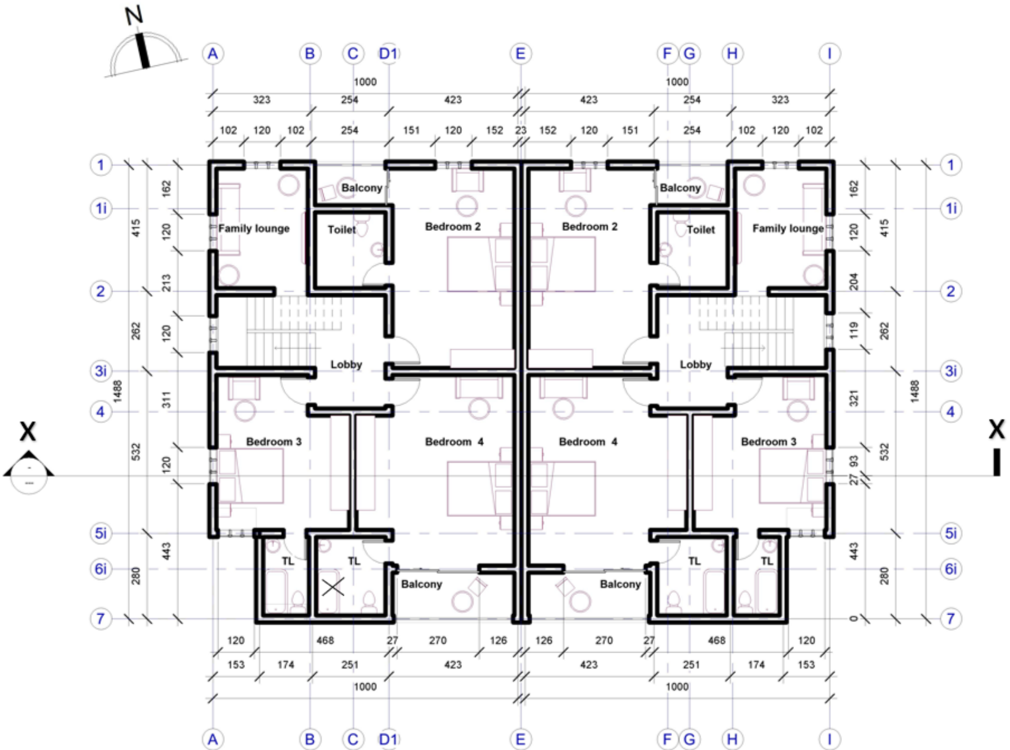


Figure 51: First Floor Plan of Case Study Three (Leptons Planet Five)
Source: Author’s field study

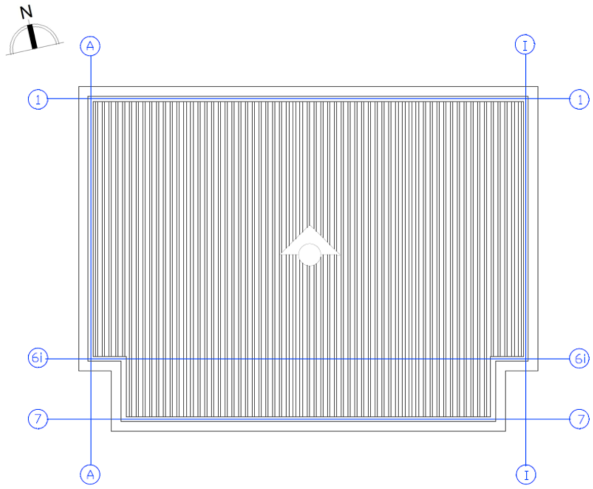


Figure 52: Roof Plan of Case Study Three (Leptons Planet Five)
Source: Author's field study

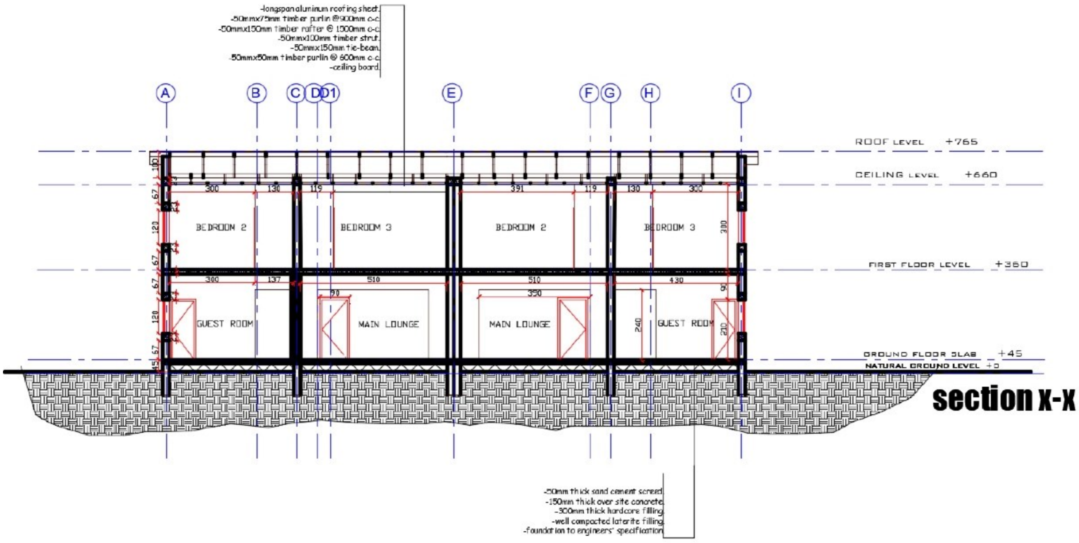


Figure 53: Section x-x of Case Study Three (Leptons Planet Five)
Source: Author's Field Study

Although case study three (Leptons planet five) also has three exposed sides just like some of the terrace units in case study one (Ivy homes) and case study two (Ivy apartments), it has the presence of prominent vegetation within and at the boundaries of the site in form of plants and dense trees respectively, this allows the cooling effect of vegetation to be analyzed.

3.2.1.5 Selected Parameters for the Analysis of Case Studies

The observations and analysis in this study were based on specific parameters that directly impact the rate of passive cooling in buildings These parameters encompass micro-climate and site design, building orientation, building form and layout, apertures, solar control, thermal mass, as well as factors influencing the cooling requirements within interior spaces, such as building user behavior, occupancy patterns, and internal heat gain levels according to Santamouris and Asimakopoulos (2013). Additionally, the study adopted exterior surfaces as an additional parameter as suggested by Hatamipour, Mahiyar & Taheri (2007) as discussed in chapter two.

3.2.1.6 Analysis of Microclimate and Site Design

The buildings in case study one (Ivy apartments) are designed to fit into the existing site layout. The location is bounded by a horizontal and curving route. Neither trees nor fences are adopted to modify the existing climatic condition within the site boundary. However, there is a presence of planted trees on the northern direction within the site's setback from the road as shown in Figure 53, and also a green area in the central zone of the buildings, bounded by plants.

Figure 54: Northern Site Context of Case Study One (Ivy Homes).
Source: Author's Field Study

Buildings in case study two (Ivy apartments) and three (Leptons planet five) similarly follow the existing site layout, and have more prominent vegetation within the site, with close proximity to the building blocks. Furthermore, case study three (Leptons planet five) has dense vegetation around the site especially on the north and south site boundaries.

The surrounding sites of case study one (Ivy homes) are not fully developed, this allows the buildings to have unobstructed flow of south-west cold breeze within the site and into the interior spaces, as there are no obstructions at close proximity as shown in Figure 54. Case study two (Ivy apartments) is however bounded by uncompleted building blocks on the south-west direction, although this doesn't obstruct air flow at the current situation, at completion the situation might differ due to its proximity to the southern façade of the building.

Surrounding sites in case study three (Leptons planet five) are however fully developed, but the buildings do not serve as obstructions to the south-west comfort wind to the case study buildings as they have an appropriate spacing between them and the case study buildings, while the trees do enhance the micro-climate by promoting cooling.

Figure 55: Aerial View of Case Study One (a: Ivy homes), Case Study Two (b: Ivy Apartments) and Case Study Three (c: Leptons planet five)
Source: Google Map (2023)

- **Evaporative Cooling Potential Based on Site Design Features**

Through the process of evapotranspiration, which is broadly categorized as an evaporative cooling technique, vegetation in form of plants and green areas in all the case studies produce a cooling effect within the surrounding. Therefore, most living spaces are cooled by the presence of vegetation as the plants are mostly present in the approach zone of the buildings in flower beds and surroundings.

Precisely, case study one (Ivy homes) and three (Leptons planet five) have the living spaces and some bedrooms on the approach being cooled by the presence of vegetation in flower beds in the front façade, the effect of vegetation is mainly felt within the surroundings and bedrooms in case study two (Ivy apartments) as plants are mainly not close to the buildings approach but rather at common outdoor spaces and by the sides. With the presence of dense trees in the northern and southern site boundaries in case study three (Leptons planet five), the bedrooms on the rear sides of the buildings (north and south facades) experience a more significant cooling effect and are further protected from the harsh dry and dusty particles from the north-east trade-wind, allowing the spaces to benefit from its cooling effect when necessary.

The green spaces due to their cooler surface temperatures also effectively cool down the adjacent concrete and asphalt surfaces, which are known for being heated due to their low albedo, thereby contributing to the rising temperature within the surrounding and indoor spaces. Although they are mainly present in the sides of the buildings in all case studies, they are also seen in the central and front part of case studies one (Ivy homes) and three (Leptons planet five) respectively.

Figure 56: Outdoor Surfaces and Vegetation in Case Study One (a: Ivy homes), Case Study Two (b: Ivy Apartments) and Case Study Three (c: Leptons Planet Five)

- **Air Movement Based on Site Layout and Building Spacing.**

According to Hussain and Lee (1980)'s findings, the flow types based on the W/H aspect ratio of spaces to buildings can be classified into three distinct categories namely: isolated roughness flow, wake interface flow, and skimming flow. Each type is associated with specific air exchange characteristics and influences the ventilation and air quality within the building environment.

In case study one (Ivy homes), it was observed that a central spacing of 55 m between block resulted in a W/H aspect ratio of 4.2. This facilitated the complete flow and exchange of air within the blocks, ensuring effective ventilation and air circulation as shown in Figure 57.

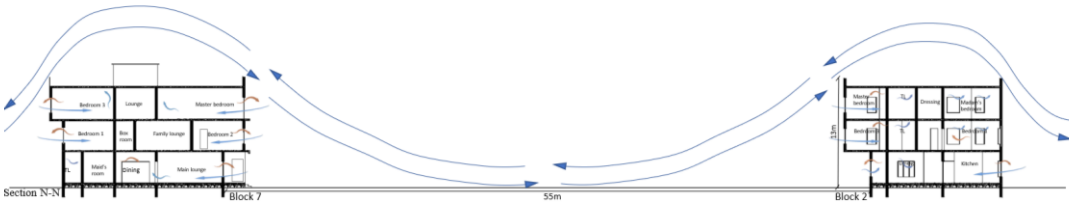


Figure 57: Illustration of Maximum Air Exchange Between Block 7 and Block 2 of Case Study One (Ivy Homes)

On the other hand, a spacing of 23 m between block 8 and block 1 yielded a W/H aspect ratio that fell within the range of 1.4 to 2.4. As a consequence, it led to a limited air exchange between the buildings, as shown in Figure 58.

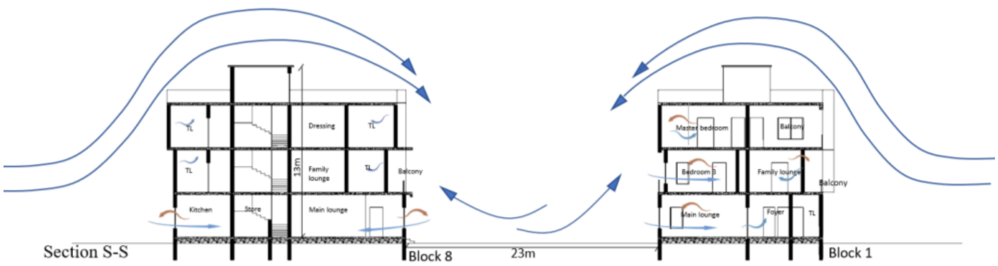


Figure 58: Illustration of Limited Air Exchange Between Block 8 and 1 of Case Study One (Ivy Homes)

Furthermore, a skimming effect was observed between blocks 4, 5, and 6, as shown in Figure 59. This implies that the W/H aspect ratio for these blocks was less than 1.4, resulting in a minimal air exchange within these building blocks.

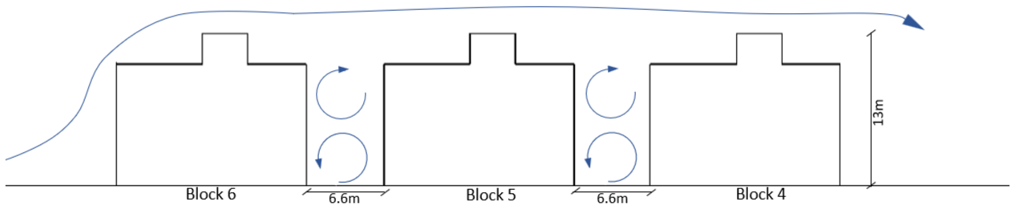


Figure 59: Illustration of a Minimum Air Exchange Rate (south-east view) Between Block 4,5 and 6 of Case Study One (Ivy homes)

Summarised categorisation of wind flow types and parameters of case study one (Ivy homes) are shown below in table 2.

Table 2: Summarised Building Parameters Influencing Wind Flow and Different Wind-Flow Categories within Building Blocks of Case Study One (Ivy Homes)

Figure	**Width**	**Height**	**W/H ratio**	**Categories based on W/H aspect ratio according to Hussein and Lee (1980)**
57	55	13m	4.2	Isolated roughness flow as W/H aspect ratio is > 2.4.
58	23	13m	1.8	Wake interface flow as W/H ratio is within the range of 1.4 to 2.4
59	6.6	13m	0.5	Skimming flow as W/H aspect ratio is < 1.4.

Currently, the uncompleted building units in the southwest area, positioned 6 meters away from case study two (Ivy apartments), do not impede the airflow from that direction as depicted in Figure 60, resulting in a W/H ratio of 3.0. However, once the building construction is completed, the flow of wind may be impeded depending on the characteristics of the completed structure. Consequently, this obstruction has the potential to result in diminished or insufficient flow of the south-west comfort wind into the building's interior spaces.

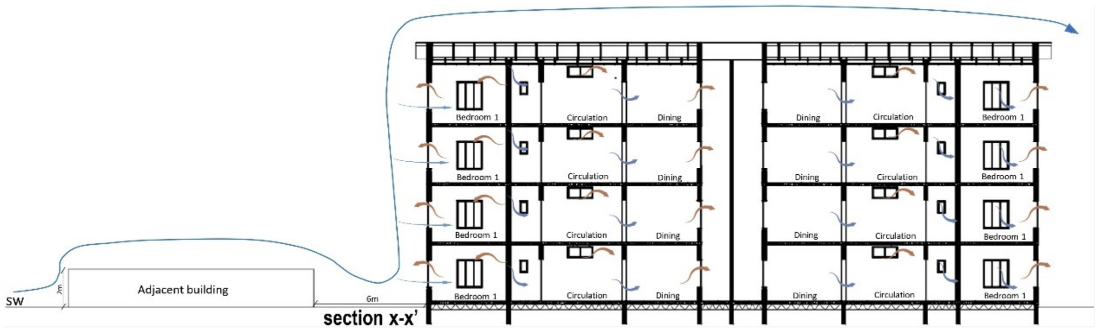


Figure 60: Illustration of Air Movement from the South-west Direction in Case Study Two (Ivy Apartments)

A central spacing of 15 m in case study three (Leptons planet five) allows blocks 1,2 and 3 to benefit from the south-west comfort wind although blocks 5 and 6 are positioned in the path of the wind flow, this is as a result of the width to height aspect ratio of the buildings on this path being within the range of 1.4 to 2.4, resulting in moderate air flow as shown in Figure 60.

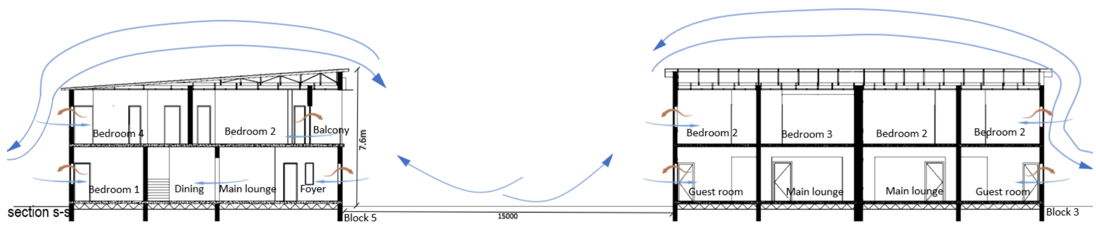


Figure 61: Illustration of Limited Air Exchange Between Block 5 and 3 of Case Study Three (Leptons Planet Five)

However, when the wind direction drifts towards the west, building openings facing each other on the side wall will experience minimum air flow and exchange as the spacing of 2.4m will lead to an aspect ratio less than 1.4. as shown in Figure 61.

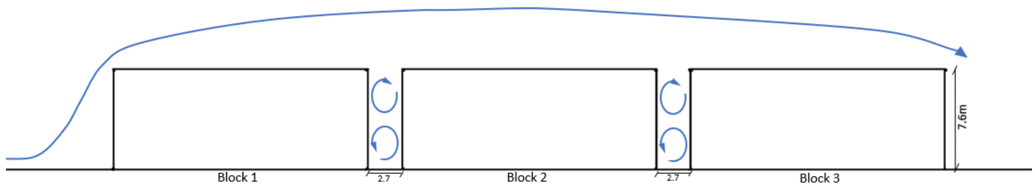


Figure 62: Illustration of Minimum Air Movement along The Southern View Between Block 1,2 And 3 of Case Study Three (Leptons Planet Five)

The summarized parameters leading to the skimming effect and the different wind flows experienced in case study two (Ivy apartments) and case study three (Leptons planet five) are presented in table 3 below.

Table 3: Summary of Building Parameters Affecting the Wind Flow/Movement within Case Study Two (Ivy Apartments) and Blocks 3 and 5 of Case Study Three (Leptons Planet Five) through Section S-S

Figure	**Width**	**Height**	**W/H ratio**	**Categories based on W/H aspect ratio according to Hussein and Lee (1980)**
60	6m	2m	3.0	Isolated roughness flow as W/H aspect ratio is > 2.4.
56	15m	7.6m	2.0	Wake interface flow as W/H ratio is within the range of 1.4 to 2.4
57	2.7m	7.6m	0.4	Skimming flow as W/H aspect ratio is < 1.4.

3.2.1.7 Analysis of Orientation

The detached duplexes in case study one (Ivy apartments) have their longer sides along the north-south axis. With blocks 1, 2 and 3 being tilted towards the north-east while blocks 4,5 and 6 are tilted towards the north-west in a curvilinear form, as such the longer sides are not fully exposed to the intense solar radiation of the east and west directions**.** While each terrace unit has its longer side along the east-west axis, thus an appropriate orientation is achieved as the longer side of each unit is shielded from intense solar radiation. Nevertheless, when examining the complete set of terrace blocks as a unified entity, the reverse is the case as the longer side of block 7 and 8 are along the north-south axis as shown in figure 62.

Case study two (Ivy apartments) is also oriented in such a way that its longer side is along the north-south axis while having its shorter side along the east-west axis as shown in Figure 63(a). The orientation in case study three (Leptons planet five) results in each semi-detached unit having its longer side along the east-west direction, while the longer side of each block lies on the east-west axis as shown in Figure 63(a).

As such, all building blocks in the case studies have their longer side being exposed to the intense solar radiation of the east and west directions. Apart from blocks 4,5 and 6 in case study one (Ivy homes), where the longer sides are towards the north-east and south-west directions and the semi-detached building blocks in case study three (Leptons planet five) where their longer sides are towards the north and south directions as shown in Figure 63(b).

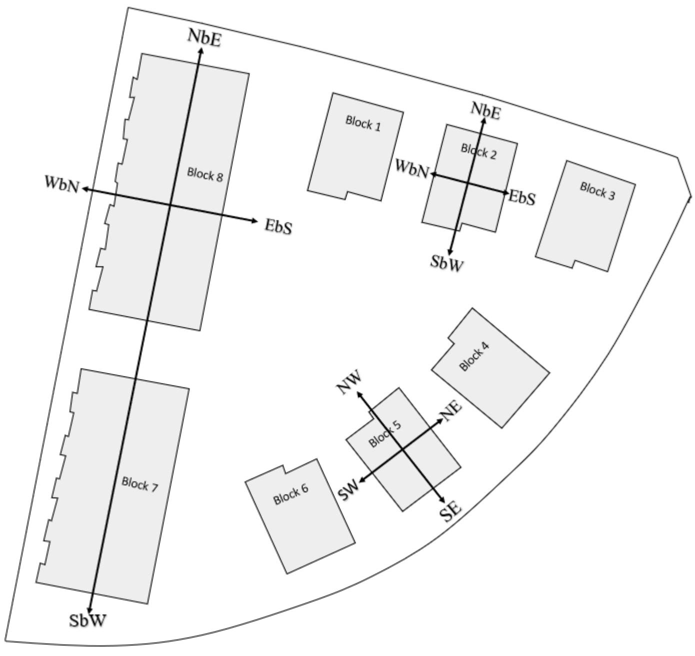


Figure 63: Orientations of Buildings in Case Study One (Ivy Homes)

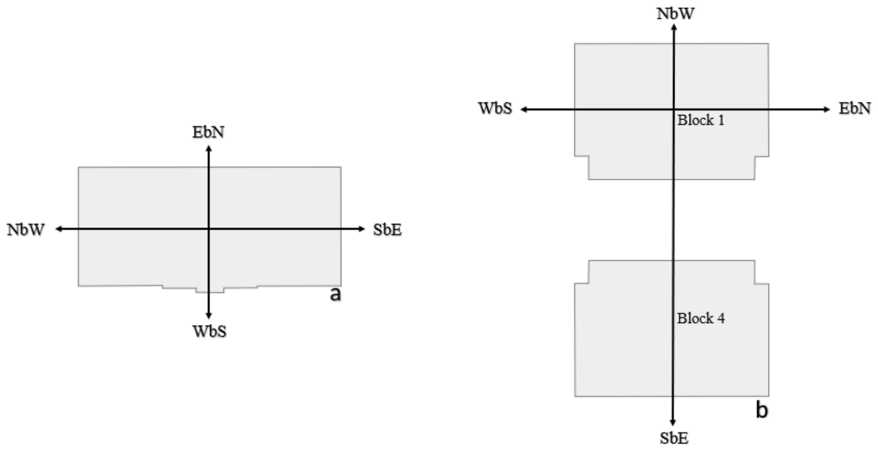


Figure 64: Orientations of Case Study Two (A: Ivy Apartments) and Block 1 And 4 of Case Study Three (B: Leptons Planet Five)

- **Natural Ventilation Potential Based on Building Orientations**

Due to seasonal variation and different wind directions, different spaces tend to benefit from different wind types and velocity over the course of the year. Figure 64 to 69 show the building facades with the potential of benefitting from a heightened level of ventilation due to the flow of the south-west comfort wind through the available openings in case study one, two and three accordingly.

The comfort wind experienced in Abuja is present within the period of rainy season, it comes through the south-west direction where no obstruction is met in case study one (Ivy homes). Therefore, it is significantly felt in spaces with openings in that direction within this period, other spaces experience lower wind velocities with less frequency. All building blocks have spaces that let in cold breeze from the south-west direction in all case studies as shown in Figure 64 to Figure 69.

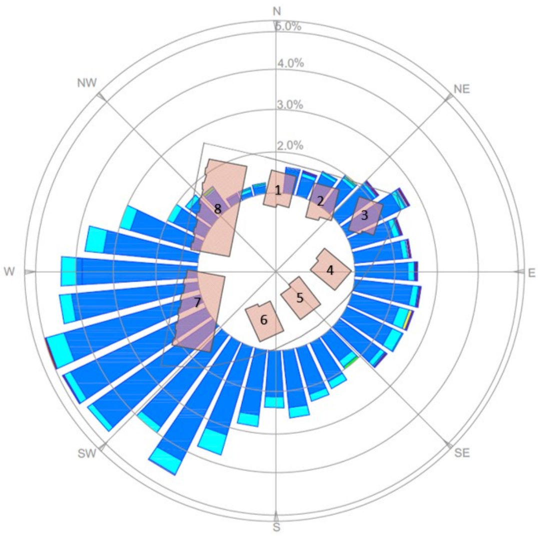


Figure 65: Analysis of Buildings in Case Study One (Ivy Homes) in Respect to the South-West Comfort Wind.

The bedrooms are the spaces benefitting directly from the south-west comfort wind in the terrace units (block 7 and 8) as they are placed on the southern facade, while the living spaces benefit more compared to bedrooms in most single duplexes (block 1,2,3 and 6) of case study one (Ivy homes) as shown in Figure 65.

Figure 66: Ground Floor Plans of Case Study One (Ivy Homes) Showing the Directional Flow of the South-West Comfort Wind

Spaces in case study two (Ivy apartments) on the south and west facades which are mainly bedrooms and kitchens experience direct flow of the comfort wind while living spaces on the east and central locations experience indirect flow as shown in Figure 66 and 67.

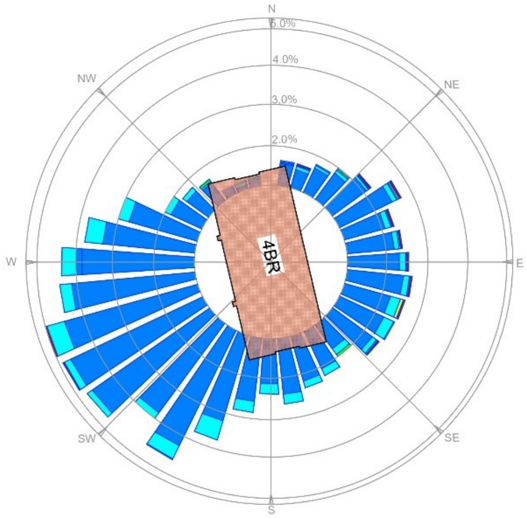


Figure 67: Analysis of Buildings in Case Study Two in Respect to the South-West Comfort Wind.

Figure 68: Floor Plan of Case Study Two (Ivy Apartments) Showing the Directional Flow of the South-West Comfort Wind

Case study three (Leptons planet five) has mainly the living spaces in block 1, 2 and 3 getting direct flow while the bedrooms get the direct flow in block 4,5 and 6 as shown in Figure 68 and Figure 69.

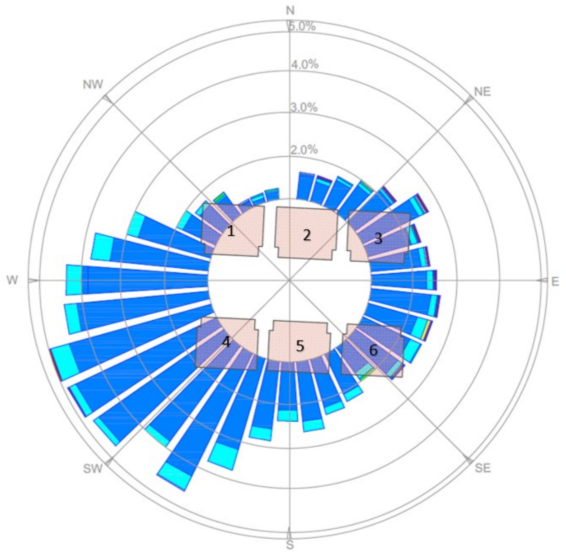


Figure 69: Analysis of Buildings in Case Study Three (Leptons Planet Five) in Respect to the South-West Comfort Wind.

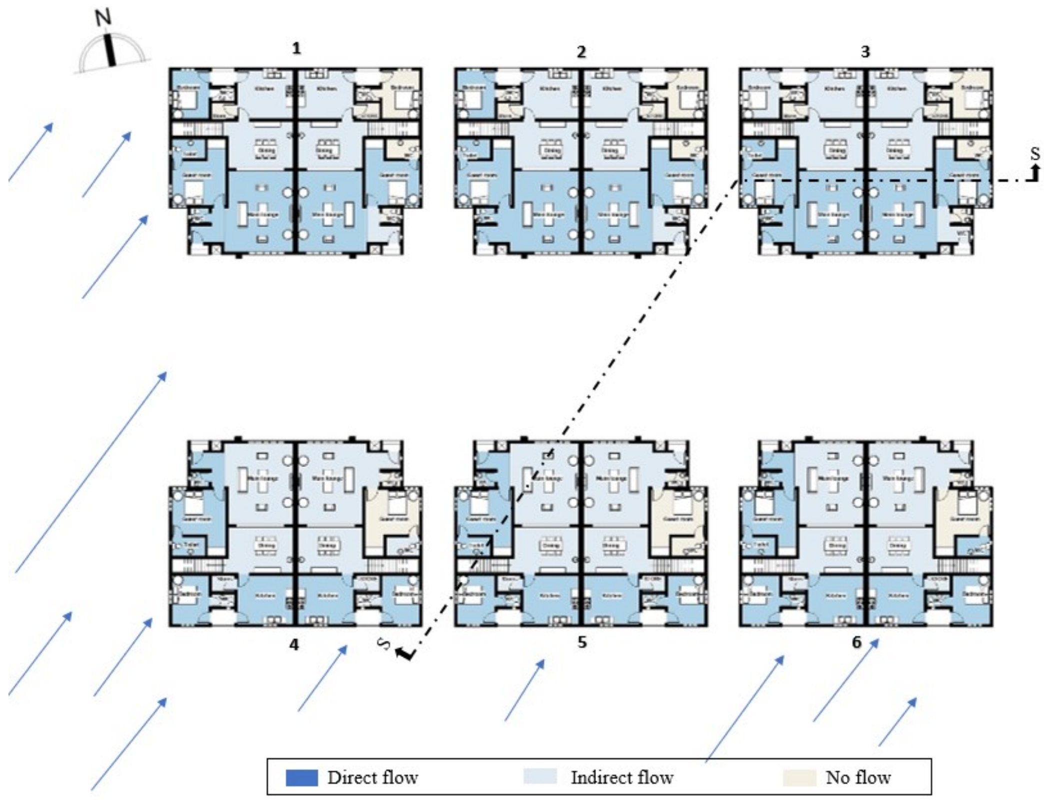


Figure 70: Floor Plans of Case Study Three (Leptons Planet Five) Showing the Directional Flow of the South-West Comfort Wind

Figure 70 shows the floor plans of a single detached unit in case study one (Ivy homes), where wind flow directions of the south-west trade winds are depicted as a result of the adopted orientation. While the living spaces which are spaces with high occupancy patterns are well ventilated due to the influence of the south-west-comfort wind, the kitchen and laundry which are the main spaces with high internal heat gain have no flow of the comfort wind. The guest bedroom and bedroom 2 are the rooms with a low potential of benefitting from the cold air.

The kitchen further experiences and indirect air flow through the circulation space in the stair hall and the dining, when the doors leading to it are opened. This usually happens when the kitchen is not being used.

Figure 71: Ground (a), First (b) and Second (c) Floor Plans of a Single Detached Unit in Case Study One (Ivy Homes) Showing the Movement of the South-West Comfort Wind

Although the wind from the south-west direction flows freely with no obstruction into the terrace units. Its effect is limited to the first interior space of contact in the first and second floors which are bedrooms. As doors remain closed due to the need for privacy. The spaces in the ground floor however experience a deeper flow as the first space is the kitchen which is a public space, therefore by opening the doors, the living spaces eventually receive a moderate ventilation rate as shown in Figure 71.

Figure 72: Floor Plans of a Single Terrace Unit in Case Study One (Ivy Homes) Showing the Flow of South-West Comfort Wind into Interior Spaces.

The living rooms on the eastern façade and dining in a central location do not have access to direct ventilation from the outdoor surrounding. However, the effect of the wind from the kitchen is experienced in these spaces as shown in Figure 70.

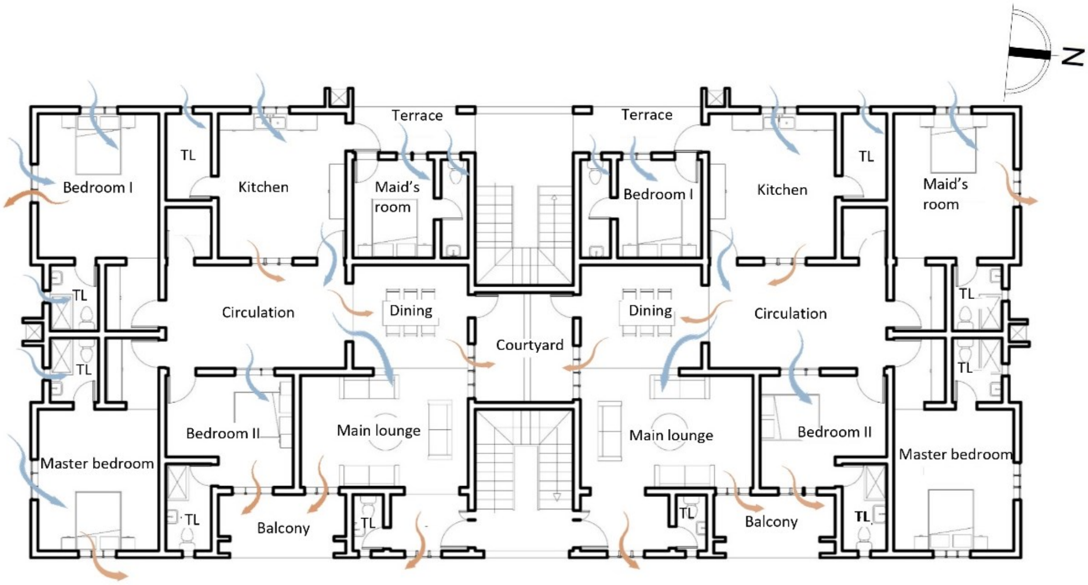


Figure 73: Floor Plan of Case Study Two (Ivy Homes) Showing the Flow of South-West Comfort Wind into Interior Spaces.

Although there is a presence of dense tress on the northern and southern boundary of the site, they do not inhibit the ventilation rate when the velocity is high but can be impeded when the wind speed is at a minimum. The kitchen and dining are the living spaces that do not benefit from the direct flow of the south-west comfort wind.

However, the effect of the wind through the living room is experienced in these spaces. Other spaces that benefit from little to no south-west wind flow due to their orientation include auxiliary spaces like stores and also the toilets as shown in Figure 73.

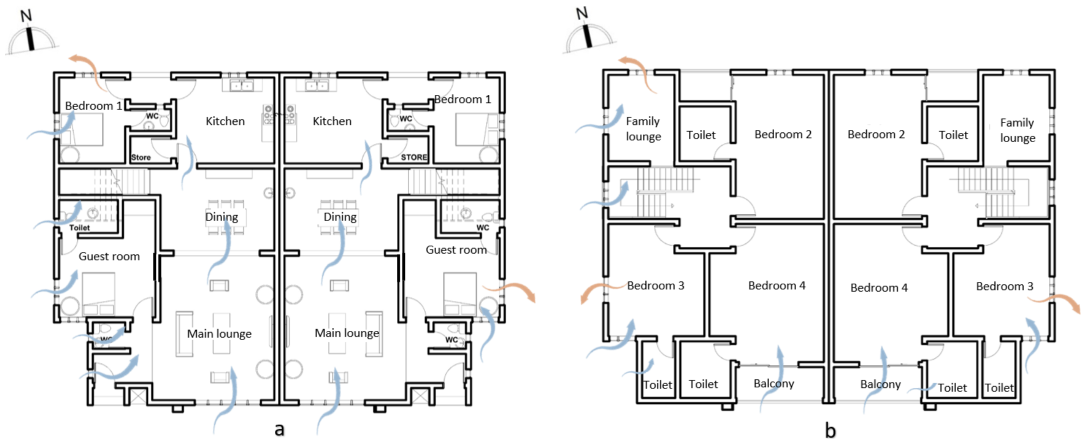


Figure 74: Floor Plans of Case Study Three (Leptons Planet Five) Showing the Flow of South-West Comfort Wind into Interior Spaces.

- **Dehumidification Potential Based on Orientation**

The orientation of buildings influencing the natural ventilation within building spaces also directly affects the level of dehumidification level within spaces. Therefore, as shown in Figure 66 and Figure 71, it is seen that while mainly the bedrooms in blocks 7 and 8 (Terraces) have high chance of getting dehumidified as they experience direct flow of comfort wind, most living rooms will mainly stay humid as the flow in and out is limited and indirect. In case study two (Ivy Apartments), kitchens and most bedrooms have high potential to be dehumidified though ventilation due to the direct flow of the comfort wind.

However, the humidity levels in the living spaces will remain high as there is no direct flow of comfort wind. In case study three (Leptons planet five), it is seen that bedroom 2s and one of the family lounges have the least potential of dehumidification through ventilation as they lack both direct and indirect flow of the comfort wind. While the living spaces have more potential to be dehumidified in block 1,2 and 3, the bedrooms have more potential in 4,5 and 6. It is seen that ventilation is the only way spaces can be dehumidified in all the case studies.

3.2.1.8 Analysis of Building Form and Layout

Buildings in all the case studies are seen to exhibit cuboid forms. However, it is noticed that the ratio between the elongated axis and the shorter axis are not significant. The case studies differ in what direction they have their elongated axis and to what extent. As the buildings in case study one (Ivy homes) and case study two (Ivy apartments) have their elongated axis along the north-south direction, while buildings in case study three (Leptons planet five) are elongated on the east-west axis.

According to the National Bureau of Statistics (2016), a typical Nigerian family consists of an average of six individuals. Based on this information, it can be inferred that the buildings being analysed do not have high occupancy levels. During the morning hours, most spaces are often unoccupied as the occupants leave for work, school, and other activities outside their homes. As a result, most spaces apart from kitchens and laundries which are utilized by maids in many families, experience low levels of activity during the day. Prior to occupants return to the buildings during the latter part of the day, when the living room and dining area become the spaces with the highest level of activity as families use these areas to relax. Late at night, everyone proceeds to their bedrooms to sleep, making the bedrooms the most frequently used spaces during the night-time.

Therefore, the analysis of the cooling needs and potential of each space will be done while considering the aforementioned activity patterns.

- **Daytime and Night-time Cooling Based of Layout of Spaces**

The spaces with high occupancy levels during the daytime are mainly the living rooms, dining and kitchen, coupled with their peak use period, these spaces also have a notable internal heat gain. In case study one (Ivy homes), block 1, 2, 3 and 6 have their dining and main lounge exposed to the west direction making the living spaces unbearable especially during the late hours of the day, when the solar angle is low as shown in Figure 74. Although the living spaces in block 7 and 8 are placed on the east, they cool down as the day progresses as such their position is not significantly problematic. Furthermore, the living spaces in blocks 4 and 5 have the least solar heat gain potential.

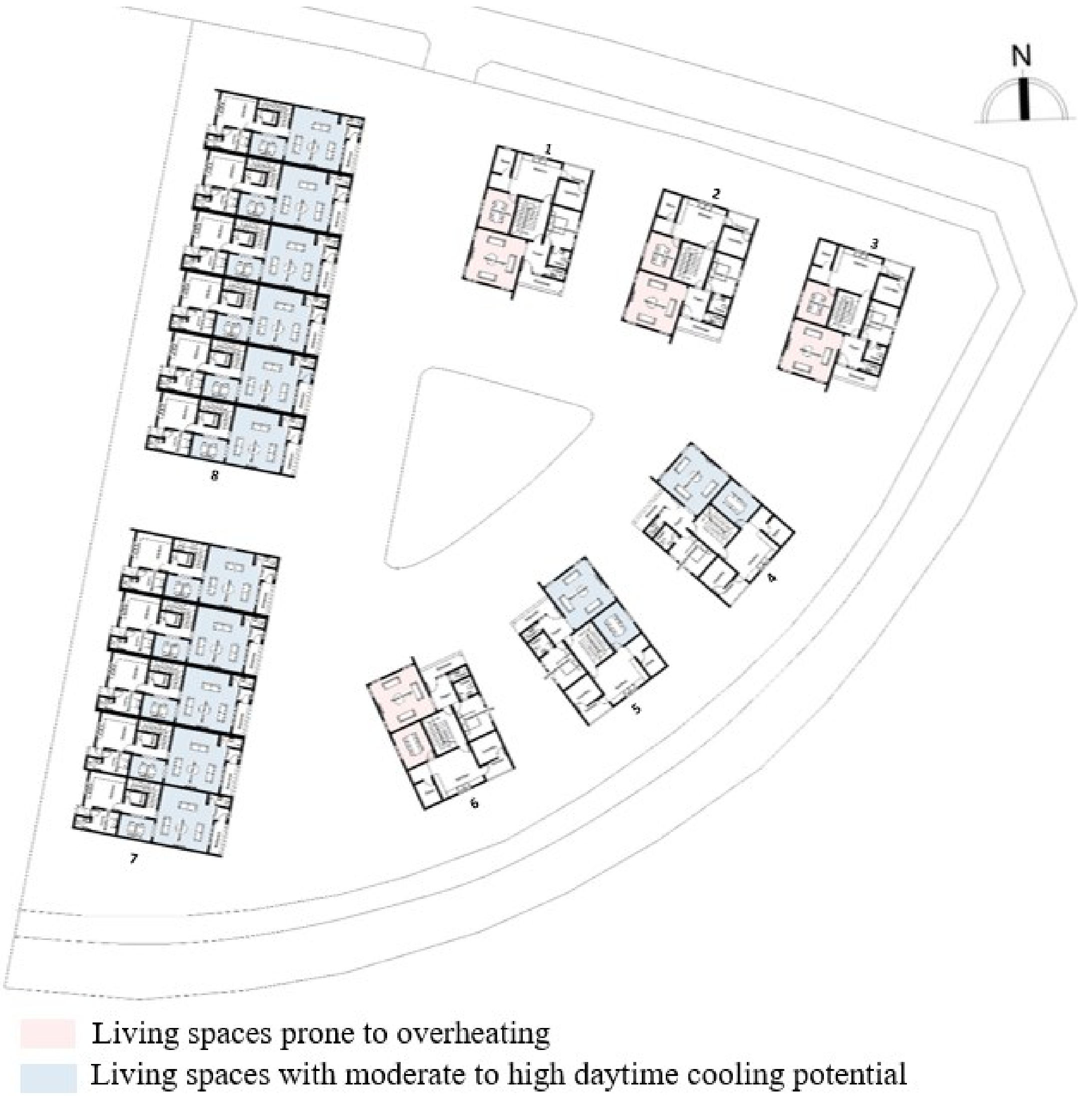


Figure 75: Location of Main Living Spaces in Case Study One (Ivy Homes)

The bedrooms are spaces that need a heightened level of cooling at night-time as that is their peak use period. Although every space with an opening and even an exposed surface towards the outdoor surrounding benefits from the cooling effect of the low night temperatures, the spaces with openings on the path of the south-west wind experience a more significant level of cooling.

Although it is mainly the bedrooms on the east that have little night-cooling potential based on the direction of the comfort wind, spaces with high cooling potential are shown in Figure 75 and Figure 76.

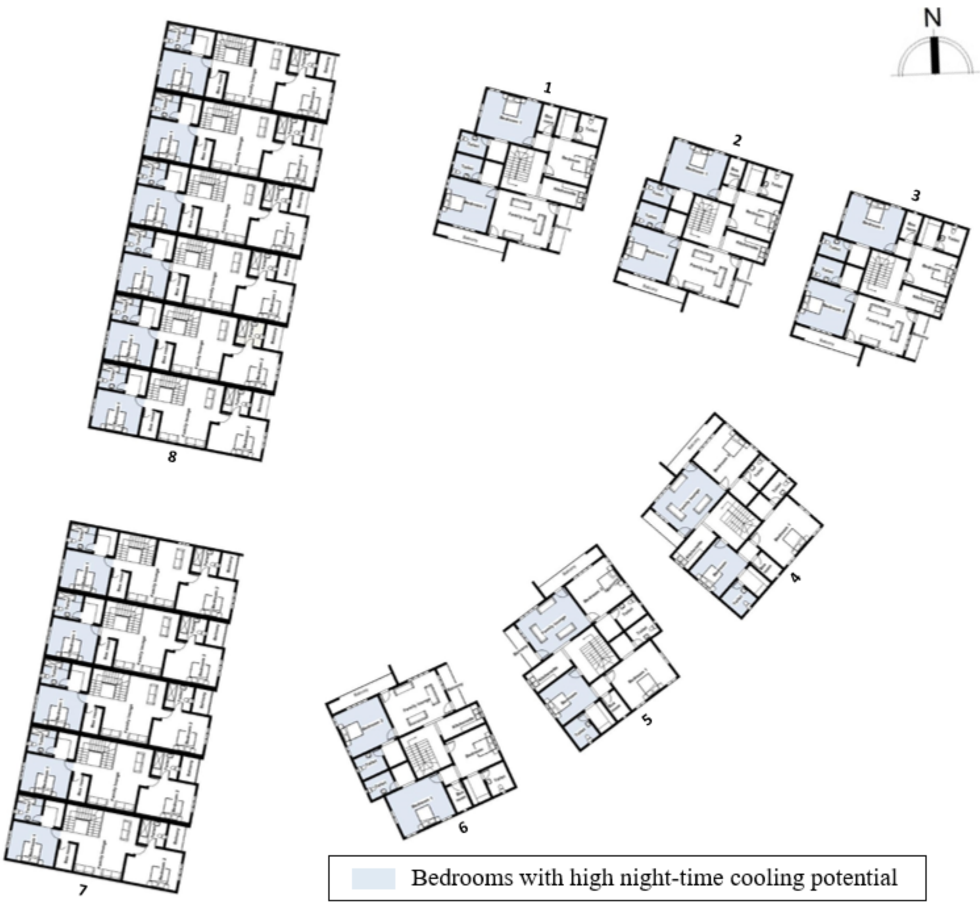


Figure 76: Bedrooms with High Night-Time Cooling Potential on the Ground Floor of Case Study One (Ivy Homes)

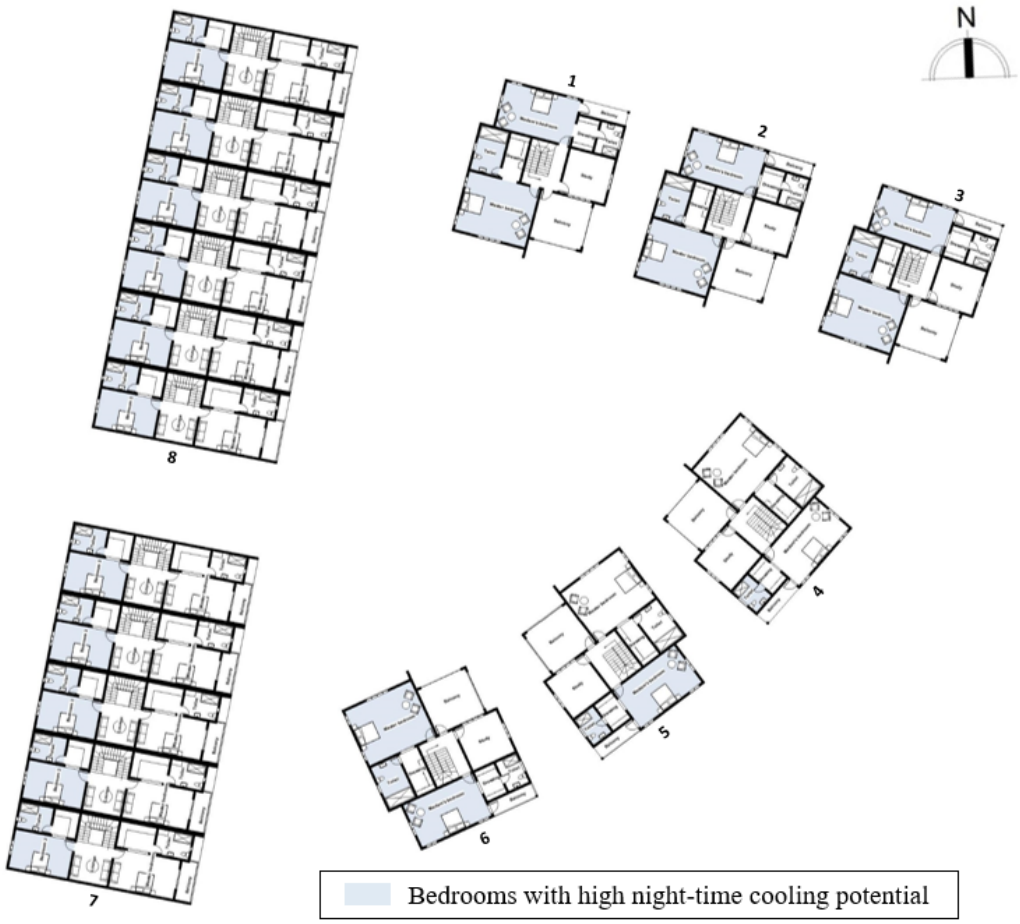


Figure 77: Bedrooms with High Night-Time Cooling Potential on the First Floor of Case Study One (Ivy Homes)

The living spaces in case study two (Ivy apartments) are placed on the east and central zones. While the dining in the central zone remains unexposed to heat from the surrounding, the living rooms experience high solar radiation in the early hours of the day although they become cooler as the day progresses as shown in Figure 77.

Figure 78: Different Occupancy Patterns, Internal Heat Gain Levels and Spaces with High Night-Cooling Potential in Case Study Two (Ivy Apartments)

Bedrooms with a heightened night-time cooling potential due to the presence of windows in the south-west direction are also shown in Figure 77.

Case study two (Ivy apartments), has a better night-cooling potential compared to other case studies due to the presence of a central open space. This allows for a high level of cooling during the night through the expulsion of hot air via the central zones as shown in Figure 78. Furthermore, this process is also experienced even when the windows remain shut during the daytime as shown in Figure 79.

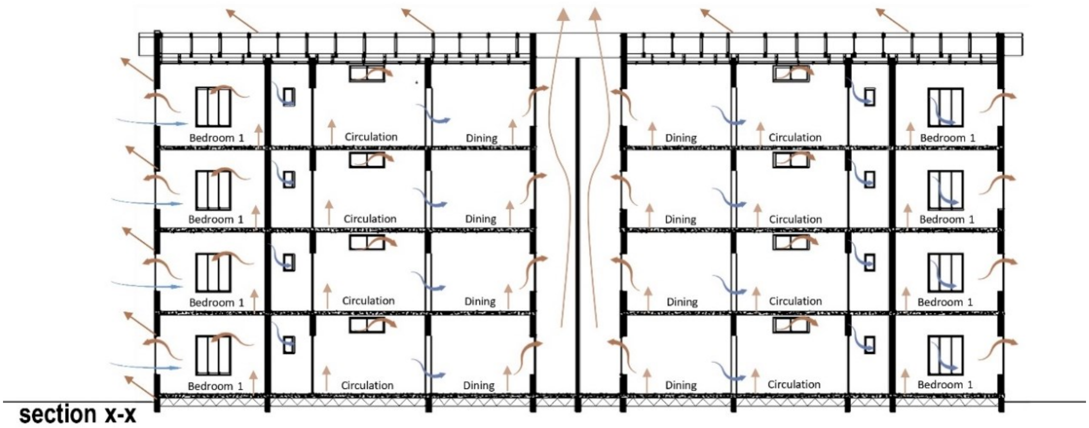


Figure 79: Section x-x Illustrating Night-Time Cooling Process in Case Study Two (Ivy Apartments)

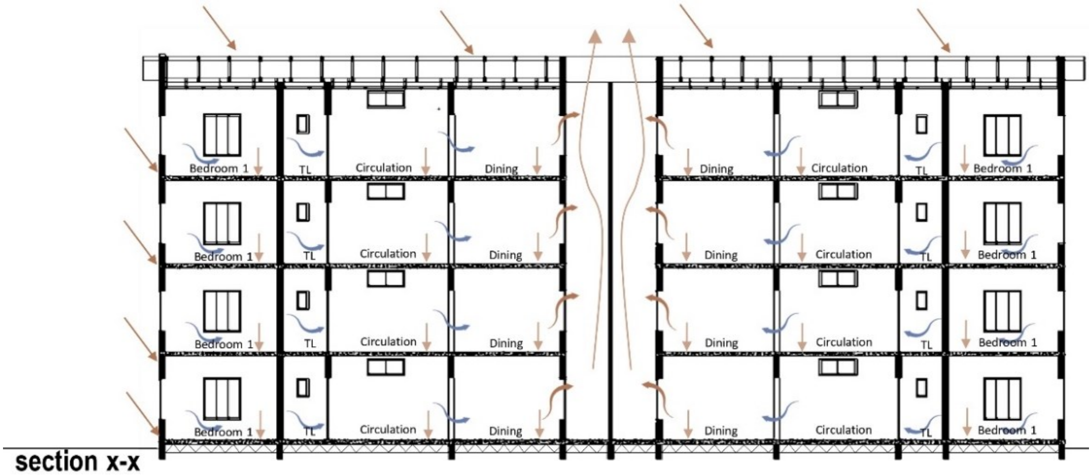


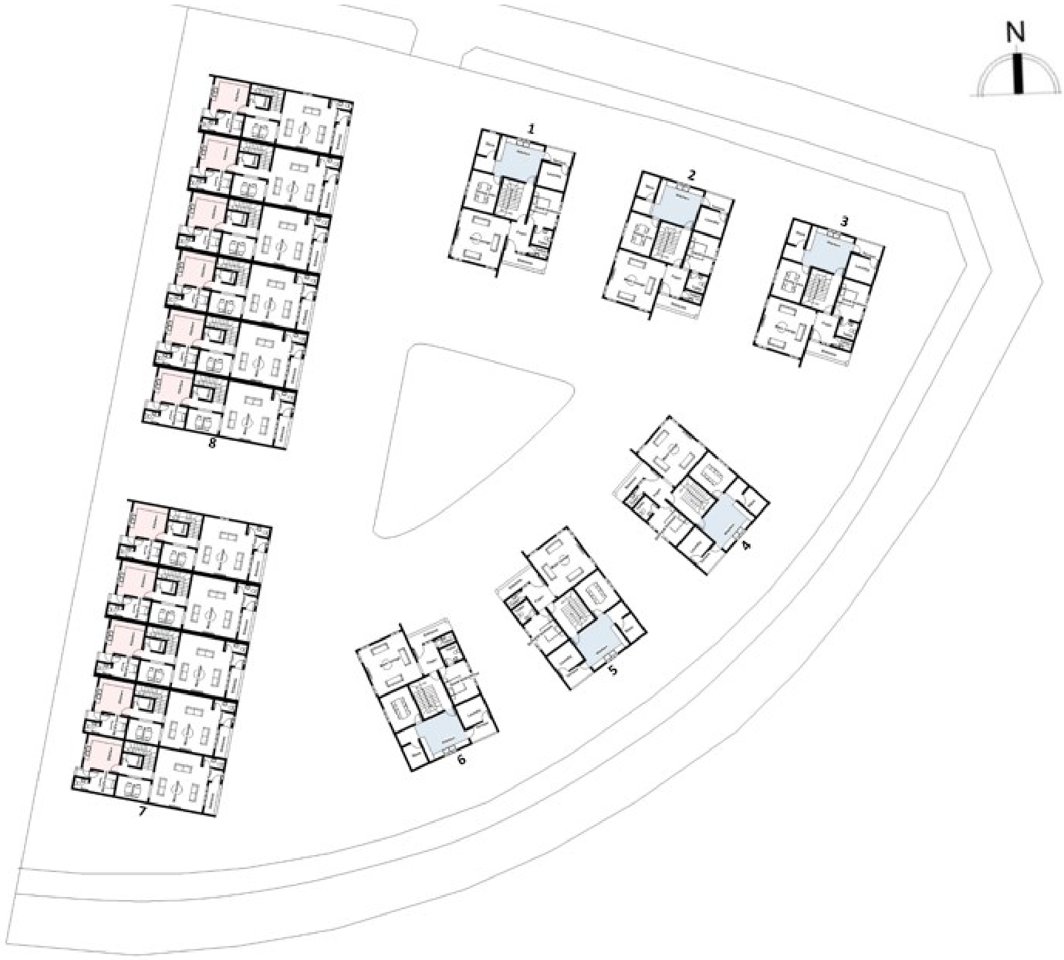
Figure 80: Section x-x Illustrating Daytime Cooling Process Following a Night-Time Cooling Process in Case Study Two (Ivy Apartments)

While the central location of the dinning protects it from solar radiation in case study three (Leptons planet three), the living rooms being bounded by spaces on both sides as shown in Figure 80, are completely protected from the intense solar radiation of the east and west direction, this allows them to stay cool during the day.

Bedrooms with a heightened night-time cooling potential due to the presence of windows in the south-west direction are also shown in Figure 80.

Figure 81: Different Occupancy Patterns, Internal Heat Gain Levels and Spaces with High Night-Cooling Potential in Case Study Three (Leptons Planet Five)

The kitchens which are spaces with high internal heat gain are mostly placed towards the north and south directions in all case studies, resulting in low solar heat gain potential as shown in Figure 80 and Figure 81. However, kitchens in case study two (Ivy apartments) and the terrace units (block 7 and 8) in case study one (Ivy homes) are placed in the western directions as shown in Figure 77 and Figure 81 respectively. Therefore, they will be uncomfortable over the course of the day.



Kitchens prone to overheating
Kitchens with moderate to high daytime cooling potential

Figure 82: Distribution of Kitchen Spaces in Case Study One (Ivy Homes)

In Abuja, the cooling effect of the wind is typically overshadowed by intense solar radiation during daytime for the majority of the year. Nevertheless, during periods of reduced solar radiation, the cooling influence of the south-west wind is experienced within most living spaces in all the case studies directly or indirectly. However, block 4 and 5 of case study one (Ivy homes) experience the least cooling effect as shown in Figure 82.

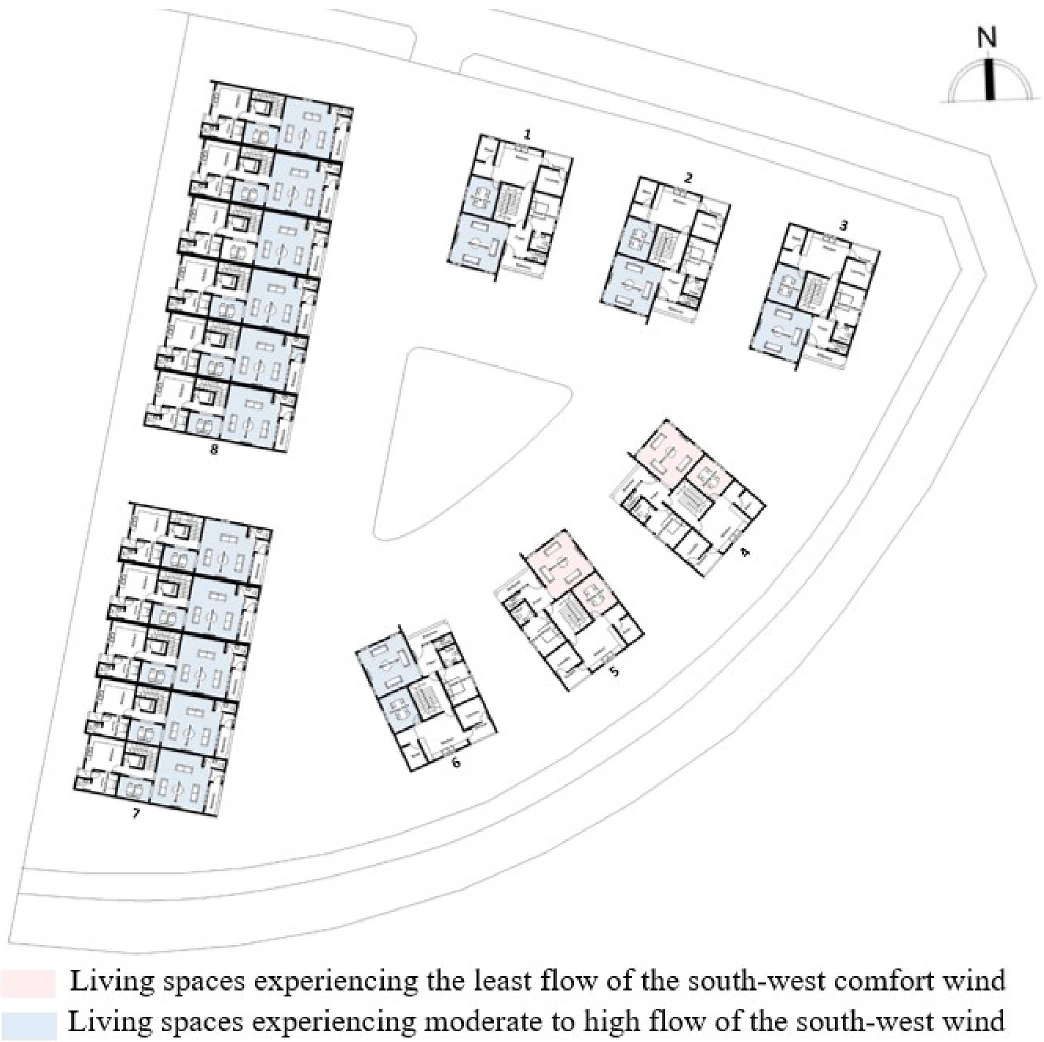


Figure 83: Daytime Cooling Potential Based on Their Access to the Flow of the South-West Comfort Wind

3.2.1.9 Analysis of Apertures

All case studies are seen to adopt the use of casement windows which provide maximum effective open area of 100% for ventilation. Additionally, the windows have an aluminum frame and 5mm tinted glass as shown in Figure 83.

Figure 84: Window Types Used in Case Study One (Ivy Homes)

The window to wall ratio (WWR) for every space was calculated by dividing the total area of the window by the total area of the wall in which it was located. The results are shown in Table. 4.

Table 4: Window to Wall Ratios of a Single Duplex Unit in Case Study One (Ivy Homes)

Space	**Orientation**	**Window Area**	**Wall Area**	**WWR**	**Recommended WWRs**
Main lounge	South	3.6	17.1	0.21	ASHRAE 90.1 – 2007 standard recommends a WWR value of 0.24 as ideal
Main lounge	West	3.6	17.7	0.23	
Dining	West	2.25	13.5	0.17	
Guest bedroom	East	3.6	13.5	0.27	
Kitchen	North	2.16	15.6	0.14	
Bedroom 1	North	3.6	17.1	0.21	
Bedroom 1	West	2.25	13.8	0.16	
Bedroom 2	East	2.25	11.7	0.19	
Bedroom 3	West	2.7	14.1	0.19	According to Korateng, Essel & Nkurmah (2015) WWRs of 0.1-0.3 are ideal however, 0.4 is tolerable for a hot-humid climate.
Bedroom 3	South	3.6	14.7	0.21	
Family lounge	South	3.6	17.1	0.21	
Family lounge	East	2.25	14.19	0.16	
Master Bedroom	West	2.7	17.7	0.15	
Master Bedroom	South	3.6	21	0.17	
Madams Bedroom	North	3.6	22.5	0.16	
Madams Bedroom	West	2.25	13.8	0.16	

Based on the ASHRAE 90.1-2007 standard which recommends the WWR of 0.24 as ideal, less than 0.24 as poor and above 0.3 as prone to overheating, only the guestroom has a WWR within the acceptable range (0.27), while the WWRs of the other spaces are below the recommended value. However, according to Korateng, Essel & Nkurmah (2015), a study carried out in the hot-humid climate of Ghana, WWRs of 0.1-0.3 are ideal, as such all spaces have appropriate WWR values in the duplex units of case study one (Ivy homes).

For the terrace units in case study one (Ivy homes), based on the ASHRAE 90.1-2007 recommendation, the master bedroom and main lounge are prone to overheating from the openings on the east, as their WWRs are above the recommended value (0.36 and 0.32 respectively), while other spaces do have WWRs that are below the recommended value. According to Korateng, Essel & Nkurmah (2015), all spaces have an appropriate WWR apart from the master bedroom and main lounge with WWRs above the recommended range (0.36 and 0.32), but still within tolerable limit from the east facade as shown in table 5 below.

Table 5: Window to Wall Ratios of A Single Terrace Unit in Case Study One (Ivy Homes)

Space	**Orientation**	**Window area**	**Wall area**	**W.W.R**	**Recommended WWRs**
Main lounge	East	3.6	11.1	0.32	ASHRAE 90.1 – 2007 recommends a WWR of 0.24
Main lounge	North	1.8	16.5	0.11	
Kitchen	West	1.8	11.4	0.16	
Bedroom 1	East	2.25	11.7	0.19	
Bedroom 2	East	2.25	11.7	0.19	According to Korateng, Essel, Nkurmah (2015) WWRs of 0.1-0.3 are ideal however, 0.4 is tolerable for a hot-humid climate
Family lounge	North	1.8	10.8	0.17	
Master Bedroom	East	4.2	11.7	0.36	
Bedroom 3	West	2.25	11.7	0.19	

Figure 85: Narrow Windows with Poor Window to Wall Ratios in a Detached Duplex Unit in Case Study One (Ivy Homes)

In case study two (Ivy apartments), windows of the bedrooms and lounges are mainly all of the same size and are spread across all directions, with those of the bedrooms placed in all facades, while the windows of the lounges are found in the eastern façade. Smaller windows of toilets are also placed on all facades as seen in Figure 83.

Figure 86: Window Placements in Case Study Two (Ivy Apartments)
Source: Company's Archive

Based on the ASHRAE recommendation, no space has a good WWR, however considering the values from Korateng, Essel & Nkurmah (2015) all spaces have WWRs within the appropriate range as shown in Table 6 below.

Table 6: Window to Wall Ratios in Case Study Two (Ivy Apartments)

Space	**Orientation**	**Window area**	**Wall area**	**W.W. R**	**Recommended WWRs**
Main lounge	East	2.25	16.92	0.13	ASHRAE 90.1 – 2007 recommends a WWR of 0.24
Main lounge	North	2.25	12.3	0.18	
Bedroom I	West	2.25	14.1	0.16	
Bedroom I	South	2.25	12.3	0.18	
Bedroom II	East	2.25	11.82	0.19	According to Korateng, Essel, Nkurmah (2015) WWRs of 0.1-0.3 are ideal however, 0.4 is tolerable for a hot-humid climate
Bedroom II	West	2.25	11.82	0.19	
Master Bedroom	East	2.25	12.3	0.18	
Master Bedroom	South	2.25	14.1	0.16	
Kitchen	West	2.16	12.81	0.17	
Maids room	West	1.44	9.0	0.16	

The adoption of a central courtyard with a 3.3m by 3.6m span dimension in case study two (Ivy apartments) serves as a way of improving the natural ventilation rate by increasing the level at which hot air is expelled out of the interior space, it is however not appropriate for bringing in cold air into the spaces.

Case study three (Leptons planet five) has its larger windows facing the north and south direction which are the windows of the main lounge and master bedroom as shown in Figure 86. Other bedrooms and family lounge that have smaller windows are facing the east and west direction, along with the small windows of the toilets.

Figure 87: Windows on the North and South Facades of Case Study Three (Leptons Planet Five)
Source: Company's report

Based on the ASHRAE 90.1-2007 recommendation, no space has a good WWR, with the main lounge window from the south having the closest value to it (0.21), while bedroom 4 is prone to overheating from the south. According to Korateng, Essel & Nkurmah (2015) all spaces have WWRs within the ideal range apart from bedroom 4 from the south (0.33) as shown in Table 7 below.

Table 7: Window to Wall Ratios of a Single Housing Unit in Case Study Three (Leptons Planet Five)

Space	**Orientation**	**Window area**	**Wall area**	**W. W. R**	**Recommended WWRs**
Main lounge	South	3.6	16.5	0.21	ASHRAE 90.1 – 2007 standard recommends a WWR value of 0.2
Bedroom 1	North	1.44	9	0.16	
Bedroom 1	West	1.44	11.7	0.12	
Kitchen	North	1.44	13.5	0.10	
Guest room	South	1.44	12.6	0.11	
Guest room	West	1.44	11.4	0.13	According to Korateng, Essel, Nkurmah (2015) WWRs of 0.1-0.3 are ideal however, 0.4 is tolerable for a hot-humid climate.
Family lounge	North	1.44	9.6	0.15	
Family lounge	North	1.44	9.6	0.15	
Bedroom 2	South	1.44	13.2	0.11	
Bedroom 2	West	1.44	15.0	0.10	
Bedroom 3	North	1.44	12.6	0.11	
Bedroom 3	West	2.4	19.5	0.12	
Bedroom 4	South	5.4	16.2	0.33	

- **Natural Ventilation Potential Based on Apertures**

This provision of two openings opposite or perpendicular to each other facilitates cross ventilation, resulting in optimal cooling for a large period of time. This is adopted in most spaces in the duplexes in case study one (Ivy homes) apart from the guest bedroom, bedroom 2 and auxiliary spaces as shown in Figure 87. In both case study one (Ivy homes) and case study two (Ivy apartments) buildings, all spaces are designed to have cross ventilation through the windows. However, it is important to note that the kitchen, being a public space, can achieve cross ventilation primarily when the door is opened, particularly during the daytime.

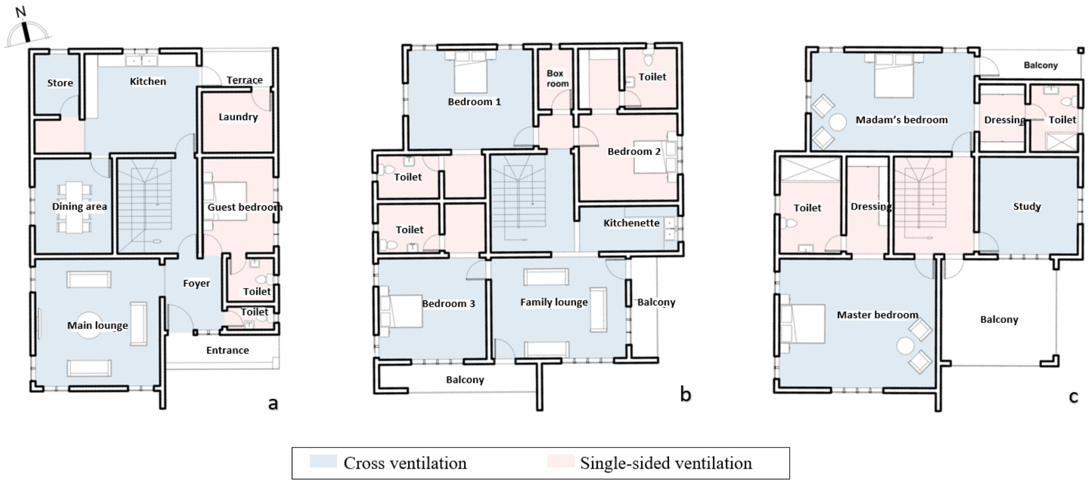


Figure 88: Ventilation Strategies in the Duplexes of Case Study One (Ivy Apartments)

Due to its typology, only the lounges have windows on two different directions, as such cross-ventilation is achieved. Nevertheless, the kitchens do achieve cross ventilation by the use of doors to serve as air outlet as shown in Figure 88. The only space designed to achieve ventilation through stack effect in this case study is the maid's room.

Figure 89: Ventilation Strategies in the Ground Floor (a), First Floor (a) and Second Floor (c) of Terraces in Case Study One (Ivy homes)

All spaces apart from the maid's bedroom on the western façade and the auxiliary spaces are provided with cross ventilation as shown in Figure 89 in case study two (Ivy apartments).

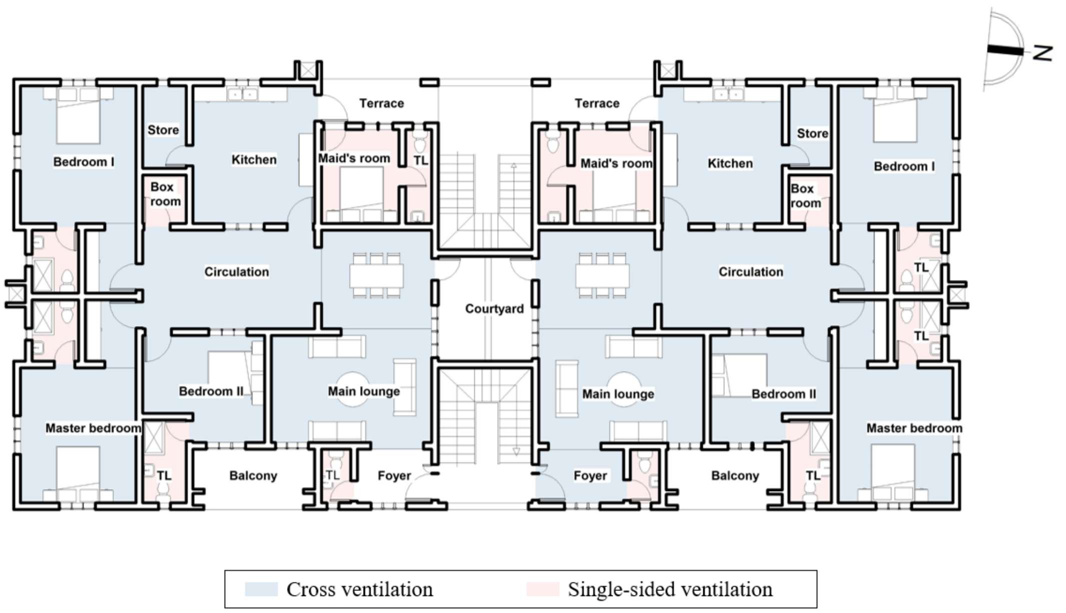


Figure 90: Ventilation Strategies in Case Study Two (Ivy Apartments)

Bedroom 4 on the approach façade along with the auxiliary spaces are the only spaces without cross ventilation in case study three (Leptons planet five) as shown in Figure 90.

Figure 91: Ventilation Strategies in Case Study Three (Leptons Planet Five)

3.2.1.10 Analysis of Solar Control

The overhangs provided by the extruding building floors above spaces like the bedrooms on the southern facades and over the dining and living spaces in the east and west facades of the detached duplexes are the main source of shading in case study one (Ivy homes). In the terraces, they are also used on the east and west facades over the bedroom 2 and bedroom 1 respectively. While the openings of bedroom 3 and the master bedroom on the east and west directions in the duplexes, as well as bedroom 2 on the east and bedroom 3 on the west in the terraces, are left exposed to intense solar radiation. However, the openings of the living spaces on the west in most blocks and in the north-east and south-west directions in some receive shading by a 90 cm cantilevered floor as shown in Figure 91.

Roofs that are one of the critical elements of a building in providing shading are also not utilized in this case study for that purpose as most part of the buildings are covered with concrete decks while others are covered with flat roofs, however extrusions and overhangs are not present. As a result of a significant area of the building envelope and openings being exposed, the interior spaces are susceptible overheating.

Figure 92: Solar Control Measures and Exposed Surface with No Shading in Case Study One (Ivy Homes)

The eastern façade of the buildings in case study two (Ivy apartments) features both horizontal and vertical extrusions, while the north, south, and western facades have vertical extrusions and recessed walls. These design elements are implemented to provide some level of solar control. Additionally, a flat roof design with a 45 cm wooden fascia that slopes backward is employed. As a result, all building facades are equipped with a 45 cm roof overhang, primarily serving as shading for the walls and openings of the third floor.

The east and west facades of case study three (planet five) lack any shading elements for the walls and openings. However, the sizable opening of bedroom 4, located on the north and south facades is provided with shading through the use of horizontal shading elements, as depicted in Figure 92. Furthermore, all sides of the building benefit from a 45 cm roof overhang.

The presence of plants in front of the building serves as a shading feature for the ground floor windows on the approach facade. Likewise, the dense trees located on the north and south sides offer shade to the bedrooms, kitchen, and family lounges in that direction.

Figure 93: Horizontal Shading Devices on the Northern Façade of Case Study Three (Leptons Planet Five)
Source: Company’s report

Appropriate spacing also serves as a form of shading, as such the moderate spacing between the building blocks allows for a reduced solar exposure of the building facades in case study one and three, although the effectiveness may vary.

3.2.1.11 Analysis of Exterior Surfaces as Absorbers

Light building finishes are used on exterior walls in form of ash and textured burnt orange paints in case study one (Ivy homes), light brown and peach textured paints in case study two (Ivy apartments) and white and dark textured paint in case study three (Leptons planet five). Roof finishes include light ceramic tiles over roof decks and a cream aluminum roofing sheet in a case study one (Ivy homes) as shown in Figure 93, light ash long-span aluminum roofing sheet in case study two (Ivy apartments) and three (Leptons planet five).

Figure 94: Flat Roofs as Absorbers in Case Study One (Ivy Homes)
Source: Author's field study

- **Heat Gain Prevention Through the Use of Light Exterior Building Surfaces**

The use of light building finishes, such as paints and coatings, as well as outdoor surfaces in form of light concrete pavements, facilitates the maintenance of a cool interior environment. As these surfaces possess high reflectivity and low absorptivity, enabling them to effectively reflect off a significant portion of the solar radiation that strikes the building envelope and outdoor surfaces. Consequently, the direct absorption of solar heat through the walls is minimized, thereby preventing an increase in the indoor temperature.

3.2.1.12 Analysis of Thermal Mass

All case studies adopt the use of 23 cm sandcrete block walls, with case study one (Ivy homes) being partially roofed by 15 cm reinforced concrete roof deck along with aluminum roofing sheets in some parts. Case study two (Ivy apartments) and three (Leptons planet five) are however completely roofed by thin long-span aluminum roofing sheet.

Despite the walls and roofing elements being lightweight, the buildings in all case studies possess a high thermal mass as a result of their slightly compact design.

- **Cooling Potential Based on Thermal Mass**

All case study buildings encounter limited cooling potential attributed to the transmission of lower temperature changes through lightweight surfaces directly exposed to the outdoor surrounding. Nevertheless, this cooling effect is not evenly distributed among all spaces, and its effectiveness is diminished by the solar heat gain taking place within other interior areas.

3.3 Questionnaires

With an estimated average of two potential respondents (adults) in each household, a total population of 74 from 32 households was deduced in which a sample size of 62 was calculated using the Yamane's formula for calculating sample size as stated below: $n = N/1 + N(e)^2$ where n is the sample size, N is the total population (74) and e is the estimated sample error (5%).

$$N=74/1+74(0.05)^2=62 \quad (3)$$

Chapter 4

RESULTS AND DISCUSSION

This chapter presents the results derived from conducting physical observations on selected case studies, evaluating the thermal comfort experienced by building users, and analyzing their perceptions of passive cooling. These outcomes were obtained by gathering data from a specific sample size and are discussed in relation to the objectives outlined in Chapter 1.

4.1 Results from Physical Observation

Results from the physical observation were analysed through an analytic approach based on certain parameters as discussed in chapter 3 which are discussed further below as the final assessments as to which passive cooling strategies are adopted, promoted or inhibited in the selected case studies are deduced.

4.1.1 Micro-climate and Site Design

While the trees in the northern site boundary of case study one (Ivy homes) have the potential of producing a cooling effect on the surroundings through evapotranspiration, it is unlikely for the interior spaces to significantly feel this impact due to the considerable distance between them. Furthermore, these trees do not provide protection against intense solar radiation or channel cold breeze towards the interior spaces of the first and second floors because of their limited height, in contrast to the tall palm trees in the neighbouring buildings towards the north.

The absence of trees on the east and west facades which are sides that are prone to overheating in all case studies apart from case study three (Leptons planet five) leaves the buildings exposed to intense solar radiation, thereby making the building interior and envelope susceptible to overheating.

Although the spacing between the building some blocks does not comply with the recommended guideline of being up to 5 times their height, as suggested by (Ayinla, Olaniyan, & Okeyinka, 2013) The spacing still facilitates a moderate to good level of airflow as previously analysed according to the flow types developed by Hussein and Lee (1988). Among the case studies, case study two (Ivy Apartments) has the most favourable spacing, while buildings in case study three (Leptons planet five) have the least favourable spacing, in terms of benefitting from optimal air movement and exchange.

These results underscore the importance of considering the W/H aspect ratio in design and planning to optimize ventilation and air quality in building environments.

4.1.2 Orientation

The appropriate orientation for a hot-humid climate aims at protecting the building envelope from the intense solar radiation while letting in the comfort wind to produce cooling effect within the spaces. To achieve this, Wong and Li (2007) suggest that the longer axis of the building should be along the east-west direction. They further determined that by following this orientation, the cooling load for a residential building can be reduced by approximately 8% to 11%.

With the exception of buildings in case study three (Leptons planet five) and block 4,5 and 6 of case study one (Leptons planet five), the orientations of the building blocks in all other case studies deviate from the recommended practice, as the longer sides of the buildings are exposed to intense solar radiation from the east and west directions. Consequently, there is a notable rise in solar heat gain, resulting in increased cooling loads within the buildings and the potential for overheating. However, this orientation does not impede the flow of south-west comfort wind into the interior spaces, as its influence is experienced within most spaces in all case studies.

Although ventilation is known to be the least energy intensive and basic method of lowering the humidity levels within indoor spaces, it is seen to be the only passive option. As such there is no little to no possibility of dehumidification when the humidity level within the surrounding is high and openings are required to be shut, which occurs for a significant period within the year.

4.1.3 Building Form and Layout

The case studies presented feature building forms that are slightly compact and dense. This contradicts Pacheco, Ordonez & Martinez (2012)'s recommendation of adopting less-compact forms in humid climates due to low cooling capacity and less cooling load and their ability to promote ventilation.

Subiyantoro, H (2017) further asserts that the ideal building form for humid tropics is achieved by elongating the axis in the east-west direction. However, this finding is only implemented to some extent in case study three (planet five) and block 4,5 and 6 of case study one (Ivy homes).

In order to achieve optimized distribution of spaces, it is necessary to group spaces with similar activity levels and types together. This approach, as suggested by Santamouris and Asimakopoulos (2013), facilitates effective heat management in the case of spaces with high internal heat gain levels and helps maintain comfortable conditions within the building. All case studies demonstrate a considerable implementation of this approach, as the kitchens are primarily located at the rear facades of each building, while toilets are grouped together. Typically, the ground floors serve as public zones with high occupancy patterns and activity levels, while the upper floors are designated as private zones with bedrooms, characterized by moderate occupancy and activity levels.

4.1.3.1 Daytime Cooling and Night-time Cooling

Daytime cooling is achieved in most living spaces based on their layout, as living spaces and bedrooms could be positioned on any of the sides of the building without adverse effects, except the west, due to the intense solar radiation caused by low solar angle during the late hours of the day. Hence auxiliary spaces should be located in that direction according to Gut and Ackerknecht (1993). It is for this reason that the living spaces in the detached duplexes have the lowest potential for daytime cooling as they are completely exposed towards the western façade.

Santamouris. M & Asimakopoulos (2013) also suggest that spaces with high level of internal heat gain should be placed in directions that are not prone to further heat gain but with significant cooling potential. Kitchens in the terrace (block 7 and 8) of case study one (Ivy homes) and case study two (Ivy apartments) are however not in line with this suggestion as they are placed in the western directions, as such they will be uncomfortable over the course of the day during the time of use.

Typically, ventilation serves as the primary method for cooling interior spaces during the day. However, when the weather is excessively hot or during the dry season the windows are shut. As such, night-time cooling becomes a valuable strategy to maintain comfortable building spaces throughout the night. Moreover, it helps in reducing and sustaining a comfortable temperature in the living areas for a significant portion of the day by utilizing the cooling effect accumulated during the night.

Although, incorporating building materials with high thermal mass is recommended to optimize the efficiency of night-time cooling if achieved sufficiently. Conversely, the lack of sufficient thermal mass in the building envelopes of all case studies prevents the prolonged transfer of the night-time cooling effect to the interior spaces during the day. Notably, the use of high thermal mass in humid climates is not recommended as the heat stored within building envelope is not effectively cooled down during night-time due to insignificant diurnal temperature change.

4.1.4 Apertures

It is generally noticed that an increase in the window to wall ratios results in higher ventilation and dehumidification potential especially in humid climates thereby improving the indoor thermal comfort.

Observing the window-to-wall Ratios (WWRs) of the case studies, it becomes evident that the duplexes in case study one (Ivy homes) and case study three (planet five) feature larger windows on the north and south directions. Conversely, narrow windows are strategically positioned on the east and west sides of the duplexes, aligning with the recommendations of Liping & Hien (2006). However, the terrace units deviate from this pattern, as they have larger windows positioned towards the east and west directions. Consequently, it becomes essential to incorporate efficient shading devices, particularly on the west facade, as the openings in that direction are susceptible to facilitating the increased solar heat gain within the building's interior spaces.

While smaller windows are suggested to prevent overheating, they can impede ventilation, as adopted in case study one (Ivy homes). In contrast, case study two (Ivy apartments) exhibits a higher ventilation rate by maintaining nearly equal sizes for the inlet and outlet. However, the drawback of this approach is the increased potential for solar heat gain from the east and west directions.

The majority of the windows in the case studies possess Window-to-Wall Ratios (WWRs) that fall within the acceptable range as determined by the calculations and recommendations outlined in chapter 3. Consequently, it can be concluded that these windows are appropriately sized and have the potential to offer a satisfactory ventilation and dehumidification rate.

4.1.4.1 Natural Ventilation Potential Based on Aperture Placement

In their investigation of window configurations, Gao and Lee (2011) found that achieving cross ventilation leads to improved natural ventilation, thereby enhancing thermal comfort within buildings. With cross ventilation, stale hot air is expelled through outlets while fresh air enters, producing cooling approximately 70% of the time according to Ahmed, T., Kumar, P., and Mottet, L. (2021). This effect is challenging to attain with a single window in a building space. It can be concluded that cross-ventilation is achieved in majority of the spaces in all case study buildings.

Notably, stack ventilation is only implemented in the maid’s room in case study one (Ivy homes). Although, it is known to be effective, cross ventilation is generally preferred due to minimal temperature differences between indoor and outdoor environments during the day in humid regions.

4.1.4.2 Dehumidification Potential Based on Aperture Placement

The implementation of cross-ventilation being the most preferred ventilation strategy also promotes dehumidification levels. Consequently, areas featuring cross-ventilation possess the highest potential for dehumidification. This is particularly evident in the case studies, with case study two (Ivy Apartments) having significant dehumidification potential, while the terraces in case study one (Ivy Homes) with the least potential due to their lower ventilation rates.

4.1.5 Solar Control

As a way of mitigating the effect of intense solar radiation in hot regions, it is recommended to use external shades such as wide overhangs, awnings, and other structures to protect building openings from external climatic conditions, while also facilitating ventilation within the building spaces.

Horizontal overhangs are utilized in all directions in case study one (Ivy homes). however, it is observed that certain overhangs are not suitable for their intended purpose as horizontal shading is most effective for the north and south facades, where it provides shade for the bedrooms, study, and lounges in those specific orientations. Rather, the use of an egg-crate type of shading element is more appropriate in the east west directions.

Undesirably, even the horizontal shading elements on the north and south directions are not designed appropriately, as recommended by (McGee 2013), which suggests that horizontal shading should extend beyond the width of the windows to effectively block solar radiation ingress. This design requirement is only met by the overhang above the study area in case study one. The living spaces on the west directions and also in the north-east and south-west directions are effectively shaded by a cantilevered floor, being on the last floor with a moderate spacing between the blocks.

The inclusion of extrusions on the eastern facade of case study two (Ivy apartments) proves to be insufficient as shading elements due to their minimal depth. Moreover, effective shading is primarily limited to the maid's room on the west side, as well as bedroom 2 and the main lounge on the east side of the building, while the third-floor walls and windows on the third floor experience a moderate level of shading provided by the roof overhang. Consequently, adequate solar control is not achieved, and improvements are necessary in order to enhance the effectiveness of shading in this case study.

In case study three (planet five), the implementation of horizontal shading on the north and south facades falls short of providing complete shading to the bedrooms throughout the day. This is primarily due to the limited depth of the shading elements. Consequently, there will still be some impact from solar radiation at certain times, particularly on the southern facades, although the extent of this effect may be limited.

Vegetation proves to be effective for solar control in all building directions. In case study three (Leptons planet five), trees primarily serve as a means of solar control, particularly on the north and south facades. However, in case studies one (Ivy homes) and two (Ivy apartment), vegetation does not meet the desired height or proximity requirements. Consequently, the east and west facades are left exposed without effective shading from trees.

Based on the findings by Shabbir, A (2005), it is important to note that even though the north and southern facades of block 7 and 8 of case study one (Ivy apartments) and the longer sides of the duplexes in case study one (Ivy homes) exhibit moderate spacing between them, their height-to-width (H/W) ratio remains below 3:1. As a result, it is still necessary to incorporate shading measures for these surfaces. On the other hand, the spacing of 2.7 m between the sides of case study three (Planet five) provides effective shading to the east and west facades as it results in a H/W ratio of 3:1. However, this impedes the air flow in those directions as buildings are recommended to have a spacing 5 times their height to achieve optimal air flow within them according to (Ayinla, Olaniyan, & Okeyinka, 2013).

4.1.6 Exterior Surfaces as Absorbers

The adoption of a light exterior building envelope is as recommended by (Hatamipour, Mahiyar, & Taheri, 2007), due to its potential in lowering cooling loads and increasing the cooling capacity of a building as opposed to dark exterior surfaces.

4.1.7 Thermal Mass

The utilization of lightweight roofing and wall materials is in accordance with Mirrahimi et al. (2016)'s recommendation for the use of building materials with low thermal mass in hot-humid climates. These materials effectively respond to rapid temperature changes, ensuring the maintenance of cool interior spaces at nighttime. This is particularly beneficial in humid climates, where diurnal temperature differences are not significant.

However, the implementation of heavyweight building envelope especially for external walls is necessary to slow down the transfer of heat within interior spaces and to ensure that it is absorbed and later released to the surroundings during nightime as achieved in traditional buildings within the study area by adopting thick mud walls.

The dense design of the case studies causes the interior spaces to experience significant heating when the stored heat in the building envelope is released. The lack of substantial diurnal temperature drop hinders passive cooling, making mechanical cooling essential in order to achieve a comfortable indoor space.

The summarized findings from the physical observation of the case studies, according to the selected criteria for analysis and discussion, are presented in the table 8.

Table 8: Findings from the Physical Observation of Case Studies

Micro-climate and Site Design
Case study one (Ivy homes)
▪ Buildings are placed in order to fit into the existing site layout ▪ Small and medium sized trees in the northern site boundary and within the boundaries of each building especially at the front. ▪ A central green space along with other green spaces on the sides of the buildings and the northern site boundary ▪ Light concrete and dark asphalt finishes on outdoor surfaces ▪ No obstruction on the south-west direction, hence free flow of the comfort wind ▪ Buildings blocks experience maximum, limited and minimum air exchange within different blocks.
Case study two (Ivy apartments)
▪ Buildings are placed in order to fit into the existing site layout ▪ Small and medium size plants more prominent within the site, with close proximity to the building blocks along with green spaces ▪ Light concrete and dark asphalt finishes on outdoor surfaces ▪ Uncompleted building blocks with a height of 2m at the current state on the south-west boundary, which do not serve as an obstruction to the south-west comfort wind
Case study three (Planet five)
▪ Medium sized plants at close proximity to building blocks especially to the approach while dense trees are present in the northern and southern site boundaries and at the neighbouring buildings.

- The 15 m distance between the building faces results in a moderate air exchange, while the spacing of 2.7m between the sides produces minimal air exchange.

Conclusion

Among the selected case studies, case study three (leptons planet five) stands out with the most substantial cooling effect, primarily due to the abundance of vegetation that promotes evaporative cooling. While case study one excels in achieving significant cooling by facilitating efficient air movement and exchange within the building blocks as a result of the optimal spacing provided within building blocks.

Orientation

Case study one (Ivy homes)

- The longer sides of block 1,2 3,7 and 8 are exposed to the intense solar radiation of the east and west directions while the longer sides of block 4,5 and 6 are not as they are oriented towards the north-east and south-west directions.
- According to the prior analysis in chapter three, the orientation of the buildings limits the direct or indirect wind flow of the south-west comfort wind to only 56% of the spaces. However, the duplexes have a higher percentage, with 73% of them benefiting from the south-west comfort wind.

Case study two (Ivy apartment)

- The longer side of the building block is placed along the north-south axis
- According to the prior analysis in chapter three, 93% of the main spaces have direct and indirect flow of the south-west comfort wind

Case study three (Leptons planet five)

- The longer axis of each semi-detached building unit is placed along the north-south axis, while the longer side of each building block is placed along the east-west axis.
- According to the prior analysis in chapter three, 81% of the main spaces benefit from the flow of the south-west comfort wind

Conclusion

The buildings in case study three (planet five) are designed with an optimal orientation therefore they have the lowest solar heat gain potential compared to other case studies. However, case study two (Ivy apartments) has the highest percentage of spaces benefitting from the ingress of the south-west comfort wind as a result of its orientation among other factors, thereby having a higher potential of cooling through natural ventilation and dehumidification.

Building Form and Layout

All case studies exhibit similar building forms in form of cuboids which are not considered compact

Case study one (Ivy homes)
▪ The building layout in this case study does not facilitate daytime cooling in the most living spaces as they are exposed to intense solar radiation of the west direction although most of them benefit from ventilative cooling within this period when the weather condition is favourable, ▪ Effective nighttime cooling potential due to the south-west comfort wind in 50% of the bedrooms according to prior analysis in chapter three.
Case study two (Ivy apartments)
▪ The building layout facilitates moderate ventilative cooling of the living spaces via the kitchen, although, they are placed on the east, the lack of direct exposure to solar radiation prevents overheating. All bedrooms apart from the master bedroom by the north have high night-time cooling potential. ▪ Effective nighttime cooling potential due to the of the south-west comfort wind in 93% of the bedrooms according to prior analysis in chapter three.
Case study three (Leptons planet five)
▪ While the living spaces experience both direct and indirect ventilative cooling which is enhanced by the linear arrangement of the living spaces. Furthermore, their placement on the north and south facades does not promote overheating throughout the day. ▪ Effective nighttime cooling potential due to the south-west comfort wind in 81% of the bedrooms according to prior analysis in chapter three
Conclusion
The living spaces in case study three (Leptons planet five) have the highest cooling potential due to their low solar heat gain potential and direct flow of the south-west comfort wind in 50% of the buildings living spaces. However, case study two (Ivy apartments) has the highest percentage of bedrooms with high nighttime cooling potential.
Apertures
All case studies adopt the use of casement windows with 0.5cm thick tinted glass
Case study one (Ivy homes)
▪ All WWRs in the spaces are within the ideal range apart from those in the main lounge and master bedroom on the east of the terraces which are tolerable. With the mean value of the ideal WWRs being 0.18 ▪ Cross ventilation is achieved in all spaces apart from the guest room and bedroom 2, while the lounges and kitchen are the only spaces with cross ventilation, some spaces do not even have any type of ventilation.
Case study two (Ivy apartments)
All WWRs are within the ideal range, with 0.17 as the average of the ideal WWR values Cross ventilation is achieved in all spaces apart from the maid's room.

Case study three (Leptons planet five)
▪ All WWRs are within the ideal range, the WWR of the bedroom from the south is the only one that is above the ideal range, while still being within the tolerable range. A mean WWR value of 0.13 being the lowest when compared to other case studies. ▪ Cross ventilation is achieved in all spaces apart from the bedroom 4 on the north and south.
Conclusion
Case study two (Ivy apartments) has a higher WWR mean value when compared to other case studies, while also having a central open space windows of equal size that facilitate ventilation in most building spaces, therefore it has the best ventilative cooling potential.
Solar Control
Case study one (Ivy homes)
▪ Shading in the form of overhangs in all directions, but being appropriate mainly for some spaces in the north and south facades, as such east and west directions do not have appropriate shading of any kind. ▪ The cantilever on the east and west facades and also the north-east and south facades in some blocks effectively shades the living spaces on that direction.
Case study two (Ivy homes)
▪ Ineffective shading in form of extrusions on all sides, although it is the appropriate type in the east and west directions, the size makes it inappropriate due to minimal depth. ▪ Roof overhangs produce moderate shading for openings and walls of the third floor.
Case study three (Leptons planet five)
▪ The sizeable opening on the north and south facades of the first floor receive moderate shading from horizontal shading elements, while other openings on the ground floor in that direction are shaded with the presence of plants in close proximity to the building openings. ▪ The east and west facades are effectively shaded by the adjacent building blocks due to 2.7 m spacing between them ▪ All spaces on the first floor experience a moderate shading by the presence of 45cm roof overhang.
Conclusion
Case study three (Leptons planet five) has the lightest building finish, as such it will reflect off the solar radiation that falls on it the most, thereby having the lowest solar heat gain potential.

Although case studies one (Ivy homes) and two (Ivy apartments) have light concrete pavements, asphalt pavements are also present, as such the surroundings of case study three (planet five) will be cooler due to the absence of dark asphalt pavements.
Exterior Surfaces as Absorbers
Case study one
▪ Light exterior finishes in form of light ash and textured burnt orange paints and ash long span aluminum roofing sheet. ▪ Outdoor surfaces made of light concrete pavements and dark asphalt paved roads.
Case study two
▪ Light exterior surface finishes in form of peach and cream paints along with cream aluminum roofing sheet. ▪ Outdoor surfaces made of light concrete pavements and dark asphalt paved roads
Case study three
▪ Light exterior surface finishes in form of white and grey along with an ash aluminum roofing sheet. ▪ Outdoor surfaces made of light concrete pavements only.
Conclusion
Case study three (Leptons planet five) has the lightest building finish in form of white and grey paints, as such its building envelope will reflect off the highest percentage of solar radiation that falls on it, thereby having the lowest solar heat gain potential. Although case studies one (Ivy homes) and case study two (Ivy apartments) have light concrete pavements, asphalt pavements are also present, therefore the surroundings of case study three (Leptons planet five) will be cooler due to the absence of dark asphalt pavements with high absorptivity.
Thermal Mass
The building envelopes in all case studies consist of common materials typically found in contemporary buildings in Abuja. However, in case study one (Ivy homes), the inclusion of reinforced concrete roof decks gives it a slightly higher thermal mass. This characteristic impedes the passive cooling in case study one (Ivy homes). As such it has the lowest cooling potential among all the case studies.

4.2 Results from Questionnaires

Results from the questionnaires are further analysed and discussed with the aim of satisfying the intended objectives related to thermal conditions and the perception of building users on certain passive cooling strategies and implementation in contemporary mutli-storey residential buildings within Abuja as shown in Appendix 1.

4.2.1 Demographic Information

Out of the 62 respondents, 40 (64.5%) were male while 22 (35.5%) were female. With 22 (35.5%) of them being within the age of 18-25, while 33 (53.2%) were within the age of 26-40 and 7 (11.3%) were within the age of 41-60 as shown in Figure 94.

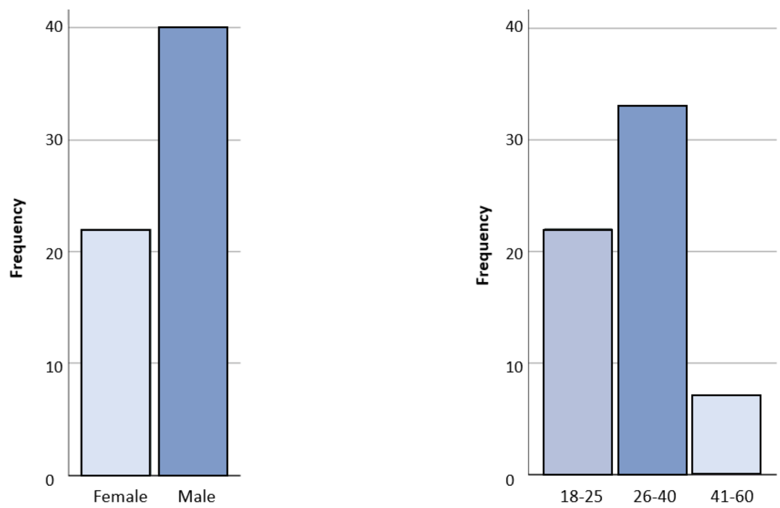
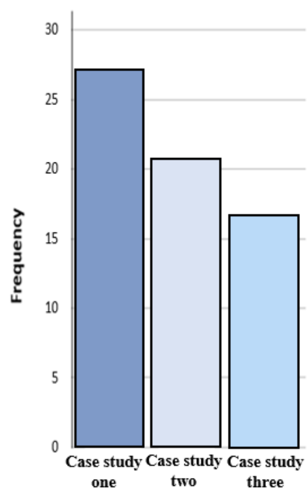


Figure 95: Distribution of the Gender and Age of Respondents

With 26 (41.9%) living in case study 1(detached buildings and terraces), 20 (32.3%) living in case study two (apartments) and 16 (25.8%) living in case study three (semi-detached buildings). It was recorded that 28 (45.2%) of the occupants have lived in the building for 1-3 years while 13(21%) and 21 (33.9%) have been occupants for 3-5 years and less than a year respectively as shown in Figure 95.



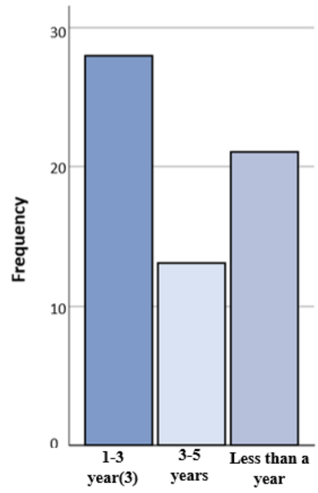


Figure 96:Distribution of Building Users and their Tenure as Occupants

4.2.2 Thermal Comfort

Various factors affecting the thermal conditions of building users were analysed and the results are discussed below.

4.2.2.1 Air Humidity

The majority of respondents considered their thermal environment to be humid in varying degrees, with 53% of them selecting the “slightly humid”, “humid” and “very humid” options. Among the different case studies, case study two (Ivy apartments) had the highest number of votes leaning towards the humid side of the scale. In this case study, 55% of the respondents reported to be classified their thermal environment as "humid" or "slightly humid," while no one considered it to be "very humid". On the other hand, case study three (leptons planet five) had the lowest percentage of humidity votes, with 50% of respondents selecting options related to humidity. This indicates that the differences between the humidity votes in all three case studies are minimal, as illustrated in Figure 96.

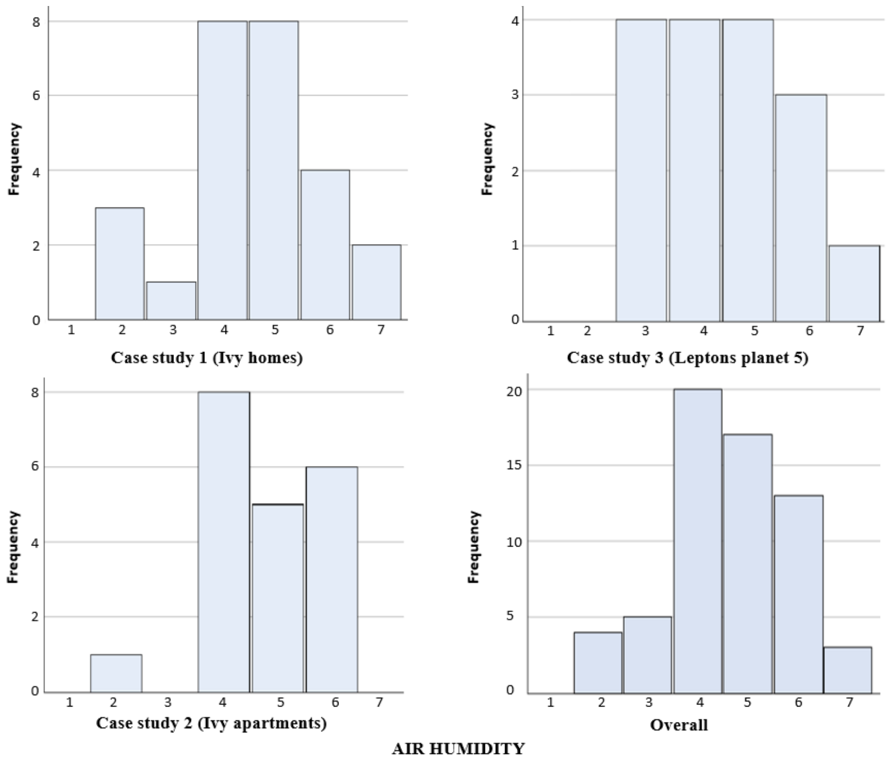


Figure 97: Distribution of Air Humidity Level across All Case Studies. (Scale: 1=very dry to 7=very humid)

4.2.2.2 Air Movement

Although the votes were averagely shared about the air movement levels, 33% of the respondents felt that the air movement was little in varying degrees. With case study one (Ivy homes) having the most respondents that voted for “slightly little” to “very little” air movement making 39% of the total votes for that category. However, case study three (leptons planet five) had the most respondents that felt the air movement was “slightly much”,” much” and “very much” with a vote of 43%, while 50% of the respondents in case study two felt neutral as shown Figure 97 below.

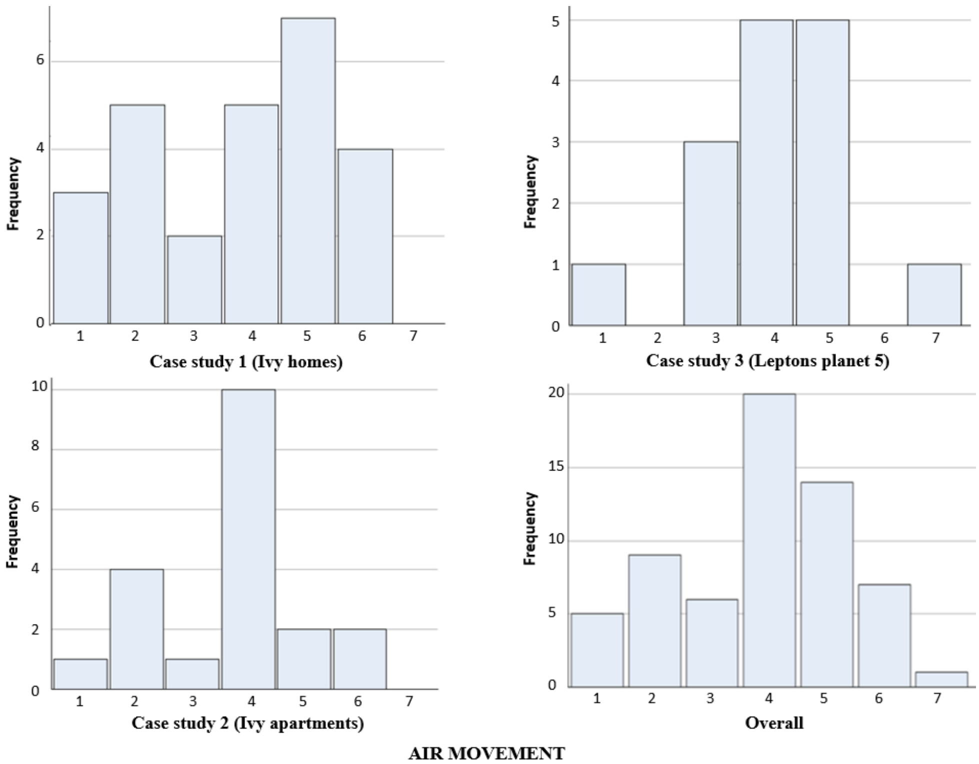


Figure 98: Distribution of Air Movement Level Votes across All Case Studies. (Scale: 1=very little to 7=very much)

4.2.2.3 Air Quality

Most respondents (60%) across the case studies classified the air quality from "slightly good" to "very good" with 70% of respondents in case study two (Ivy apartments) making up most of the vote., However, 25% of respondents in case study three (Leptons planet five) felt the air quality was stuffy which was the most across all case studies as shown in Figure 98.

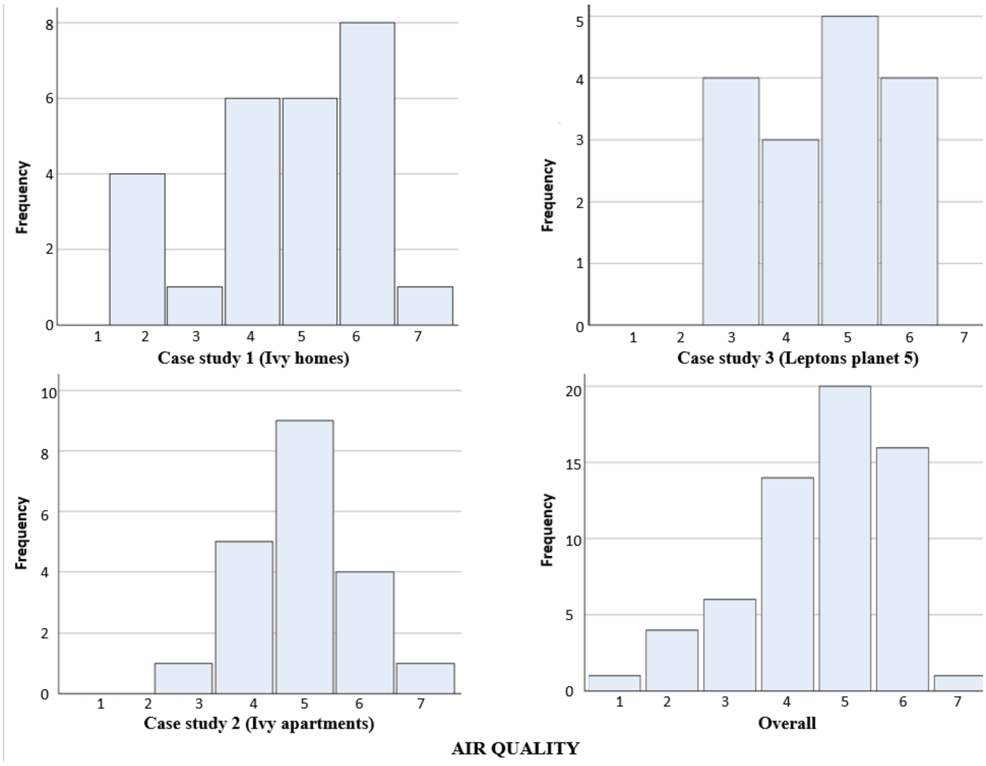


Figure 99: Distribution of Air Quality Level Votes across All Case Studies. (Scale: 1=very stuffy to 7=very good)

4.2.2.4 Air Temperature

A surprising response for air temperature levels across all case studies was recorded as most respondents (44%) felt "cool" or "slightly cool". With occupants in case study three (leptons planet five) being those that felt some level of coolness the most as 50% of them felt "cool" or "slightly cool", while respondents in case study one (Ivy homes) had the highest votes of warmth as 31% of them felt 'slightly warm' and 'warm', although no one felt 'very warm' as shown in Figure 99.

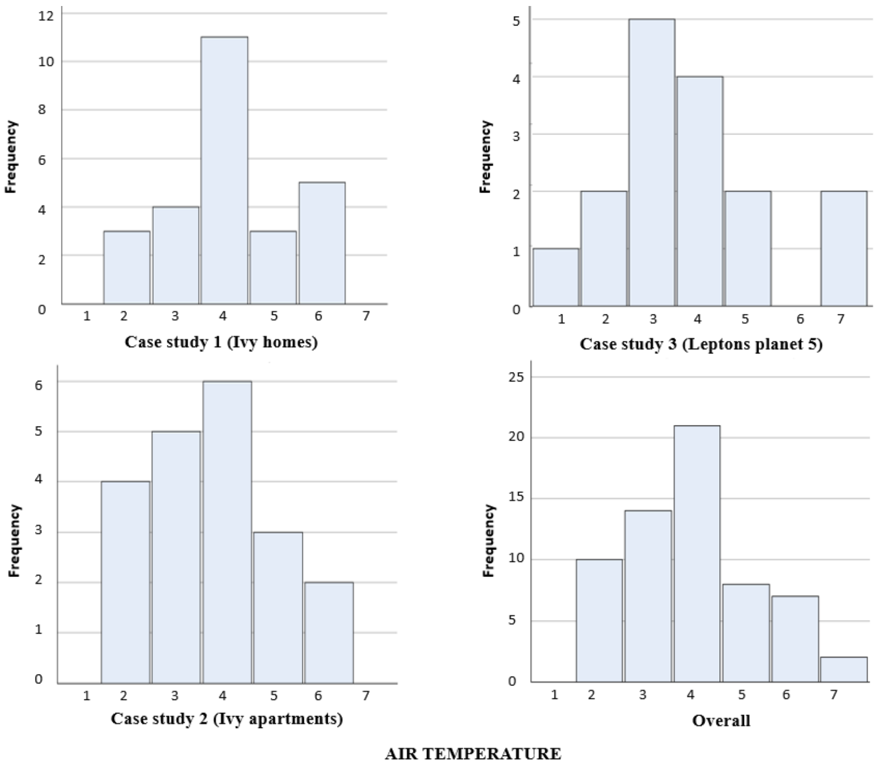


Figure 100: Distribution of Air Temperature Level Votes across All Case Studies. (Scale: 1=cold to 7=very warm)

4.2.2.5 Thermal Preference

Overall, it is seen that most of the respondents (78%) preferred their air temperature to be “slightly cooler”, “cooler” and “much cooler” with only 5% of them wanting it to be warmer, while 18% felt neutral. Although case study two (Ivy apartments) showed great cooling potential through ventilation, it has the most respondents (80%) that voted for their thermal environment to be cooler in varying degrees, this may be due to the lack the orientation of windows into consideration before placement as windows on all directions are of equal size. Case study three (Leptons planet five) recorded the lowest vote for a cooler thermal environment as shown in Figure 100.

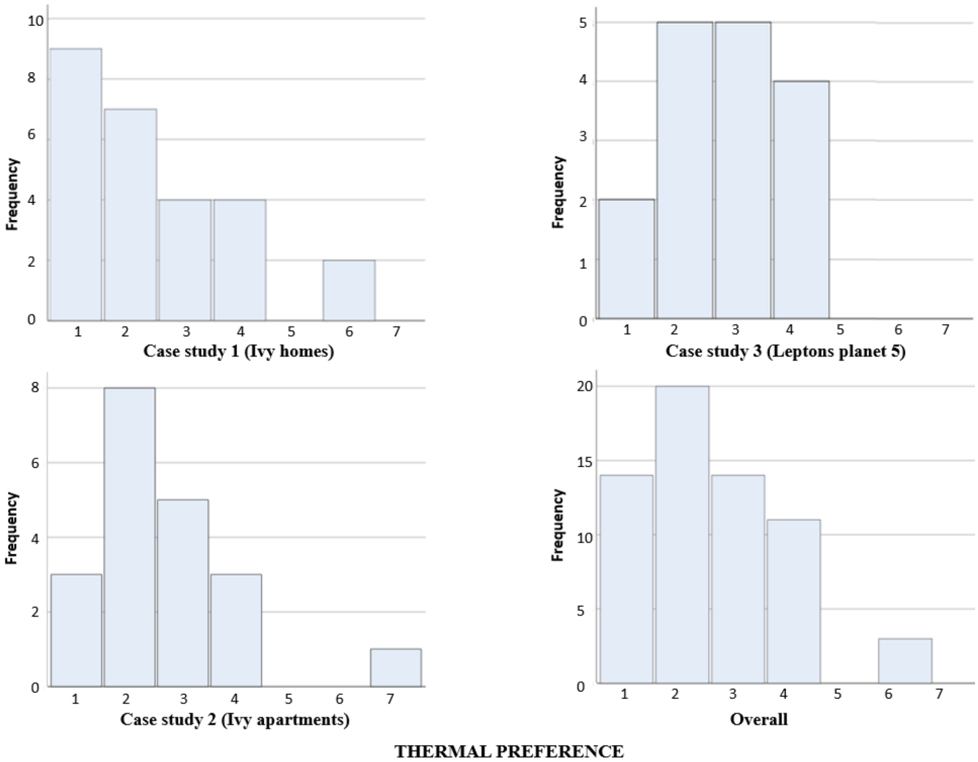


Figure 101: Distribution of Thermal Preference Votes across All Case Studies. (Scale: 1=much cooler to 7=much warmer)

4.2.2.6 Comfort Levels

Conclusively, it is seen that 58% of the respondents, who make up the majority, voted to be slightly comfortable, comfortable and very comfortable. Separately case study one (Ivy homes), two (Ivy apartments) and three (leptons planet five) had 54%, 70% and 50% of comfortable votes accordingly, with case study two (Ivy apartments) being the most comfortable. Case study one (Ivy homes) however has the highest discomfort votes with 31% of its respondents feeling uncomfortable compared to the 19% in case study two (Ivy apartments) and 17% in case study three (planet five), while the neutral votes were mainly from case study two (Ivy apartments) with 25% of the respondents feeling neutral as shown in Figure 101.

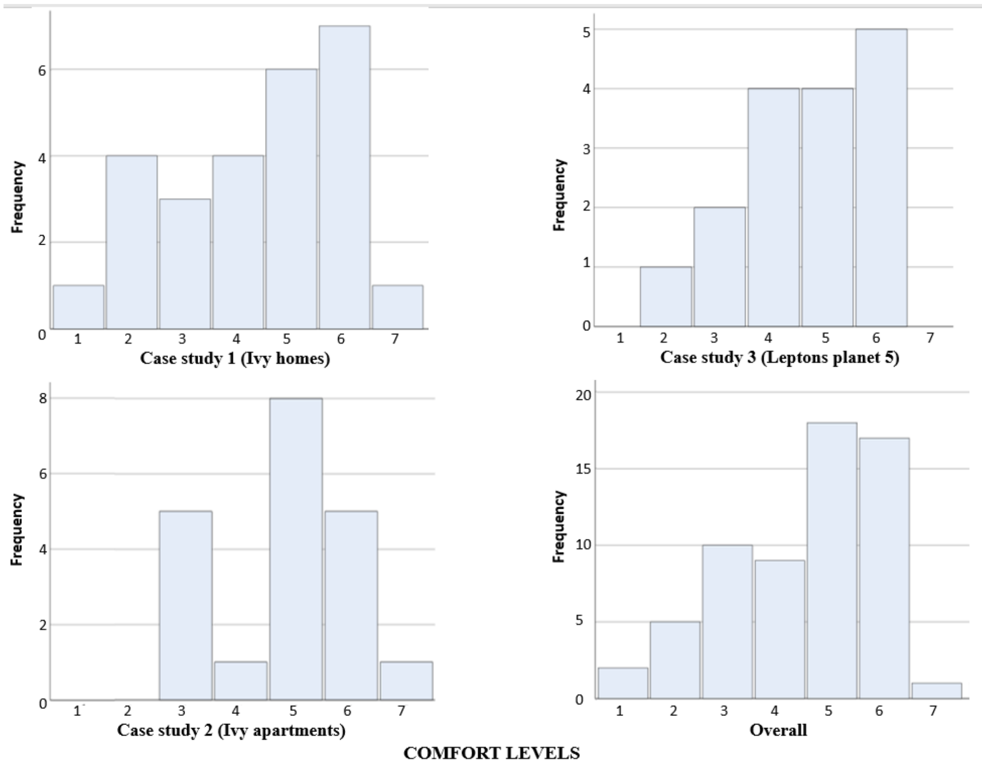


Figure 102: Summary of Respondents' Comfort Votes across All Case Studies (Scale 1=very uncomfortable to 7=very comfortable)

4.2.2.7 Controls

It can be concluded that respondents use a variety of controls, with some even using multiple options simultaneously. However, it is evident that air conditioning (A/C) is the most popular choice, as 81% of respondents reported using it. This high adoption rate may be attributed to the perceived effectiveness of A/C. On the other hand, fans and windows were used at similar levels by the respondents. Personal clothing items and multiple showers were found to be less commonly utilized options.

The data revealed that approximately a substantial number of the respondents utilized mechanical cooling methods such as air conditioners (A/Cs) and fans. This indicates a significant reliance on mechanical cooling systems to achieve comfort. Additionally, it can be inferred that windows were the most commonly employed passive cooling strategy among respondents as shown in Figure 93.

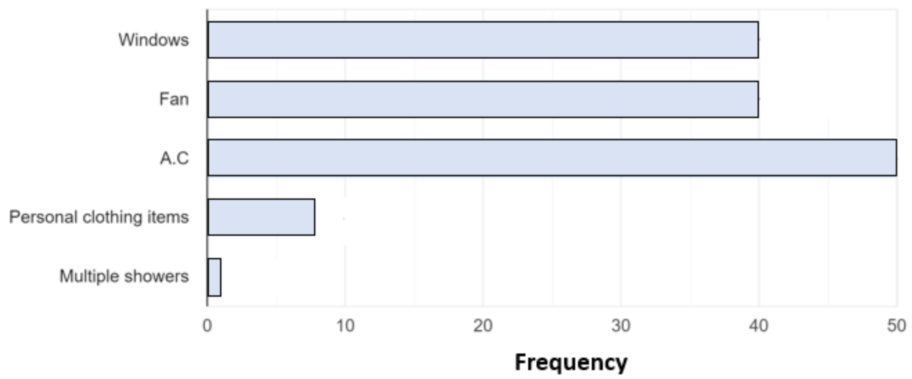


Figure 103: Distribution of Respondents' Overall Use of Controls across All Case Studies

A majority of the respondents, accounting for 65% of the votes on the scale, indicated a significant level of reliance on controls to achieve comfort. Specifically, 26% of the respondents reported using controls to a moderate extent ("slightly much"), while only 21% expressed a lower level of reliance ("slightly little" to "very little"), as shown in Figure 103(a).

Figure 103(b) and 103(c) show that the use of controls is most prevalent during the afternoon and the dry season, with 46% and 71% of respondents respectively indicating their usage during those times, compared to other parts of the day and the rainy season. Notably, no respondent reported using controls the most in the morning.

According to Figure 103(d), the air conditioning (A/C) system was found to be the most commonly utilized control option, with about 52% of respondents reporting its frequent use. This high adoption rate can be attributed to the A/C's perceived effectiveness in enhancing the comfort levels of building users. Surprisingly, adjusting clothing items received the least votes, with only 14% of respondents choosing this option. This unexpected finding contradicts the assumption that adjusting clothing would be used more frequently due to its perceived effectiveness and ease in achieving comfort.

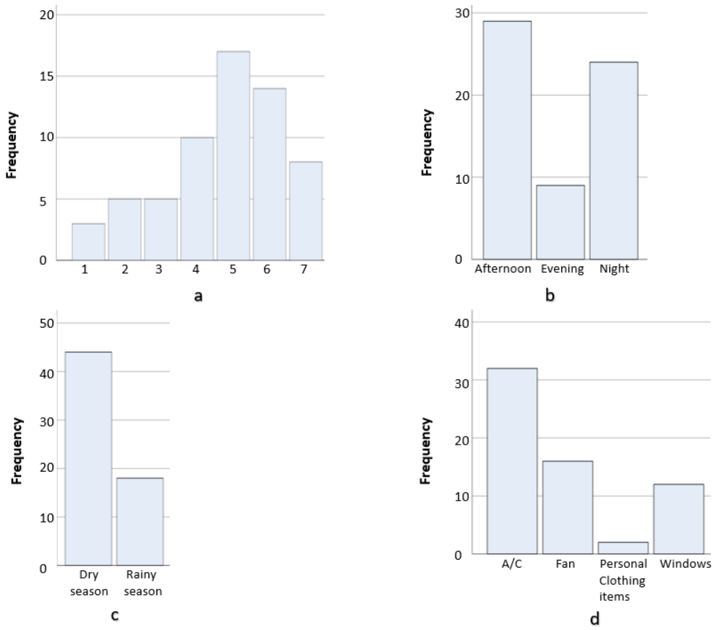


Figure 104: Distribution of Respondents' Overall Use of Controls across All Case Studies

4.2.3 Passive Cooling

The objective of assessing the level of awareness among respondents was to ascertain whether a lack of knowledge could be a contributing factor to their relatively low demand for passive cooling solutions. While further questions aimed at assessing how effective the implemented strategies are from the view of the building users and also their level of satisfaction with the adopted strategies.

4.2.3.1 Level of Awareness

It was recorded that most of the respondents (34%) across all case studies only had a basic knowledge of passive cooling, while 27% of respondents have never heard of it, only 19% of the respondents have a good knowledge of passive cooling, as shown in Figure 104. Out of which most might be professionals in the construction industry, this shows that a slight number of respondents have little to no knowledge of the subject and that might be a reason why there is a low demand for this cooling approach in buildings. However, a significant number of individuals possess the necessary knowledge to effectively implement these strategies within their buildings, this is particularly true for professionals who are more likely to be knowledgeable and capable.

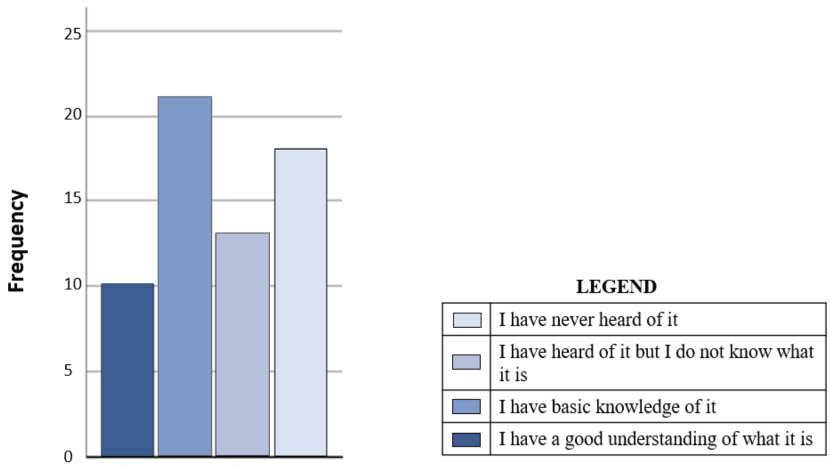


Figure 105: Distribution of Passive Cooling Level of Awareness Votes across All Case Studies

4.2.3.2 Level of Effectiveness

Based on the occupants' responses, the most effective cooling strategy identified in the case study one (Ivy apartments) is the use of windows, with 100% of the respondents considering it effective. On the other hand, the use of light exterior building finishes was perceived as the least effective strategy, with only 73% of respondents considering it effective, as shown in Figure 105.

The most effective passive cooling strategy in case study two (Ivy apartments) based on the response votes of the occupants is the building orientation with 100% votes agreeing to that, however with the prior analysis in chapter three, it suggests that the building occupants might have little to no knowledge on how their building orientation aids or impedes cooling within building spaces as the longer sides of the building is facing the east and west directions while being ineffectively shaded. It is therefore not expected to contribute positively. Shading was perceived to be the least effective strategy, having the lowest efficiency vote of 70% as shown in Figure 96.

With 100% of the respondents considering windows in case study three (Leptons planet five) effective it remains the most effective strategy, while the use of light exterior finishes was perceived as the least effective strategy in this case study, with only 56% of the respondents considering it effective.

Across all case studies, it is recorded that the most effective passive cooling strategy is through the use of windows as 97% of the respondents considered it effective as shown in table 18. In contrast, the use of light building exterior finishes was deemed the least effective passive cooling strategy across all case studies, with only 71% of the respondents considering it effective, as shown in Figure 105.

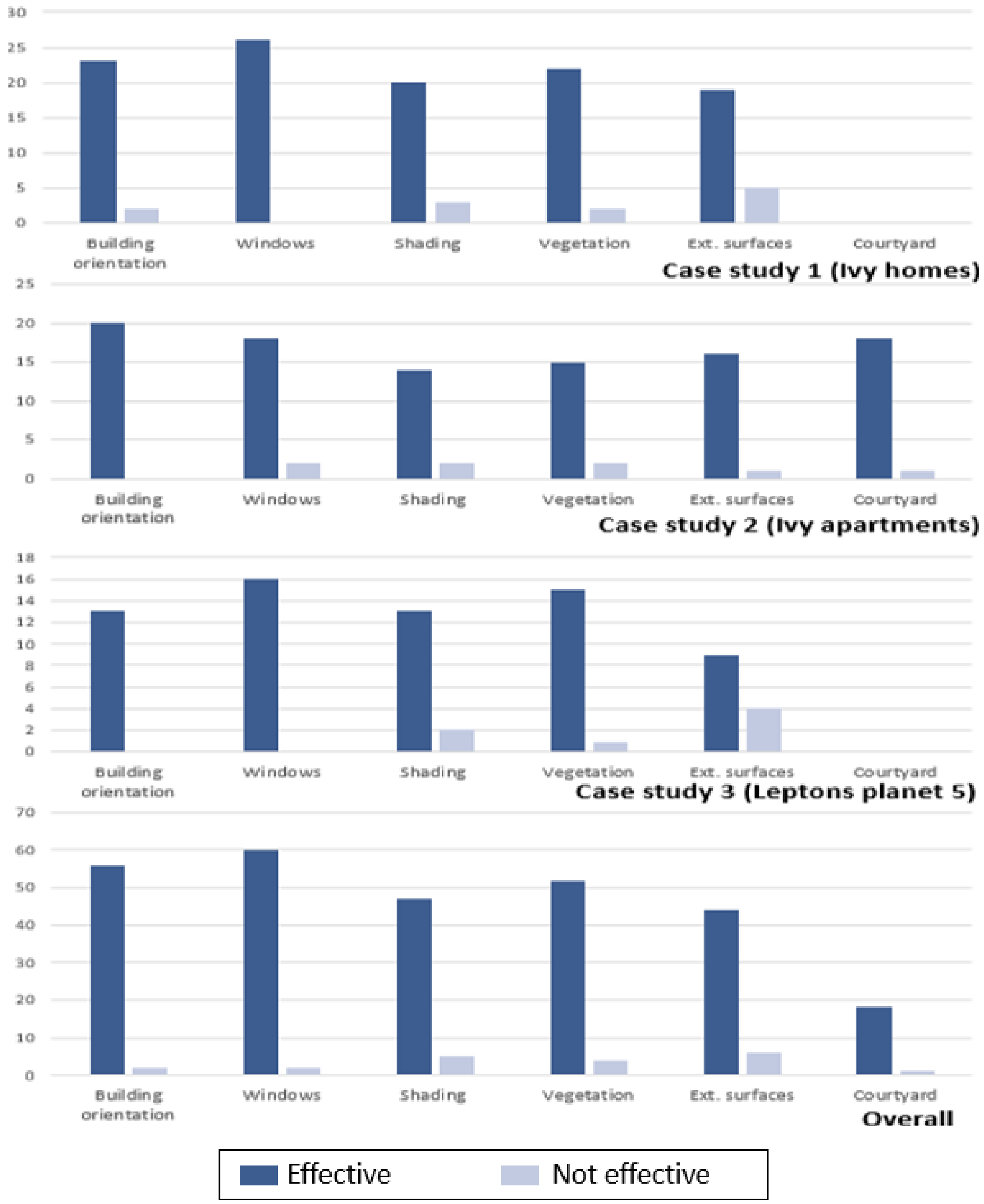


Figure 106: Distribution of the Level of Effectiveness of Respective Passive Cooling Strategies across All Case Studies

4.2.3.3 Need for Improvements

Respondents in case study one (Ivy homes) voted that the vegetation around the site was the strategy that needed to be improved upon the most where 77% of them voted for that, accordingly the building orientation and shading were the next in line of strategies that needed to be improved upon with a vote of 58% and 54% respectively.

All of which are strategies that have had their shortcomings highlighted in the analysis done in chapter three, as such these two findings are simultaneous to each other.

45% of the respondents in Case study two (Ivy apartments) voted that both the shading and courtyard design in their buildings needed to be improved, while 40% of the users felt that the building orientation also needed to be improved, which may have been as a result of the effect of the longer side of the building facing the east and west axis.

Although the window configurations in case study three (Leptons planet five) were seen to be appropriate, they also had the lowest WWR mean value based on the prior analysis, as a result, 50% of the respondents voted that they needed to be improved, this supports the finding deduced from the physical observation, and makes it the strategy with the highest votes to be improved on in the case study.

Generally, it was seen that the strategies had similar votes in the need for improvement, while the exterior finishes serving as absorbers, spacing between buildings and humidity reduction are strategies that have the low need for improvement according to the votes as seen in Figure 106.

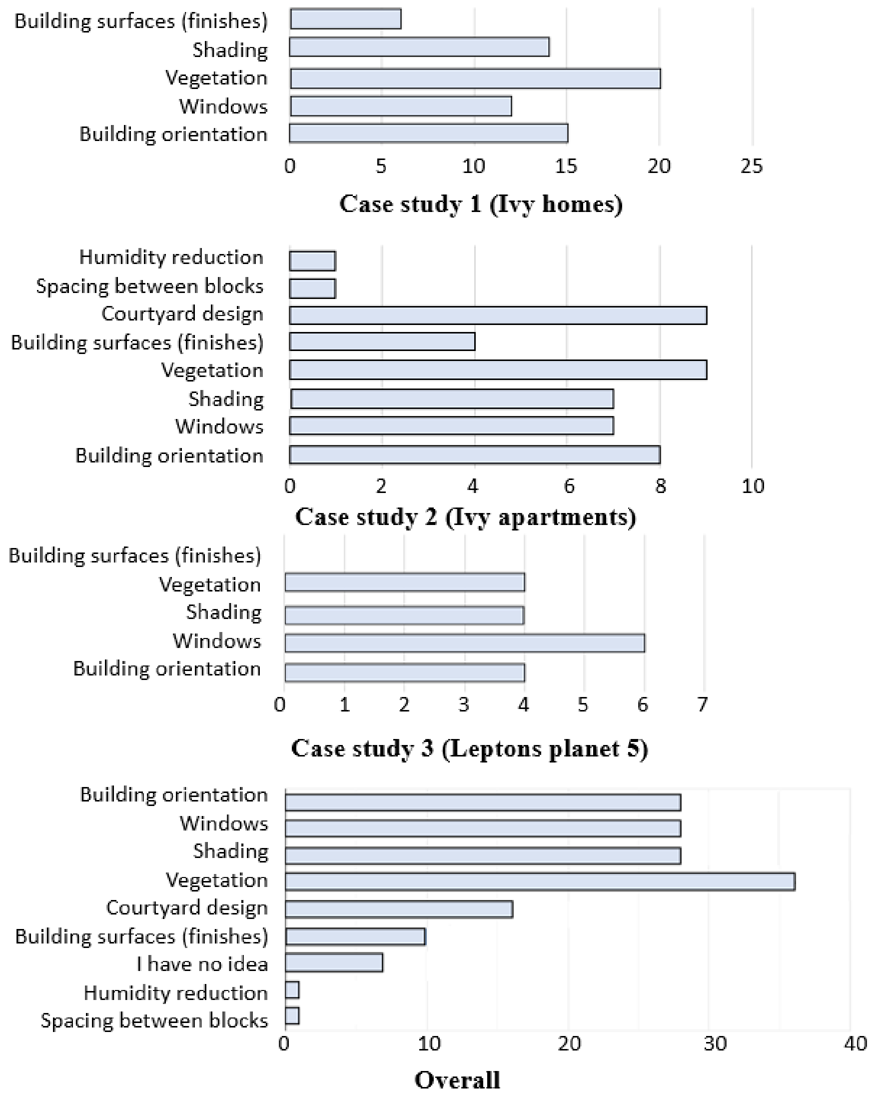


Figure 107: Distribution of The Need for Improvement Votes by Respondents across All Case Studies.

4.2.3.4 Future Implementation

A significant proportion of the respondents (77%) expressed their willingness to implement more passive cooling strategies in their buildings in the future. Among the various options, the most preferred strategy was adopting building materials with appropriate thermal mass, receiving 56% of the votes in support. The second most preferred strategy was cool roof with 47% votes in support. However, strategies such as fountains and courtyards received lower implementation votes, as shown in Figure 107.

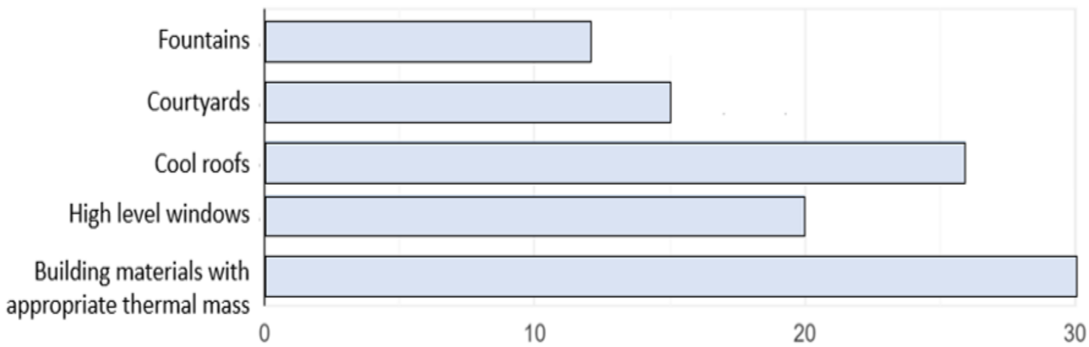


Figure 108: Distribution of Preferred Strategies for Future Implementation

4.2.3.5 Drivers and Barriers

In order to evaluate to what extent certain factors, promote or inhibit the adoption of passive cooling strategies, respondents were asked to rate the influence of the benefits and drawbacks accordingly.

It was recorded that their potential of improving the thermal comfort within buildings was the most influential benefit that will encourage respondents to adopt the strategies according to 61% of the respondents. While other factors had lesser votes in the "much" and "very much" categories as shown in Figure 108.

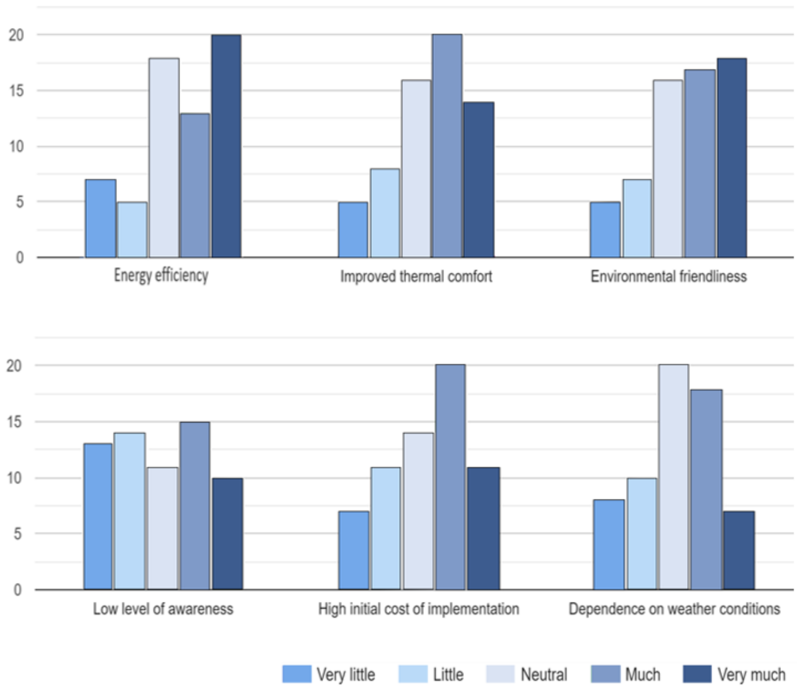


Figure 109: Distribution of the Influence of the Benefits of Passive Cooling on its Adoption in Buildings

It was recorded that the drawback that had the highest influence in inhibiting the adoption of passive cooling strategies was the high initial implementation cost according to 51% of the respondents, which is often the case in the implementation of advanced strategies like green roofs, while other drawbacks had lesser votes in the “much” and “very much categories as shown in Figure 108.

Chapter 5

CONCLUSION

This chapter highlights the summary and conclusions drawn from the research study, presenting the main findings that will serve as responses to the research questions outlined in chapter 1. In light of these research findings, essential recommendations to ensure the full realization of the potential of passive cooling strategies was also discussed, as well as additional measures that can be adopted in order to achieve the desired level of comfort in residential buildings within Abuja.

The research was conducted with the proposition that passive cooling strategies could enhance the thermal comfort of residents in Abuja's residential buildings. Therefore, the study centred on the application of these strategies in mid-rise residential buildings within Abuja, aiming to assess their capability to enhance occupants' thermal comfort. Additionally, the study examined the comfort levels and the efficiency of the existing strategies through the administration of questionnaires and analysis of three case studies with different building typologies.

A review of five passive cooling strategies within the context of hot-humid climate zones like Abuja was conducted, these strategies include: Ventilative cooling, nocturnal cooling, radiative cooling, evaporative cooling and earth coupling.

During the study, it was observed that the passive cooling strategies adopted within the selected case studies include:

- Ventilative Cooling: Which was the most prominent strategy. It was implemented through the use of suitable building orientation, layout of spaces, provision of courtyards and window placement and sizes. Furthermore, the use of windows that conformed with the prescribed window-to-wall ratios (WWRs) standard provided sufficient airflow.

  In certain building sections where the building forms were not compact and with sufficient spacing between them, air circulation within and between the buildings was also enhanced. The orientation and the layout of spaces also facilitated nocturnal cooling.
- Evaporative Cooling: The inclusion of plants and greenery in the outdoor areas of the buildings contributed in modifying the micro-climate of the buildings.
- Heat gain prevention which is vital for maintaining a comfortable temperature, was accomplished by the optimal distribution of spaces and implementing various forms of solar control. Furthermore, selecting light exterior building surfaces and utilizing suitable thermal mass also played a role in achieving this goal.

Across all case studies, it was recorded that the most effective passive cooling strategy was through the use of windows as 97% of the respondents considered it effective, 90% of the respondents considered the courtyard and adoption of appropriate orientation to be effective while the vegetation around the site was considered to be effective by 84% of the respondents. Shading and the use of light building exterior surfaces were strategies that were considered to be not very effective with 76% and 71% of the respondents considering them effective respectively.

So, it can be concluded that the strategies applied in the case studies are generally effective. Nevertheless, certain approaches, such as vegetation and courtyard features, received substantial votes for enhancement, with approximately 50% and 45% of the survey participants expressing the need for improvements in these areas. While all the analysed strategies are deemed to be effective within the study area, the incorporation of evaporative cooling through vegetation presents a challenge by potentially increasing the moisture content in the surroundings. Without effective methods to diminish this moisture content, this approach is deemed imperfect. Although certain strategies were implemented.

Even with the effectiveness levels of most strategies, with further analysis carried out within this research and some in the past show and support that the use of passive strategies alone will not produce the desired level of comfort within thermal environments of houses in Abuja.

Given that around 80% of survey participants depend on air conditioners for indoor comfort, and considering the lack of dehumidification strategies in the examined cases beyond ventilation, utilizing renewable energy sources to power active cooling and dehumidification methods emerges as a highly effective approach for achieving sustainability and comfort. In Nigeria, various options such as solar panels, wind, geothermal energy through heat pumps, and hydropower are viable. However, the considerable abundance of solar energy in Abuja for a significant part of the year makes it the most suitable choice, particularly because residents have shown a strong preference for it, positioning it as the primary alternative to fossil fuel-generated electricity. While there is potential to explore geothermal energy in Abuja, it remains underutilized at present. Consequently, conducting further research in these areas could help alleviate the excessive exploitation of natural resources, addressing their depletion while also contributing to the mitigation of climate change—a crucial global concern.

Moreover, the implementation of roof vents, fans, and blowers can facilitate forced ventilation to enhance both ventilation and dehumidification. Additionally, exploring further dehumidification strategies involves the utilization of desiccants, such as hygroscopic materials capable of absorbing moisture, as well as cooling coils and condensation humidifiers, among other methods.

It was seen that 58% of the respondents voted to be “slightly comfortable”, “comfortable” and “very comfortable”, however this is below the recommendation set by the ASHRAE standard as a building is considered comfortable only if at least 80% of the respondents are comfortable. The ASHRAE standard was used as a benchmark in the absence of other standards that are fully created or heavily consider hot-humid climates like Abuja.

Although the percentage was below the recommendation, a thorough examination of the responses unveiled an unexpected degree of contentment among the participants. This deferred with the findings from the physical observations and analysis, underscoring the subjective nature of the questionnaire's evaluation of comfort, especially when accounting for diverse climatic zones, social backgrounds, and status. It also emphasizes on the importance of establishing distinct standards tailored to a specific location, as the existing benchmarks were not specifically designed for Abuja or Nigeria as a whole.

While a significant number of respondents expressed their willingness to adopt these strategies in the future, it remains crucial to ensure the actual implementation of the strategies is done. To achieve this, professional organizations such as the Nigerian Institute of Architects (NIA) and the Nigerian Green Building Council (NGBC) should take the lead in developing building codes and standards. For those standards that have not been officially established, research results can serve as a valuable guide. Furthermore, regulatory bodies like the Federal Housing Authority should consider delaying design approvals until designers adhere to these standards.

Architects should take additional steps to educate their clients about the benefits of these approaches and ensure that their designs align with them. Meanwhile, developers should consistently bear in mind that prioritizing cost savings and profits should never supersede the comfort of their clients. They can also collaborate closely with researchers to determine the comfort levels of their occupants and explore ways to enhance them. It's also important for clients to keep in mind that heeding to the advice of professionals can prevent numerous problems they may be unaware of.

This research serves as a foundation for creating a more sustainable and comfortable living environment in Abuja, ultimately contributing to the region's energy efficiency and environmental sustainability goals.

Further research areas should include exploring more passive and active strategies that can enhance the current methods for achieving cooling and dehumidification in buildings within the specified study area. Particular interest should be given on dehumidification due to its critical importance in hot-humid climates and the comparatively limited research on it. It is also crucial to investigate new and suitable renewable resources to be harnessed in Abuja.

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APPENDICES

Appendix 1: Results from Questionnaires

Table A: Respondents Demographic Information

Gender				**Age**					
Male		Female		18-25		26-40		41-60	
N	%	N	%	N	%	N	%	N	%
40	65	22	36	22	36	33	53	7	11

Table B: Summary of Respondents' Location and Duration of Occupancy

Respondents						**Occupancy duration**					
Case study one		Case study two		Case study three		Less than a year		1-3 years		4-6 years	
N	%	N	%	N	%	N	%	N	%	N	%
26	42	20	32	16	26	13	21	28	45	21	34

Table C: Summary of Respondents' Air Humidity Levels across All Case Studies

		Case study one		**Case study two**		**Case study three**		**Overall**	
Air Humidity		N	%	N	%	N	%	N	%
	Very dry	0	0	0	0	0	0	0	0
	Dry	3	12	1	5	0	0	4	7
	Slightly dry	1	4	0	0	4	25	5	8
	Neutral	8	31	8	40	4	25	20	32
	Slightly humid	8	31	5	25	4	25	17	27
	Humid	4	15	6	30	3	19	13	21
	Very humid	2	8	0	0	1	6	3	5

Table D: Summary of Respondents' Air Movement Levels across All Case Studies

		Case study one		**Case study two**		**Case study three**		**Overall**	
Air Movement		N	%	N	%	N	%	N	%
	Very little	3	12	1	5	1	6	5	8
	Little	5	19	4	20	0	0	9	15
	Slightly little	2	8	1	5	3	19	6	10
	Neutral	5	19	10	50	5	31	20	32
	Slightly much	7	27	2	10	5	31	14	23
	Much	4	15	2	10	1	6	7	11

	Very much	0	0	0	0	1	6	1	2

Table E: Summary of Respondents' Air Quality across All Case Studies

		Case study one		**Case study two**		**Case study three**		**Overall**	
Air quality		N	%	N	%	N	%	N	%
	Very stuffy	0	0	0	0	0	0	1	2
	Stuffy	4	15	0	0	0	0	4	7
	Slightly stuffy	1	4	1	5	4	25	6	10
	Neutral	6	23	5	25	3	19	14	23
	Slightly good	6	23	9	45	5	31	20	32
	Good	8	31	4	20	4	25	16	26
	Very good	1	4	1	5	0	0	1	2

Table F: Summary of Respondents' Thermal Sensation across All Case Studies

		Case study one		**Case study two**		**Case study three**		**Overall**	
Air temp/ Thermal sensation		N	%	N	%	N	%	N	%
	Cold	0	0	1	6	0	0	0	6
	Cool	3	12	2	13	4	20	10	16
	Slightly cool	4	15	5	31	5	25	14	22
	Neutral	11	42	4	25	6	30	21	33
	Slightly warm	3	12	2	13	3	15	8	13
	Warm	5	19	0	0	2	10	7	11
	Very warm	0	0	2	13	0	0	2	3

Table G: Summary of Respondents' Thermal Preference Votes Across All Case Studies

		Case study one		**Case study two**		**Case study three**		**Overall**	
Thermal preference		N	%	N	%	N	%	N	%
	Much cooler	9	35	3	15	2	13	14	23
	Cooler	7	27	8	40	5	31	20	32
	Slightly cooler	4	15	5	25	5	31	14	23
	Neutral	4	15	3	15	4	25	11	18
	Slightly warmer	0	0	0	0	0	0	0	0

	Warmer	2	8	1	5	0	0	1	5
	Much warmer	0	0	0	0	0	0	0	0

Table H: Summary of Respondents' Comfort Level Votes across All Case Studies

		Case study one		**Case study two**		**Case study three**		**Overall**	
Comfort Levels		N	%	N	%	N	%	N	%
	Very uncomf.	1	4	0	0	0	0	2	3
	Uncomf.	4	15	0	0	1	6	5	8
	Slightly uncomf.	3	12	5	25	2	13	10	16
	Neutral	4	15	1	5	4	25	9	15
	Slightly comf.	6	23	8	40	4	25	18	29
	Comf.	7	27	5	25	5	25	17	27
	Very comf.	1	4	1	5	0	0	1	2

Table I: Summary of the Frequency of Use of Controls Used by Respondents to Achieve Comfort

Windows		**Fan**		**A/C**		**Personal clothing items**		**Multiple showers**	
N	%	N	%	N	%	N	%	N	%
42	68	42	68	49	73	10	16	1	2

Table J: Summary of Respondents' Use of Controls

Very little		**Little**		**Slightly little**		**Neutral**		**Slightly much**		**Much**		**Very much**	
N	%	N	%	N	%	N	%	N	%	N	%	N	%
3	5	4	7	6	10	8	13	16	26	14	23	11	18

Table K: Summary of the Time Controls are Used the Most

Morning		**Afternoon**		**Night**	
N	%	N	%	N	%
9	15	29	46	24	39

Table L: Summary of the Season Controls are Used the Most

Dry season		**Rainy season**	
N	%	N	%
44	71	18	29

Table M: Summary of Respondents' Awareness Levels across All Case Studies

	N	%
I have never heard of it	17	28
I have heard of it but I do not know what it is	12	19
I have basic knowledge of it	21	34
I have a good understanding of what it is	12	19

Table N: Summary of the Level of Effectiveness of Respective Passive Cooling Strategies in Case Study One and Two According to Respondents' Votes

	Case study one				**Case study two**			
	Effective		Not effective		Effective		Not effective	
Strategies	N	%	N	%	N	%	N	%
Building orientation	23	88	2	8	20	100	0	0
Windows	26	100	0	0	18	90	2	10
Shading	20	77	3	12	14	70	2	10
Vegetation	22	85	2	8	15	75	2	10
Ext. surfaces	19	73	5	19	16	80	1	5
Courtyard	-		-	-	18	90	1	5

Table O: Summary of the Level of Effectiveness of Respective Passive Cooling Strategies across All Case Studies according to Respondents' Votes

	Case study three				**Overall**			
	Very effective		Not effective		Very effective		Not effective	
Strategies	N	%	N	%	N	%	N	%
Building orientation	13	81	0	0	56	90	2	3
Windows	16	100	0	0	60	97	2	3
Shading	13	81	2	13	47	76	5	8
Vegetation	15	94	1	6	52	84	4	7
Ext. surfaces	9	56	4	25	44	71	6	10
Courtyard	-	-	-	-	18	90	1	5

Table P: Summary of the Need for Improvement Votes across all Case Studies

	Case study one		**Case study two**		**Case study three**		**Overall**	
Strategies	N	%	N	%	N	%	N	%

Building orientation	15	58	8	40	4	25	27	44
Windows	12	46	7	35	8	50	25	40
Vegetation	20	77	7	35	4	25	31	50
Shading	14	54	9	45	4	25	27	44
Finishes	6	23	4	20	0	0	10	16
Courtyard design	0	0	9	45	0	0	9	45
Adequate spacing between blocks	0	0	0	0	1	5	1	5
Humidity reduction	0	0	0	0	1	5	1	5

Table Q: Summary of Preferred Strategies for Future Adoption

Strategies	N	%
Fountains	13	23
Courtyards	16	28
Cool roofs	27	47
Green roofs	23	40
High level windows	22	39
Building materials with good thermal mass	32	56

Table R: Summary of Respondents' Votes on the Extent Some Benefits May have on Encouraging them to Adopt Passive Cooling Strategies

	Very little		Little		Neutral		Much		Very much	
Benefits	N	%	N	%	N	%	N	%	N	%
Energy efficiency	7	11	4	7	18	29	12	19	21	34
Improved thermal comfort	4	7	8	13	15	21	23	37	15	24
Environmental friendliness	6	10	7	11	14	23	16	26	19	31

Table S: Summary of Respondents' Votes on The Extent Some Drawbacks May have on Discouraging them from the Adoption of Passive Cooling Strategies

Drawbacks	Very little		Little		Neutral		Much		Very much	
	N	%	N	%	N	%	N	%	N	%
Low awareness	11	18	14	23	12	19	15	24	10	16
High initial implementation cost	5	8	18	11	14	23	20	32	12	19
Dependence on weather condition	6	10	10	16	20	32	18	29	8	13

Appendix 2: Questionnaire

The Use of Passive Cooling Strategies To Improve The Thermal Comfort Of Contemporary Mid-rise Residential Buildings In Abuja, Nigeria.

Dear respondent, you are invited to participate in this survey, which is designed to collect data for an ongoing Masters thesis research with the aim of assessing the existing and future potential of passive cooling strategies in improving the thermal comfort of contemporary mid-rise residential buildings within Abuja.
Participating in this survey is voluntary, therefore if at any point you wish to withdraw from being part of this survey, you may terminate it or contact the researcher to exclude your response. Your responses along with other details obtained will be used for academic purposes only.

You can contact the researcher via:
Phone: +905338537310
Email: 22501319@emu.edu.tr
Name of researcher: Abida Ibrahim Umar Signature: ______________
Name of Volunteer: ______________________ Signature:_______________

Would you like to proceed with this survey?

☐ Yes

☐ No

BACKGROUND INFORMATION

Kindly select the appropriate responses

1. Gender

☐ Male

☐ Female

2.Age

☐ 18-25

☐ 26-40

☐ 41-60

☐ 61 and above

3.What is your building type?

☐ Detached

☐ Semi-detached

☐ Terrace

☐ Apartments (Block of flats)

4. How long have you been an occupant of this building?

☐ Less than a year

☐ 1-3 years

☐ 3-5 years

☐ More than 5 years

THERMAL COMFORT

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

☐ Very dry

☐ Slightly dry

☐ Dry

☐ Neutral

☐ Slightly humid

☐ Humid

☐ Very humid

6.How do you feel about the air movement (ventilation) at this moment?

☐ Very little

☐ Little

☐ Slightly little

☐ Neutral

☐ Slightly much

☐ Much

☐ Very much

7. How do you feel about the general air quality at this moment?

☐ Very stuffy

☐ Stuffy

☐ Slightly stuffy

☐ Neutral

☐ Slightly good

☐ Good

☐ Very good

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

☐ Cold

☐ Cool

☐ Slightly cool

☐ Neutral

☐ Slightly warm

☐ Warm

☐ Very warm

9. How would you prefer the temperature at this moment?

☐ Much cooler

☐ Cooler

☐ Slightly cooler

☐ Neutral

☐ Slightly warmer

☐ Warmer

☐ Much warmer

10. How would you rate your comfort level at this moment?

☐ Very uncomfortable

☐ Uncomfortable

☐ Slightly uncomfortable

☐ Neutral

☐ Slightly comfortable

☐ Comfortable

☐ Very comfortable

11. Which of the following option(s) do you personally use or adjust to achieve comfort in your indoor space?

You may select more than one option

○ Windows

○ Fan

○ A.C

○ Personal clothing items

○ Others: ________________________________

12. How often do you use or adjust the option(s) you selected in 11?

☐ Very little

☐ Little

☐ Slightly little

☐ Neutral

☐ Slightly much

☐ Much

☐ Very much

13. What is your most preferred option to use or adjust in order to achieve comfort in terms of efficiency?

☐ Windows

☐ Fan

☐ A/C

☐ Personal clothing items

☐ Other: ______________________________

14. At what time of the day do you use or adjust the option(s) the most?

☐ Morning

☐ Afternoon

☐ Evening

☐ Night

15. During which season do you use the option(s) the most?

☐ Dry season

☐ Rainy season

PASSIVE COOLING

16. What is your level of awareness on passive cooling in buildings?

☐ I have never heard of it

☐ I have heard of it but I do not know what it is

☐ I have basic knowledge of it

☐ I have a good understanding of what it is

17. How effective do you think these strategies are in keeping your building cool?

Mark only one square per row

	Very effective	Moderate	Not effective	I have no idea	Not used in my building
Building orientation	☐	☐	☐	☐	☐
Windows	☐	☐	☐	☐	☐
Shading devices	☐	☐	☐	☐	☐
Vegetation	☐	☐	☐	☐	☐
Courtyard	☐	☐	☐	☐	☐
Light building finishes	☐	☐	☐	☐	☐

18. Which of the strategies below do you think need to be improved upon to promote passive cooling in your building

Check all that apply

○ Building orientation

○ Windows

○ Shading devices

○ Vegetation

○ Courtyard

○ Building surfaces

○ I have no idea

○ Others: ______________________________

19. Would you like additional passive cooling strategies to be adopted in your residential building in the future?

☐ Yes

☐ No

☐ Maybe

20. If yes, pick your preferred strategies

Check all that apply

○ Fountains

○ Courtyards

○ Cool roofs

○ High-level windows

○ Building materials with appropriate thermal insulation

○ Other: ______________________________

21. Rate how the benefits below may motivate you in adopting passive cooling strategies in your residential building

Mark only one square per row

	Very little	Little	Neutral	Much	Very much
Energy saving	☐	☐	☐	☐	☐
Improved thermal comfort	☐	☐	☐	☐	☐
Environmental friendliness	☐	☐	☐	☐	☐

22. Rate how the drawbacks below may discourage you from adopting passive cooling strategies in your residential building

Mark only one square per row

	Very little	Little	Neutral	Much	Very much
Low level of awareness	☐	☐	☐	☐	☐
High initial cost of implementation	☐	☐	☐	☐	☐
Dependence on weather conditions	☐	☐	☐	☐	☐